MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(Autonomous Institution – UGC, Govt. of India)

Recognized under 2(f) and 12 (B) of UGC ACT 1956

(Affiliated to JNTUH, Hyderabad, Approved by AICTE - Accredited by NBA & NAAC –‘A’ Grade - ISO 9001:2015 Certified)

Maisammaguda, Dhulapally (Post Via. Kompally), Secunderabad – 500100, TelanganaState, India

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

DIGITAL NOTES for ELECTRICAL & HYBRID VEHICLES

(R18AO227)

For

B.Tech (EEE) – IV YEAR – II SEMESTER

Prepared by

K.SRAVAN KUMAR

Assistant Professor

MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY

IV B.Tech EEE II SEM **L T/P/D C**

3 -/ - / - 3

(CORE ELECTIVE - VI)

(R18A0231) ELECTRICAL AND HYBRID VEHICLES

COURSE OBJECTIVES:

- To understand the basic working and characteristic performance of EHV & PHEVs.
- To study and understand the basic functioning of both Electric and Hybrid vehicles and the drive traintopologies.
- To study in detail electric propulsion systems, types of motors in Electric vehicles.
- To understand the different concepts of charging related to both EHV & PHEV operation & energymanagement.
- To study and understand different possible energy storage systems for both EHV & PHEV

UNIT 1:

INTRODUCTION TO EV: History of hybrid and electric vehicles, social and environmental importance of hybrid and electric vehicles, Classification of EV.

ARCHITECTURE OF HEV: Series HEV, Parallel HEV and Series-Parallel HEV, Power flow control inhybrid drive train topologies: Series hybrid drive train, Parallel hybrid drive train and Series-Parallel hybrid drive train

UNIT 2:

FUNDAMENTALS OF ELECTRIC VEHICLES: General description of vehicle movement, Vehicle resistance: Rolling Resistance, Aerodynamic drag, Grading résistance, Dynamic Equation, Vehicle Transmission Characteristics: Manual gear transmission and Hydro dynamic transmission, Vehicle performance: Maximum Cruising Speed, Gradeability, Acceleration performance.

UNIT 3:

PLUG-IN HYBRID ELECTRIC VEHICLES: Introduction, Functions and Benefits of PHEV, Operating Principles of Plug- in Hybrid Vehicle: Charge-Depleting Mode, Charge-Sustaining Mode, AER Mode, Engine-Maintenance Mode, Control Strategy of PHEV, PHEV-Related Technologies and Challenges

FUNDAMENTALS OF CHARGERS: Charger Classification and Standards, Charger Requirements,Topology Selectionfor Level 1 and 2 AC Chargers: Front-End AC–DC Converter Topologies, Isolated DC–DC Converter Topologies, Wireless Chargers.

UNIT 4:

ELECTRIC PROPULSION SYSTEMS: Introduction to electric components used in HEV’s, DC Motor drives: Combined armature and Field Control method, Chopper control DC drives, Multi quadrant control of Chopper fedDC drive.

PERMANENT MAGNET BLDC & SRM MOTOR DRIVES: Closed loop Torque control of BLDC motor drive and Sensorless Control of BLDC Motor drive using Back EMF method, Switch Reluctance Motor drives: Basic Magneticstructure, Modes of operation, different Inverter topologies of SRM drives.

UNIT 5:

ENERGY STORAGE: Introduction to Energy Storage Requirements in Electric Vehicles, Battery Parameters, Battery based energy storage: Lead acid battery, Lithium Ion Battery and Metal Air batteries, Super Capacitor based energy storage, Fuel Cell based energy storage, Hybridization of different energy storage device.

TEXT BOOKS:

1. M. Ehsani, Y. Gao, S. E. Gay and A. Emadi, “Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design”, CRC Press, 2004.
2. Ali Emadi, “Advanced Electrical Hybrid Vehicles” CRC Press, 2015, Taylor & FrancisGroup.
3. C. Mi, M. A. Masrur and D. W. Gao, “Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives”, John Wiley & Sons, 2011.

REFERENCE BOOKS:

1.T. Denton, “Electric and Hybrid Vehicles”, Routledge,2016.
2.S. Onori, L. Serrao and G. Rizzoni, “Hybrid Electric Vehicles: Energy Management Strategies”,Springer, 2015.

COURSE OUTCOMES:

At the end of this course, students would be able to:

1.Get a good understanding of the basic functioning of both Electric and Hybrid vehiclesand their performance2.Develop a good concept of the electrical vehicle modeling and its power plantcharacteristics.
3. To understand the fundamentals of chargers related to both electric & hybrid vehicle operation & energy management.
4. Have a detailed understanding of electric propulsion systems, types of motors and the other important subsystems in Electric vehicles.
5. Have clear concepts of the different possible energy storage systems for both electricand hybrid vehicles.

UNIT – I
INTRODUCTION TO HYBRID ELECTRIC VEHICLES

Hybrid electric vehicle (HEV):

The hybrid electric vehicle combines a gasoline engine with an electric motor. An alternate isa diesel engine and an electric motor.

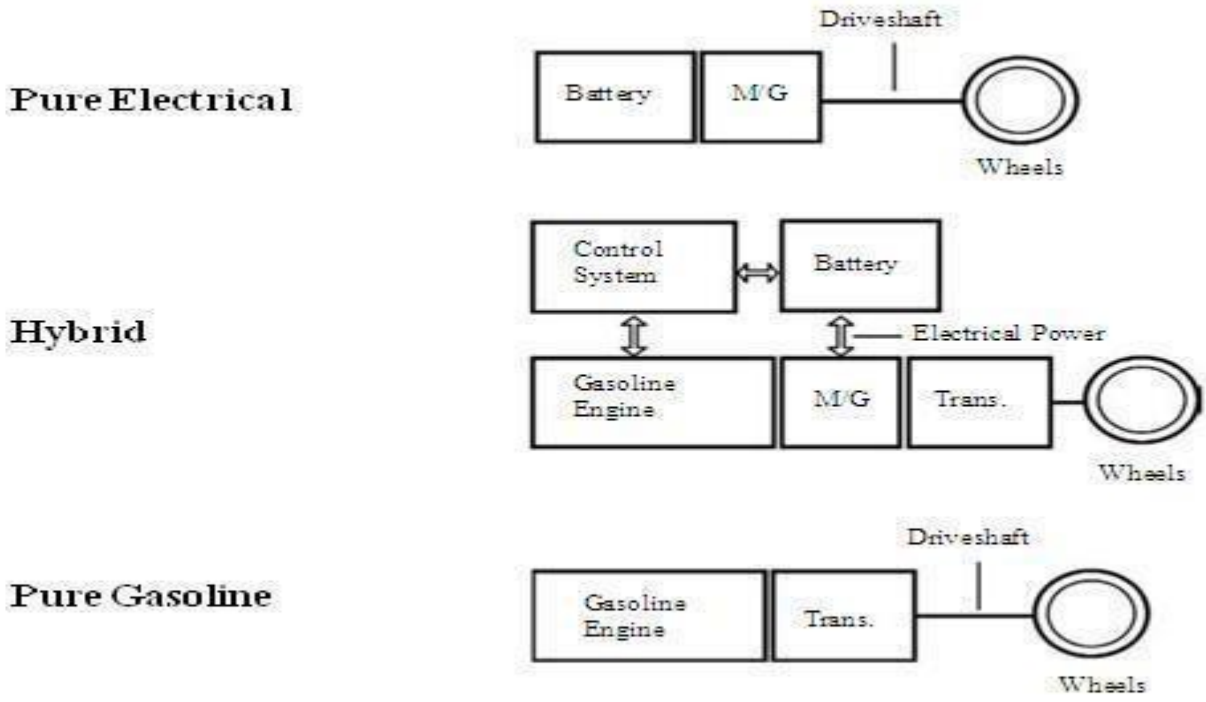


Figure 1: Components of a hybrid Vehicle that combines a pure gasoline with a pure EV.

As shown in **Figure 1**, a HEV is formed by merging components from a pure electrical vehicle and a pure gasoline vehicle. The Electric Vehicle (EV) has an M/G which allows regenerative braking for an EV; the M/G installed in the HEV enables regenerative braking. For the HEV, the M/G is tucked directly behind the engine. In Honda hybrids, the M/G is connected directly to the engine.

The transmission appears next in line. This arrangement has two torque producers; the M/G in motor mode, M-mode, and the gasoline engine. The battery and M/G are connected electrically.
HEVs are a combination of electrical and mechanical components. Three main sources of electricity for hybrids are batteries, FCs, and capacitors. Each device has a low cell voltage, and, hence, requires many cells in series to obtain the voltage demanded by an HEV. Difference in the source of Energy can be explained as:

- The FC provides high energy but low power.
- The battery supplies both modest power and energy.
- The capacitor supplies very large power but low energy.

The components of an electrochemical cell include anode, cathode, and electrolyte (shown in fig2). The current flow both internal and external to the cell is used to describe the current loop.

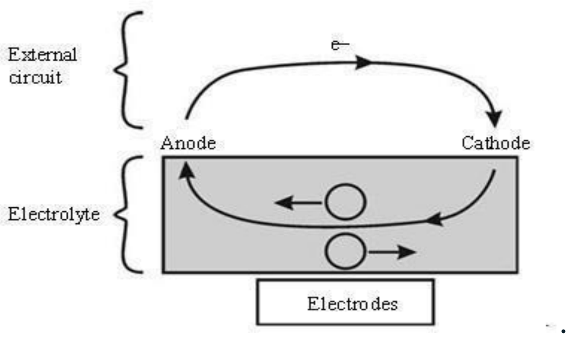


Figure 2: An electrode, a circuit for a cell which is converting chemical energy to electrical energy. The motion of negative charges is clockwise and forms a closed loop through external wires and load and the electrolyte in the cell.

A critical issue for both battery life and safety is the precision control of the Charge/Discharge cycle. Overcharging can be traced as a cause of fire and failure. Applications impose two boundaries or limitations on batteries. The first limit, which is dictated by battery life, is the minimum allowed State of Charge. As a result, not all the installed battery energy can be used. The battery feeds energy to other electrical equipment, which is usually the inverter. This equipment can use a broad range of input voltage, but cannot accept a low voltage. The second limit is the minimum voltage allowed from the battery.

HISTORY OF ELECTRIC VEHICLES:

In 1900, steam technology was advanced. The advantages of ***steam-powered cars*** included high performance in terms of power and speed. However, the disadvantages of steam-powered cars included poor fuel economy and the need to –fire up the boiler‖ before driving. Feed water was a necessary input for steam engine, therefore could not tolerate the loss of fresh water. Later, Steam condensers were applied to the steam car to solve the feed water problem. However, by that time Gasoline cars had won the marketing battle.

Gasoline cars of 1900 were noisy, dirty, smelly, cantankerous, and unreliable. In comparison, electric cars were comfortable, quiet, clean, and fashionable. Ease of control was also a desirable feature. Lead acid batteries were used in 1900 and are still used in modern cars. Hence lead acid batteries have a long history (since 1881) of use as a viable energy storage device. Golden age of ***Electrical vehicle*** marked from 1890 to 1924 with peak production of electric vehicles in 1912. However, the range was limited by energy storage in the battery. After every trip, the battery required recharging. At the 1924 automobile show, no electric cars were on display. This announced the end of the Golden Age of electric-powered cars.

The range of a ***gasoline car*** was far superior to that of either a steam or an electric car and dominated the automobile market from 1924 to 1960. The gasoline car had one dominant feature; it used gasoline as a fuel. The modern period starts with the oil embargoes and the gasoline shortages during the 1970s which created long lines at gas stations. Engineers recognized that the good features of the gasoline engine could be combined with those of the electric motor to produce a superior car. A marriage of the two yields the hybrid automobile.

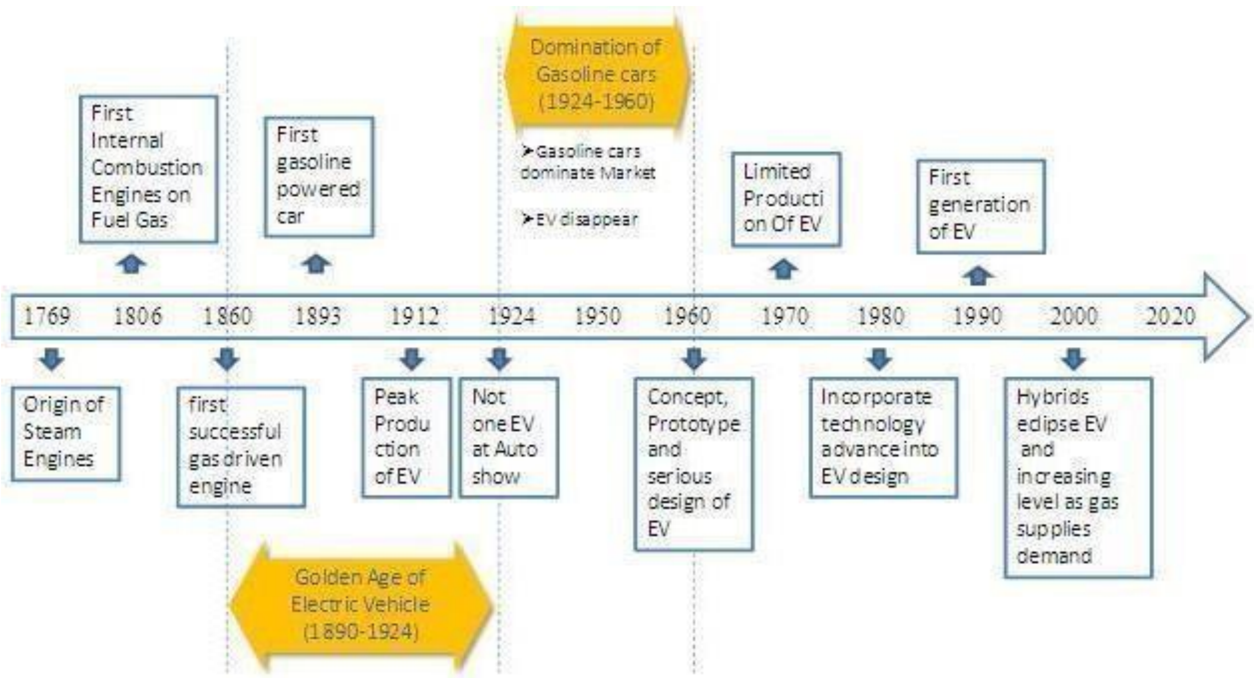


Figure 3: Historical development of automobile and development of interest and activity in the EV from 1890 to presentday. Electric Vehicle merged into hybrid electric vehicle.

1769:

The first steam-powered vehicle was designed by Nicolas-Joseph Cugnot and constructed by M. Brezin that could attain speeds of up to 6 km/hour. These early steam-powered vehicles were so heavy that they were only practical on a perfectly flat surface as strong as iron.

1807:

The next step towards the development of the car was the invention of the internal combustion engine. Francois Isaac de Rivaz designed the first internal combustion engine in, using a mixture of hydrogen and oxygen to generate energy.

1825:

British inventor Goldsworthy Gurney built a steam car that successfully completed an 85 mile round-trip journey in ten hours' time.

1839:

Robert Anderson of Aberdeen, Scotland built the first electric vehicle**.**

1860:

In, Jean Joseph Etienne Lenoir, a Frenchman, built the first successful two-stroke gas driven engine**.**

1886:

Historical records indicate that an electric-powered taxicab**,** using a battery with 28 cells and a small electricmotor, was introduced in England.

1888:

Immisch& Company built a four-passenger carriage, powered by a one-horsepower motor and 24-cell battery, for the Sultan of the Ottoman Empire. In the same year, Magnus Volk in Brighton, England made a three-wheeled electric car. *1890 – 1910 (*Period of significant improvements in battery technology)

INVENTION OF HYBRID VEHICLES:

1890

Jacob Lohner, a coach builder in Vienna, Austria, foresaw the need for an electric vehicle that would be lessnoisy than the new gas-powered cars. He commissioned a design for an electric vehicle from Austro-Hungarian engineer Ferdinand Porsche, who had recently graduated from the Vienna Technical College. Porsche's first version of the electric car used a pair of electric motors mounted in the front wheel hubs of a conventional car. The car could travel up to 38 miles. To extend the vehicle's range, Porsche added a gasolineengine that could recharge the batteries, thus giving birth to the first hybrid, the ***Lohner-Porsche Elektromobil.***

EARLY HYBRID VEHICLES:

1900:

Porsche showed his hybrid car at the Paris Exposition of 1900. A gasoline engine was used to power a generator which, in turn, drove a small series of motors. The electric engine was used to give the car a little bit of extra power. This method of ***series hybrid engine*** is still in use today, although obviously with furtherscope of performance improvement and greater fuel savings.

1915:

Woods Motor Vehicle manufacturers created the Dual Power hybrid vehicle, second hybrid car in market. Rather than combining the two power sources to give a single output of power, the Dual Power used an electric battery motor to power the engine at low speeds (below 25km/h) and used the gasoline engine to carry the vehicle from these low speeds up to its 55km/h maximum speed. While Porsche had invented theseries hybrid, Woods invented the parallel hybrid.

1918:

The Woods Dual Power was the first hybrid to go into mass production. In all, some 600 models were built by.However, the evolution of the internal combustion engine left electric power a marginal technology

1960:

Victor Wouk worked in helping create numerous hybrid designs earned him the nickname of the -Godfather of the Hybrid‖. In 1976 he even converted a Buick Skylark from gasoline to hybrid.

1978:

Modern hybrid cars rely on the regenerative braking system. When a standard combustion engine car brakes, a lot of power is lost because it dissipates into the atmosphere as heat. Regenerative braking means that the electric motor is used for slowing the car and it essentially collects this power and uses it to help recharge the electric batteries within the car. This development alone is believed to have progressed hybrid vehicle manufacture significantly. The Regenerative Braking System, was first designed and developed in 1978 by David Arthurs. Using standard car components he converted an Opel GT to offer 75 miles to the gallon and many home conversions are done using the plans for this system that are still widely available on the Interne

MODERN PERIOD OF HYBRID HISTORY:

The history of hybrid cars is much longer and more involved than many first imagine. It is, however, in the last ten years or so that we, as consumers, have begun to pay more attention to the hybrid vehicle as a viable alternative to ICE driven cars. Whether looking for a way to save money on spiralling gas costs or in an attempt to help reduce the negative effects on the environment we are buying hybrid cars much more frequently.

1990:

Automakers took a renewed interest in the hybrid, seeking a solution to dwindling energy supplies and environmental concerns and created modern history of hybrid car.

1993:

In USA, Bill Clinton's administration recognized the urgency for the mass production of cars powered by means other than gasoline. Numerous government agencies, as well as Chrysler, Ford, GM, and USCAR combined forces in the PNGV (Partnership for a New Generation of Vehicles), to create cars using alternative power sources, including the development and improvement of hybrid electric vehicles.

1997:

The Audi Duo was the first European hybrid car put into mass production and hybrid production andconsumer take up has continued to go from strength to strength over the decades.

2000:

Toyota Prius and Honda Insight became the first mass market hybrids to go on sale in the United States, with dozens of models following in the next decade. The Honda Insight and Toyota Prius were two of the first mainstream Hybrid Electric Vehicles and both models remain a popular line.

2005:

A hybrid Ford Escape, the SUV, was released in 2005. Toyota and Ford essentially swapped patents with one another, Ford gaining a number of Toyota patents relating to hybrid technology and Toyota, in return, gaining access to Diesel engine patents from Ford.

PRESENT OF HYBRID ELECTRIC VEHICLES:

Toyota is the most prominent of all manufacturers when it comes to hybrid cars. As well as the specialist hybrid range they have produced hybrid versions of many of their existing model lines, including several Lexus (now owned and manufactured by Toyota) vehicles. They have also stated that it is their intention to release a hybrid version of every single model they release in the coming decade. As well as cars and SUVs, there are a select number of hybrid motorcycles, pickups, vans, and other road going vehicles available to the consumer and the list is continually increasing.

FUTURE OF HYBRID ELECTRICAL VEHICLE:

Since petroleum is limited and will someday run out of supply. In the arbitrary year 2037, an estimated one billion petroleum-fuelled vehicles will be on the world's roads. Gasoline will become prohibitively expensive. The world need to have solutions for the –400 million otherwise useless cars**”.** So year 2037 –gasoline runs out year‖ means, petroleum will no longer be used for personal mobility. A market may develop for solar-powered EVs of the size of a scooter or golf cart. Since hybrid technology applies to heavy vehicles, hybrid buses and hybrid trains will be more significant.

SOCIAL AND ENVIRONMENTAL IMPORTANCE OF HYBRID ELECTRIC VEHICLES:

As modern culture and technology continue to develop, the growing presence of global warming and irreversible climate change draws increasing amounts of concern from the world's population. It has only been recently, when modern society has actually taken notice of these changes and decided that something needs to change if the global warming process is to be stopped.

Countries around the world are working to drastically reduce CO_2 emissions as well as other harmful environmental pollutants. Amongst the most notable producers of these pollutants are automobiles, which are almost exclusively powered by internal combustion engines and spew out unhealthy emissions.

According to various reports, cars and trucks are responsible for almost 25% of CO_2 emission and other major transportation methods account for another 12%. With immense quantities of cars on the road today, pure combustion engines are quickly becoming a target of global warming blame. One potential alternative to the world's dependence on standard combustion engine vehicles are hybrid cars. Cost-effectiveness is also an important factor contributing to the development of an environment friendly transportation sector.

ENVIRONMENTAL IMPACT ANALYSIS*:*

All stages of the life cycle were considered, starting from

a. The extraction of natural resources to produce materials and

b. Ending with conversion of the energy stored on board the vehicle into mechanical energy for vehicle displacement and

c. Other purposes (heating, cooling, lighting, etc.).

In addition, vehicle production stages and end-of-life disposal contribute substantially whenquantifying the life cycle environmental impact of fuel-propulsion alternatives.

The analysis were conducted on six vehicles, each was representative of one of the above discussedcategories. The specific vehicles were:

1. Toyota Corolla (conventional vehicle),
2. Toyota Prius (hybrid vehicle),
3. Toyota RAV4EV (electric vehicle),
4. Honda FCX (hydrogen fuel cell vehicle),
5. Ford Focus H_2 -ICE (hydrogen ICE vehicle),
6. Ford Focus H_2 -ICE adapted to use ammonia as source of hydrogen (ammonia-fuelled ICE vehicle).

Two environmental impact elements were accounted for in the:

a. Air pollution (AP) and

b. Greenhouse gas (GHG) emissions.

The main GHGs were CO_2,CH_4, N_2O, and SF_6 (sulphur hexafluoride), which have GHG impactweighting coefficients relative to CO_2 of 1, 21, 310, and 24,900, respectively.

For AP, the airborne pollutants CO, NO_X,SO_X, and VOCs are assigned the following weighting coefficients: 0.017, 1, 1.3, and 0.64, respectively.

The vehicle production stage contributes to the total life cycle environmental impact through the pollution associated with

a. The extraction and processing of material resources,

b. Manufacturing and

c. The vehicle disposal stage.

Additional sources of GHG and AP emissions were associated with the fuel production and utilization stages. The environmental impacts of these stages have been evaluated in numerous life cycle assessments of fuel cycles.

Regarding electricity production for the electric car case, three case scenarios were considered here:

1. When electricity is produced from renewable energy sources and nuclear energy;
2. When 50% of the electricity is produced from renewable energy sources and 50% fromnatural gas at an efficiency of 40%;
3. When electricity is produced from natural gas at an efficiency of 40%.

AP emissions were calculated assuming that GHG emissions for plant manufacturing correspond entirely to natural gas combustion. GHG and AP emissions embedded in manufacturing a natural gas power generation plant were negligible compared to the direct emissions during its utilization. Taking those factors into account, GHG and AP emissions for the three scenarios of electricity generation were presented in Table 2.

Electricity-generation scenario	Description of Electricity generation Scenario	GHG emission (g)	AP emission (g)
1	Electricity produced = 100% (Renewable Energy + Nuclear Energy)	5.11	0.195
2	Electricity produced = (50% Renewable Energy + 50% Natural gas)	77.5	0.296
3	Electricity produced = 100% Natural Gas	149.9	0.573

Table2: GHG and air pollution emissions per MJ of electricity produced

Hydrogen charging of fuel tanks on vehicles requires compression. Therefore, presented caseconsidered the energy for hydrogen compression to be provided by electricity.

Fuel	GHG emissions, g	AP emissions, g
Hydrogen from natural gas		
Scenario 1	78.5	0.0994
Scenario 2	82.1	0.113
Scenario 3	85.7	0.127

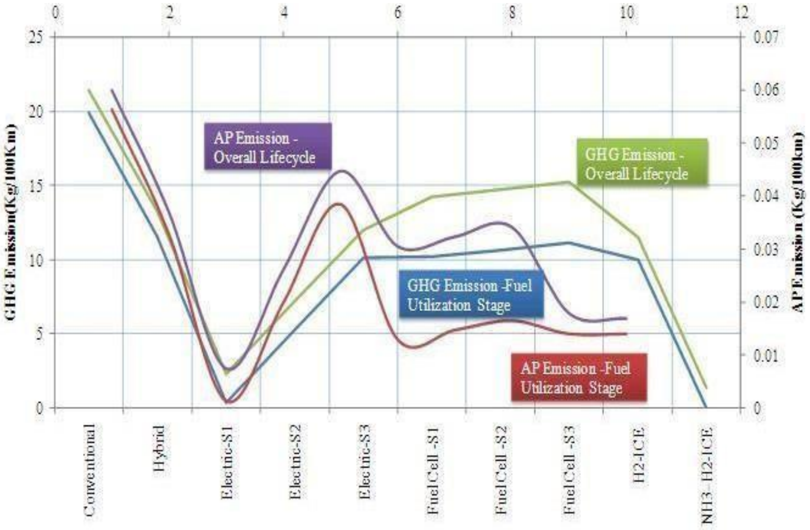
Table 3: GHG and air pollution emissions per MJ fuel of Hydrogen from natural gas produced

GHG and AP emissions were reported for hydrogen vehicles for the three electricity-generation scenarios considered (see table 3), accounting for the environmental effects of hydrogen compression.

	Fuel utilization stage		Overall life cycle	
Vehicle type	GHG emissions	AP emissions	GHG emissions	AP emissions
	(kg/100 km)	(kg/100 km)	(kg/100 km)	(kg/100 km)
Conventional	19.9	0.0564	21.4	0.06
Hybrid	11.6	0.0328	13.3	0.037
Electric-S1	0.343	0.00131	2.31	0.00756
Electric-S2	5.21	0.0199	7.18	0.0262
Electric-S3	10.1	0.0385	12	0.0448
Fuel Cell -S1	10.2	0.0129	14.2	0.0306
Fuel Cell -S2	10.6	0.0147	14.7	0.0324
Fuel Cell -S3	11.1	0.0165	15.2	0.0342
H2-ICE	10	0.014	11.5	0.018
NH3–H2-ICE	0	0.014	1.4	0.017

Table 4. Environmental impact associated with vehicle Overall Life cycle and Fuel UtilizationState.

The environmental impact of the fuel utilization stage, as well as the overall life cycle is presented inTable 4. The H2-ICE vehicle results were based on the assumption that the only GHG emissions during the utilization stage were associated with the compression work, needed to fill the fuel tank of the vehicle. The GHG effect of water vapor emissions was neglected in this analysis due its little value,. For the ammonia fuel vehicle, a very small amount of pump work was needed therefore, ammonia fuel was considered to emit no GHGs during fuel utilization.



ECONOMICAL ANALYSIS

A number of key economic parameters that characterize vehicles were:

a. Vehicle price,

b. Fuel cost, and

c. Driving range.

This case neglected maintenance costs; however, for the hybrid and electric vehicles, the cost of battery replacement during the lifetime was accounted for. The driving range determines the frequency (number and separation distance) of fuelling stations for each vehicle type. The total fuel cost and the total number of kilometres driven were related to the vehicle life (see Table 1).

Vehicle type	Fuel Type	Initial Price (USk$)	Specific fuel Price (US$/100 km)	Driving Range (Km)	Price of battery Changes During Vehicle Life cycle (USk$)
Conventional *(Toyota Corolla)*	Gasoline	15.3	2.94	540	1 x 0.1
Hybrid *(Toyota Prius)*	Gasoline	20	1.71	930	1 x 1.02
Electric *(Toyota RAV4EV)*	Electricity	42	0.901	164	2 x 15.4
Fuel cell *(Honda FCX)*	Hydrogen	100	1.69	355	1 x 0.1
H2-ICE *(Ford Focus H_2-ICE)*	Hydrogen	60	8.4	300	1 x 0.1
NH3–H2-ICE *(Ford Focus H_2-ICE and ammonia Adaptive)*	Ammonia	40	6.4	430	1 x 0.1

Table1: Technical and economical values for selected vehicle types

For the Honda FCX the listed initial price for a prototype leased in 2002 was USk$2,000, which is estimatedto drop below USk$100 in regular production. Currently, a Honda FCX can be leased for 3 years with a total price of USk$21.6. In order to render the comparative study reasonable, the initial price of the hydrogen fuel cell vehicle is assumed here to be USk$100. For e electric vehicle, the specific cost was estimated to be US$569/kWh with nickel metal hydride (NiMeH) batteries which are typically used in hybrid and electric cars. Historical prices of typical fuels were used to calculate annual average price.

RESULTS OF TECHNICAL–ECONOMICAL–ENVIRONMENTAL ANALYSIS:

In present situation this case study provides a general approach for assessing the combined technical–economical–environmental benefits of transportation options.

This analysis showed that the hybrid and electric cars have advantages over the others. The economics and environmental impact associated with use of an electric car depends significantly on the source of the electricity:

- a. If electricity is generated from renewable energy sources, the electric car is advantageous to the hybrid vehicle.

  b. If the electricity is generated from fossil fuels, the electric car remains competitive only if theelectricity is generated on-board.

  c. If the electricity is generated with an efficiency of 50–60% by a gas turbine engine connected to ahigh-capacity battery and electric motor, the electric car is superior in many respects.

  d. For electricity-generation scenarios 2 and 3, using ammonia as a means to store hydrogen onboard a vehicle is the best option among those analysed (as shown in figure 2).

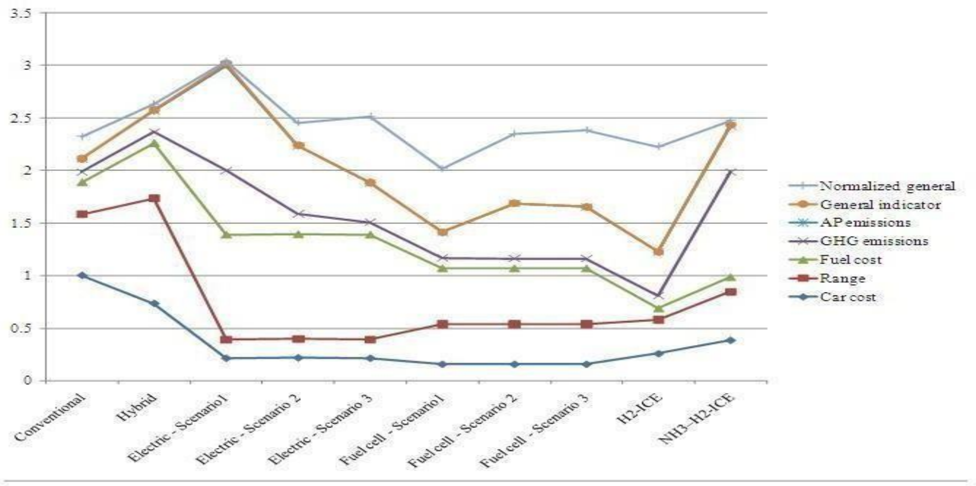


Figure2: Normalized economic and environmental indicators for six vehicle types

The electric car with capability for on-board electricity generation represents a beneficial option and is worthy of further investigation, as part of efforts to develop energy efficient and ecologically benign vehicles.

The main limitations of this study were as follows:

(i) The use of data which may be of limited accuracy in some instances;
(ii) The subjectiveness of the indicators chosen; and
(iii) The simplicity of the procedure used for developing the general indicator without using uniqueweighting coefficients.

Despite these limitations, the study reflects relatively accurately and realistically the present situation and provides a general approach for assessing the combined technical–economical–environmental benefits of transportation options.

ARCHITECTURE OF HEV

The term hybrid vehicle refers to a vehicle with at least two sources of power. Hybrid-electric vehicle indicates that one source of power is provided by an electric motor. The other source of motive power can come from a number of different technologies, but is typically provided by an internal combustion engine designed to run on either gasoline or diesel fuel. As proposed by Technical Committee (Electric Road Vehicles) of the International Electro technical Commission, an HEV is a vehicle in which propulsion energy is available from two or more types of energy sources and at least one of them can deliver electrical energy. Based on this general definition, there are many types of HEVs, such as:

- the gasoline ICE and battery
- diesel ICE and battery
- battery and FC
- battery and capacitor
- battery and flywheel
- Battery and battery hybrids.

Most commonly, the propulsion force in HEV is provided by a combination of electric motor and an ICE. The electric motor is used to improve the energy efficiency (improves fuel consumption) and vehicular emissions while the ICE provides extended range capability.

HEV Configurations

In **Figure** the generic concept of a hybrid drivetrain and possible energy flow route is shown. The various possible ways of combining the power flow to meet the driving requirements are:

i. power train 1 alone deliverspower
ii. power train 2 alone deliverspower
iii. both power train 1 and 2 deliver power to load at the sametime
iv. power train 2 obtains power from load (regenerativebraking)
v. power train 2 obtains power from power train1
vi. power train 2 obtains power from power train 1 and load at the sametime
vii. power train 1 delivers power simultaneously to load and to power train2
viii. power train 1 delivers power to power train 2 and power train 2 delivers power aton load
ix. power train 1 delivers power to load and load delivers power to power train 2.

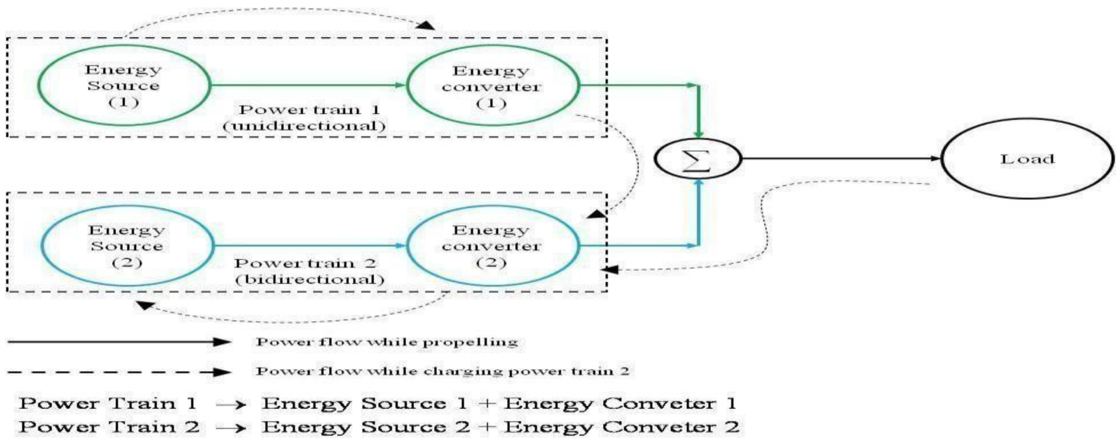


Figure : Generic Hybrid Drivetrain

The load power of a vehicle varies randomly in actual operation due to frequent acceleration, deceleration and climbing up and down the grades. The power requirement for a typical driving scenario is shown in **Figure 3**. The load power can be decomposed into two parts:

i. steady power, i.e. the power with a constant value

ii. dynamic power, i.e. the power whose average value is zero

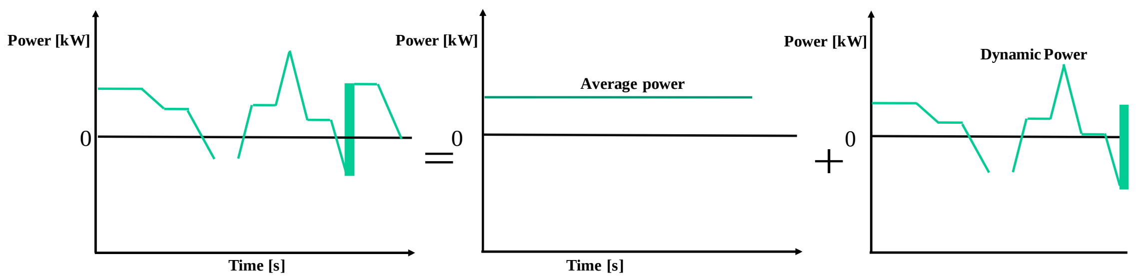


Figure3: Loadpower decomposition

In HEV one power train favours steady state operation, such as an ICE or fuel cell. The other power train in the HEV is used to supply the dynamic power. The total energy output from the dynamic power train will be zero in the whole driving cycle. Generally, electric motors are used to meet the dynamic power demand. This hybrid drive train concept can be implemented by different configurations as follows:

- Series configuration
- Parallel configuration
- Series-parallel configuration
- Complex configuration

In **Figure 4** the functional block diagrams of the various HEV configurations isshown. From **Figure 4** it can be observed that the key feature of:

- series hybrid is to couple the ICE with the generator to produce electricity forpure electric propulsion.
- parallel hybrid is to couple both the ICE and electric motor with thetransmission via the same drive shaft to propel the vehicle

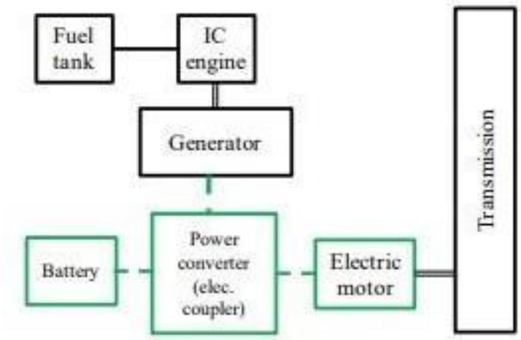


Figure 4a: Series hybrid

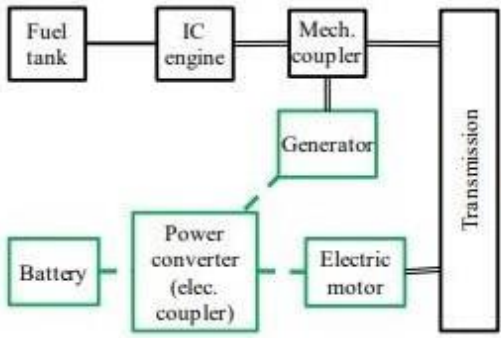


Figure 4b: Series-Parallel hybrid

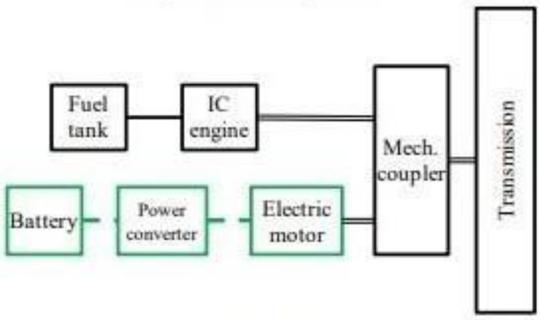


Figure 4c: Parallel hybrid

Series Hybrid System:

In case of series hybrid system (**Figure 4a**) the mechanical output is first converted into electricity using a generator. The converted electricity either charges the battery or can bypass the battery to propel the wheels via the motor and mechanical transmission. Conceptually, it is an ICE assisted Electric Vehicle (EV). The advantages of series hybrid drive trains are:

- Mechanical decoupling between the ICE and driven wheels allows the IC engine operating at its very narrow optimal region as shown in **Figure5**.
- Nearly ideal torque-speed characteristics of electric motor make multi gear transmission unnecessary.

However, a series hybrid drive train has the following disadvantages:

- The energy is converted twice (mechanical to electrical and then to mechanical) and this reduces the overall efficiency.
- Two electric machines are needed and a big traction motor is required because it is the only torque source of the driven wheels.

The series hybrid drive train is used in heavy commercial vehicles, military vehicles and buses. The reason is that large vehicles have enough space for the bulky engine/generator system.

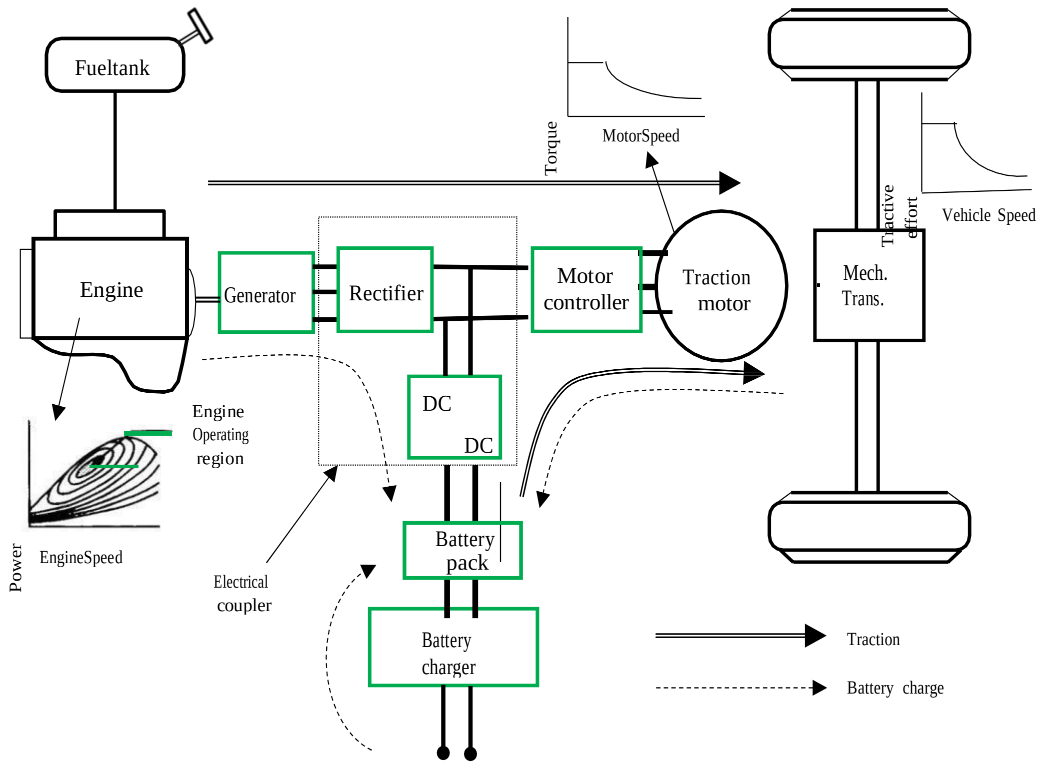


Figure 5: Detailed Configuration of Series Hybrid Vehicle

2.Parallel Hybrid System:

The parallel HEV (**Figure 4b**) allows both ICE and electric motor (EM) to deliver power to drive the wheels. Since both the ICE and EM are coupled to the drive shaft of the wheels via two clutches, the propulsion power may be supplied by ICE alone, by EM only or by both ICE and EM. The EM can be used as a generator to charge the battery by regenerative braking or absorbing power from the ICE when its output is greater than that required to drive the wheels. The advantages of the parallel hybrid drivetrainare:

- both engine and electric motor directly supply torques to the driven wheels and no energy form conversion occurs, hence energy loss isless
- Compactness due to no need of the generator and smaller traction motor. The drawbacks of parallel hybrid drive trains are:
- Mechanical coupling between the engines and the driven wheels, thus the engine operating points cannot be fixed in a narrow speed region.
- The mechanical configuration and the control strategy are complex compared to series hybriddrivetrain.

Due to its compact characteristics, small vehicles use parallel configuration. Most passenger cars employ this configuration.

3.Series-Parallel System:

In the series-parallel hybrid (**Figure 4c**), the configuration incorporates the features of both the series and parallel HEVs. However, this configuration needs an additional electric machine and a planetary gear unit making the control complex.

POWER FLOW CONTROL:

Due to the variations in HEV configurations, different power control strategies are necessary to regulate the power flow to or from different components. All the control strategies aim satisfy the following goals:

- maximum fuel efficiency
- minimum emissions
- minimum system costs
- good driving performance

The design of power control strategies for HEVs involves different considerations such as:

- ***Optimal ICE operating point:*** The optimal operating point on the torque- speed plane of the ICE can be based on maximization of fuel economy, the minimization of emissions or a compromise between fuel economy and emissions.
- ***Optimal ICE operating line:*** In case the ICE needs to deliver different power demands, the corresponding optimal operating points constitute an optimal operating line.
- ***Safe battery voltage:*** The battery voltage may be significantly altered during discharging,

generator charging or regenerative charging. This battery voltage should not exceed the maximum voltage limit nor should it fall below the minimum voltage limit.

POWER FLOW CONTROL IN SERIES HYBRID:

In the series hybrid system there are four operating modes based on the power flow:

Mode 1: During startup (**Figure 1a**), normal driving or acceleration of the series HEV, both the ICE and battery deliver electric energy to the power converter which then drives the electric motor and hence the wheels via transmission.

Mode 2: At light load (**Figure 1b**), the ICE output is greater than that required to drive the wheels. Hence, a fraction of the generated electrical energy is used to charge the battery. The charging of the batter takes place till the battery capacity reaches a properlevel.

Mode 3: During braking or deceleration (**Figure 1c**), the electric motor acts as a generator, which converts the kinetic energy of the wheels into electricity and this, is used to charge thebattery.

Mode 4: The battery can also be charged by the ICE via the generator even when the vehicleomes to a complete stop (**Figure)**

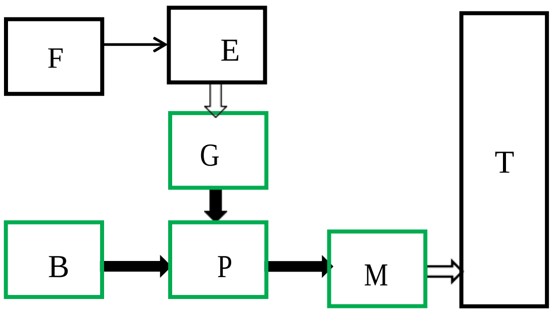


Figure 1a: Mode 1, normal driving or acceleration

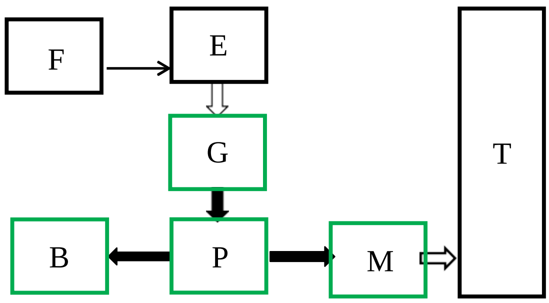


Figure 1b: Mode 2, light load

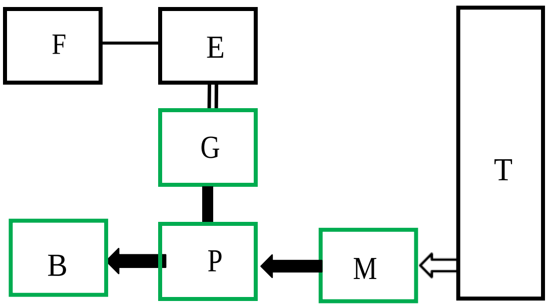


Figure 1c: Mode 3, braking or deceleration [1]

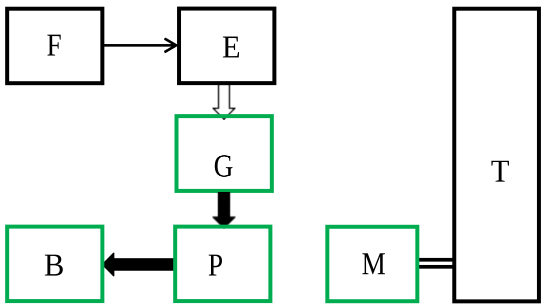


Figure 1d: Mode 4, vehicle at stop

T: Transmission (including brakes, clutches and gears)

B:Battery G: Generator Electrical link

E: ICE M: Motor Hydraulic link

F: Fueltank P: PowerConverter Mechanical link

Power Flow Control in Parallel Hybrid

The parallel hybrid system has four modes of operation. These four modes of operation are

Mode 1: During start up or full throttle acceleration (**Figure 2a)**; both the ICE and the EM share the required power to propel the vehicle. Typically, the relative distribution between the ICE and electric motor is80-20%.

Mode 2: During normal driving (**Figure 2b**), the required traction power is supplied by the ICE only and the EM remains in off mode.

Mode 3: During braking or deceleration (**Figure 2c**), the EM acts as a generator to charge the battery via the power converter.

Mode 4: Under light load condition (**Figure 2d**), the traction power is delivered by the ICE and the ICE also charges the battery via the EM.

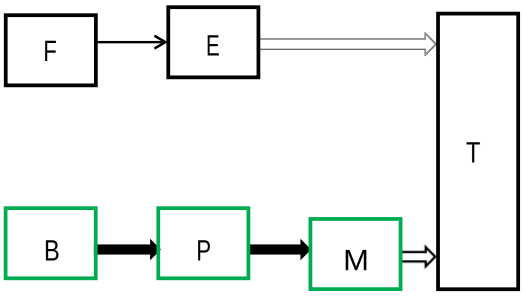


Figure 2a: Mode 1, start up

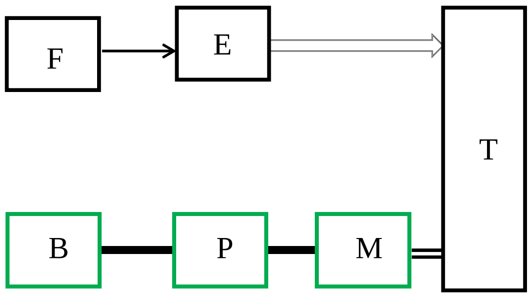


Figure 2b: Mode 2, normal driving

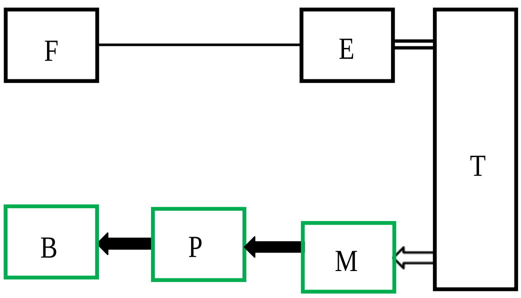


Figure 2c: Mode 3, braking or deceleration [1]

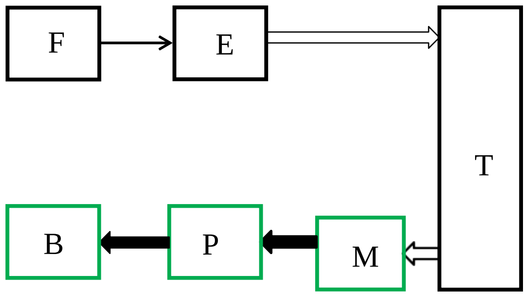


Figure 2d: Mode 4, light load

B:Battery
E: ICE
F: Fuel tank

G:Generator
M: Motor
P:Power converter

Electrical link
Hydraulic link
Mechanicallink

T:Transmission(including brakes, clutches and gears

Power Flow Control Series-Parallel Hybrid

The series-parallel hybrid system involves the features of series and parallel hybrid systems. Hence, a number of operation modes are feasible. Therefore, these hybrid systems are classified into two categories: **the ICE dominated** and the **EM dominated**.

The various operating modes of **ICE dominated** system are:

Mode 1: At startup (**Figure 3a)**, the battery solely provides the necessarypower to propel the vehicle and the ICE remains in offmode.

Mode 2: During full throttle acceleration (**Figure 3b**), both the ICE and the EM share the required tractionpower.

Mode 3: During normal driving (**Figure 3c**), the required traction power isprovided by the ICE only and the EM remains in the offstate.

Mode 4: During normal braking or deceleration (**Figure 3d**), the EM acts as a generator to charge the battery.

Mode 5: To charge the battery during driving (**Figure 3e**), the ICE delivers the required traction power and also charges the battery. In this mode the EM acts as a generator.

Mode 6: When the vehicle is at standstill (**Figure 3f**), the ICE can deliver power to charge the battery via the EM.

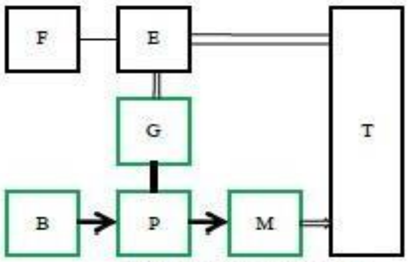


Figure 3a: Mode 1, startup [1]

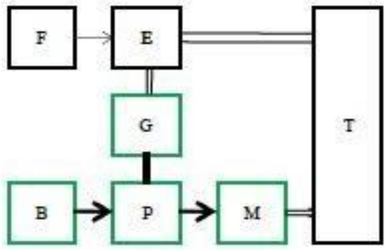


Figure 3b: Mode 2, acceleration[1]

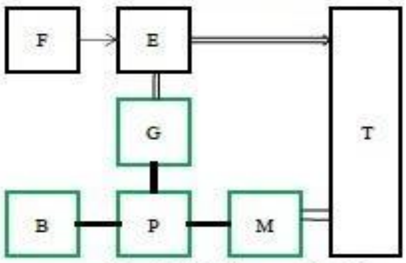


Figure 3c: Mode3, normaldrive[1]

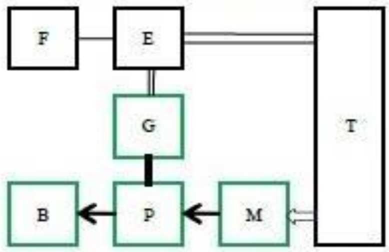


Figure 3d: Mode 4, braking or deceleration[1]

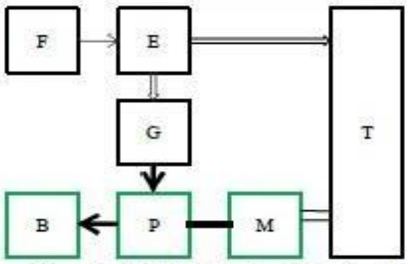


Figure 3e: Mode 5, battery charging duringdriving[1]

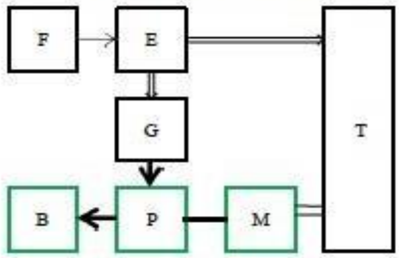


Figure 3f: Mode 6, battery charging duringstandstill [1]

B : Battery
E : ICE
F : Fuel Tank
G : Generator
M : Motor
P : Power Converter
T : Transmission(including brakes, clutches and gears)

— Electrical link
= Hydraulic link
≡ Mechanical link

The operating modes of **EM dominated** system are:

Mode 1: During startup (**Figure 4a**), the EM provides the traction power and the ICE remains in the offstage.

Mode 2: During full throttle (**Figure 4b**), both the ICE and EM provide the traction power.

Mode 3: During normal driving (**Figure 4c**), both the ICE and EM provide thetraction power.

Mode 4: During braking or deceleration (**Figure 4d**), the EM acts as a generator to charge the battery.

Mode 5: To charge the battery during driving (**Figure 4e**), the ICE delivers the required traction power and also charges the battery. The EM acts as a generator.

Mode 6: When the vehicle is at standstill (**Figure 4f**), the ICE can deliver power to charge the battery via the EM.

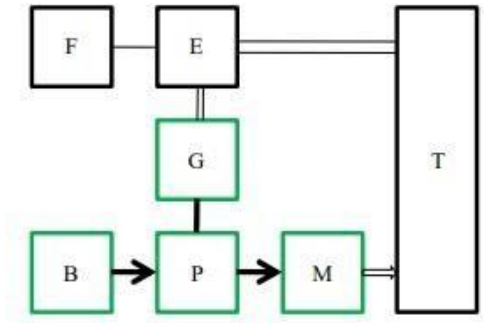


Figure 4a: Mode 1, start up [1]

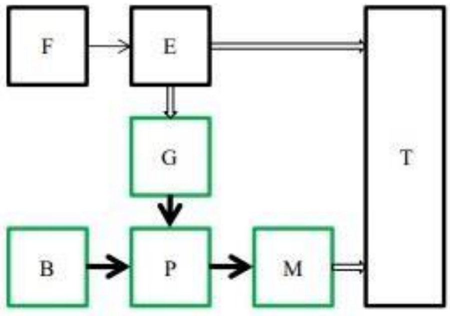


Figure 4b: Mode 2, acceleration [1]

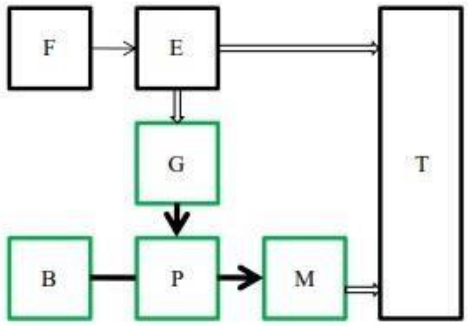


Figure4c: Mode 3, normal drive [1]

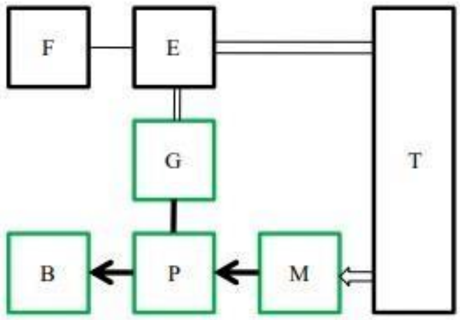


Figure 4d: Mode 4, braking or deceleration [1]

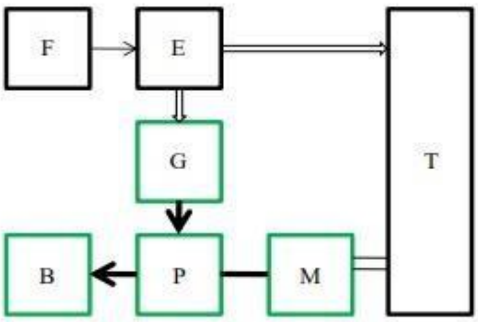


Figure 4e: Mode 5, battery charging during driving [1]

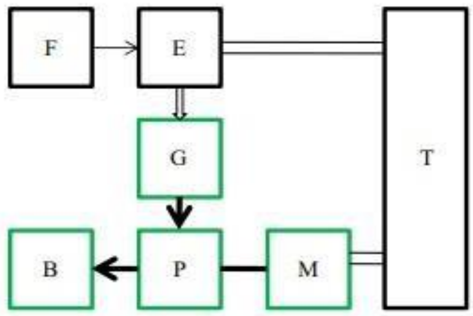


Figure 4f: Mode 6, battery charging during standstill [1]

B : Battery
E : ICE
F : Fuel Tank
G : Generator
M : Motor
P : Power Converter
T : Transmission(including brakes, clutches and gears)

— Electrical link
= Hydraulic link
≡ Mechanical link

UNIT – II

FUNDAMENTALS OF ELECTRIC VEHICLES

INTRODUCTION:

A hybrid vehicle combines any two power (energy) sources. Possible combinations include diesel/electric, gasoline/fly wheel, and fuel cell (FC)/battery. Typically, one energy source is storage, andthe other is conversion of a fuel to energy. The combination of two power sources may support two separate propulsion systems. Thus to be a True hybrid, the vehicle must have at least two modes of propulsion. For example, a truck that uses a diesel to drive a generator, which in turn drives several electrical motors for all-wheel drive, is *not a hybrid*. But if the truck has electrical energy storage to provide a second mode, which is electrical assists, then it is a hybrid Vehicle. These two power sources may be paired in series, meaning that the gas engine charges the batteries of an electric motor that powers the car, or in parallel, with both mechanisms driving the car directly.

CONVENTIONAL VEHICLES:

A conventional engine-driven vehicle uses its engine to translate fuel energy into shaft power, directing most of this power through the drive train to turn the wheels. Much of the heat generated by combustion cannot be used for work and is wasted, both because heat engines have theoretical efficiency limit. Moreover, it is impossible to reach the theoretical efficiency limit because:

• Some heat is lost through cylinder walls before it can do work

• Some fuel is burned at less than the highest possible pressure

• Fuel is also burned while the engine is experiencing negative load (during braking) or when the vehicle iscoasting or at a stop, with the engine idling.

1.5. 1. BASIC VEHICLE PERFORMANCE:

The performance of a vehicle is usually described by its maximum cruisingspeed, gradeability, and acceleration. The predication of vehicle performanceis based on the relationship between tractive effort and vehicle speeddiscussed in Sections 2.5 and 2.6. For on-road vehicles, it is assumed thatthe maximum tractive effort is limited by the maximum torque of thepower plant rather than the road adhesion capability.

General Description of Vehicle Movement

Figure 2.1 shows the forces acting on a vehicle moving up a grade. The tractiveeffort, *Ft*, in the contact area between tires of the driven wheels and theroad surface propels the vehicle forward. It is produced by the power planttorque and is transferred through transmission and final drive to the drive wheels. While the vehicle is moving, there is resistance that tries to stop itsmovement. The resistance usually includes tire rolling resistance, aerodynamicdrag, and uphill resistance. According to Newton’s second law, vehicle acceleration can be written aswhere*V*is vehicle speed, Σ*Ftr*is the total tractive effort of the vehicle, Σ*Ftr*isthe total resistance, *Mv*is the total mass of the vehicle, and δ is the mass factor,which is an effect of rotating components in the power train. Equation.

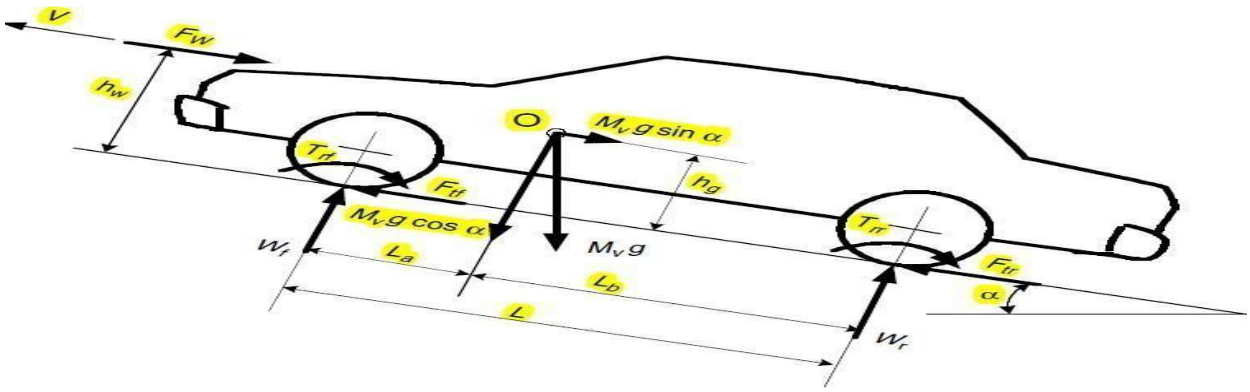


Figure 2.1. Forces acting on a vehicle

The above fig indicates that speed and acceleration depend on tractive effort, resistance&vehicle mass.

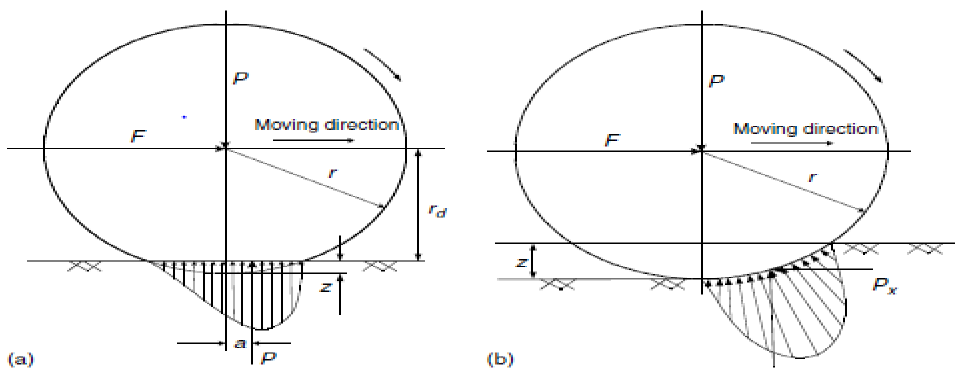
Vehicle Resistance

As shown in Figure2.1, vehicle resistance opposing its movement includes rolling resistance of the tires, appearing in Figure 2.1 as rolling resistance torque *Trf* and *Trr*, aerodynamic drag, *Fw*, and grading resistance (the term *Mv g* sin α in Figure). All of the resistances will be discussed in detail in the following sections.

Rolling Resistance

The rolling resistance of tires on hard surfaces is primarily caused by hysteresis in the tire materials. This is due to the deflection of the carcass while the tire is rolling. The hysteresis causes an asymmetric distribution of ground reaction forces. The pressure in the leading half of the contact area is larger than that in the trailing half, as shown in Figure .This phenomenon results in the ground reaction force shifting forward. This forwardly shifted ground reaction force, with the normal load acting on the wheel center, Creates a moment that opposes the rolling of the wheel. On soft surfaces, the rolling resistance is primarily caused by deformation of the ground surface as shown in Figure 2.2 (b). The ground reaction force almost completely Shifts to the leading half.

Figure 2.2 (a)&(b): Tire deflection and rolling resistance on a (a) hard and (b) soft road surface



The moment produced by the forward shift of the resultant ground reaction force is called the rolling resistant moment, as shown in Figure 1.5.1.1(a),and can be expressed as

$$T_r = Pa.$$

.........................eq.1

To keep the wheel rolling, a force *F*, acting on the center of the wheels, is required to balance this rolling resistant moment. This force is expressed as

$$F = \frac{T_r}{r_d} = \frac{Pa}{r_d} = Pf_r,$$

...........................eq.2

Where*rd*is the effective radius of the tire and *fr*= *a/rd*is called the rolling resistance coefficient. In this way, the rolling resistant moment can be replaced equivalently by horizontal force acting on the wheel center in the opposite direction of the movement of the wheel. This equivalent force is called rolling resistance with a magnitude of

$$F_r = Pf_r,$$

……….. eq.3

Where *P* is the normal load, acting on the center of the rolling wheel. When a vehicle is operated on a slope road, the normal load, *P*, should be replaced by the component, which is perpendicular to the road surface. That is

$$F_r = Pf_r \cos\alpha,$$

…………………. eq.4

The rolling resistance coefficient, *fr*, is a function of the tire material, tirestructure, tire temperature, tire inflation pressure, tread geometry, road roughness,road material, and the presence or absence.

The rolling resistance coefficient of passenger cars on concrete road may be calculated from the following equation:

$$f_r = f_0 + f_s\left(\frac{V}{100}\right)^{2.5},$$

…………………. eq.5

Where*V*is vehicle speed in km/h, and *f*0 and *fs* depend on inflation pressure of the tire.1

In vehicle performance calculation, it is sufficient to consider the rolling resistance coefficient as a linear function of speed. For the most common range of inflation pressure, the following equation can be used for a passenger car on concrete road.

$$f_r = 0.01\left(1 + \frac{V}{100}\right).$$

………………. eq.6

This equation predicts the values of *fr*with acceptable accuracy for speeds upto128km/h.

Aerodynamic Drag:

A vehicle traveling at a particular speed in air encounters a force resisting its motion. This force is referred to as aerodynamic drag. It mainly results fromtwo components: shape drag and skin friction.

Shape drag: The forward motion of the vehicle pushes the air in front of it. However, the air cannot instantaneously move out of the way and its pressures thus increased, resulting in high air pressure. In addition, the air behind the vehicle cannot instantaneously fill the space left by the forward Motion of the vehicle. This creates a zone of low air pressure. The motion has therefore created two zones ofpressure that oppose the motion of a vehicle by pushing it forward (high pressure in front) and pulling it backward (low pressure in the back) as shown in Figure . The resulting force on the vehicle is the shape drag.3

Skin friction: Air close to the skin of the vehicle moves almost at the speedof the vehicle while air far from the vehicle remains still.

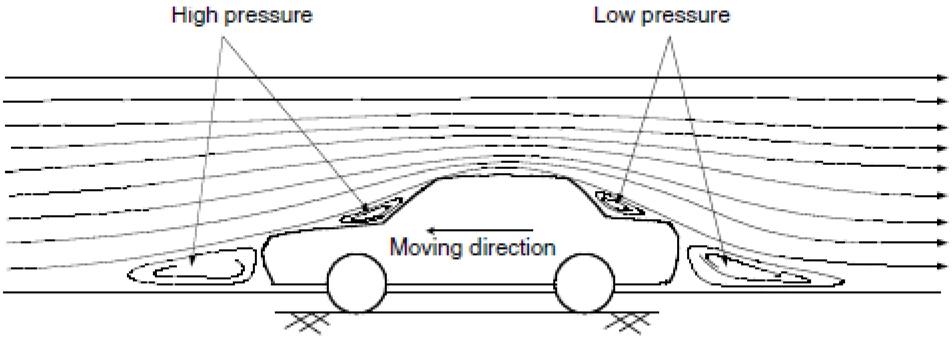


Figure 2.3 . Shapedrag

molecules move at a wide range of speeds. The difference in speed betweentwo air molecules produces a friction that results in the second componentof aerodynamic drag.Aerodynamic drag is a function of vehicle speed *V*, vehicle frontal area *Af*,shape of the vehicle, and air density ρ. Aerodynamic drag is expressed as

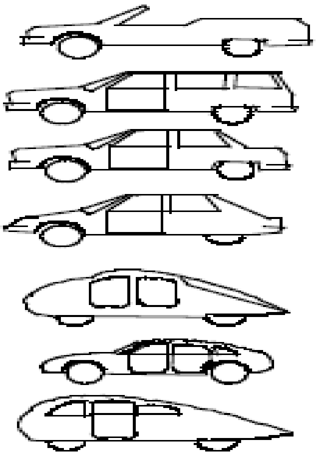
$$F_w = \frac{1}{2}\rho A_f C_D (V+V_w)^2,$$ eq7

where *CD* is the aerodynamic drag coefficient that characterizes the shape of the vehicle and*Vw*isthecomponent of wind speed on the vehicle's moving direction, which has a positive sign when this component is opposite to thevehicle speed and a negative sign when it is in the same direction as vehiclespeed. The aerodynamic drag coefficients for a few types of vehicle bodyshapes are shown in Figure.

Grading Resistance

When a vehicle goes up or down a slope, its weight produces a component,which is always directed to the downward direction, as shown in Figure This component either opposes the forward motion (grade climbing) orhelps the forward motion (grade descending). In vehicle performance analysis,onuphill operation is considered. This grading force is usually calledgrading resistance.

Figure2.4. Indicative drag coefficients for different body shapes



Vehicle Type	Coefficient of Aerodymanic Resistance
Open convertible	0.5–0.7
Van body	0.5–0.7
Ponton body	0.4–0.55
Wedge-shaped body; headlamps and bumpers are integrated into the body, covered underbody, optimized cooling air flow	0.3–0.4
Headlamp and all wheels in body, covered underbody	0.2–0.25
K-shaped (small breakway section)	0.23
Optimum streamlined design	0.15–0.20
Trucks, road trains	0.8–1.5
Buses	0.6–0.7
Streamlined buses	0.3–0.4
Motorcycles	0.6–0.7

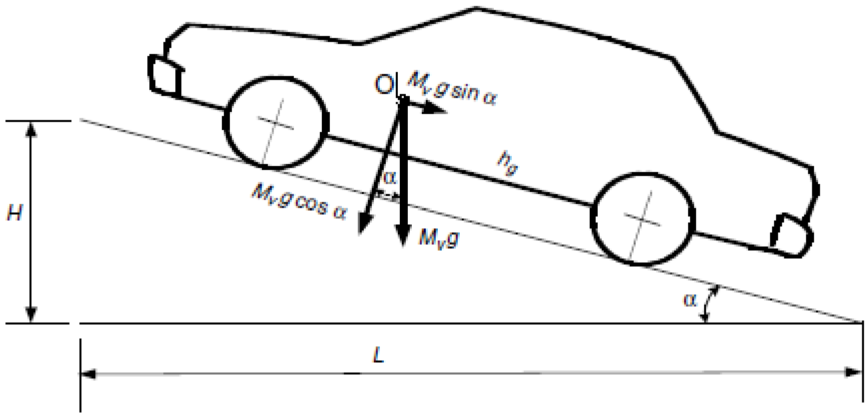


Figure 2.5. Automobile climbing a grade

The grading resistance, from Figure 2.5, can be expressed as

$$F_g = M_v g \sin\alpha.$$ ………...eq8

To simplify the calculation, the road angle, α, is usually replaced by grade valuewhen the road angle is small. As shown in Figure 2.5, the grade is defined as

$$i = \frac{H}{L} = \tan\alpha \approx \sin\alpha.$$ ………...eq9

In some literature, the tire rolling resistance and grading resistance togetherare called road resistance, which is expressed as

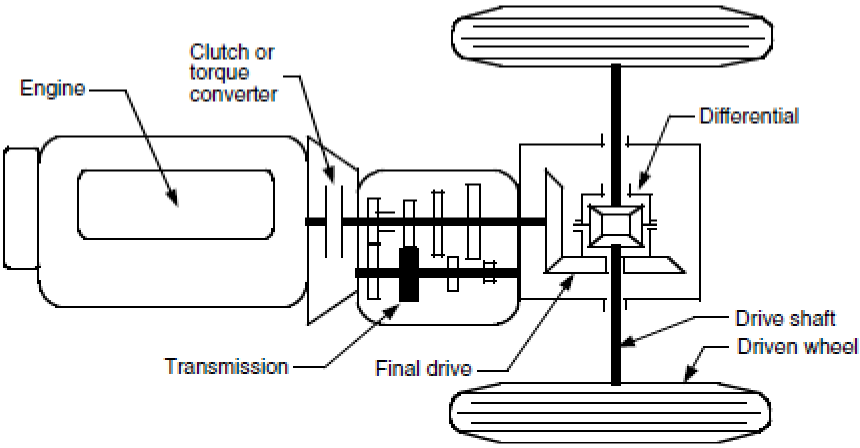
$$F_{rd} = F_f + F_g = M_v g(f_r \cos\alpha + \sin\alpha).$$ ……………eq10

When the road angle is small, the road resistance can be simplified as

$$F_{rd} = F_f + F_g = M_v g(f_r + i).$$

VEHICLE POWER SOURCE CHARACTERIZATION:

An automotive power train, as shown in Figure, consists of a power plant(engine or electric motor), a clutch in manual transmission or a torque converter in automatic transmission, a gearbox (transmission), final drive, differential, drive shaft, and driven wheels. The torque and rotating speed of the power plant output shaft are transmitted to the drive wheels through the clutch or torque converter, gearbox, final drive, differential, and drive shaft.



The clutch is used in manual transmission to couple the gearbox to or decouple it from the power plant. The torque converter in automatic transmission is a hydrodynamic device, functioning as the clutch in manual transmission with a continuously variable gear ratio.

The gearbox supplies a few gear ratios from its input shaft to its output shaft for the power plant torque–speed profile to match the requirements of the load.

The final drive is usually a pair of gears that supply a further speed reduction and distribute the torque to each wheel through the differential.

The torque on the driven wheels, transmitted from the power plant, is expressed as

$$T_w = i_g i_0 \eta_t T_p \quad \text{……………...eq1}$$

where *ig* is the gear ratio of the transmission defined as *ig_Nin/Nout* (*Nin* —input rotating speed, *Nout* —output rotating speed), *i*0 is the gear ratio of the final drive, η*t* is the efficiency of the driveline from the power plant to the driven wheels, and *Tp* is the torque output from the power plant.

The tractive effort on the driven wheels, as shown in Figure 1.6, can be expressed as

$$F_t = \frac{T_w}{r_d}. \quad \text{....................eq2}$$

Substituting (eq1) into (eq2) yields the following result

$$F_t = \frac{T_p i_g i_0 \eta_t}{r_d}$$ eq3

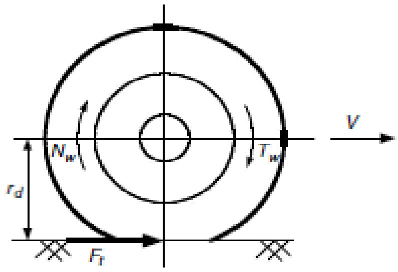


Figure : Tractive effort and torque on a driven wheel

The friction in the gear teeth and the friction in the bearings create losses in mechanical gear transmission. The following are representative values of the mechanical efficiency of various components:

Clutch: 99%

Each pair of gears: 95–

97% Bearing and joint:

98–99%

The total mechanical efficiency of the transmission between the engine outputshaft and drive wheels or sprocket is the product of the efficiencies of allthe components in the driveline. As a first approximation, thefollowing average values of the overall mechanical efficiency of a manual gear-shift transmission may be used:

Direct gear: 90%

Other gear: 85%

Transmission with a very high reduction ratio: 75–80%

The rotating speed (rpm) of the driven wheel can be expressed as

$$N_w = \frac{N_p}{i_g i_0},$$ eq4

where *Np* is the output rotating speed (rpm). The translational speed of thewheelcenter (vehicle speed) canbe expressed as

$$V = \frac{\pi N_w r_d}{30} \text{(m/s)}.$$ eq5

Substituting (eq4) into (eq5) yields

$$V = \frac{\pi N_p r_d}{30 i_g i_0} \text{(m/s)}$$ eq6

VEHICLE POWER PLANT AND TRANSMISSION CHARACTERISTICS:

There are two limiting factors to the maximum tractive effort of a vehicle. One is the maximum tractive effort that the tire–ground contact can support and the other is the tractive effort that the power plant torquewith given driveline gear ratios can provide (equation [2.29]). The smaller of these two factors will determine the performance potential of the vehicle. For on-road vehicles, the performance is usually limitedby the second factor.

In order to predict the overall performance of a vehicle, its power plant and transmission characteristics must be taken into consideration.

1. POWER PLANT CHARACTERISTICS:

For vehicular applications, the ideal performance characteristic of a power plant is the constant power output over the full speed range. Consequently, the torque varies with speed hyperbolically as shown in Figure 2.5.2.1.

At low speeds, the torque is constrained to be constant so as not to be over the maximaimited by the adhesion between the tire–ground contact areas. This constant power characteristic will provide the vehicle with a high tractive effort at low speed, where demands for acceleration, drawbar pull, or grade climbing capability are high.

Since the internal combustion engine and electric motor are the most commonly used power plants for automotive vehicles to date, it is appropriate to review the basic features of the characteristics that are essential to predicating vehicle performance and driveline design.

Representative characteristics of a gasoline engine in full throttle and an electric motor at full load are shown in Figure 2.5.2.2 and Figure 2.5.2.3, respectively.

The internal combustion engine usually has torque–speed characteristics far from the ideal performance characteristic required by traction. It starts operating smoothly at idle speed.

Good combustion quality and maximum engine torque are reached at an intermediate engine speed. As the speed increases further, the mean effective pressure decreases because of the growing losses in the air-induction manifold and a decline in engine torque.

Power output, however, increases to its maximum at a certain high speed. Beyond this point, the engine torque decreases more rapidly with increasing speed. This results in the decline of engine power output. In vehicular applications, the maximum permissible

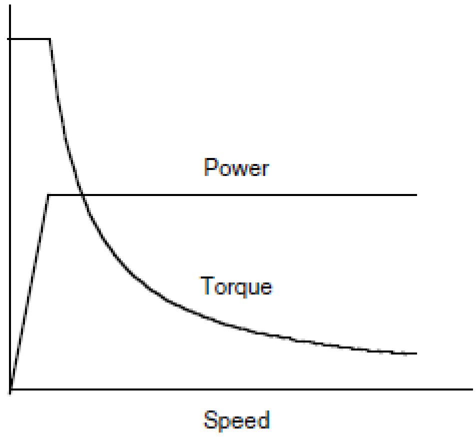


Figure2.5.2.1: Ideal performance characteristics for a vehicle traction power plant

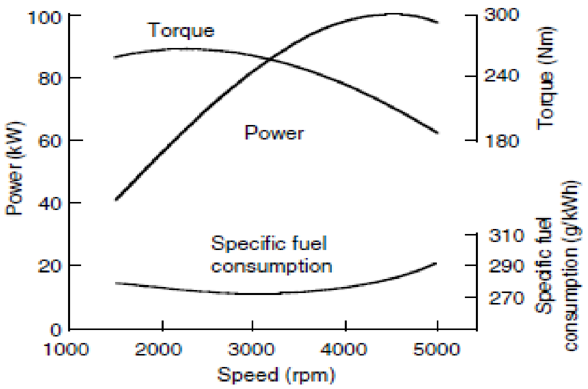


Figure2.5.2.2: Typical performance characteristics of gasoline engines

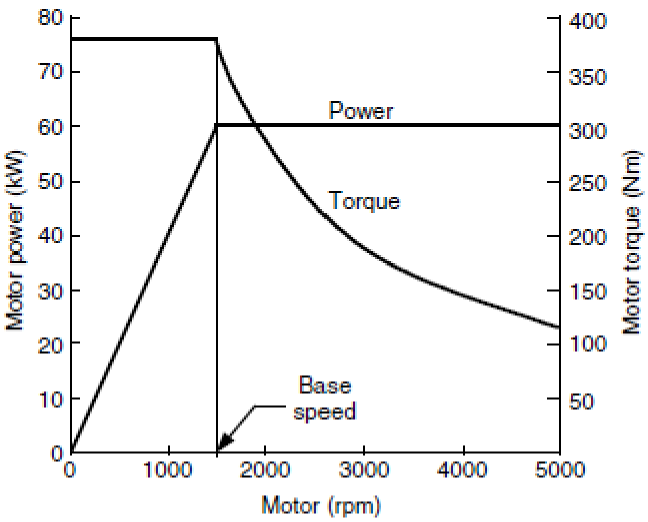


Figure2.5.2.3: Typical performance characteristics of electric motors for traction

Speed of the engine is usually set just a little above the speed of the maximum power output. The internal combustion engine has a relatively flat torque–speed profile (compared with an ideal one), as shown in Figure2.5.2.1.Consequently, a multigear transmission is usually employed to modify it, as shown in Figure

2.5.2.3.Electric motors, however, usually have a speed–torque characteristic that ismuch closer to the ideal, as shown in Figure 2.5.2.2. Generally, the electric motorstarts from zero speed.

As it increases to its base speed, the voltage increasesto its rated value while the flux remains constant.Beyond the base speed, the

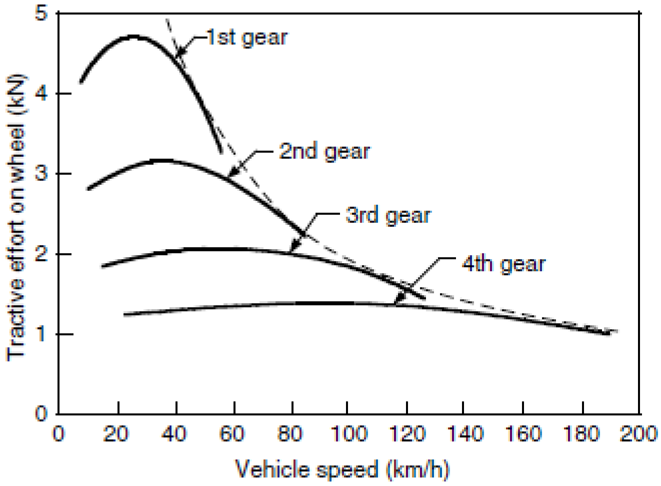


Figure 2.5.2.4: Tractive effort of internal combustion engine and a multigear transmission vehicle vs. vehiclespeed

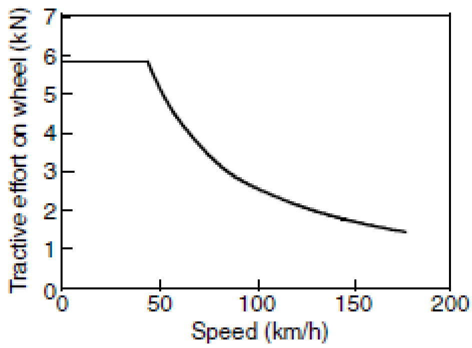


Figure2.5.2.5: Tractive effort of a single-gear electric vehicle vs. vehicle speed

Voltage remains constant and the flux is weakened. This results in constant output power while the torque declines hyperbolically with speed. Since the speed–torque profile of an electric motor is close to the ideal, a single-gear or double-gear transmission is usually employed, as shown in Figure 2.5.2.5.

TRANSMISSION CHARACTERISTICS:

The transmission requirements of a vehicle depend on the characteristics of the power plant and the performance requirements of the vehicle. As mentioned previously, a well-controlled electric machine such as the power plant of an electric vehicle will not need a multigear transmission. However, an internal combustion engine must have a multigear or continuously varying transmission to multiply it s torque at low speed. The term transmission here includes all those systems employed for transmitting engine power to the drive wheels.

For automobile applications, there are usually two basic types of transmissions: manual gear transmissionand hydrodynamic transmission.

Manual Gear Transmission

Manual gear transmission consists of a clutch, gearbox, final drive, and driveshaft. The final drive has a constant gear reduction ratio or a differential gear ratio. The common practice of requiring direct drive (non-reducing) in the gearbox to be in the highest gear determines this ratio.

The gearbox provides a number of gear reduction ratios ranging from three to five for passenger cars and more for heavy commercial vehicles that are powered with gasoline or diesel engines. The maximum speed requirement of the vehicle determines the gear ratio of the highest gear (i.e., the smallest ratio). On the otherhand, the gear ratio of the lowest gear (i.e., the maximum ratio) is determined by the requirement of the maximum tractive effort or the grade ability. Ratios between them should be spaced in such a way that they will provide the tractive effort–speed characteristics as close to the ideal as possible, as shown in Figure

In the first iteration, gear ratios between the highest and the lowest gear may be selected in such a way that the engine can operate in the same speed range for all the gears. This approach would benefit the fuel economy and performance of the vehicle. For instance, in normal driving, the proper gear can be selected according to vehicle speed to operate the engine in its optimum speed range for fuel-saving purposes. In fast acceleration, the engine can be operated in its speed range with high power output. This approach is depicted in Figure 2.5.3.2.For a four-speed gear box, the following relationship can be established.

$$\frac{i_{g1}}{i_{g2}} = \frac{i_{g2}}{i_{g3}} = \frac{i_{g3}}{i_{g4}} = K_g$$

……….eq1 and

$$K_g = \sqrt[3]{\frac{i_{g1}}{i_{gg4}}},$$

…………..eq2

where *ig*1, *ig*2, *ig*3, and *ig*4 are the gear ratios for the first, second, third, and fourth gear, respectively. In amore general case, if the ratio of the highest

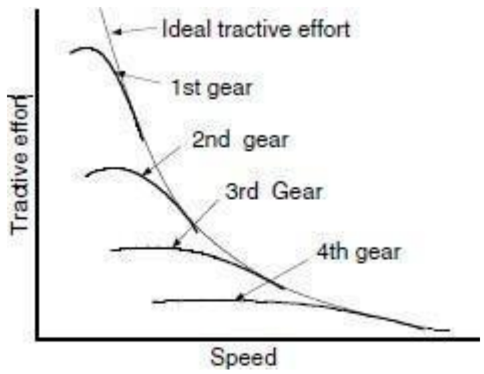


Figure2.5.3.1: Tractive effort characteristics of a gasoline engine-powered vehicle

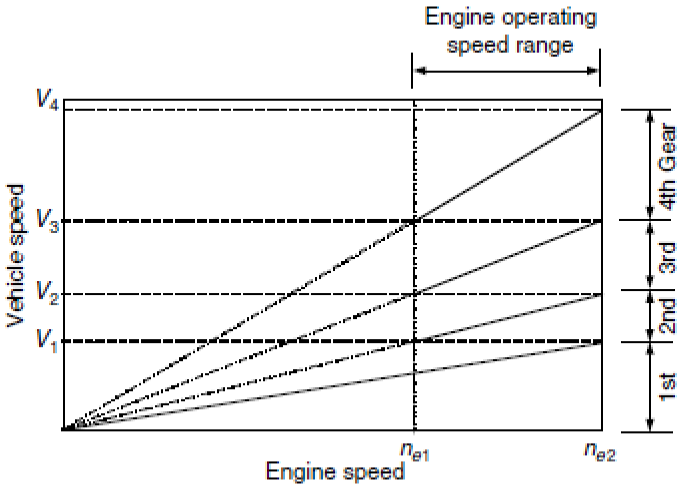


Figure 2.5.3.2: Demonstration of vehicle speed range and engine speed range for each gear

gear, *ign*(smaller gear ratio), and the ratio of the lowest gear, *ig*1 (largest gearratio), have been determinedand the number of the gear *ng* is known, thefactor*Kg* can be determined as

$$K_g = \left(\frac{i_{g1}}{i_{gn}}\right)^{(n_g-1)},$$ …………eq3

and each gear ratio can be obtained by

$$\begin{aligned} i_{gn-1} &= K_g i_{gn} \\ i_{gn-2} &= K_g^2 i_{gn} \\ &\vdots \\ i_{g2} &= K_g^{n_g-1} i_{gn}. \end{aligned}$$ …………eq4

For passenger cars, to suit changing traffic conditions, the step between the ratios of the upper two gears isoften a little closer than that based on (eq4).That is,

……..eq5 $$\frac{i_{g1}}{i_{g2}} > \frac{i_{g2}}{i_{g3}} > \frac{i_{g3}}{i_{g4}}.$$

This, in turn, affects the selection of the ratios of the lower gears. For commercialvehicles, however, thegear ratios in the gearbox are often arrangedbased on (eq5).

Figure 2.5.3.3 shows the tractive effort of a gasoline engine vehicle with fourgeartransmission and that of an electric vehicle with single-gear transmission. It is clear that electric machines with favorable torque–speed characteristicscan satisfy tractive effort with simple single-gear transmission.

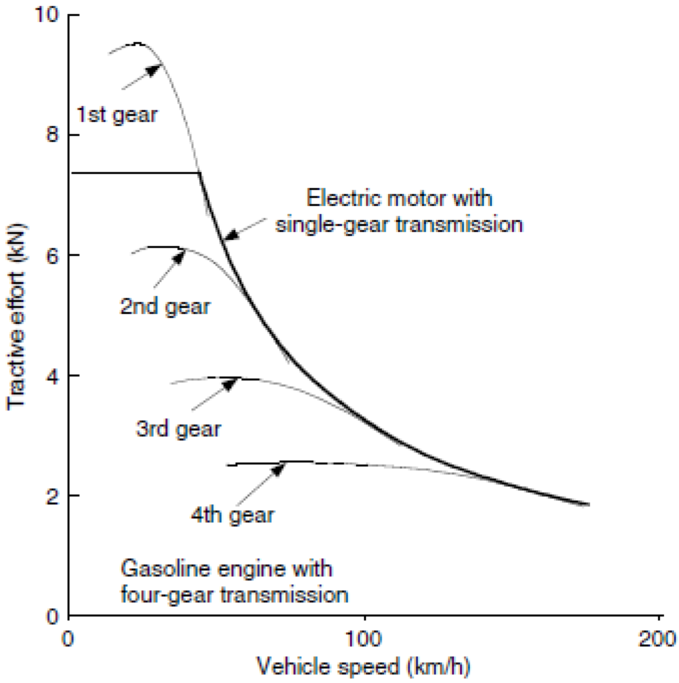


Figure2.5.3.3: Tractive efforts of a gasoline engine vehicle with four-gear transmission and an electricvehiclewith single-gear transmission

HYDRODYNAMIC TRANSMISSION

Hydrodynamic transmissions use fluid to transmit power in the form oftorque and speed and arewidely used in passenger cars. They consist of atorque converter and an automatic gearbox. The torque converter consists ofat least three rotary elements known as the impeller (pump), the turbine, andthe reactor, as shown in Figure **1.5.3.2.1**

The impeller is connected to the engineshaft and the turbine is connected to the output shaft of the converter, whichin turn is coupled to the input shaft of the multispeed gearbox. The reactor iscoupled to external housing to provide a reaction on the fluid circulating in theconverter. The function of the reactor is to enable the turbine to develop anoutputtorque higher than the input torque of the converter, thus producingtorque multiplication. The reactor is usually mounted on a free wheel (one-wayclutch) so that when the starting period has been completed and the turbinespeed is approaching that of the pump, the reactor is in free rotation. Atthis point, the converter operates as a fluid coupled with a ratio of output torque to input torque that is equal to 1.0.

The major advantages of hydrodynamic transmission may be summarizedas follows:

• When properly matched, the engine will not stall.

• It provides flexible coupling between the engine and the drivenwheels.

• Together with a suitably selected multispeed gearbox, it providestorque–speed characteristics that approach the ideal.

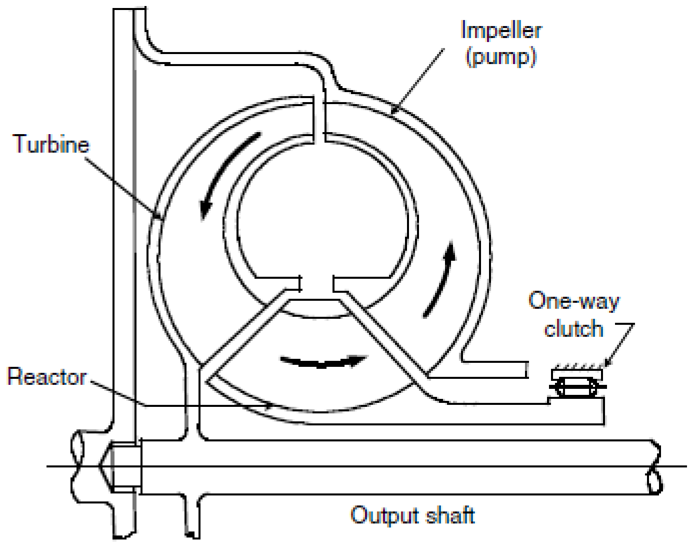


Figure1.5.3.2.1. Schematic view of a torque converter

The major disadvantages of hydrodynamic transmission are its low efficiencyin a stop–go driving pattern and its complex construction.
The performance characteristics of a torque converter are described interms of the following four parameters:

1. *Speed ratio*:

$$C_{sr} = \frac{output\_speed}{input\_speed}, \quad \text{………………….eq1}$$

Which is the reciprocal of the gear ratio mentioned before.
2. Torque ratio:

$$C_{tr} = \frac{output\_torque}{input\_torque}. \quad \text{…………..eq2}$$

3. Efficiency:

$$\eta_c = \frac{output\_speed \times output\_torque}{input\_speed \times input\_torque} = C_{sr}C_{tr}. \quad \text{…………eq3}$$

4. Capacity factor (size factor):

$$K_{tc} = \frac{speed}{\sqrt{torque}}. \quad \text{…………eq4}$$

The capacity factor, *Kc*, is an indicator of the ability of the converter to absorber transmits torque, which is proportional to the square of the rotary speed. Typical performance characteristics of the torque converter are shown inFigure 1.5.3.2.2, in which torque ratio, efficiency, and input capacity factor — thatis the ratio of input speed to the square root of input torque — are plotted against speed ratio. The torque ratio has the maximum value at stall condition, where the output speed is zero. The torque ratio decreases as the speedratio increases (gear ratio decreases) and the converter eventually acts as a hydraulic coupling with a torque ratio of 1.0. At this point, a small difference between the input and output speed exists because of the slip between the impeller (pump) and the turbine. The efficiency of the torque converter is zero at stall condition and increases with increasing speed ratio (decrease in the gear ratio). It reaches the maximum when the converter acts as a fluid coupling (torque ratio equal to 1.0).

To determine the actual operating condition of the torque converter, the engine operating point has to be specified because the engine drives the torque converter.

To characterize the engine operating condition for the purpose of determining the combined performance of the engine and the converter, an engine capacity factor, *Ke*, is introduced and defined as

$$K_e = \frac{n_e}{\sqrt{T_e}}, \quad \text{........eq5}$$

Where *ne* and *Te* are engine speed and torque, respectively.

The variation of the capacity factor with speed for a typical engine is shown in Figure 1.5.3.2.3.

To achieve proper matching, the engine and the torque converter should have a similar range in the capacity factor.

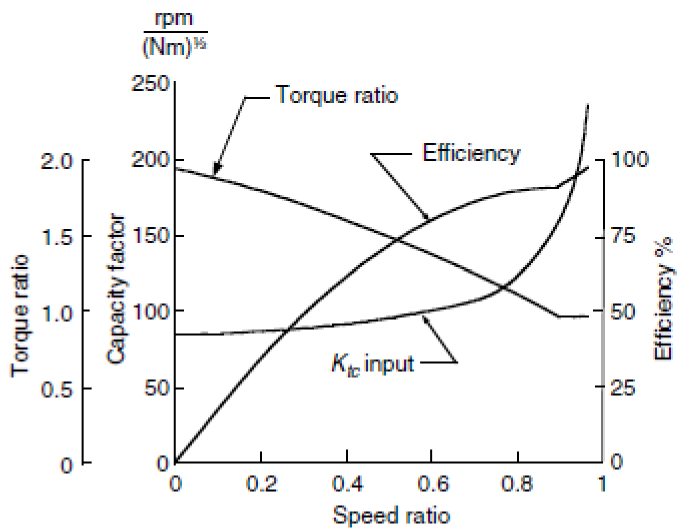


Figure 1.5.3.2.3.: Performance characteristics of a torque converter

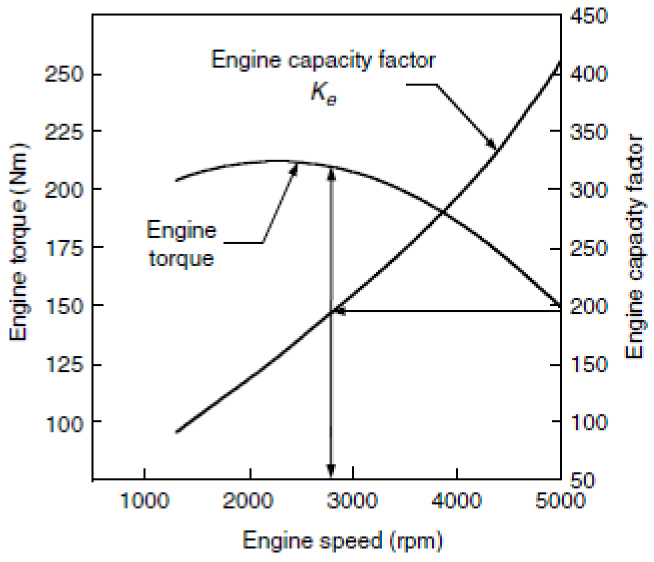


Figure 1.5.3.2.4: Capacity factor of a typical engine

The engine shaft is usually connected to the input shaft of the torque converter, as mentioned above. That is,

$$K_e = K_c. \quad \text{..........eq6}$$

The matching procedure begins with specifying the engine speed and engine torque. Knowing the engine operating point, one can determine the engine capacity factor, *Ke*(see Figure 1.5.3.2.5). Since *Ke_ Kc*, the input capacity factor of the torque converter corresponding to the specific engine operating point is then known. As shown in Figure 1.5.3.2.4, for a particular value ofthe input capacity factor of the torque converter, *Ktc*, the converter speed ratio, *Csr*, and torque ratio, *Ctr*, can be determined from the torque converter performance characteristics. The output torque and output speed of the converter are then given by

$$T_{tc} = T_e C_{tr} \quad \text{........................eq7}$$

and

$$n_{tc} = n_e C_{sr}, \quad \text{................eq8}$$

Where *Ttc* and *ntc* are the output torque and output speed of the converter, Respectively.

Since the torque converter has a limited torque ratio range (usually less than 2), a multispeed gearbox is usually connected to it. The gearbox comprises several planetary gear sets and is automatically shifted. With the gear

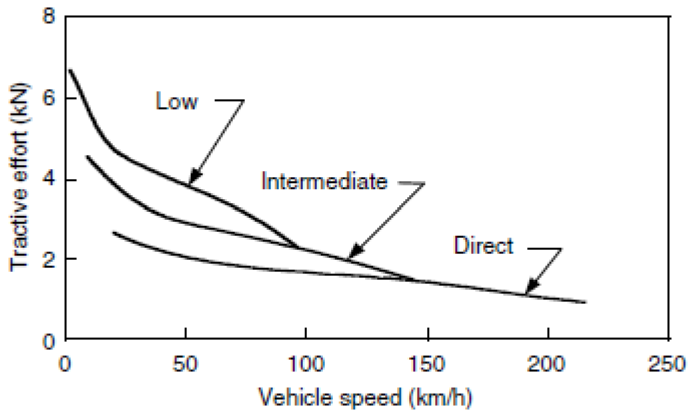


Figure 1.5.3.2.5.: Tractive effort–speed characteristics of a passenger car with automatic transmission

Ratios of the gearbox, the tractive effort and speed of the vehicle can be calculated by

$$F_t = \frac{T_e C_{tr} i_g i_0 \eta_t}{r}$$ ………eq9

and

$$V = \frac{\pi n_e C_{sr} r}{30 i_g i_0} (\mathrm{m/s}) = 0.377 \frac{n_e C_{sr} r}{i_t} (\mathrm{km/h}).$$ …………eq10

Above fig shows the variation of the tractive effort with speed for a passenger car equipped with a torque converter and a three-speed gearbox.

Vehicle Model

For the purpose of this section, the vehicle is modeled as a load, where the load resistance felt by the vehicle is due to the road profile. In other words, the engine, and the electric motor will basically see some speed and torque against which they have to work, in order to drive the vehicle under the particular road profile.

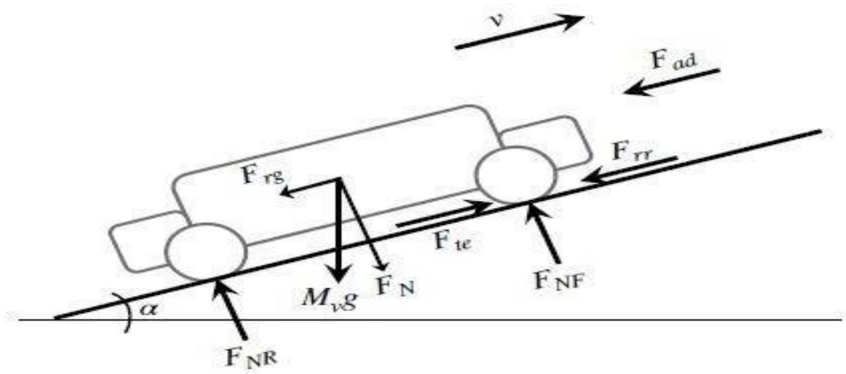


Figure 2.6. Vehicle Model

Consider the vehicle and the associated forces illustrated in Figure. Here, a vehicle of mass $\boldsymbol{M_v}$ is considered, moving at a velocity ***v*,** and moving up a slope of **angle α** (in degrees). The propulsion force or the tractive force (i.e. driving force) is $\boldsymbol{F_{te}}$**.** This force has to overcome rolling resistance $\boldsymbol{F_{rr}}$**,** aerodynamic drag $\boldsymbol{F_{ad}}$, the climbing resistance force $\boldsymbol{F_{rg}}$ (the component of the vehicle's weight acting down the slope), and the force to accelerate the vehicle (the acceleration force), if the velocity is not constant. The total of the first three terms is the road load force $\boldsymbol{F_{RL}}$. The road load, therefore, can be written as

$$F_{RL} = F_{rr} + F_{ad} + F_{rg}$$ **---------------------- (1)**

The rolling resistance F_{rr} is really produced at the tire's internal material level due tothe hysteresis of the tire, and ultimately arising from the interaction of the tire with the roadway. Rolling resistance depends on the coefficient of rolling friction between thetire and the road C_f, the normal force F_N due to the vehicle's weight $M_v g$, and the gravitational acceleration g. If the vehicle is at rest and the force applied to the road is not great enough to overcome the rolling resistance, then the rolling resistance must exactly cancel out the applied tractive force to keep the vehicle from moving. Hence, the equation for rolling resistance can be written as

$$F_{rr} = -F_{te} \qquad \text{if} \quad v = 0 \quad \text{and} \quad F_{te} < C_f \ M_v g \cos\left(\frac{\alpha\pi}{180^\circ}\right)$$
$$F_{rr} = -C_f \ M_v g \cos\left(\frac{\alpha\pi}{180^\circ}\right) \qquad \text{otherwise}$$

______(2)

The aerodynamic drag depends on the air **density ρ** (kg/m^3), coefficient **of drag C_d,** frontal **area** of thevehicle $\boldsymbol{A}$, and vehicle speed $\boldsymbol{v}$. The equation for the aerodynamic drag is

$$F_{ad} = 0.5\rho C_d A v^2 \operatorname{sgn}(v)$$

where

$$\begin{aligned} \operatorname{sgn}(v) &= +1 \quad \text{if} \quad v > 0 \\ &= -1 \quad \text{if} \quad v < 0 \end{aligned} \qquad \text{\_\_\_\_\_ (3)}$$

The force due to the road grade (slope of the road) depends on the mass of the vehicle M_v, slope angle indegrees α, and gravitational acceleration g. The equation for this force is

$$F_{rg} = -M_v g \sin\left(\frac{\alpha\pi}{180°}\right) \qquad \text{\_\_\_\_\_\_\_\_\_\_(4)}$$

The force to accelerate the vehicle is governed by Newton's second law, and leads tothe linear accelerationof the vehicle. This is given by

$$F_{acc} = M_v a = M_v \frac{dv}{dt} \qquad \text{\_\_\_\_\_\_\_\_\_\_(5)}$$

The total tractive effort is the sum of all the above forces:

$$F_{te} = F_{rr} + F_{ad} + F_{rg} + F_{acc} \qquad \text{\_\_\_\_\_\_\_\_(6)}$$

The vehicle's velocity is calculated by integrating the vehicle's acceleration from time t = 0 seconds to adesired time t, with the initial velocity set to 0 km/h. This is given by

$$V = \frac{1}{M_v} \int_{t}^{t=0} \left(F_{te} - F_{rr} - F_{ad} - F_{rg}\right) dt \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_(7)}$$

In the case of an ICE-driven vehicle, the vehicle tractive force comes from the engineshaft torque. The axletorque and engine torque are related as

$$T_{axle} = (T_{ICE})(GR_{trans})(GR_{diff})(\eta_{trans})(\eta_{diff}) \qquad \text{\_\_\_\_\_\_\_\_\_\_(8)}$$

where T denotes torque, GR denotes gear ratio, η denotes efficiency, subscript "*trans*" denotes transmission, and subscript "*diff*" denotes differential. Thus, the tractiveforce is

$$F_{te} = \frac{T_{axle}}{\text{tire radius}} \qquad \text{\_\_\_\_\_\_\_\_\_\_(9)}$$

In the case of series hybrid vehicles, the tractive (propulsion) force to the wheels comes from electric motor shaft torque;

In the case of parallel hybrid vehicles, the propulsion torque can come either from the combination of the torques from the ICE and electric traction motor, or it can come from only one of these entities, depending onthe algorithm used to make the decision.

UNIT 3
PLUG-IN HYBRID ELECTRIC VEHICLES

INTRODUCTION

Plug-in hybrid electric vehicle (PHEV) is another type of emerging vehicle that combines alternative fuels to displace the oil consumptions in conventional vehicles. As the name suggests, PHEVs are a special type of hybrid electric vehicles (HEVs). Similar to HEVs, PHEVs integrate the electric power path with the mechanical power path by using both conventional combustion engines (ICE) and electric machines. They can also be charged directly by plugging the wire into the wall to get power from the grid (hence the name).The differences between PHEVs and HEVs primarily lie in battery capacity and recharging methods. PHEVs are equipped with larger battery capacities that are capable of operating on battery power alone for a considerable range, which is called all-electric driving range. Typically, this all-electric range (AER) is designed to meet the daily driving requirements of PHEV owners, especially city drivers and suburban commuters. It is estimated that in Europe, 50% of trips are less than 10 km (6.25 miles) and 80% of trips are less than 25 km (15 miles). In the United Kingdom, 97% of trips are less than 80 km (50 miles). In the United States, about 60% of vehicles are driven less than 50 km (31.25 miles) daily, and about 85% are driven less than 100 km (60miles). Therefore, a PHEV with an electric range of 60 miles would meet most of the trip range requirements in Europe and America, which is denoted as PHEV-60 (or PHEV-100 km). Figure 3.1 shows the typical U.S. daily travel distance distributions.

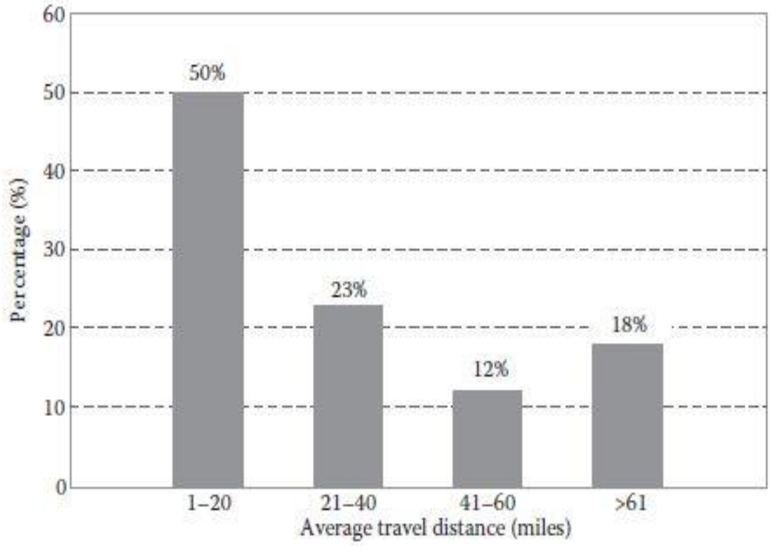


Figure 3.1 U.S. Daily Travel Distances Distributions

In addition, a Figure 3.2 plot the single-trip distance within the day trips publishes the 1995 National Household Travel Survey in the United States that combined the survey results for more than 400 thousand interviewees.

It is apparent that the majority of the single-trip travel distance lies less than 10 miles per trip, which is kept well within the AER of almost all the PHEVs. In between any of the two trips, it is possible to recharge the vehicle batteries at home, at work, at the parking lots in front of the grocery stores, at the electric charging station in public, and so on.

The battery-recharging capability in PHEVs by plugging the vehicle directly into external electric power outlets makes another major difference compared to HEVs. This is also the key benefit of PHEVs since petroleum is no longer the only fuel source for the vehicle. In fact, electricity serves the larger part of the energy supply in PHEVs and thus, the energy dependence on petroleum products is greatly reduced. Typically, the electric energy comes from the electrical grids, which might be a selection from conventional coal energy, nuclear energy, or the renewable energies such as wind energy and solar energy. Depending on how energy is generated at different regions, different levels of well-to-wheel fuel economy and emission reductions can be achieved. Thus, compared with conventional ICEs that exclusively rely on petroleum fuel, PHEVs offer the option to choose from cheap and clean energy sources that generate electricity, reducing the reliance on either petroleum energy or any other single form of energy. In the United States, the number of renewable electricity generation plants is substantially increasing as shown in Figure 3.3.

Generally speaking, PHEVs involve higher degrees of electric power portion and require higher performance from the electric power system, while the mechanical power system is reduced to a minimal level so that it can help sustain the electric power system. Table 3.1 compares PHEVs, different configurations of HEVs, and conventional vehicles.

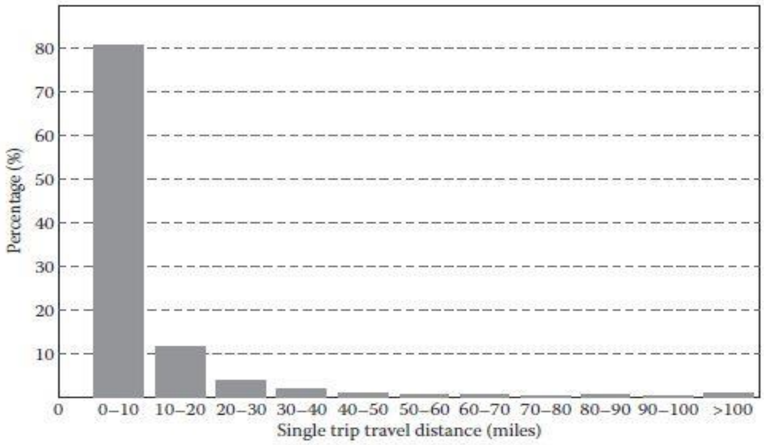


Figure 3.2 Single-Trip Travel Distance. (Adapted From Day Trips, 1995. National Personal Transportation Survey (NPTS)).

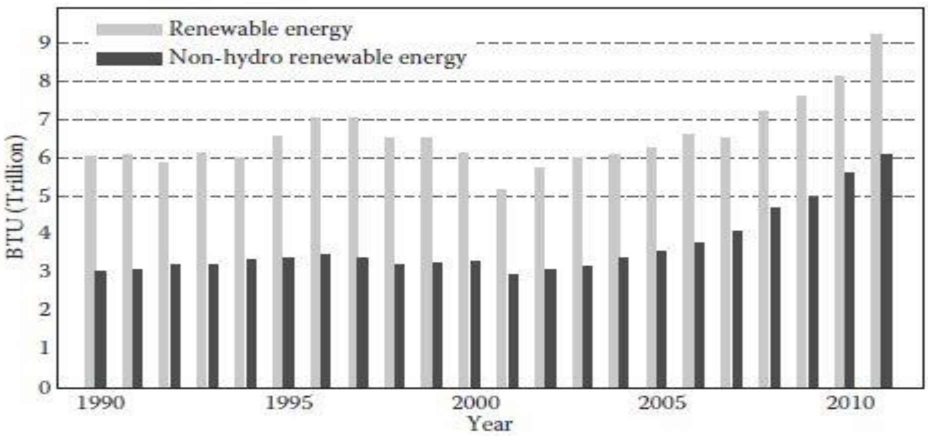


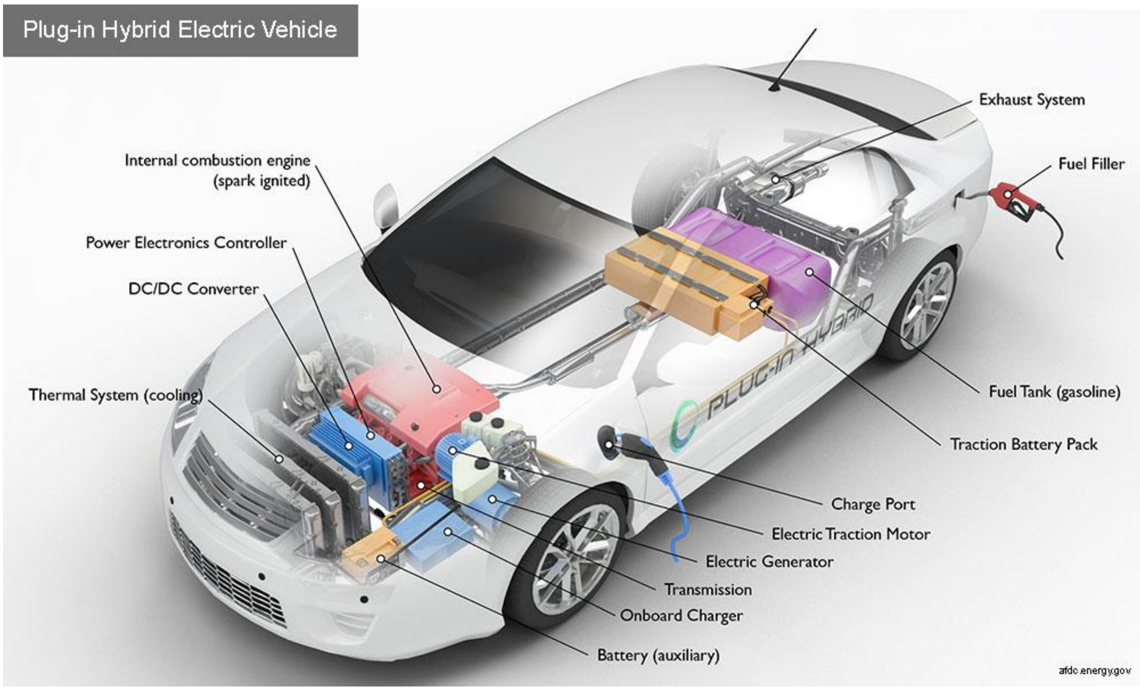
Figure 3.3 U.S. Renewable Electricity Generation. (Adapted From U.S. Energy Information Administration, Electric Power Annual And Electric Power Monthly (March 2012) Based On Preliminary 2011 Data.)

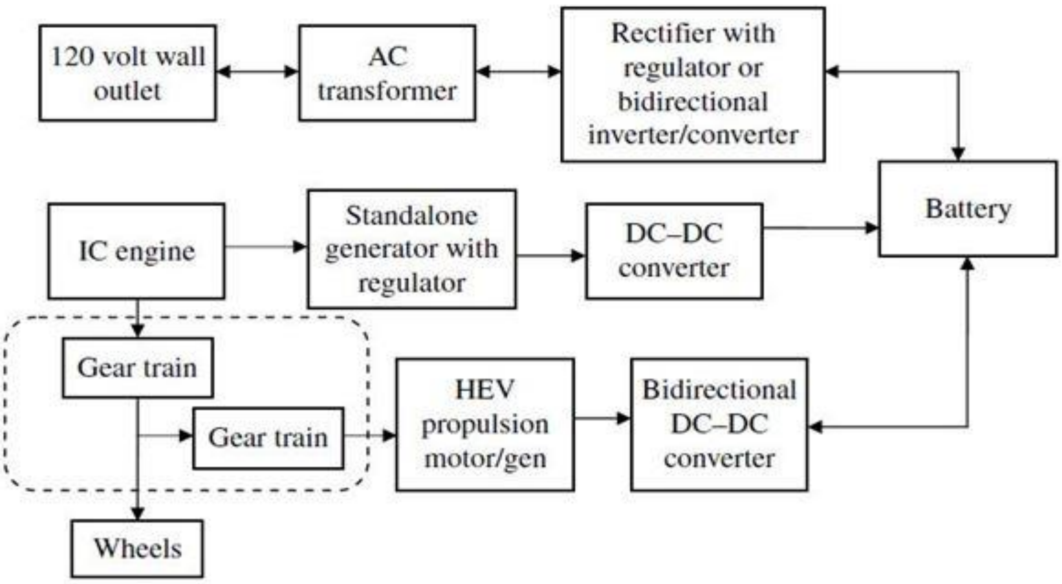
Table 3.1

TABLE

PHEVs, Different Types of HEVs, and Conventional Vehicle Comparisons

	Stop and Start	Regenerative Braking	Motor Assistance	Electric Driving	External Battery Charge
Conventional vehicles	Mostly no	No	No	No	No
Micro-HEVs	Yes	Minimum	No	No	No
Mild HEVs	Yes	Yes	Minimum	No	No
Full HEVs	Yes	Yes	Yes	Yes	No
PHEVs	Yes	Yes	Yes	Yes	Yes





Battery (auxiliary): In an electric drive vehicle, the low-voltage auxiliary battery provides electricity to start the car before the traction battery is engaged; it also powers vehicle accessories.

Charge port: The charge port allows the vehicle to connect to an external power supply in order to charge the traction battery pack.

DC/DC converter: This device converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery.

Electric generator: Generates electricity from the rotating wheels while braking, transferring that energy back to the traction battery pack. Some vehicles use motor generators that perform both the drive and regeneration functions.

Electric traction motor: Using power from the traction battery pack, this motor drives the vehicle's wheels. Some vehicles use motor generators that perform both the drive and regeneration functions.

Exhaust system: The exhaust system channels the exhaust gases from the engine out through the tailpipe. A three-way catalyst is designed to reduce engine-out emissions within the exhaust system.

Fuel filler: A nozzle from a fuel dispenser attaches to the receptacle on the vehicle to fill the tank.

Fuel tank (gasoline): This tank stores gasoline on board the vehicle until it's needed by the engine.

Internal combustion engine (spark-ignited): In this configuration, fuel is injected into either the intake manifold or the combustion chamber, where it is combined with air, and the air/fuel mixture is ignited by the spark from a spark plug.

Onboard charger: Takes the incoming AC electricity supplied via the charge port and converts it to DC power for charging the traction battery. It also communicates with the charging equipment and monitors battery characteristics such as voltage, current, temperature, and state of charge while charging the pack.

Power electronics controller: This unit manages the flow of electrical energy delivered by the traction battery, controlling the speed of the electric traction motor and the torque it produces.

Thermal system (cooling): This system maintains a proper operating temperature range of the engine, electric motor, power electronics, and other components.

Traction battery pack: Stores electricity for use by the electric traction motor.

Transmission: The transmission transfers mechanical power from the engine and/or electric traction motor to drive the wheels.

FUNCTIONS AND BENEFITS OF PHEV

PHEVs combine the function of HEVs and electric vehicles (EVs) in a large sense, running both on electricity and liquid petroleum fuels. Large battery capacities enable PHEVs to operate in all-electric mode as much as possible, thus reducing fuel consumption with the use of cheaper and cleaner electricity. However, PHEVs still have a much shorter all-electric driving range compared with pure EVs due to battery costs, which limit battery capacities. Therefore, all-electric driving mode is mostly used within urban driving or daily commuting. After discharging the battery power to a certain low level, the engine starts to charge the battery, and the PHEV switches from operating like an EV to working as an HEV instead. Both the electric power system and the mechanical power sys- tem are utilized to supply the vehicle power, and an extended driving range is achieved in the form of hybrid operation. In addition, the range anxiety associated with EV drivers that the battery might deplete while driving is much alleviated in PHEVs since the engine provides a backup source of power and extends the driving range of PHEVs as good as other conventional gas-powered vehicles. Similar to HEVs, PHEVs have been mainly developed to deal with the three emerging issues in the vehicle transportation sector: fossil energy security, vehicle air pollution, and climate change due to greenhouse gas (GHG) emissions.

Reducing oil consumption in the transportation sector is the primary objective for which PHEVs are designed. According to the International Energy Outlook 2010 released by the U.S. Energy Information Administration, the world's annual oil consumption reached 495 quadrillion Btu in 2007, increasing by 36% from the 1980 level. And it is the transportation sector that accounts for the largest oil consumption and shows the largest growth in oil demand during the past few decades. Especially with the current soaring demand from developing countries, the oil consumption rate is increasing faster than ever, which can also be revealed in the substantial increase trend of the crude oil price. Figure 3.4 shows the U.S. crude oil refiner acquisition costs from 1968 to 2011.

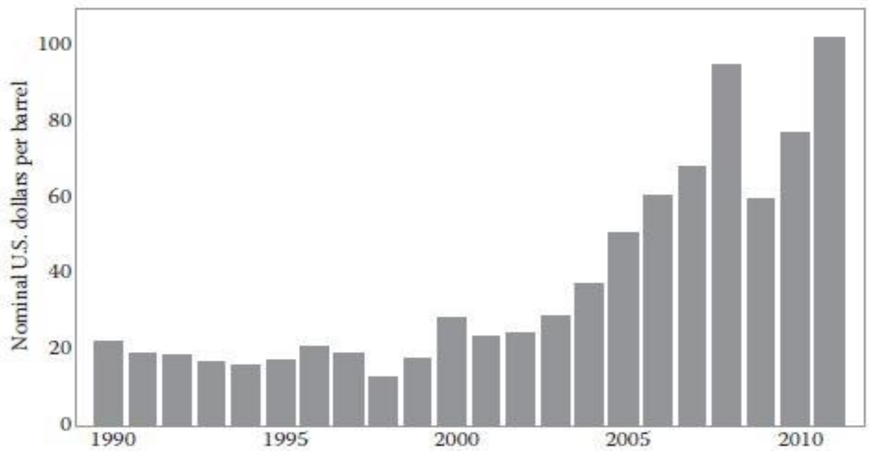


Figure 3.4 U.S. Crude Oil Refiner Acquisition Costs. (Adapted From *Annual Energy Review* 2010, U.S. Energy Information Administration, Report Number: DOE/EIA-0384, 2010).

In addition, energy security is emphasized by many nations as a major priority. Take the United States (U.S.) as an example, the U.S. reliance on imported crude oil has been declining since 2009 as shown in Figure 3.5, and the government is still urging for less-imported crude oil by producing more domestic crude oil and alternative energy as well as encouraging measures to increase vehicle fuel efficiency. The fuel efficiency standard released by the U.S. government in 2012 in collaboration with major auto manufacturers, the United Auto Workers, consumers, and environmental groups required cars and light trucks to achieve an average of 54.5 miles per gallon by 2025, saving the average family an estimated $8000 at the pump and helping the United States halfway to its goal to cut imported oil by a third. European and Asian countries are also implementing similar fuel efficiency regulations to reduce oil consumption to ensure national energy security. Therefore, vehicles such as PHEVs and EVs that provide means to achieve better fuel efficiency and less or no petroleum consumption are highly desired in the transportation sector to lessen their dependence on petroleum energy and to alleviate or even avoid the upcoming potential energy crisis.

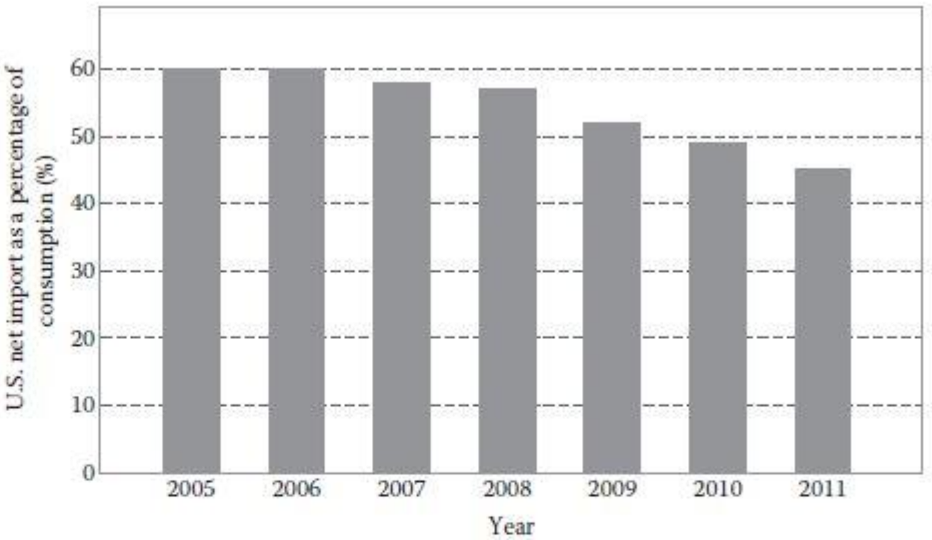


Figure 3.5 U.S. dependence on imported oil declining. (Adapted from M. Slack, Our dependence on foreign oil is declining

Another important objective that PHEVs are designed to resolve is the reduction of environmen-tal pollution from vehicle emissions. Emissions are generated as a form of vehicle exhaust after the fuel–air burning process in ICEs. They are also produced by fuel evaporation during uncompleted fuel burning or simply during fueling process. Poorly treated emissions can cause severe environ- mental problems and health problems such as cancers due to significant, chronic exposures. Table lists the most commonly found pollutants in vehicle emissions.

The development of PHEVs is considered by many policy makers as one of the most promising and currently practical strategies to reduce environmental pollution from the transportation sector. Regulations have been adopted and incentives have been offered throughout the world to stimulate research and development in PHEVs. Conventionally, ICEs are highly inefficient, with an average efficiency of less than 30% due to the maximum heat–work conversion constraint, and they producea wide range of emissions even with the assistance of after-treatment systems. By comparison, machines that use electricity as their energy source have much higher efficiency, and thus produce larger power output with the same input power. There are essentially no tailpipe emissions generated because the only by-product of using electric machines is the used battery, which can be recycled or reused for other applications.

In general, PHEVs produce much lower tailpipe emissionsthan similar conventional vehicles while they produce zero tailpipe emissions during the all-electric driving range. Even when compared with the well-to-wheel emissions, PHEVs significantly reducethe emissions by a third compared with the conventional gas vehicles as shown in Figure 3.6.This is because power plants that generate electricity typically have higher efficiency than ICEs; meanwhile, more and more renewable electricity has been generated such as hydropower and wind power so that the emissions at the generation side are further reduced. In addition, since many power stations are far away from cities, the emissions are away from human residential areas while conventional ICEs produce emissions in cities significantly. Thus, by taking advantage of electricity in electric machines, PHEVs can considerably reduce emissions from vehicle tailpipes.

TABLE 3.2

TABLE [redacted]

Commonly Found Pollutants in Vehicles

Greenhouse and ground-level gases	Carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x), and sulfur dioxide (SO_2)
Air toxics	Hydrocarbons (HC)
Solids/liquids	Particulate matter (PM)

Source: Adapted from U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Just the Basics: Vehicle emissions, freedom CAR AND vehicle technologies program, August, 2003.

PHEVs have many benefits:

1. ***Petroleum consumption reduction:*** The AER enables the switch from using conventional petroleum energy to electricity, which can be generated by various forms of resources. This significantly reduces the dependence on fossil fuel energy in the transportation sector, and provides a wide range of choices to charge the vehicles by generating electricity from renewable energies such as wind energy and solar energy. The benefit of the potential fuel reduction could be substantial. As a U.S. National Laboratory report found out, a 45% of fuel reduction can be achieved by replacing the conventional vehicle by a PHEV with 20 miles of electric travel range.
2. ***Emissions reduction****:* As petroleum consumption is reduced, vehicle emissions due to the burning of the fossil fuels are remarkably reduced as a consequence. And, as discussed

above, both the centralized generation of electricity and the use of renewable energy sources contribute to significant emission reductions. However, it should also be noted that since PHEVs typically work in the electric-only range that requires minimal engine operations, emissions might increase at the beginning of the engine start due to infrequent, multiple-engine cold starts. Methods and control algorithms have existed to address such problems so that the overall emissions of PHEVs still remain much less than typical conventional vehicles under the same comparable size.

3. ***Energy cost saving:*** Besides the fuel consumption and emission reduction benefits, PHEVs also bring in the benefits of much lower energy costs. Although the exact cost saving depends on both long-term fossil fuel prices and electricity prices, it is estimated that, on an average, the fuel cost per mile of electricity is one-quarter to one-third of the cost per mile of fossil fuels for PHEV owners. Meanwhile, governmental green energy incentives and certain privileges of lower auto-insurance compensate for the higher initial costs of PHEVs.
4. ***Maintenance cost saving:*** Since the mechanical components such as transmission and clutches are downsized and less frequently used, there are relatively fewer maintenance requirements regarding these parts, which are normally the maintenance concerns of conventional vehicles. Reducing the use of the engine also extends the engine life and reduces the frequency of oil changes. Besides, by taking advantage of regenerative braking, there is less friction wear on the mechanical brake, thus reducing the costs of frequently replacing the brake pad.
5. ***Vehicle-to-grid (V2G) benefits:*** PHEVs have the ability to supply the power back to the grid when they are connected to the grid; this serves to maintain a stable grid power level and to reduce power ripples. PHEVs could potentially serve as a temporary backup power source for home usage when grid power is not available.
6. ***Customer benefits of home recharging:*** PHEV owners enjoy the benefits of charging their vehicles in their garages or near their homes instead of looking for public-charging stations. This also allows the benefit of charging the vehicles at night when the vehicles are typically not in use and the electricity rate is the cheapest

COMPONENTS OF PHEVs

PHEV power trains are composed of the electric motor, generator, battery, and engine, which are all similar to those in HEV configurations. However, different sizes and power ratings are used in PHEVs.

1.BATTERY

Battery serves as the major energy source in PHEVs. Owing to the increased portion of the electric power system and the desired all-electric driving range, large quantities of batteries with sufficient energy capacity and power density are required in the PHEV power train to meet the demanded all-electric driving range. It is capable of supplying all the power required to propel the vehicle throughout the entire speed range, and it should be equipped with sufficient energy capacity to sustain the desired AER. Moreover, the battery also needs to provide all the power to the accessories such as air conditioning and power steering during the all-electric driving range. Thus, higher battery performance is demanded by PHEVs.

On the other hand, the overall vehicle weight and manufacturing costs are prone to the amount of the battery, which increases significantly as the battery packs increase. Moreover, large quantities of onboard vehicle batteries also bring in safety concerns about the fire hazards or high-voltage short circuits in either normal vehicle operations or accidents. Thus, battery technology plays the most critical role in developing PHEVs with regard to performance, costs, and reliability.

Different types of batteries are used in PHEVs. Lithium-ion batteries are currently the most widely used battery in PHEVs. They provide high-energy density and high-power density so that for the same weight of the battery, they enable longer all-electric driving range and better vehicle performance. They also have low self-discharge rate that may reduce the charging frequency and perform better under low usage rate.[19] On the other hand, safety is a big issue associated with lithium-ion batteries. To operate lithium-ion batteries in a continuous stable state, well-designed battery management system (BMS) and cooling systems are required. Specific conditions such as vibration, humidity, overcharge, short circuit, extreme weather, fire, and water immersion should all be taken into account during the design and manufacturing process. These add up the cost of lithium-ion batteries and how to bring down the cost is a hot topic in both academic research and industrial manufacturing. Despite the high price currently, lithium-ion batteries dominate the PHEV battery market due to their high performance. The top three best-selling PHEVs currently are: GM's Chevy Volt, Toyota's Prius Plug-in Hybrid, and Ford's C-Max Energi, and all these use lithium-ion battery technologies. Other variations of lithium-ion battery are also developed. For instance, BYD implemented lithium iron phosphate ($LiFePO_4$) batteries into F3DM PHEV and Qin PHEV.

Nickel–metal hydride (NiMH) batteries are another type of commercialized battery that has been implemented into PHEVs. It is capable of comparably high-power density and energy den- sity. NiMH batteries operate in a much more stable state that is abuse tolerant compared with lithium-ion batteries. It also has a much longer life cycle than the lead-acid batteries. NiMH batteries are mostly used as the energy source for the first generation of HEVs developed before 2005 such as Toyota Prius and Ford Escape Hybrid because of their lower cost. However, they are gradually replaced by lithium-ion batteries as the technologies are getting better and the cost is coming down.

There are some other types of batteries that can also be used in PHEVs. Lead-acid batteries are the oldest rechargeable battery. The technology has been developed for more than 150 years and the cost is very inexpensive compared with other types of PHEV batteries. They have been widely applied as the low-voltage batteries in the automotive industry for starting, lighting, and ignition. Electric scooters, electric bicycles, wheelchairs, golf carts, and some microhybrid vehicles can also be equipped with lead-acid batteries. In addition, lithium-air batteries are also under research and development. They are capable of extremely high-energy density compared to the conventional gasoline fuels. Toyota is collaborating with BMW on the advanced battery development includ- ing lithium-air batteries. IBM is also developing the lithium-air batteries for automotive traction applications.

2.ELECTRIC MACHINE

Electric machine is another core component in PHEVs. They serve as the primary movers in PHEVs to output speed and torque to the output shafts that are connected with vehicle wheels. Regenerative braking is also achieved by running the electric machine in generating modes so that the kinetic energy is retrieved from the electric machine into batteries. Meanwhile, because the electric machine is the only power source to propel the vehicle in all-electric driving mode, a higher power rating is required for the electric machine so that it can meet the required speed and torque. For instance, GM’s Chevy Volt is capable of 35 miles of all-electric driving range in which all the propulsion power and the accessory power come from the onboard electric machine that outputs the peak power of 111 kW and peak torque of 370 Nm.

It is common in PHEVs that a second electric machine is utilized to serve as a generator and engine starter. The secondary electric machine can also operate as in the motoring mode to assist with the vehicle performance such that both the electric machines operate in the motoring mode that maximum power and torque are generated. In the operations of none all-electric driving mode, the secondary generator helps to charge the battery so that the battery state of charge (SOC) remains above the threshold level and the vehicle can operate under hybrid electric mode, thus significantly increasing the driving range of PHEVs.

Compared with conventional gasoline engines, electric machines typically have much higher efficiency that is greater than 90% in most of the speed and torque range. The lifetime ofonboard electric machines is also expected to be more than 15 years, which is competitive with conventional gasoline engines and there is no need for customs to replace the electric machines within the factory warranty time. Currently, interior permanent magnet machine is the mostpopular choice for traction drive applications due to its high efficiency, high torque density, and high-power density. The achieved power density of electric machines in vehicle propulsion applications is 1.2 kW/kg at the current stage. Research is still going on to increase the power density of electric machines to further reduce the size and increase the power. The targeted power density of electric machines for traction drive in 2020 published by the U.S. Department of Energy is 1.6 kW/kg, requiring 33% increase on electric machine power density within thenext 5–7 years.

3. ENGINE

Similar to HEVs, PHEVs are also equipped with onboard internal combustion engines. The engines applied differ by the configurations of PHEVs. If the engine is connected in series with the electric machines, since the electric machines serve as the primary mover to supply the majority of power, the engine only functions to support the electric machines to share the peak load or charge the battery when the vehicles operate in the hybrid electric mode to extend the PHEV range. Thus, the size and power rating of the engine can be minimized and high engine efficiency is required at constant operating regions. On the other hand, if the engine outputs power in parallel with the electric machines, the engine is responsible for a substantial portion of power demanded from the power train. Thus, the engine should still retain its power and size accordingly, based on the power ratios in PHEVs between mechanical and electric power. In some PHEVs with large battery packs, the engine may only serve as a backup when the battery is depleted so as to extend the driving range and alleviate the range anxiety of customers.

Engines in PHEVs may also apply different technologies compared with engines in conventional vehicles. Atkinson cycle is used instead of the conventional Otto cycle in some of the PHEVs to fur- ther improve the vehicle efficiency. Atkinson cycle allows the engine intake, compression, power, and exhaust strokes that all happen in one revolution of a special designed crankshaft. A greater thermal efficiency is achieved at the expense of losing power density, which is acceptable in most ofthe PHEVs since the engine is not the major energy source and higher efficiency is preferred. Toyota Prius Plug-in Hybrid, Ford C-Max Energi, and Honda Accord Plug-in Hybrid all use Atkinson cycle for their engine propulsion.

Toyota Prius Plug-in Hybrid, for instance, achieved 38.5% thermal effi- ciency by using Atkinson cycle in its 1.8-L gasoline engines.In addition, since the demand for engine power is downsized in PHEVs, systems associated with mechanical power system such as exhaust systems and mechanical transmissions can also be reduced to smaller scales.

4.POWER ELECTRONICS

Power electronics in PHEVs include inverters, DC–DC converters, chargers, and BMS, which also typically come along with battery systems. Inverters serve to transform the DC power from the bat- teries into AC power to propel the electric machines. It is also necessary to retrieve the regenerative energy from the electric machines back into the battery pack by using the motor drive components Besides, an inverter and associated controller are typically needed for the onboard air conditioners that use AC machines.

Multiple DC–DC converters are used to step up and step down the voltages at different levels to suit for various applications. A boost converter is used to increase the DC bus voltage up to a high level from the voltage of the battery pack, which is desired for the electric machines so that the constant torque region is extended and higher power and higher speed can be outputted at the rated operation point. This DC–DC converter should also be capable of bidirectional power transfer so that the power retrieved from the electric machines by regenerative braking can be transferred back into the battery. Multiple DC–DC converters are also needed to adjust the battery voltage to differ- ent low-voltage levels. For instance, a DC–DC converter is used to supply the power for the 12-V accessory loads and charge the 12-V low-voltage battery, while another DC–DC converter may be used to step down the battery voltage to a higher level to operate the high- power applications such as power-steering systems and compressing pumps.

AC–DC converters are needed in battery chargers to convert the AC power from the grid into DC power to charge the battery. Power factor correction and programmable digital controllers with proper voltage–current profiles are needed for high-energy battery packs. Proprietary BMS are used to actively monitor the battery SOC and state of health (SOH). The power and state of each individual battery cell is also regulated and balanced by the BMS system. A good thermal performance is also ensured by properly adjusting the temperature on the battery cells, as well as controlling the flow rate of intake and outtake coolant.

OPERATING PRINCIPLES OF PLUG-IN HYBRID VEHICLE

The operation modes of PHEVs largely depend on the battery SOC. Battery SOC is the term to describe the current state of the battery from 0% to 100%, with 0 standing for an empty batteryand 100 meaning a full-charged battery. In comparison, HEVs typically remain battery SOC in a narrow range, for instance, 60%, to optimize the battery performance and ensure the required bat- tery life. However, PHEVs typically demand greater depth of discharge (DOD) due to the higher dependence on the electricity energy source.

Because of the different operation patterns that PHEVs have from the HEVs, PHEV operations are more often classified by another set of specific operation modes[23]: charge-depleting (CD) mode, charge-sustaining (CS) mode, AER mode, and engine-maintenance mode. Figure 3.9 shows the battery SOC comparison between HEVs and PHEVs. Different modes result in different require- ments on batteries and also affect the performance of the vehicle. Table 3.3 relates the battery requirements with the vehicle operation modes and performance

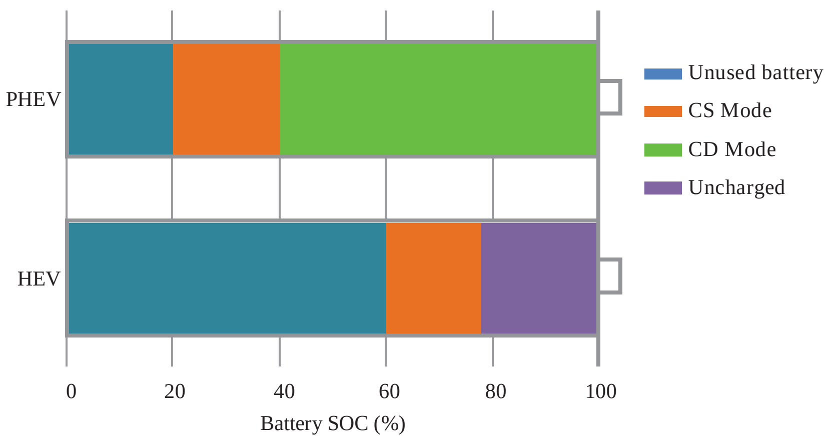


Figure 3.9 Battery Performance Comparison Between Hevs And Phevs. (From U.S. Department Of Energy, Office Of Energy Efficiency And Renewable Energy, Plug-In Hybrid Electric Vehicle R&D Plan, Freedom Car And Vehicle Technologies Program, June 2007.)

CHARGE-DEPLETING MODE

CD mode refers to the PHEV operation mode in which the battery SOC on an average decreases while it may fluctuate along this trend. CD mode is frequently used at the first phase of PHEV operations, in which the SOC of the battery is sufficient to power the vehicle largely by electricity for a certain range. It prioritizes the use of electricity by drawing most of the power from the batterypack as long as the battery SOC stays above the preset threshold. However, if the demanded road power exceeds the battery power, the engine will also be running to assist the electric machine, thusenhancing the output tractive power.

CD mode is the primary operation mode in PHEV operations. In most city-driving and sub-urban-commuting cases, the round-trip distances are well within the PHEV battery power range. Thus, CD mode is largely utilized to take advantage of electric driving so that less fuel is used and fewer emissions are produced.

The extent of CD mode depends on the battery energy capacities and the frequencies of external battery charging. A larger battery pack with higher energy density would result in a longer CD mode range. However, this also contributes to much higher battery costs as well as vehicle weight increases. Recharging the PHEVs also helps to extend the CD range. With the installation of charg- ing stations and the implementation of charging infrastructures at public places such as workplaces, parking lots, or in front of grocery stores, PHEVs can be readily recharged and CD ranges can be significantly increased in daily driving.

CHARGE-SUSTAINING MODE

CS mode refers to the PHEV operation mode in which the battery SOC on average maintains a certain level while it may frequently fluctuate above or below this level. CS mode utilizes both the engine and the electric machine to supply the vehicle power while keeping the SOC of the battery pack at a constant level. It is equivalent to the HEV operation mode in which the engine is mostly running within its optimal fuel efficiency range and the electric machines supply the power ripples. Engine power assistance and hybrid battery charging are realized in the CS mode to extend the driving range.

In PHEV operations, CS mode is more often used after the CD range when the battery power is discharged to a certain low threshold. Once the battery power is insufficient to power the vehicle on its own, the engine starts to supply the vehicle with petroleum combustion power. Both the engine and the electric machine operate together, coordinated under HEV operation mode. This takes advantage of the HEV operation benefits; so, high fuel efficiency is gained while the battery SOC is maintained at a certain level. Thus, the CS mode operation significantly increases the PHEV driv- ing range compared with the CD mode without further increasing battery costs.

The combination of CD and CS mode enables energy use from two energy sources. The electric- ity works as the primary energy carrier to drive the vehicles in the preferred CD mode. The batter- ies can be recharged from external electric energy sources by plugging the vehicles into external power outlets. They can also be recharged by operating the vehicle in the CS mode, in which the engine utilizes the secondary energy carrier, the petroleum fuel, to generate power. In PHEVs, both energy sources are carried onboard the vehicles as they are stored in battery packs and fuel tanks. However, electricity is much preferred because it can be generated by a wide variety of cheaper energy sources, including coal, nuclear, natural gas, wind, hydro, and solar energy, and it greatly reduces vehicle tailpipe emissions. Thus, large packs of battery are normally required on PHEVs while relatively small fuel tanks are used.

AER MODE

As the name suggests, the AER mode uses electricity exclusively as its energy source to powerthe vehicles. The engine is shutoff during the AER mode while the electric machine supplies allthe power by drawing energies from the battery pack. AER mode is similar to CD mode to a large extent, except that AER mode does not use the engine to assist the power output. The maximal range per charge depends on the onboard battery capacities. AER mode is often activated by manu- ally switching under the command of the vehicle driver either to gain more fuel economy or to obeythe rules in certain electric-only driving zones.

ENGINE-MAINTENANCE MODE

Unlike the other operation modes, the engine-maintenance mode is not designed to propel the vehicle in PHEVs. Instead, it mainly functions to maintain the engine and prevent the fuel from being stale. This is useful for situations in which the driving range is always less than the AER and the vehicle gets recharged frequently. Thus, only AER mode is used and the engine never starts, whichmay cause problems for both engine components and fuel after a long time of nonuse.

PLUG-IN HYBRID VEHICULAR ARCHITECTURE

PHEVs combine the energy from the electric power path and the mechanical power path by utilizingtwo energy sources. Depending on the way these two power paths are integrated, different typesof PHEV architectures are realized, which can also be categorized into series hybrids, parallel hybrids, and compound hybrids.

PHEV SERIES HYBRIDS

In the series hybrid PHEV configuration, the engine, generator, battery, and motor are connectedin a series sequence, and the battery has the ability to be recharged from external power outlets, as shown in Figure 3.10. In PHEVs, battery power supplies the majority of power demands, and the motor plays the full role in propelling the vehicle. The engine combines with the generator to assist the electric motor or to charge the battery by using power from fossil fuel. Typicallyin series PHEV architecture, the engine has a small power rating since it is decoupled from the driving wheels and is mainly used to assist the electric motor to achieve better overall vehicle performance. The engine mostly operates in its fuel-optimal regions so that fuel efficiency signifi- cantly increases and a smaller engine is required. Consequently, the fuel tank can be reduced to a relatively small size.

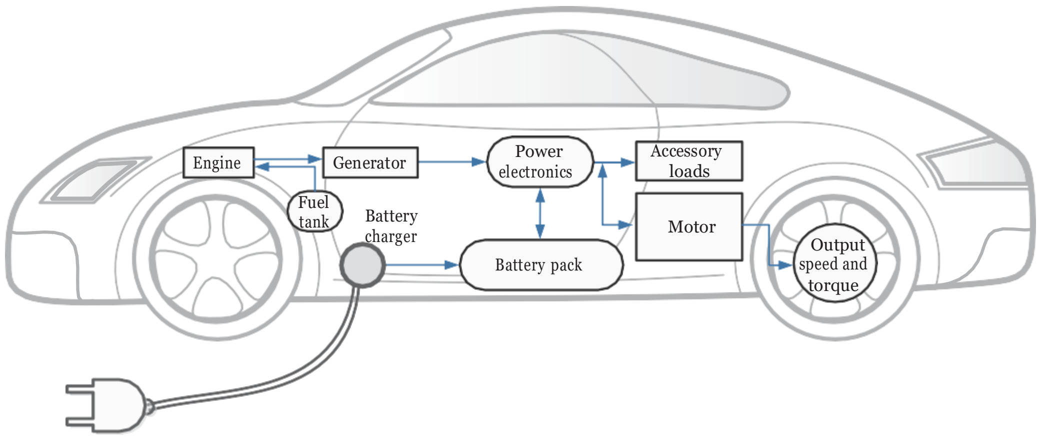


Figure 3.10 CONFIGURATION OF SERIES PHEV.

The relatively large battery capacity and the ability to recharge the vehicle by plugging into power Outlets allow the engine to be turned off as much as possible. Thus, the series PHEV hybrids typically operate in electric-dominant mode until the battery reaches the lower SOC threshold. This helps the PHEV series hybrids have much less power conversion losses compared with the HEV series hybrids, as in HEV series hybrids, a significant portion of the engine power is lost due to the mechanical–electric–mechanical conversions. Regenerative braking can also be achieved by operating the electric machine as a generator to convert kinetic energy into electricity so that charging can be done during braking.

Figure 3.11 presents a simulation case for a typical series PHEV. The vehicle operated for more **Q1** than four UDDS cycles. It can be clearly observed that the electric machine provides all the power and drives the vehicle in AER mode at first. Then the engine starts when the battery SOC decreases to a low threshold level. The vehicle then operates in the CD mode to extend the drive range while the battery SOC is regulated around the constant level.

PHEV PARALLEL HYBRIDS

PHEV parallel hybrids allow the power from both the primary and the secondary energy source to drive the vehicle. Typically, the battery would serve as the primary energy source in PHEV parallel configuration, and it can be charged by external power sources by plugging the charging cords into power outlets. The engine is used to propel the driving wheels directly, assisting the electric machine when additional power is needed, or it is used to charge the battery during hybrid operating mode. Figure 3.12 illustrates the PHEV parallel hybrid architecture.

Compared with parallel HEVs, parallel PHEVs further downsize the mechanical power system since the engine is not used to supply the majority of the power. Thus, smaller engines and smaller fuel tanks are installed on parallel PHEVs. On the other hand, parallel PHEVs significantly increase the power portion from the electric power system to prioritize electricity as the primary energy source. The electric system is required to power the vehicle on its own for a certain range without the assistance from the engine, and therefore, a much larger battery pack and a more powerful motor are required to realize a higher power rating of the electric power system compared with parallel HEVs.

In addition, since the engine is directly coupled with the output-driving wheels in the parallel PHEV configuration, the engine needs to be detached from the drive train when AER mode is demanded. This can be achieved by using clutches or torque converters so that the engine can be shutoff when the vehicle is operating in AER mode.

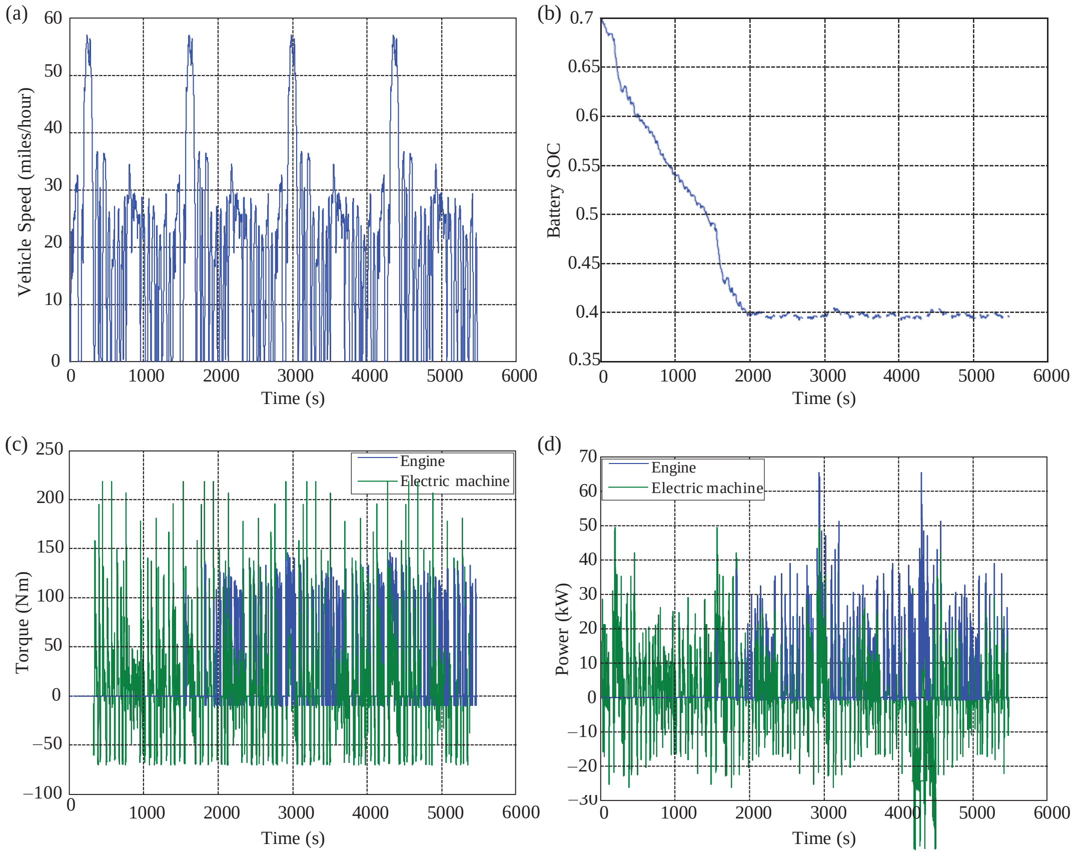


FIGURE 3.11 Engine and electric machine performance in series PHEV. (a) Vehicle speed, (b) battery SOC, (c) engine and electric machine torque, and (d) engine and electric machine power.

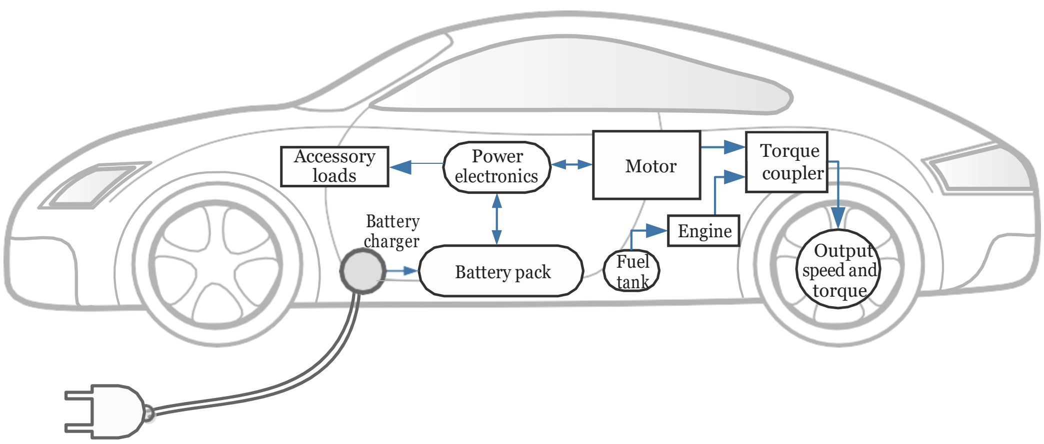
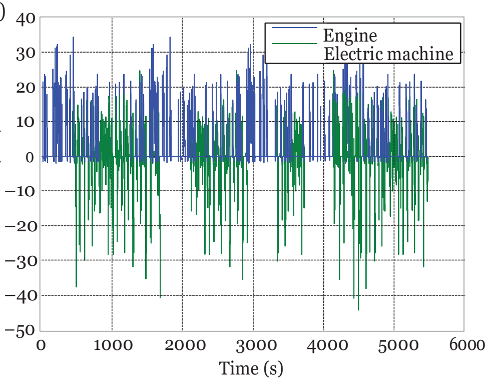


Figure 3.12 Parallel hybrid architecture.

(a)


Engine
Electric machine
Power (kW)
Time (s)

(b)

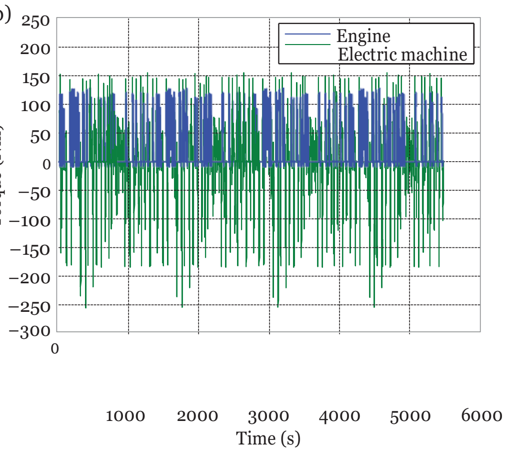

Engine
Electric machine
Torque (Nm)
Time (s)

Figure 3.13 Engine and electric machine performance in parallel PHEV. (a) Engine and electric machine power output in parallel PHEV; (b) engine and electric machine torque output in parallel PHEV.

Figure 3.13 presents the power and torque output from the engine and the electric machine, respectively in a typical parallel PHEV. Both the engine and the electric machine provide power and torque throughout the whole drive cycles and the vehicle is operating in the CD mode.

PHEV COMPOUND HYBRIDS

The power flow in compound PHEV does not follow a simple series pattern or a parallel pattern; instead, the mechanical and the electric power path interact with each other in a compound way, in which a planetary gear set is typically implemented to divide and combine the power. Similar to other types of PHEV hybrids, PHEV compound hybrids implement a much powerful electric power system to satisfy the performance requirements in AER mode. When driving in the compound mode where the engine starts to assist the electric machine, both the mechanical and the electric power path are integrated to supply the vehicle power together. Figure 3.14 illustrates the architec-ture of a compound PHEV power train.

Compound PHEVs combine the benefits of both series and parallel PHEVs when the vehicle is propelled by both the mechanical and the electric power system. Unlike in parallel PHEVs, the engine is decoupled from the output-driving shaft by taking advantage of the power-split devices, so that it can operate in its fuel-optimal regions. Besides, compound hybrids have less power conversion losses compared with series hybrids, as part of the engine power is directly transmitted by the mechanical path. In addition, both electric machines can operate either as motors or as generators, thus increasing the flexibility of the system control as well as vehicle- driving performance.

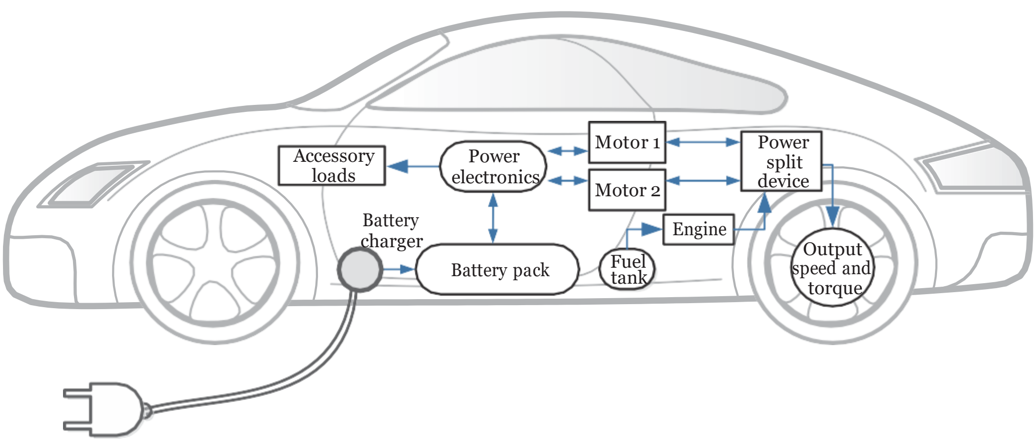


Figure 3.14 Compound Phev Architecture.

Figure 3.15 presents the power and torque output from the engine and the two electric machines, respectively in a typical compound PHEV. The vehicle first operates in CD mode. Electric machine 1 provides the dominant power and torque to the output shaft while the engine only provides power occasionally when the power demand from the power train is large. The vehicle then operates in CS mode to extend the drive range. Both the engine and electric machine 1 are providing power while electric machine 2 operates in the generating mode to convert the engine power into electric power and charge the battery.

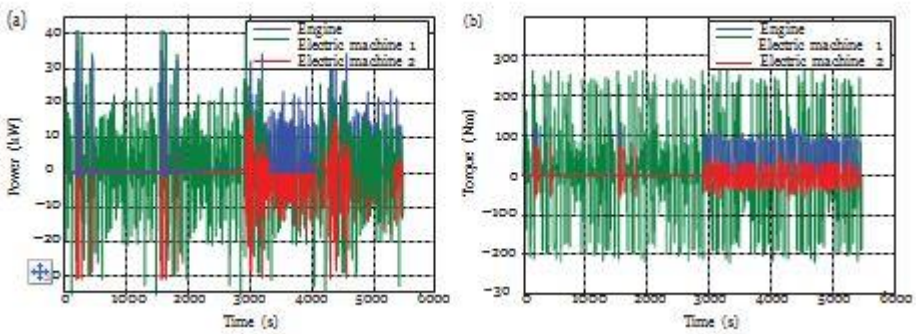


Figure 3.15 Engine And Electric Machines Performance In Compound PHEV. (A) Engine And Electric Machines Power Output In Compound PHEV; (B) Engine And Electric Machines Torque Output In Compound PHEV.

3.6 CONTROL STRATEGY OF PHEV

PHEV operation modes can be either manually selected by the driver or automatically controlled based on the feedback signals of various vehicle systems such as the battery SOC, power demands, road loads, and expected trip length, among others. In terms of the control strategies, two methods are typically applied in PHEVs: the AER-focused and the blended control strategy.

The AER-focused control strategy takes the greatest advantage of the electric power and runs the vehicles intensively in AER mode before the battery SOC drops below a certain threshold level, after which, the engine starts and the system operates in CS mode. The AER-focused control strat- egy prioritizes fuel reduction and emissions reduction in short-range trips by running exclusively onbattery power.

It is more suitable for city drives and short-range suburban commuting where daily round-trip distance is normally within the electric range. Since all the power in AER mode comes from the electrical systems, batteries with large energy capacity and electrical machines and power electronics with high-power density are needed to satisfy all the drive performance requirements.

The blended control strategy utilizes both the engine and the electric machines to power the vehicle. On the basis of expected travel distance, the blended control strategy picked the most appro- priate fuel/electricity combination so that the battery SOC decreases smoothly in a linear trend. It operates the vehicle under CD mode with the engine running in its high efficiency region all the time until the battery SOC drops below the preset threshold level, after which, the vehicle operates in CS mode, similar to the AER-focused control strategy. The blended control strategy prioritizes the range extent. It achieves an extended range in CD mode by using either the engine dominant strategy or the electric dominant strategy. In the former strategy, the engine is operating in its opti- mal fuel regions and the electric machine is used to subsidize the additional power demands. The latter strategy mainly utilizes electric power; the engine turns on only when the road loads exceed the electric capacity.

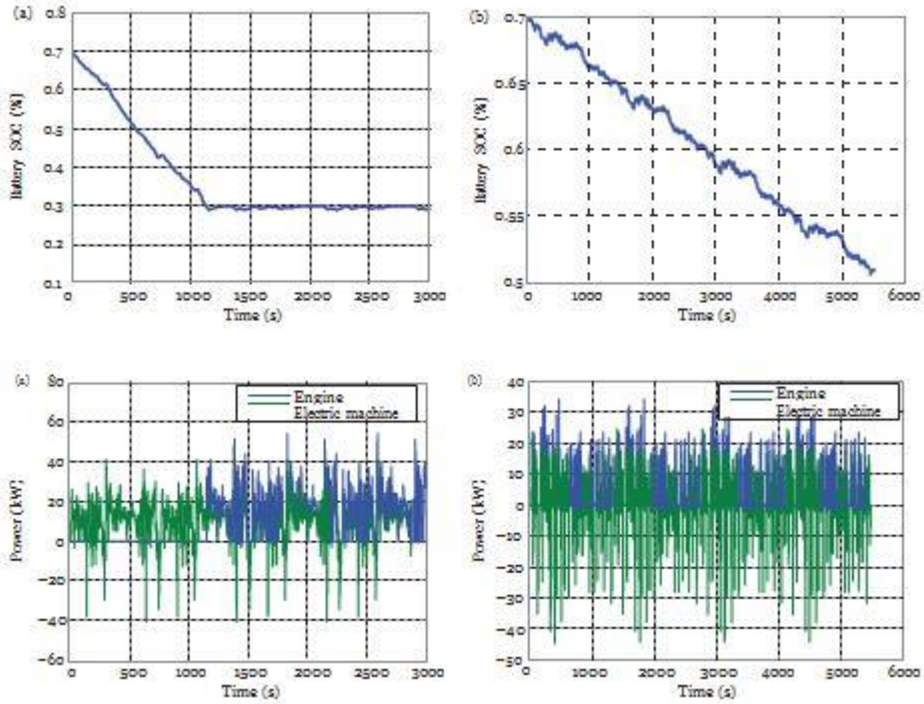


Figure 3.16 Control Strategy Effects On Battery SOC And Power Composition. (A) Battery SOC Under AER Control Strategy, (B) Battery SOC Under Blended Control Strategy, (C) Engine And Electric Machine Power Output Under AER Control, And (D) Engine And Electric Machine Power Output Under Blended Control

Figure 3.16 illustrates the battery SOC based on AER- focused control strategy and the blended control strategy, respectively. Four of the UDDS driving cycles are applied for a typical series PHEV. Power from both the engine and the electric machine is presented under each control strategy as well.

The optimum control strategy thus should rely on the trip distance that one PHEV is going to travel. If the trip distance is well within the battery AER, AER-focused control strategy should be applied so as to achieve the maximum fuel displacement. When the trip distance is greater than the AER, the blended control strategy is preferred with the engine running in its high efficiency region throughout the trip to achieve the optimum fuel efficiency.

In addition, Figure 3.17 presents the difference in engine and electric machine operation points **Q1** between UDDS cycle and HWFET cycle, which simulate the vehicle-driving behaviors on local and highway, respectively. It can be observed that the electric machine operates frequently in the low- speed regions under the local driving scenario while it operates more frequently in the high-speed regions on the highway. It can also be observed that the electric machine operates frequently in the negative torque region under local driving so as to retrieve more regenerative braking energy. For

both local and high way driving, the engine is largely controlled to be operated at high efficiency level. Different control strategies will result in different operation points for both the engine and the electric machine, thus affecting the fuel consumption as well as the emissions of the vehicle.

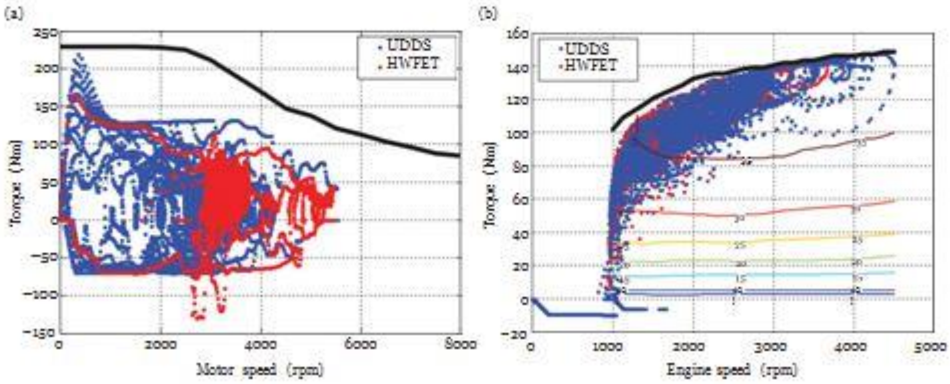


Figure 3.17 Operation Points Comparisons Between Drive Cycles. (A) Motor Operation Point Comparison, And (B) Engine Operation Point Comparison.

PHEV-RELATED TECHNOLOGIES AND CHALLENGES

Compared with HEVs, PHEVs take a further step in the transition from conventional fossil fuel combustion vehicles to electric power vehicles. They employ a large set of electric power systems, with electricity serving as the primary power source and electric machines serving as the primary propulsion drives. Engines and fuel tanks are retained onboard, but they are downsized to smaller scales and only function to assist the motors and batteries with additional power and additional drive range. All these changes bring in higher standards for the electric power system, including battery, electric motors and generators, power electronics, and their related controls. The massive component changes also require different platforms or even the reconstruction of the mechanical drive train. In addition, PHEVs change the way of refueling the vehicles, which enables drivers to charge the vehicles at home from grids instead of looking for public gas stations. However, this also brings in concerns regarding the grid's capability as well as the installation of power-charging outlets and public-charging access.

The above-discussed issues are closely related to the development of PHEVs. These issues significantly determine the performance, costs, and consumer acceptance of PHEVs in competing with conventional vehicles as well as HEVs and EVs. The following section will discuss these PHEV- related technologies and their challenges.

PHEV BATTERIES

High-performance battery is one of the most important components in realizing PHEV architectures. Vehicle performance, costs, and reliability are heavily dependent on the battery. Owing to the increased portion of the electric power system and the desired all-electric driving range, large quantities of batteries are required in PHEV power trains.

Batteries with large energy capacities are highly desired in PHEVs. In AER mode, the electric

machine draws power exclusively from the battery pack, and the battery pack also needs to supply the power to all the accessories. Although the kinetic power retrieved by using the regenerative braking system helps to recharge the battery during the vehicle-driving process, it actually con- tributes very little to battery SOC in terms of the entire range. It is the battery energy capacity that
directly determines the extent of the all-electric driving range, which in turn determines the degree of the displacement of fossil fuel and emission reductions. From the consumers' point of view, the more energy that the battery carries onboard, the fewer range anxieties the owners might have. Large battery energy capacity also provides sufficient energy for accessories such as air condition- ing and radios while they are on AER mode.

In addition to battery energy capacity, battery power density is another key metric that consider- ably accounts for PHEV performance. Battery power density defines the maximal power that the battery can supply to the vehicle in terms of a certain weight or volume. It largely contributes to the acceleration time that the vehicles need from speed zero to the demanded driving speed with the engine shutoff. It also determines the maximal torque the vehicles can output from the electric power system when sudden acceleration is demanded at certain levels of speed. In AER mode, the battery power is designed to supply both the propulsion system and the other internal power acces- sories, and thus sufficient power density is highly demanded to meet vehicle driving performance without sacrificing the operations of the power accessories.

Both large energy density and high-power density are demanded in PHEVs to achieve the desired high-standard PHEV performance and the operating functions. These high requirements dramatically increase battery costs and thus the overall PHEV manufacturing costs. Compared with HEVs, these increased costs result in a significant economic hurdle for customers to over- come. Therefore, how to reduce battery costs while improving performance is a great challenge in battery technology. The increased battery requirement also leads to the increase of battery size and weight, which reduces the vehicle dynamic performance as well as the fuel economy. Furthermore, a major challenge that battery technology encounters is that the goals of large energy density and high-power density contradict each other most of the time, due to the inherent chemical trade-offs in battery technology.[25] High-power density is often achieved in advanced battery technologies by using thinner electrodes. However, high-energy density is typically real- ized oppositely by implementing thicker electrodes. Therefore, the development of high-perfor- mance batteries still faces the challenge of improving the power density and energy density at the same time.

Batteries in PHEVs also face another challenge regarding the discharge cycles, which are dif- ferent from those in either HEV batteries or EV batteries. In HEVs, batteries typically go through shallow discharge cycles as the engine functions to operate the battery SOC at a relatively constant level in CS mode, while in EVs, batteries typically experience one deep discharge before the next recharge as a result of the larger energy capacity. However, batteries in PHEVs have to go through repeated one deep charge–discharge cycle per charge as well as a number of shallow charge–dis- charge cycles in both CD mode and CS mode for power assistance and regenerative braking. This brings in particularly high standards and great challenges in battery technology development so as to meet the typical 8 years or 80,000 miles automotive battery warranty standard.

The safety and reliability of the batteries are also among the top concerns for PHEVs since bat- teries take such heavy portions in PHEVs. High-voltage and high-current components should be carefully packaged and isolated from the chassis and accessory systems completely. Coolants are needed and should be regularly maintained to keep the batteries working in safe operating temper- atures. Hazards protection methods should be taken into account during design and manufacturing process. In addition, batteries applied to the vehicles are not only required to be safe for drivers and passengers during the driving process; but they should also not cause any hazardous situations in the maintenance and repair of vehicles. For instance, it is necessary to keep all high-voltage components labeled, fused, and well insulated to reduce the risk during maintenance. On the other hand, appropriate safety gears such as safety glass, insulating boots, and insulating gloves are absolutely required when dealing with batteries.

In addition, the risks surrounding batteries during accidents or collisions should be reduced to the minimal level when the PHEV configurations are designed. Trainings of emergency response should also be provided regarding the high- voltage battery and the electric system. Many codes and standards have already been established to address the technical issues relating to PHEVs. For example, in the United States, a list of SAE and NFPA codes and standards are applied to regulate PHEV vehicle safety, emergency response, and infrastructure safety

PHEV COSTS

The costs of PHEVs extensively challenge the development of such vehicles, with the increased elec- tric power system adding a significant part on the manufacturing costs. The large demands for bat- tery energy capacity and power density require a remarkable quantity of batteries, which accounts for a substantial part of the cost increment. It is estimated that only when battery technologies advance to a further stage and can be mass produced to reduce the costs will PHEVs be competi- tive with conventional petroleum-powered vehicles. For example, NiMH batteries and lithium-ion batteries are currently the two most popular batteries in HEVs and PHEVs market. The production battery price by 2011 is roughly around \$700/kWh to \$900/kWh, which is many times of the United States Advanced Battery Consortium (USABC) long-term goal of \$100/kWh. The large torque and speed requirements for the electric motor and generator also add considerable manufacturing costs due to the implementation of high-powered electric machines and power electronics.

PHEV reconstructions in most of the cases also significantly contribute to the total manufactur- ing costs. Typically, the large battery pack installation, integrated transmission power train, added electric motors and generators, and the control power electronics all together require redesigns of the vehicle chassis to accommodate these added components and their corresponding weights. Additional safety components are required to be added onboard the vehicles to prevent the hazardous situations regarding the electric power system. For instance, high-voltage shutdown mechanism is required to be added to prevent battery fire during a vehicle crash or in the event of air bag deployment.

In addition, the maintenance of the electric power system may add potential costs to the overall investment in PHEVs. Diagnosis and repair become more difficult due to the more complicated power train integrated by the mechanical power path and the electric power path. Battery replacement within the vehicle's driving life also brings in substantial maintenance costs for PHEV owners. Therefore, the reliability of the added electric system in PHEVs is critically desired to bring down the overall costs of PHEVs.

CHARGING OF PHEVS

Since PHEVs switch the charging method from the conventional fuel station refueling to the primarily plug-in electricity recharging, charging-related issues become important in terms of PHEV development. These issues include charging strategies, charging types, and the corresponding charging infrastructures.

Charging strategies greatly influence battery SOC and the all-electric trip range based on a fixed battery energy capacity. There are several charging scenarios that can be applied onto daily PHEV driving.[28] The first scenario is that the driver charges the PHEV whenever the car is parked, which maximizes the all-electric driving range and achieves the greatest fossil fuel displacement. It can be applied on daily commute driving where recharging access can be found at work places, parking lots, grocery stores, and so on. The second scenario is to recharge the PHEV once every night, when the vehicle is typically parked at home and the price of electricity is relatively low. This enables driv- ers to recharge their vehicles in their garages or somewhere near their home while they stay at home or sleep. The third scenario is to recharge the vehicle during the lowest utility load demands. This recharging strategy helps balance the grid utility loads and achieves the maximal savings for PHEV owners. However, this requires control and communication between the vehicles and the grids, and the battery may end up without being fully charged. The fourth commonly used scenario is to recharge the PHEV at any time and at any day. This charging method is also called unconstrained charging. This is more like the conventional way that people fuel up their petroleum-powered cars, and it offers the largest freedom to the drivers in terms of recharging schedule. However, it generally requires a quick charging speed so that PHEV drivers would not feel uncomfortable waiting at the charging station for a relatively long time.

Different charging levels are applied to suit different charging scenarios. There are typically three charging levels that vary by charging voltage and charging currents. The first level is the home-charging level, in which PHEVs are generally charged by the home power outlets, such as those in garages. The second level supplies higher charging voltages and currents so that the charging time will be reduced. It is typically used by implementing high-power charging equip- ment to boost the voltage and current output. The third level is the highest charging level, which carries hundreds of volts and hundreds of amps. It significantly reduces the charging time to the level that is competitive with the conventional petroleum refill. The third charging level is typically applied in public charging stations where fast recharging is demanded and safety is prioritized.

All three levels of charging are desired to realize PHEV charging convenience, and the imple- mentation of these charging facilities is critical to the development of PHEVs. Both the low-level and the high-level home-charging systems should be well regulated so that they would not overload the existing home power system or the local power distribution system, and they should be easily installed by customers. And large numbers of the public-charging stations or charging vehicles are needed to provide PHEVs with fast and convenient recharging choices outside their home. Thus, the development of both home-charging facilities and public-charging infrastructures considerably influences customer acceptance of PHEVs.

PHEV-RELATED GRID CHALLENGES

PHEV-related grid challenges also bring in considerable concerns with regard to PHEV develop- ment. First, grid capacity will be a potential issue with the increasing use of electricity displacing conventional fossil fuels. PHEVs will bring in a large amount of utility load increase since electric- ity serves as the primary energy carrier to meet drivers' daily trip demands. Therefore, the grid should be able to tolerate the maximal utility loads when the worst scenario happens, that is, when all PHEVs and even EVs are plugged in at the same time.

Second, the increase in overnight utility loads caused by PHEV night recharging may result in the change of the control strategies to manage the grid balance. Currently, utility loads hit a valley at night when most people are asleep and household utilities are turned off. With the increase in PHEVs, more electricity will be consumed during the night hours; control strategies to balance util- ity loads will need to be adjusted accordingly.

Finally, the grid may also implement V2G technology to take advantage of the plug-in features so that the battery power of PHEVs can be turned back to the grids when the load demand is at its peak, provided the vehicle is parked. The V2G technology helps to balance the grid loads and reduces the utility expense of PHEV owners. Besides, the vehicle batteries can also be used as the backup power storage to send power to homes in case the utility is temporarily out of service. The V2G communication requires new grid technologies such as the implementation of smart meters and new power distribution and control strategies.

PHEV MARKET

In spite of the challenges, PHEVs still emerge as one of the most promising transitional vehicles from conventional petroleum-powered vehicles to electric-powered vehicles and combine the ben- efits of both. Production and sales of PHEVs gradually picked up after 2008. Table 3.4 summarizes the current PHEV production models up to September 2013 and Table 3.5 summarizes the sched- uled models with market launch between 2013 and 203.

TABLE 3.4

PHEV Production Up to September 2013

Models	Manufacturer	Production Since	Electric Range (km)
F3DM	BYD	2008	64–97
Volt	GM Chevolet	2010	56
Karma	Fisker	2011	51
Prius Plug-in Hybrid	Toyota	2012	18
C-Max Energi	Ford	2012	34
V60 Plug-in Hybrid	Volvo	2013	50
Accord Plug-in Hybrid	Honda	2013	21
Fusion Energi	Ford	2013	21
Panamera S E-Hybrid	Porsche	2013	32
Outlander P-HEV	Mitsubishi	2013	60

With the increasing price of global crude oil as well as the increasing concerns about environ- mental pollution, PHEVs will be more promising in resolving these problems and will become more competitive with conventional petroleum-powered vehicles. Figure 3.18 predicts the PHEV, HEV, as well as EV sales number from 2010 to 2050 based on International Energy Agency (IEA)'s energy technology perspectives analysis that aims to achieve a 50% reduction in global CO_2 emis- sions from 2005 levels by 2050.PHEVs sales number will boost exponentially from 2015 and will remain a significant portion of the light-duty passenger vehicles.

Beside the plug-in hybrid electric light-duty passenger vehicles, there are also research and developments on medium-duty PHEVs. Medium-duty vehicles are used in a broad array of fleet applications, including transit buses, school buses, and parcel delivery. These vehicles are all excellent candidates for hybrid electrification due to their transient-intensive duty cycles, operation in densely populated areas, and relatively high fuel consumption and emissions.The home-based parking facility also facilitates overnight charging. Local governments and agencies such as Southern California Air Quality Management District and Milwaukee County in Wisconsin have been working on the conversion of PHEV shuttle buses and PHEV utility trucks.IC bus offers diesel PHEV school buses and has already been delivered to many school districts. Parcel delivery PHEVs have also been tested and deployed to Fedex and UPS for evaluation.In addition, plug-in hybrid electric motorcycle Piaggio MP3 Hybrid has been commercialized in Europe.

TABLE 3.5

PHEV Scheduled Models with Market Launch between 2013 and 2014

Models	Manufacturer	Production Since	Electric Range (km)
P1	McLaren	2013	20
i3	BMW	2013	130–160
XL1	Volkswagon	2013	50
A3 Sportback e-tron	Audi	2013	50
Qin	BYD	2013	50
918 Spyder	Porsche	2014	24
ELR	Cadillac	2014	64
i8	BMW	2014	35
S 500 Plug-in Hybrid	Mercedez-Benz	2014	NA

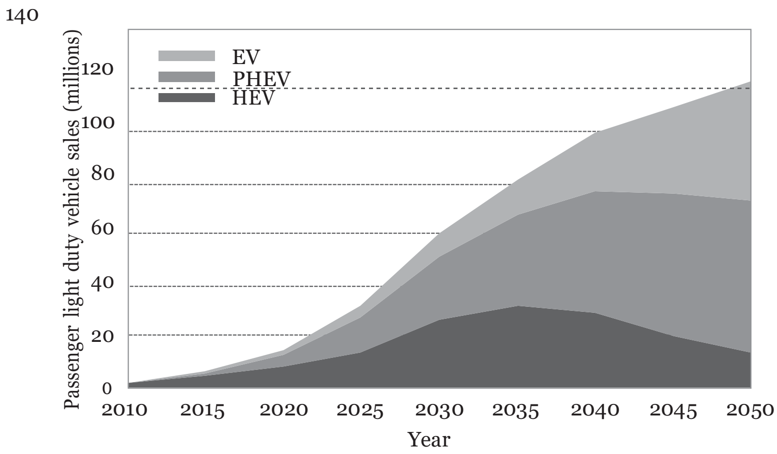


Figure **3.18** Light-duty HEVs, PHEVs, and EV sales prediction scenario.

CONCLUSION

PHEV is a special type of HEVs that make use of both conventional petroleum energy and electric energy as their energy sources. PHEVs have the full capability to operate on the AER for a certain demanded range and can be directly charged from off-board power grid. They provide high degrees of fuel displacement and emission reductions. The major components for PHEVs are similar to those in HEVs, but with much larger electric systems. Different configurations and control strate- gies exist that enable PHEVs to combine the benefits of both HEVs and EVs. In addition, PHEV- related technologies and challenges have been discussed and the current and future markets for PHEV have also been presented.

FUNDAMENTALS OF CHARGERS

Introduction

In the last decade, worldwide challenging concerns including the global call for clean energy, imminent energy crises, depletion of conventional resources, and fossil fuel dependence are driving the demand to adopt the new eco-friendly technologies. Transport and power sectors are directly linked with all the considerable climate and environmental issues as contributing largely to utilizing fossil fuels and CO_2 emissions. The emission rate can be considerably reduced by electrifying the transport sector with smart grid involvement. Recently, EVs as an eco-friendly power source are gaining much popularity with a promising objective to replace internal combustion engines (ICEs) and to reduce CO2 emissions. Worldwide, the government and researchers are working collaboratively to lessen fossil fuel dependence with clean energy solutions. The development and deployment of EVs are rapidly observed with new incentive-based policies introduced by the government and policy-makers.

The incentive policies formulated by the government are based on financial measures, which include tax exemption (vehicle purchase tax), exemption from road tolling, and preferred parking place for extensive consumer adoption.The rapid demand of EVs in the transportation sector is the result of growing alarms about clean energy and environmental problems. Regular increments in fuel prices and high standard environmental policies are driving the need for an energy system, which has a much higher contribution of EVs. In the transportation sector, the EVs act as an emerging approach and an alternative technology, which can alleviate the nonrenewable fossil fuel dependency? Lower operating costs and better fuel economy with reduced carbon emissions are the reasons for higher preferences of EVs.The participation of EVs in a smart grid environment offers many substantial features including load balancing, peak load shaving, revenue generation, and tracking of renewable energy resources (RES).Advancements in EV charging technology based on converter topologies contribute toward many significant benifits of EVs over many other traditional clean energy applications. Recent research revealed that EVs can be integrated with many RES including wind, solar panels, fuel cells, etc. to realize the improved performance of power networks].The current technological trends in EV charging technology are presented in Table 1 .

Technological trends	Description
Fast charging	Various research activities are in progress for fast-charging solutions of EVs such as 1-min fast recharge by StoreDot. Currently, researchers are putting utmost efforts to overcome the problems in existing chargers by providing upgraded fast-charging solutions through universal fast chargers, bidirectional fast chargers, and ultrafast chargers
Wireless charging	Several wireless charging solutions are being provided by considering the reduced recharging time of EV such as dynamic wireless charging. Presently, research is being carried out to overcome the drawbacks of wireless charging including (1) EV charger alignment, (2) external object interference, etc.
Battery swapping	Battery swapping network could be a fast and an efficient source of recharging; however, the available battery swapping services are facing failures due to battery degradation, expensive infrastructure, and incompatible available batteries. Brand compatible features and accessible battery design should be provided to make further improvements
Renewable-based charging	To solve the challenging issues regarding EVs charging, innovative charging solutions are provided based on renewable energy charging. Example of such charging solutions are (1) no dependency on the grid and (2) self-charge EV. Various research activities in sun-tracking technologies and solar-wind-based hybrid charging strategies show the improvements which can enhance the efficiency of chargers depending on renewable energy
Integrated solutions	Collaborative working of ABB and Tesla, the major key players in EVs fast-charger industry, shows the potential of renewable energy chargers. V2V, V2G, and V2H technologies can be improved by integration of fast charging, wireless charging, and renewable-based charging

Table 1 Technological trends in EV charging

New opportunities and applications are introduced by the National Renewable Energy Laboratory in terms of advanced simulation tools to make optimal charging strategies and further advancement in EV charging technology. International standards for utility interface are developed by many reputed organizations such as IWC (Infrastructure Working Council), SAE (Society of Automotive Engineers), and the Institute of Electrical and Electronics Engineers (IEEE). Despite several developments in EV technology, there are still some potential barriers including charging infrastructure, a suitable design of battery chargers (converter topologies), battery degradation, and driving range issues for widespread adoption. Harmful harmonics are introduced by EV chargers, which lead to potential issues for distribution networks in terms of its stability and power quality. Harmonic compensation techniques and improved converter topologies are employed to reduce power quality issues. As far as charging power levels are concerned, Level 1 charging is employed at residential levels. Higher charging levels (Levels 2 and 3) are required at commercial locations including shopping malls, rest areas, and various parking lots. Comparative analysis of various AC and DC charging power levels as explained by several international standards is summarized in Table 2.

Charging power levels	Location for charger	Expected power level
AC and DC charging based on SAE standards		
Basic: Level 1 charging	Single phase	• P = 1.4 kW with (12 A)
• Vac = 230 (EU)	• On-board	• P = 1.9 kW with (20 A)
• Vac= 120 (US)		
Main: Level 2 charging	Single phase/three phase	• P = 4 kW with (17 A)
• Vac=400 (EU)	• On-board	• P = 8 kW with (32 A)
• Vac=240 (US)		• P = 19.2 kW with (80 A)
Fast: Level 3 charging	Three Phase	• P = 50 kW
• Vac=208–600	• Located off-board	• P = 100 kW
Level 1: DC charging	• Located off-board	• P = 40 kW with (80 A)
• Vdc=200–450		
Level 2: DC charging	• Located off-board	• P = 90 kW with (200 A)
• Vdc=200–450		
Level 3: DC charging	• Located off-board	• P = 240 kW with (400 A)
• Vdc=200–600		
AC and DC charging based on IEC standards		
AC power level 1	Single phase	• P = 4–7.5 kW with (16 A)
	• On-board	
AC power level 2	Single phase/three Phase	• P = 8–15 kW with (32 A)
	• On-board	
AC power level 3	Three Phase	• P = 60–120 kW with (250 A)
	• On-board	
DC rapid charging	• Off-board	• P = 1000–2000 kW with (400 A)
CHAdeMo charging standard		
DC rapid charging	• Off-board	• 62.5 kW with (125 A)

Table 2 International standards for AC and DC charging

The main interface between the power network and EV battery system is a power electronics converter; therefore, there is a considerable need of new power converters with low cost and high reliability for advance charging mechanism of EVs. Consequently, in this paper, several power converter topologies are investigated by considering various important requirements including capability of bidirectional power flow, high efficiency, and high power density.

There has been several review articles published on various important features of power converters for charging of EVs. In the study, EV charging levels, battery chargers, and charging infrastructure with on-board and off-board chargers are thoroughly reviewed. Similarly, in the study, the details of EV charging power levels and EV charging infrastructure along with optimization techniques for optimal charging of EVs are provided. The work presented in and briefly highlighted the classification of EV converters topologies along with a comparison of unidirectional and bidirectional power flows. Charging systems, charging standards, and EV charging impacts are broadly described. A thorough discussion regarding energy management strategies for EVs is presented in Research presented in discussed several DC-DC converter topologies incontext to unidirectional and bidirectional charging for EVs.

Shortcomings and Contributions

In view of foregoing discussion, it is clear that most of the previous review studies are limited to some specific area. To the best knowledge of authors, this study is thefirst to present a broad perspective of power electronics converters through an in-depth assessment of several power converters in EV charging technologies. The tenacity of the work is to outline an ample, well-organized, and updated analysis on various types of power converters. Moreover, quantitative aspects of converter topologies including voltage and power ratings along with expected efficiency are not addressed in most of the earlier studies. Additionally, power electronics chal- lenging issues that exist in the transport sector are not covered.

Battery chargers of EVs must have higher efficiency in power conversion along with high power density for wide-spread deployment of EVs. Several types of power converters may be required depending on the type of EV and needs of manufacturers. Attributes of battery chargers are dependent on the design conditions and market requirements. Consequently, a comprehensive discussion regarding the isolated and non-isolated power converters is presented in this manuscript, as these power converter topologies can be the potential candidates for charging applications of electric vehicles. Each type of converter holds its own benefits and drawbacks; therefore, isolated and non-isolated topologies with soft switching techniques are classified and rigorously analyzed with a view to their respective issues and benefits. Moreover, isolated and non-isolated power converters with soft switching tech- niques are presented, as these switching techniques are implemented to perform the operation at higher frequencies, while reducing switching losses, increasing theefficiency, and lowering the cost and size, which outcomes in higher power densi- ties. These switching techniques also improve the converter reliability by lowering the stress on the switching devices. Higher variations in dv/dt and di/dt can be eliminated by using the soft-switching techniques due to a significant reduction in EMI. Moreover, ripples for output voltage and input current should be minimum to efficiently charge the battery of electric vehicles. Therefore, the power converters are required to design in such a way that they can operate under different conditions of soft-switching to ensure the high efficiency. Therefore, the main objective of this paper is to investigate the present needs, recent progress, and challenging issues associated with power electronics converters to suggest possible improvements in the charging mechanisms of EVs. This work comprehensively provides the recent state-of-the-art on power converters depending on possible charging solutions of EVs. Furthermore, significant and up-to-date aspects of power converter topologies are summarized in detail. The principle understanding of several power converter configurations are well explained. Several power electronics converters for charging solution of EVs are presented in Fig. 1.

Organization

The investigation begins with a concise background of battery chargers. Afterward, the operating principles of various front-end converters are briefly highlighted. Moreover, an extensive analysis of back-end (DC/DC) topologies with their corresponding issues and benefits is performed. This is followed by a detailed comparison of several DC-DC converter configurations. A comparative analysis of resonant converter topologies is also addressed in this study. Isolated and non-isolated topologies with soft switching techniques are classified and rigorously reviewed with a view to their respective constraint analysis. Furthermore, the idea of an integrated battery charger along with front-end (AC-AC) and back-end (AC-DC) converters for battery charging of EVs are briefly described. Power electronics challenges that exist in the transport sector are further highlighted. Finally, the concluding remarks are drawn in the last section.

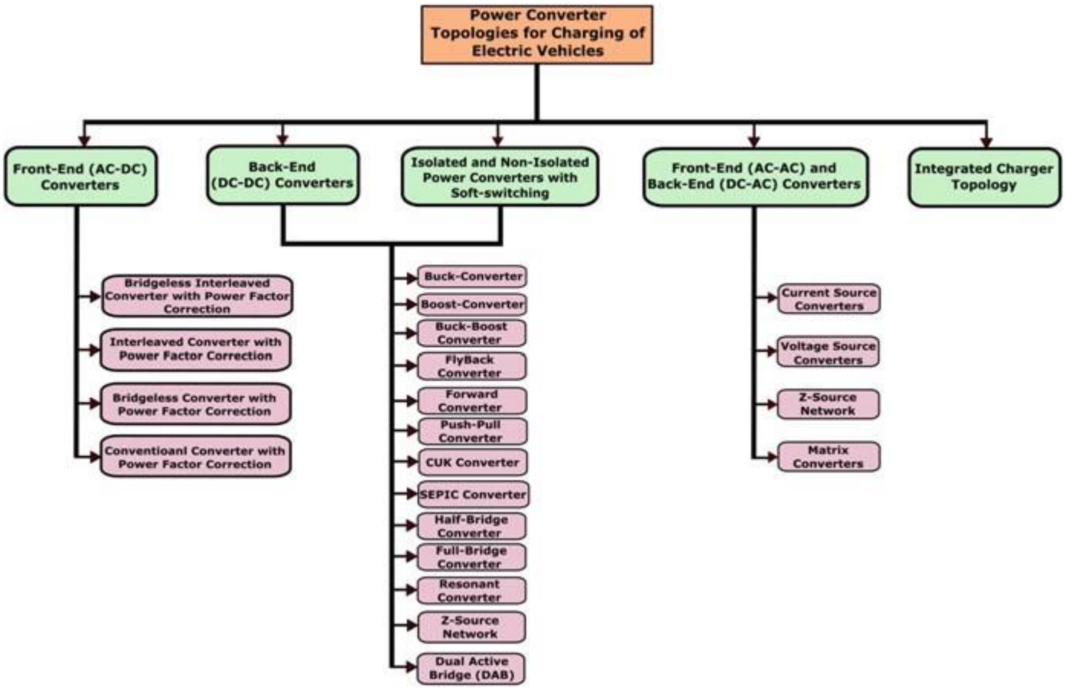


Fig. 1 Power electronic converters for charging solution of EVs

1.Converter Topologies for EV Battery Charges

Improved converter topologies of a battery charger have a substantial role in the further development process of charging infrastructure of EVs. The standard properties of a battery charger reflect the battery life degradation and required charging time. EV design challenges are introduced by various types of battery chargers as being the main power source. Driving range of EV is significantly dependent on design constraints of battery chargers including weight, volume, and power density. Several switching techniques with control connections are involved in proper working of a battery charger. However, the hardware configurations related to battery charging decide the required control algorithm and type of switching methodology. Various control algorithms needed for charging can be implemented with the help of converters, integrated circuits, microcontrollers, and signal processors. The EV power architecture of a battery charger is shown in Fig. 2.

Power quality issues can be reduced by observing high power factor and less distorted utility current drawn by EV chargers. DC current injection and contents of harmonics should be minimized as supported by various international standards such as SAE: J2894, IEEE: 1000-3-2, and National Electric Code (NEC): 690 [28–31]. Various requirements prescribed in different standards must be met by EV. Various international standards emphasizing on the safety concerns for EVs are summarized in Table 3.

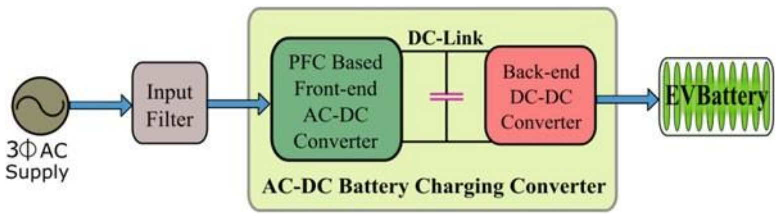


Fig. 2 EV power architecture of a battery charger

Table 3 Safety standards for EVs

Technical code	Details
SAE J-2464:	Safety rules for recharge energy storage systems (RESS) are described
SAE-J2929:	Safety for EV propulsion battery system
ISO 6469-1: 2009(IEC):	Electrically propelled road vehicles, inside and outside protection of a person, on-board RESS are described
UL 2202:	Protection of charging system is described
IEC 61851-21:	Requirements for conductive connection of EVs
ECE R100:	Electric shock protection
NFPA 70/70E:	Workplace safety, branch circuit protection, and charging system safety
IEC TC 69/64	Electric shock protection, EV infrastructure safety, and electrical installation

.

In EV charging market, sales up to 23.13 million units are projected for AC chargers by 2020 with a compound annual growth rate (CAGR) of 27.29%, conse- quently, highlighting the dominance of AC chargers. Wireless chargers are in emerging phase with a 3% contribution in the EV market.

Large-scale deployment of EVs contributes toward a bigger market of battery chargers. Globally, the key market leaders in AC/DC EV battery charger industry are (1) ABB, (2) Siemens,(3) Evatran, (4) Leviton, (5) Plugin Now, (6) Addenergie, (7) AeroVironment,(8) POD Point, and (9) Delphi Automotive.

In case for wireless chargers, the major companies are (1) Duracell Powermat, (2) Fulton Innovation, (3) Qualcommand WiTricity, and (4) Texas Instruments.

First Stage Front-End Converters (AC-DC)

Several converter topologies are used by charging systems of EVs including recti- fiers (AC to DC converters), inverters (DC to AC converters), DC-DC, and AC to AC converters based on the necessity of certain applications. Numerous studies related to EV chargers recommended that a basic EV charger has a front-end (AC-DC) topology with a back-end DC-DC configuration. Some studies also focused on a front-end AC to AC converter with a back-end AC to DC device. The AC to DC power converter has its input from the utility mains and converts it into an isolated DC output. As these converters are connected to a utility main, they can inject and generate current harmonics. The power factor correction (PFC) techniques are implemented to overcome the issue of current harmonics. The PFC techniques applied to these converters support to control the input currents to be sinusoidal and in phase with their respected phase voltages. These converters are developed with two independent converter stages. Rectification is the first stage to get a middle-level DC voltage, while PFC technique is parallelly implemented to achieve an input power factor close to unity, and this is performed by a front-end converter, while the second stage is used to get converted and desired isolated dc voltage to charge the battery of an EV from a back-end converter. The PFC technique is implemented in such a way that at first it senses the input currents and voltages and then turn on and turn off the witches such that to control the input currents to be sinusoidal and in phase with their respected phase voltages. A summarized discussion about a few three-phase front-end topologies is presented only.

Figure 3a shows a case for a converter with two stages where the first stage (AC-DC front-end) has a converter with six switches and the second stage (DC-DC back-end) has a full-bridge converter. The use of six switches in the front-end part of a two-stage converter could make it costly and complicated, particularly when we are considering the related gate drivers, input current sensors, and control circuitry. The significant aspects, which need to be considered before an appropriate selection is made about the PFC converter/rectifier configurations, are power factor, cost issues, complications in control circuitry, efficiency, robustness, and total harmonic distortion (THD). The main topologies used for the rectification process with PFC involve configurations of the boost type and their variations. A lot of research activities in the field of power electronics are in ongoing stages to find alternative approaches for a converter to do AC to DC conversion and PFC with minimum number of switches.

One alternative way is to have three units of one-phase boost PFC converter as shown in Fig. 3b. Each unit consists of a front- end converter with PFC technique followed by a back-end converter to find the desired voltage. The main benefits are the wide range availability of the existing units of a single-phase converter and do not need much information of sophisticated control of three-phase circuitry. The drawbacks of this method are the difficulties in keeping synchronism between the three units, the triplen harmonics created in the units due to parametric variations, and a greater number of components to implement it.

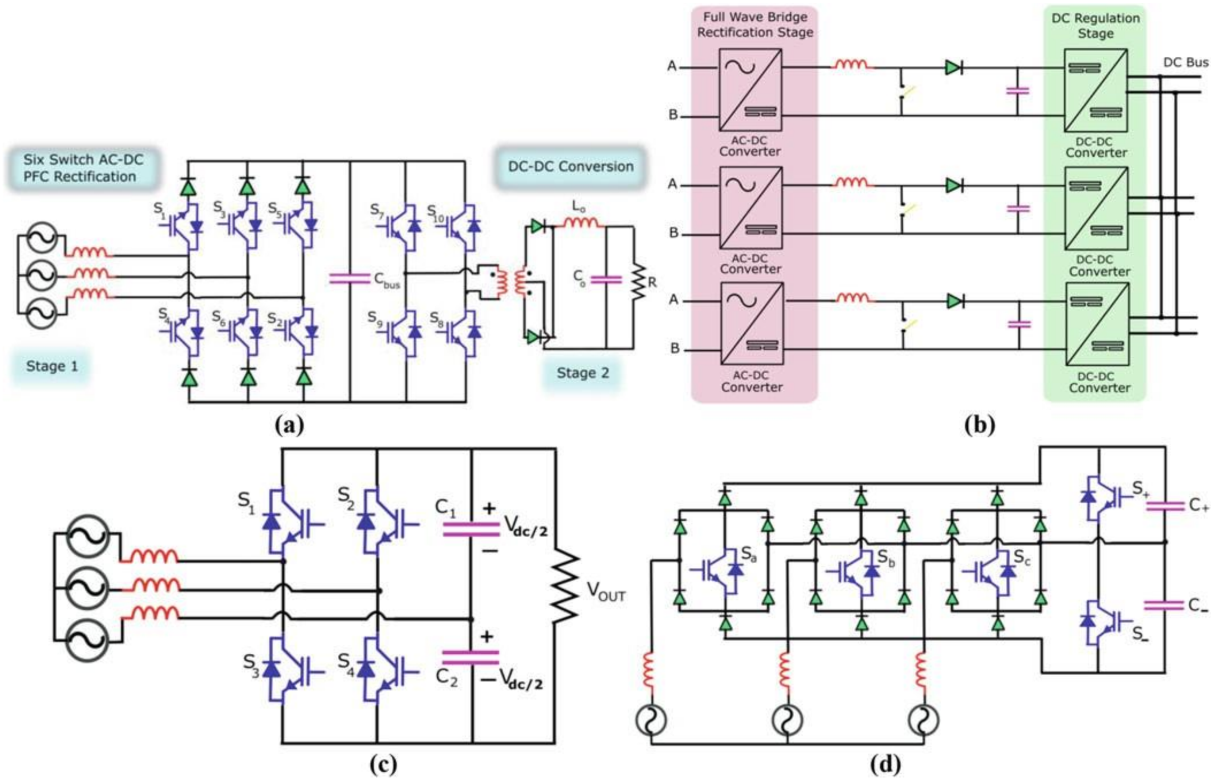


Fig. 3 AC-DC power converters: (a) three-phase two-stage AC-DC power converter, (b) three-phase converter using three one-phase units, (c) front-end converter with four switches,
(d) topology of Vienna rectifier

The basic requirements for a high-power AC-DC converter are to achieve max- imum power factor and a distortion-less operation to avoid major damages to power networks. Inclusion of all the required factors at a front-end converter stage permits to remove the bulky and expensive filters at the input side. The other much needed aspect is reducing the cost of power converter itself in such a way that it has less stress on the active and passive components and has lesser number of active switches. Type of application is also one significant prospect for the selection of converter configuration. Output of the rectifier should be high to have a proper operation of back-end DC-DC converter stage. As fast charger will supply power to an extensive range of batteries with different initial state of charge (SOC), high voltage DC link must be present to ensure high PFC near unity and desired regulation of charging voltage.

On the other hand, there are some famous front-end converter configurations with lesser number of switches such as four switch front-end converter and a Vienna rectifier. Figure 3c represents a four-switch front-end converter. Each leg in the converter consists of two switches and the third leg with two capacitors. One phase from three-phase source is connected at the center point of each leg. The basic operating principle of this converter is that if somehow the phase currents are controlled that are linked with legs of converter which have switches, then the phase current of the third leg which is without switches will be constrained by the phase current of other two legs, so that currents will become sinusoidal and in phase with its respected phase voltage.

The other significant front-end converter configuration is a Vienna rectifier which is shown in Fig. 3d. It consists of 18 diodes with three main power switches. Diodes are arranged in such a way that four diodes to each power switch to enable the bidirectional operation and permits the flow of current in both directions. The operation of this converter can be similar to a conventional converter with six switches, but each converter leg has one bidirectional switch rather than two unidirectional switches. The noteworthy benefits of a Vienna rectifier are higher reliability, low cost, lower EMI, higher power density, lesser switches, low input inductance, less voltage component stress, and higher efficiency.

Even if the lower number of switches make these converters cost-effective than the six switch converters, however, the conventional six switch converters use much simpler control techniques than are used in the reduced switch converters, which required more complex control methods. It is possible that a single switch performs PFC for the low power three-phase applications. Presently, many researchers have managed to overcome the issues of complex control and cost therewith in two switch-mode converters by combining the functionality of the first stage of a converter, i.e., AC-DC conversion with PFC technique, with DC-DC conversion stage into a single converter.

Second Stage Back-End Converters (DC-DC)

The most extensively accepted EV charging topology consists of front-end (AC-DC) and back-end (DC-DC) converters. The front-end topology completes the rectifica- tion process with PFC, whereas the voltage level from the rectification process is adjusted by the back-end DC/DC converter to make it suitable for EV battery charging. Assuming if a high regulated DC voltage, e.g., 750 V, is applied at input side of a back-end converter, then the chosen converter should be able to control the output current from 50 to 350 A. The designing of a battery charger for EVs faces substantial challenges, which includes obtaining higher efficiency, lower cost, higher power density, isolation, and meeting safety requirements. The increase in switching frequency permits to decrease the cost of passive elements. Turn on/off time and switching losses are the reason to limit the switching frequency. Therefore, to increase the switching frequency, resonant circuits and soft-switching methods are widely adopted. The other problem for designing such kind of topology is linked with reverse recovery losses and noise due to higher dv/dt and di/dt at the output rectifier. To reduce the switching losses and to minimize the high-frequency EMI due to higher dv/dt, a soft transition configuration is needed to operate from higher input voltage. The selected converter topology must be able to control the higher output current. The converter configurations of back-end DC-DC converters can bedivided into isolated and non-isolated categories, depending on whether there is a galvanic isolation present between the input source and the output circuitry. To achieve galvanic isolation, low-frequency transformer is used at the grid side, or integration of high-frequency transformer is needed in

DC-DC converter stage.

Table 4 Comparative properties of front-end converters for battery charging (where + represents the best quality, 0 for neutral one, – for poor quality)

Converter configuration	Conventional converter withPFC	Bridgeless converter withPFC	Interleaved converter withPFC	Bridgeless interleaved converter withPFC
Power ratings (W)	Less than 1000	Less than 2000	Less than 3000	Greater than 3000
Ripples for capacitor	-	-	+	+
Noise or EMI	0	-	+	0
Ripples for input main	-	-	+	+
Magnetic size	-	0	+	+
Efficiency	-	0	0	++
Cost	+	0	0	-

Table 5 Quantitative specs of several PFC AC-DC boost topologies

Quantitative parameters	PFC-based front-end (AC-DC) boost topologies				
	Conventional boost topology	Symmetrical boost topology	Interleaved boost topology	Three-level boost Topology	Half-bridge boost topology
Number of boost inductors	1	1	2	1	1
Boost inductor size	L	L	L/2	L	L
Voltage output	Vo	Vo	Vo	2Vo	2Vo
Maximum semi-conductors in cur-rent path	3	2	3	2	1
Diode bridge existence	Yes	No	Yes	No	No
Active switches	1	2	2	2	2

Usually, switching of semiconductor devices, e.g., MOSFET and IGBT, is not ideal.If the switch has ideal characteristics, then it can be turned on/off instantaneously, and there is no delay exit between voltage across a switch and current passing through it. However, ideally such delays happen during the switching transition state (turn on/off). These delays in switching states cause switching losses to occur in a semiconductor device. If somehow during the transition state switching current/ voltage is made to be zero, switching losses can be reduced.

Soft switching methods are implemented to make these switching transitions soft (gradual) to minimize the switching losses. Two most widely adopted soft switching techniques are (a) zero voltage switching (ZVS) and (b) zero current switching (ZCS). The design of the new converter topologies incorporates these soft switching techniques to improve the efficiency of EVs chargers. In ZCS techniques when the switch is turned on, the rate of rise in current through the switch is slowed down by placing a small inductor in series with the switch. Usually, an active auxiliary circuit is used in zero current transition methods which have a switch of lower-rated current to change the path of a current from the switch of themain converter each time it turns to be off.

Comparison of Various DC-DC Converters

Conventionally, the required level of output power decides the selection criteria of a DC-DC converter. Examining the basic configurations of converter, the output power level (low- to high-power converter), is fly-back, forward, push-pull, half- bridge, and full-bridge. Generally, for low-power applications, the most commonlyused isolated topology with low possible cost is fly-back converter. For a fly-back converter, a separate output inductor is not required; however, only a single active switch is essential, which makes it less costly and easy to implement. Unsatisfactoryutilization of the transformer and necessity of supplementary capacitors due to high input and out ripple currents are the drawback of the topology. As for medium power-level applications, forward and active clamp forward converters are often implemented. The topology has the similar problems as in case for fly-back converter, i.e., limited duty cycle causes the unsatisfactory utilization of the transformer. During the steady-state operation, both quadrants are utilized by the transformer for forward and active clamp forward converters. However, maximum duty cycle is limited during transformer reset process, as peak flux during startup and transient states can increase to higher levels. The remaining three topologies (push-pull, half, and full-bridge) are much appropriate for applications which require high power/ high density as (1) there is a full utilization of a transformer core, (2) power transfer occurs in both the quadrants, (3) no need for special provisions to reset the trans- former, (4) further optimization of a transformer due to large available range of duty cycle, and (5) higher duty cycle at the output filter inductor (100%). The turns ratio of the transformer is designed in such a way to effectively maximize the duty cycle to decrease the RMS current and size of an output filter.

The drawback of a push-pull topology is the higher voltage stress on the input switches during the off-state, much higher than the input voltage. This issue is not arising in a half-bridge topology, i.e., the voltage stress is not higher than the input voltage. This is the added benefit of half-bridge topology over push-pull configura- tion. The other major benefit is much better utilization of a transformer core, depending on the switching of active switches, either operating in a buck or aboost mode. Comparing the half-bridge topology with the CUK and SEPIC, onlya single inductor is required (half of the size) as two in other configurations (CUK and SEPIC) and active components have less current ratings. This would lead to less switching and conduction losses which subsequently raise the efficiency of a half- bridge converter. The problem with this topology is the discontinuity in its output current during the boost mode operation. CUK has the benefit of reduced ripple current at the input and output, but the problem is higher voltage rating (Vin + Vout) on the transfer capacitor (Ct). This issue is resolved in SEPIC topology with less rated voltage (Vin). The topology of split-pi converter has a smaller size of passive components with benefits of reduced switching losses, less harmonics in the current waveform, and higher efficiency.

The full-bridge topology has the benefits of best core utilization, switch voltage less than the input, and much less current for a given power as compared to half- bridge topology. All these benefits raise the efficiency of a full-bride converter as compared to half-bridge converter particularly at high load currents. The cost of extra switches and complications for driving the switches are the drawbacks of full- bridge converter configuration. Furthermore, a cascaded DC-DC converter (back- end) has many benefits,e.g., lower thermal and electrical stress, and interleaved topologies are much beneficial to reduce the current ripples. Simply to represent charging operation of a charger, some studies focused on a simple buck or boost converter for a back-end operation of an EV charger.The comparative properties of several DC-DC converters are summarized in Table 6.

Table 6 Comparative properties of various DC-DC converter topologies

Topologies		Comparative properties	Performance enhancement methods
• One-phase isolated or non-isolated topology with less power and slow charging	• Different configurations including:	• Flyback	• Power factor correction
• Three-phase isolated or non-isolated topology with high power and fast charging	– Flyback	– Lower cost of converter, fewer components	• Bridgeless boost topology with power factor correction
	– Push-pull	– Input current is pulsating	• Simple inter-leaved topologies have advantages such as
	– Forward	– O/P filter inductor is not required	– Less charging current of battery
	– Half-bridge	– Offer DC isolation which make it available in applica-tions which need isolation conversion	– Reduced inductor size
	– Full-bridge	– Converter can perform the step-up or step-down operation and work as either non-inverting or inverting converter	– Less stress on output capacitor but power level is limited
	– CUK	– Higher current and volt-age stresses, however, simple and inexpensive	• Bridgeless inter-leaved topologies

– SEPIC	– Inductor efficiency is low due to leakage problem	– Power levels are higher
– Multi-level and matrix converters	• Forward	• Multicell converter topologies
	– Converter can perform the step-up or step-down operation	• Resonant circuit topologies
	– Unsatisfactory utilization of magnetic core and input current is pulsating	– Switching stress is lesser
	– Benefit of lower cost	– Lesser losses
	• Push-pull	– Efficiency is higher
	– Converter can perform the step-up or step-down operation Buck derived converter and voltage stresses are higher	• Soft switching topologies
	– Imbalance magnetic flux	• Hard switching Topologies

Topologies		Comparative properties	Performance enhancement methods
		• CUK	• Zero voltage, zero current switching topologies (ZVS, ZCS)
		– Inverting converter, i.e., getting a −ve polarity output	– ZVS and ZCS provide reduced size and weight
		– Continuous current at input and output	
		– Large inductors with higher electrical stresses	
		– Reduced ripple current at input and output	
		– More passive components are required	
		• SEPIC	
		– Non-inverting buck-boost	
		– Gate drive circuitry is simpler	
		– Less voltage stresses as compared to CUK	
		– Input current is non-pulsating	

		CUK and SEPIC Bidirectional power conversion can be achieved with two active switches; however, both suffer by high current stress in diodes and switches as compared to half-bridge with similar voltage and power conditions
		• Half-bridge and full-bridge
		– Can be used as step-up or step-down converter
		– Transformer core is effectively utilized
		– Conduction and switching losses are lesser
		– Lower component stress, higher conversion ratio, and higher power level are benefits of full-bridge; however, higher cost and complex control are the main issues
		– Less components, lower cost, and high component stress are benefits and issues of half-bridge, respectively
		– Higher efficiency as compared to CUK and SEPIC
		• Multi-level and matrix converters
		– Higher efficiency, less losses, less component stress, and reduced switching frequency are the main benefits, whereas added circuitry with complex control is an issue of multilevel converters
		– Sinusoidal input and output waveforms, reduced higher-order harmonics with no subharmonics, maximum voltage transformation ratio, controlled input power factor, least energy storage requirements, inherently presented bidirectional flow, and exclusion of bulky storage capacitors are the significant benefits of matrix converters

Isolated and Non-isolated Topologies with Variations

1.Isolated Full-Bridge Converter Topologies with ItsVariations

Among various converter configurations, the current and voltage-fed bridges, a suitable combination of both and resonant converters with different variations, are the best appropriate and mostly utilized DC-DC back-end converters. Appropriate modifications in control logics and replacement of switches with MOSFETS enable to convert unidirectional converters to bidirectional converters. One famous topology is the combination of current- and voltage-fed full-bridge (VCFFB) converter topology, where ZVS used for current-fed side and for voltage-fed side either ZCS or ZVS can be attained. The schematic illustration of full-bridge DC-DC converter is represented in Fig. 5a.

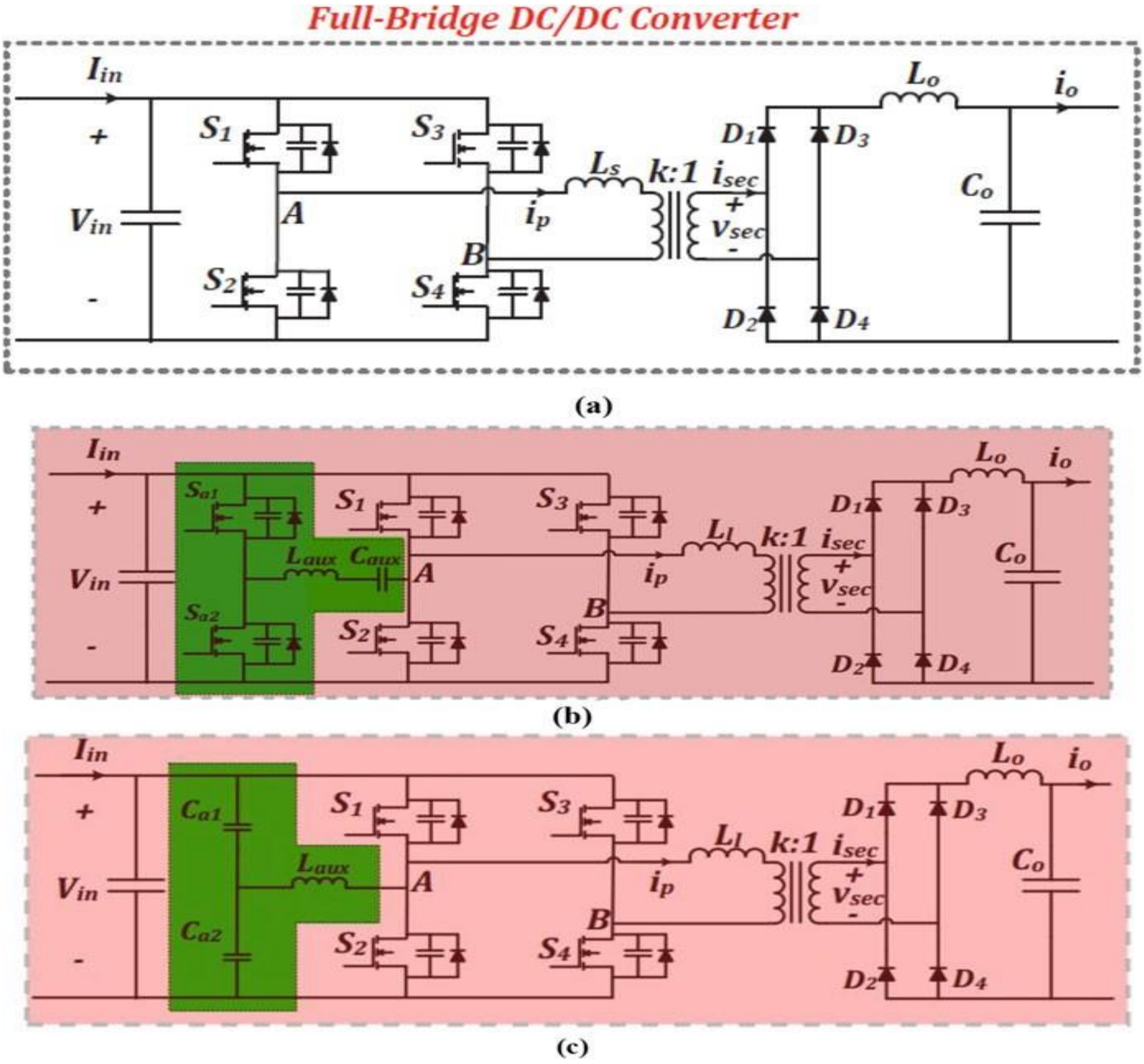


Fig. 5 Full-bridge DC-DC converter with soft-switching auxiliary circuits: (a) full-bridge power converter, (b) active auxiliary circuit, (c) passive auxiliary circuit

The DC-DC power converters are usually required to operate at high switching frequencies to gain higher power densities; however, the increase in switching frequency of a transistor not only rise the total switching losses but also decrease the supply efficiency. With the rise in switching frequencies, the turn-on/turn-off losses (switching losses) of semiconductor devices become higher. Therefore, ZCS and ZVS techniques are implemented to allow the operation at higher frequencies, while reducing the switching losses, increase the efficiency, and lower the cost and size, which outcomes in higher power densities. These switching techniques also improve the converter reliability by lowering the stress on the switching devices. Higher variations in dv/dt and di/dt can be eliminated by using the soft-switching techniques due to a significant reduction in EMI. Moreover, ripples for output voltage and input current should be minimum to efficiently charge the battery. The interleaved design is implemented to achieve the target. Bidirectional non-isolated configuration is preferred due to involvement of cost issue. The common implementation of traditional phase shift modulation is based on the reason that there is no need to use an extra circuitry to deliver soft switching. For DC-DC converters, the major reasons which make phase shift modulation technique extremely widespread are much simpler implementation, soft-switching operation, and obtaining symmetrical pulses.

Currently, numerous studies have been conducted for the development of effi- cient and reliable chargers for EVs. For several DC-DC converters, phase-shifted full-bridge (PSFB) converter and resonant power converters have gained much consideration and ensured three main aspects for an effective EV charger: (1) soft-switching operation, (2) reduction in rectified voltage peak, and (3) extended regu-lated range for output voltage. Quantitative design specs of high-power isolated DC-DC converters are summarized in Table 7.

Another topology related to full-bridge configuration is the PSFB converter used in high-power applications. The topology is same as the traditional full-bridge converter; however, the control method is different; it implements the zero voltage transitions (ZVT) and ZCS combined (ZVZCS) while maintaining the switching frequency constant. The oscillations can be reduced by shifting the phases of a gate pulse for switches S3 and S4 in accordance with switches S1 and S2.For both lagging and leading leg switches, zero voltage and zero current switching can be realized over a particular level of power. The transformer is used in such kind of converter topology to provide galvanic isolation [46]. Reduced switching and circulating conducting losses, PWM control and less current stress are the benefits of this topology, which makes its efficiency higher for several load conditions and a wider range of output voltage. So, it becomes one best dc/dc converter option that is appropriate for high input voltage, high frequency, and high-power applications due to the aforementioned advantages. The main issues reported in PSFB topology are

(1) higher circulating currents, (2) secondary side hard switching, (3) light load efficiency, (4) small effective duty cycle, and (5) secondary side switching losses and voltage stress.

Table 7 Quantitative design specs of high-power DC-DC converter topologies (converter topol- ogies are designed for 40 kW output power, 200 V output voltage and switching frequency 8.5 kHz)

Quantitative parameters	PSFB topology	LLC topology	Interleaved buck topology
Ouput capacitor (µF)	100	50	1
Output inductor (µH)	96	–	–
Switch count	4	2	3
Transfer capacitor (µF)	–	11 µF (820) V	–
Transfer inductor (mH)	–	–	3 × 1.1 mH (66 A)
Transformer	1	1	–
Isolation	Yes	Yes	No
Control	PWM	Frequency	PWM
Efficiency (%)	94	97	96

The PSFB performs regulation of output voltage through changing the phase shift among the two legs, but the problem of hard switching at secondary side switches and lose of ZVS at lighter load conditions are major concerns for PSFB. The batteries of EVs function as variable loads, so it is expected that DC-DC converters can be operated under lighter load conditions as it majorly depends on the battery state of charge (SOC). The operation of ZVS is no longer implemented and hard- switching losses may arise when the current parameters of EVs drop down to the lowest critical value of output current.

EVs, RES, and many other applications usually have a wider range of operating conditions. For higher duty cycle, conventional phase-shift techniques perform well in the case for heavier loads. However, to keep soft-switching under lighter loads, it is hard for conventional techniques to sustain the good performance for DC-DC converters. Generally, to implement the soft-switching techniques, switching frequency of DC-DC converter topologies should have much higher range of frequency. The higher switching frequency has a potential impact on the overall performance evaluation of DC-DC converters. The performance of a converter topology is affected due to core losses and losses in a drive circuitry. Therefore, to effectively control the losses associated with the gate drive circuitry and the core, higher switching frequency of a converter is restricted to an appropriate limit and soft-switching is limited. The other potential issues in a conventional phase-shiftedtechnique are the larger amount of circulating currents even without the flow of current to the output and peak voltage stress around output rectifier diodes. Conse- quently, under lighter load circumstances, these circulating currents and voltage peak stress further enhance the conduction losses and lower the efficiency.

Integrated Charger and Charger Configuration with Front-End AC-AC and Back-End AC-DC Converters

The second most extensively implemented battery charger configuration for EVs consists of two stages. Front-end AC-AC converter is employed in the first stage, and back-end AC-DC converter is applied in the second stage. Initially, this kind of charger topology utilizes front-end device (AC-AC) to appropriately change the level of AC input supply before the operation of rectification that is performed by aback-end AC-DC converter to properly charge the batteries of EVs. In previous research studies, two main topologies have been used to present front-end AC-ACdevice that includes three-phase transformers and *Z*-source network. Thebenefits which can be achieved by three-phase transformers are (1) altering the ACinput supply to a suitable level of voltage for EV charging and (2) galvanic isolation is provided between the input side and the vehicle.

Meanwhile, the benefits offered by Z-source AC-AC converter network are (1) capability to perform buck and boost operation of output voltage with fewer components, (2) harmonic and inrush cur- rents can be reduced by acting as static transformer, (3) control and structure are simpler; (4) voltage sag can be easily controlled by Z-source network in any power network, (5) continuous input currents, (6) improvement in input profiles by oper- ating in continuous current mode (CCM), (7) common ground is shared between the input and output, thus maintaining the phase angle, (8) turns ratio of the transformers is regulated to adjust the voltage gain of the converter, therefore achieve the desired voltage gain, and (9) high efficiency, reliability, and reduced cost.

Z-source networks can act in two ways: one as a voltage source converter andother as a current source converter. It is implemented like an impedance network to join main converter circuit to load/power source. On the other hand, three converter topologies can be implemented to represent a back-end AC-DC converter for such kind of charging configurations of EVs, which includes (1) three-phase three-level converter with diode clamping, (2) uncontrolled rectifier, and (3) active rectifier. The main benefit which can be realized from a three-phase three-level converter with diode clamping is the capability to perform bidirectional flow,which further offers the fundamental feature of an EV called vehicle-to-grid technology. Ancillary services to a power network such as voltage and frequency control can also be achieved by using this type of converter topology. The uncontrolled rectifier only has the capability to provide the process of rectification excluding the feature of an active control. Conversely, controllable rectification is achievable with active rectifier configuration. The conve- nience of fast charging to EV owners along with unity power factor can be attained using active rectifier converter configuration.

The third major type of charging topology, which is adopted for EVs chargers, can be understood by an interesting concept that utilize the already available electric drive parts for the representation of an EV charger named as integrated charger. The major reasons to employ the concept of an integrated charging function into an electric drive component system are (1) weight, volume, and sizeof the system are minimized, (2) cost is reduced, and (3) better efficiency]. When the traction and charging of an EV do not perform simultaneously, then integration of a charging system can be obtained. The concept of an integrated charging function can be realized practically because at that time, charging of an EV is performed externally when it is stopped. Consequently, the components of the electric drive system can be operated as charger of an EV. The working of an inverter in electric drive system is similar to rectification process during the reverse opera- tion. Thus, modification can be performed for an inverter in electric drive system frequently to use it as charger of an EV. On the other hand, the electric motor windings are employed to behave as inductors and to perform function as a filter device, and inverter of motor drive acts as an AC-DC converter in the EV power train. The benefits which can be obtained to utilize inductors of the motor drive as a filtering device are (1) ripple current is reduced, (2) reduce harmonics,(3) system components are minimized, (4) optimization of weight and space, and(5) cost is saved.

The most beneficial advantage is the achievement of higher charging power levels (level 2 and 3) having bi directional fast-charging support with reduced cost and unity power factor. Complications in control structure and designing of hardware are major challenges to employ this concept in different products commercially. Many market-leading companies in automotive industry sector, e.g., FORD Motor Company, are currently utilizing battery recharge and electric motor drive system combined, depending on an induction motor, and split winding AC motor has been implemented for non-isolated integrated charger. Few appli- cations related to the two-wheeled vehicles and electric scooter are employed in. A structure of an EV charger based on integrated charging system is shown in Fig. 10. Comparative parameters of single converter integrated topologies are highlighted in Table 13

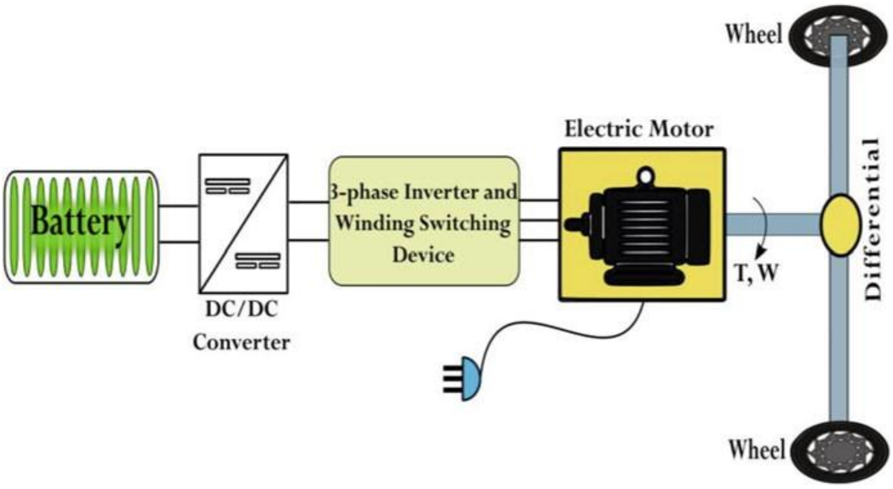


Fig. 10 EV charger based on integrated charging system

Table 13 Comparative parameters of single-stage converter integrated topologies

Comparative parameters	Positive buck/boost diode rectifier	Three-level AC-DC topology	Bridgeless direct AC-DC topology	Buck/boost diode AC-DC topology
Inductor count	1	2	1	1
Switch count	6	11	9	4
Diode count	9	14	3	7
Diode bridge existence	Yes	No	No	Yes
Bidirectional operation	No	Yes	Yes	No
Control difficulty	Moderate	High	Moderate	Low
THD suppression	Low	High	Moderate	Moderate

UNIT –IV
ELECTRIC PROPULSION SYSTEMS,
PERMANENT MAGNET BLDC & SRM MOTOR DRIVES

ELECTRICAL PROPULSIONS IN EVS AND HEVS:

Vehicle propulsion has specific requirements that distinguish stationary and onboard motors. Every kilogram onboard the vehicle represents an increase in structural load. This increase structural load results in lower efficiency due to increase in the friction that the vehicle has to overcome. Higher efficiency is equivalent to a reduction in energy demand and hence, reduced battery weight. The fundamental requirement for traction motors used in EVs is to generate propulsion torque over a wide speed range. These motors have intrinsically neither nominal speed nor nominal power. The power rating mentioned in the catalog and on the name plate of the motor corresponds to the maximum power that the drive can deliver. Two most commonly used motors in EV propulsion are Permanent Magnet (PM) Motors and Induction Motors (IM). These two motors will be investigated in detail in the coming lectures. However, before going into the details of these machines some basic fundamentals of electrical machines, such as torque production, are discussed in this chapter.

DC MOTOR DRIVES

DC motor drives have been widely used in applications requiring adjustable speed, good speed regulation, and frequent starting, braking and reversing. Various DC motor drives have been widely applied to different electric traction.

Principle of Operation:

The operation principle of a DC motor is straightforward. When a wire carrying electric current is placed in a magnetic field, magnetic force acting on the wire is produced. The force is perpendicular to the wire and the magnetic field as shown in Figure 4.1. The magnetic force is proportional to the wire length, magnitude of the electric current, and the density of the magnetic field, that is,

$$F = BIL. \qquad \ldots\ldots\ldots\ldots \text{ eq1}$$

When the wire is shaped into a coil, as shown in Figure 6.3, the magnetic forces acting on both sidesproduce a torque, which is expressed as

$$T = BIL\cos\alpha, \qquad \ldots\ldots\ldots\ldots\ldots\text{eq2}$$

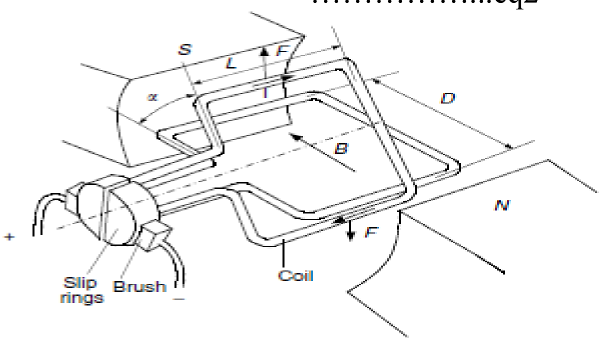


Figure 4.1: Operation principle of a DC motor

where α is the angle between the coil plane and magnetic field as shown in Figure 4.1. The magnetic field may be produced by a set of windings or permanent magnets. The former is called wound-field DC motor and the latteris called the PM DC motor.

The coil carrying the electric current is called the armature. In practice, the armature consists of a number of coils. In order to obtain continuous and maximum torque, slip rings and brushes are used to conduct each coil at the position of α=0.

Practically, the performance of DC motors can be described by the armature voltage, back electromotive force (EMF), and field flux. Typically, there are four types of wound-field DC motors, depending onthe mutual interconnection between the field and armature windings. They are separately excited, shunt excited, series excited, and compound excited as shown in Figure 3.2.

In the case of a separately excited motor, the field and armature voltage can be controlled independently of one another.

In a shunt motor, the field and armature are connected in parallel to a common source. Therefore, an independent control of field current and armature or armature voltage can be achieved by inserting a resistance into the appropriate circuit.

This is an inefficient method of control. The efficient method is to use power electronics-based DC–DC converters in the appropriate circuit to replace the resistance.

The DC–DC converters can be actively controlled to produce proper armature and field voltage. In the case of a series motor, the field current is the same as the armature current; therefore, field fluxis a function of armature current.

In a cumulative compound motor, the magnetomotive force (mmf) of a series field is a function of the armature current and is in thesame direction as the mmf of the shunt field.

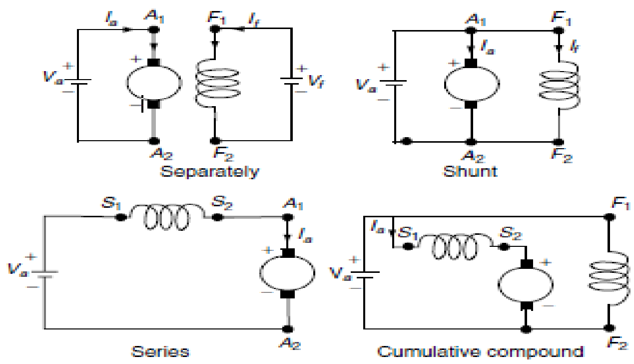


Figure 4.2: Wound-field DC motors

The steady-state equivalent circuit of the armature of a DC motor is shown in Figure 4.3. The resistor*Ra* is the resistance of the armature circuit. For separately excited and shunt DC motors, it is equal to the resistance of the armature windings; for the series and compound motors, it is the sum of armature and series field winding resistances.

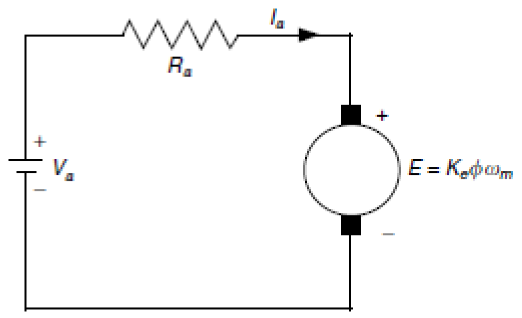


Figure 4.3: Steady-state equivalent circuit of the armature circuit of a DC motor

$$V_a = E + R_a I_a,\ E = K_e\phi\omega_m,$$
$$T = K_e\phi I_a, \qquad \text{……..eq3}$$

where φ is the flux per pole in Webers, *Ia*is the armature current in *A*, *Va* is the armature voltage in volt, *Ra* is the resistance of the armature circuit in ohms, ω*m*is the speed of the armature in rad/sec, *T* is the torque developed by the motor in Nm, and *Ke*is constant.

From equations 3 one can obtain

$$T = \frac{K_e\phi}{R_a}V - \frac{(K_e\phi)^2}{R_a}\omega_m. \qquad \text{……………. eq4}$$

Equations 3 are applicable to all the DC motors, namely, separately (or shunt) excited, series, and compound motors. In the case of separately excited motors, if the field voltage is maintained as constant, one can assume the flux to be practically constant as the torque changes. In this case, the speed–torque characteristic of a separately excited motor is a straight line, as shown in Figure 3.4.

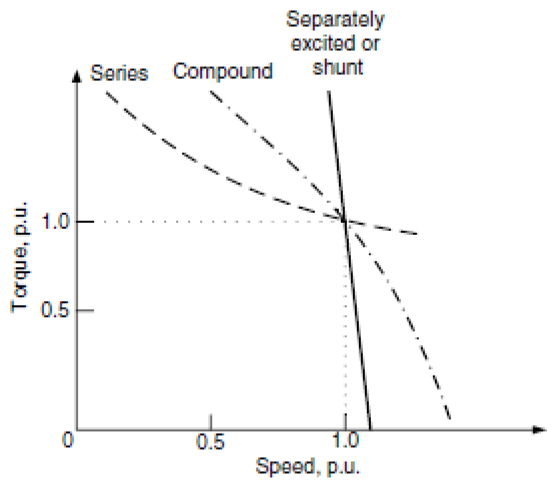


Figure 4.4 Speed characteristics of DC motors

The non load speed ω*m*0 is determined by the values of the armature voltage and the field excitation. Speed decreases as torque increases, and speed regulation depends on the armature circuit resistance. Separately excited motors are used in applications requiring good speed regulation and proper adjustable speed.

In the case of series motors, the flux is a function of armature current. Inan unsaturated region of themagnetization characteristic, φ can be assumed to be proportional to *Ia*. Thus

$$\phi = K_f I_a. \qquad \text{…………eq5}$$

By equations 3&5, the torque for series excited DC motors can obtained as

$$T = \frac{K_e K_f V_a^2}{(R_a + K_e K_f \omega_m)^2}, \qquad \text{………………eq6}$$

A speed–torque characteristic of a series DC motor is shown in Figure 3.4.In the case of series, any in magnetic flux. Because flux increases with the torque, the speed drops to maintain a balance between the induced voltage and the supply voltage. The characteristic, therefore, shows a dramatic drop. A motor of standard design works at the knee point of the magnetization curve at the rated torque. At heavy torque (large current) overload, the magnetic circuit saturates and the speed–torque curve approaches a straight line.

Series DC motors are suitable for applications requiring high starting torque and heavy torque overload, such as traction. This was just the case for electric traction before the power electronicsand micro control era. However, series DC motors for traction application have some disadvantages. They are not allowed to operate without load torque with full supply voltage. Otherwise, their speed will quickly increase up to a very high value. Another disadvantage is the difficulty in regenerative braking. Performance equations for cumulative compound DC motors can be derived from equations (3).

The speed–torque characteristics are between series and separately excited (shunt) motors, as shown in Figure 4.4.

COMBINED ARMATURE VOLTAGE AND FIELD CONTROL

The independence of armature voltage and field provides more flexible control of the speed and torque than other types of DC motors. In EV and HEV applications, the most desirable speed–torque characteristic is to have a constant torque below a certain speed (base speed), with the torque dropping parabolically with the increase of speed (constant power) in the range above the base speed, as shown in Figure 4.5. In the range of lower than base speed, the armature current and field are set at their rated values, producing the rated torque. From equations (3), it is clear that the armature voltage must be increased proportionally with the increase of the speed. At the base speed, the armature voltage reaches its rated value (equal to the source voltage) and cannot be increased further. In order to further increase the speed, the field must be weakened with the increase of the speed, and then the back EMF *E* and armature current must be maintained constant. The torque produced drops parabolically with the increase in the speed and the output power remains constant, as shown in Figure 4.5.

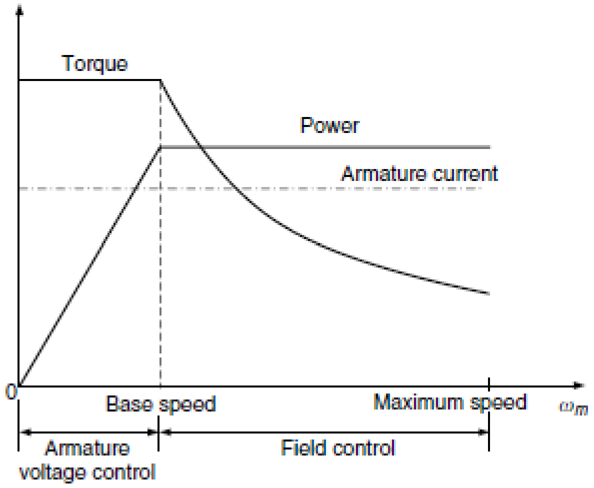


Figure 4.5: Torque and power limitations in combined armature voltage and field control

CHOPPER CONTROL OF DC MOTORS

Choppers are used for the control of DC motors because of a number of advantages such as high efficiency, flexibility in control, light weight, small size, quick response, and regeneration down to very low speeds. Presently, the separately excited DC motors are usually used in traction, due to the control flexibility of armature voltage and field.

For a DC motor control in open-loop and closed-loop configurations, the chopper offers a number of advantages due to its high operation frequency. High operation frequency results in high-frequency Output voltage ripples and therefore less ripples in the motor armature current and smaller region of discontinuous conduction in the speed–torque plane. A reduction in the armature current ripple reduces the armature losses. A reduction or elimination of the discontinuous conduction region improves speed regulation and the transient response of the drive.

The power electronic circuit and the steady-state waveform of a DC chopper drive are shown in Figure 4.6

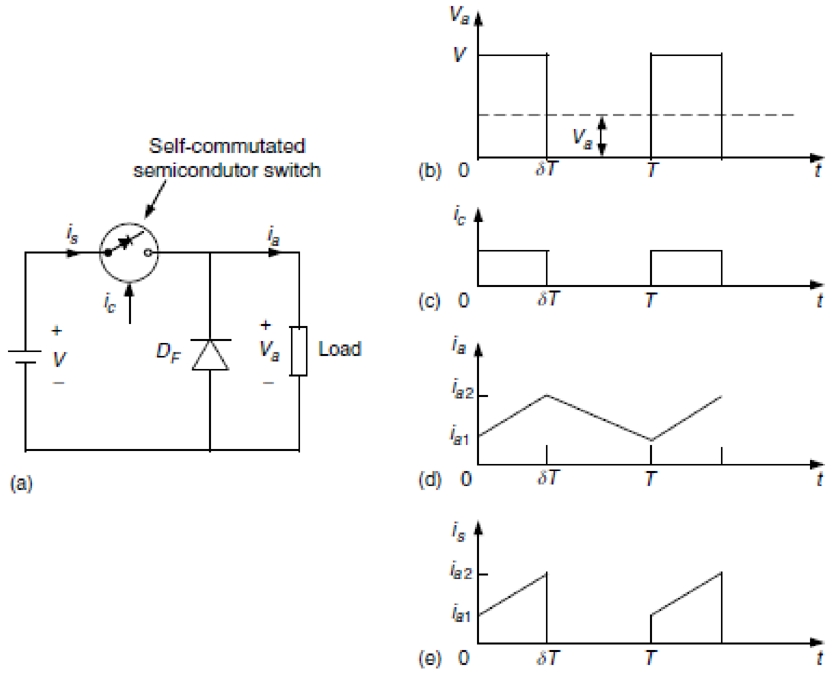


Figure4.6: Principle of operation of a step down (or class A) chopper:
(a) basic chopper circuit; (b)to (e)waveforms

A DC voltage source, *V*, supplies an inductive load through a self-commutated semiconductor switch *S*. The symbol of a self-commutated semiconductor switch has been used because a chopper can be built using any device among thyristors with a forced commutation circuit: GTO, power transistor, MOSFET, and IGBT. The diode shows the direction in which the device can carry current. A diode *DF* is connected in parallel with the load. The semiconductor switch *S* is operated periodically overa period *T* and remains closed for a time $ton=\delta T$ with $0\leq\delta\leq1$. The variable $\delta=ton/T$ is called the duty ratio or duty cycle of a chopper. Figure 4.6 also shows the waveform of control signal *ic*. Control signal *ic* will be the base current for a transistor chopper, and a gate current for the GTO of a GTO chopper or the main thyristor of a thyristor chopper. If a power MOSFET is used, it will be a gate to the source voltage. When the control signal is present, the semiconductor switch *S* will conduct, if forward biased. It is assumed that the circuit operation has been arranged such that the rem oval of *ic* will turn off the switch.

During the on interval of the switch ($0\leq t\leq\delta T$), the load is subjected to a voltage and the load current increases from *ia*1 to *ia*2. The switch is opened at $t=\delta T$. During the off period of the switch ($\delta T\leq t\leq1$),the load inductance maintains the flow of current through diode *DF*. The load terminal voltage remains zero (if the voltage drop on the diode is ignored in comparison to *V*)and the current decreases from *ia*2 to *ia*1. The internal $0\leq t\leq\delta T$ is called the duty interval and the interval $\delta T\leq t\leq T$ is known as the freewheeling interval.

Diode *DF* provides a path for the load current to flow when switch *S* isoff, and thus improves the load current waveform. Furthermore, by maintaining the continuity of the load current at turn off, it prevents transient voltage from appearing across switch *S*, due to the sudden change of the load current.

The source current waveform is also shown in Figure. The source current flows only during the duty interval and is equal to the load current. The direct component or average value of the load voltage *Va* is given by

$$V_a = \frac{1}{T}\int_0^T \bar{v}_a \, dt = \frac{1}{T}\int_0^{\delta T} V \, dt = \delta t \text{…….eq7}$$

By controlling δ between 0 and 1, the load voltage can be varied from 0 to *V*;thus, a chopper allows a variable DC voltage to be obtained from a fixed voltage DC source. The switch *S* can be controlled in various ways for varying the duty ratio δ.

The control technologies can be divided into the following categories:

1. Time ratio control (TRC).
2. Current limit control (CLC).

In TRC, also known as pulse width control, the ratio of on time to chopper period is controlled. The TRC can be further divided as follows:

1. Constant frequency TRC
2. The chopper period *T* is kept fixed and the on period of the switch is varied to control the duty ratio δ.
3. Varied frequency TRC:

Here, δ is varied either by keeping *ton* constant and varying *T* or by varying both *ton* and *T*. In variable frequency control with constant on-time, low-output voltage is obtained at very low values of chopper frequencies. The operation of a chopper at low frequencies adversely affects the motor performance. Furthermore, the operation of a chopper with variable frequencies makes the design of an input filter very difficult. Thus, variable frequency control is rarely used.

In current limit control, also known as point-by-point control, δ is controlled indirectly by controlling the load current between certain specified maximum and minimum values. When the load current reaches a specified maximum value, the switch disconnects the load from the sourceand reconnects It when the current reaches a specified minimum value. For a DC motor load, this type of control is, in effect, a variable frequency variable on time control.

The following important points can be noted from the waveform of Figure4.5:

The source current is not continuous but flows in pulses. The pulsed current makes the peak input power demand high and may cause fluctuation in the source voltage. The source current waveform can be resolved into DC and AC harmonics. The fundamental AC harmonic frequency is the same as the chopper frequency. The AC harmonics are undesirable because they interfere with other loads connected to the DC source and cause radio frequency interference through conduction and electromagnetic radiation.

Therefore, anL-C filter is usually incorporated between the chopper and the DC source. At higher chopper frequencies, harmonics can be reduced toa tolerable level by a cheaper filter. From this point, a chopper should be operated at the highest possible frequency.

The load terminal voltage is not a perfect direct voltage. In addition to a direct component, it has harmonics of the chopping frequency and its multiples. The load current also has an AC ripple.

The chopper of Figure 4.6 is called a class A chopper. It is one of a number of chopper circuits that are used for the control of DC motors. This chopper is capable of providing only a positive voltage and a positive current. It is therefore called a single-quadrant chopper, capable of providing DC separately excited motor control in the first quadrant, positive speed, and positive torque. Since it can vary the output voltage from V to 0, it is also a step-down chopper or a DC to DC buck converter. The basic principle involved can also be used to realize a step-up chopper or DC to DC boost converter. The circuit diagram and steady-state waveforms of a step-up chopper are shown in Figure 4.6. This chopper is known as a class B chopper. The presence of control signal ic indicatesthe duration for which the switch can conduct if forward-biased. During a chopping period T, it remains closed for an interval $0 \leq t \leq \delta T$ and remains open for an interval $\delta T \leq t \leq T$. During the on period, iS increases from $iS1$ to $iS2$, thus increasing the magnitude of energy stored in inductance L. When the switch is opened, current flows through the parallel combination of the load and capacitor C. Since the current is forced against the higher voltage, the rate of change of the current is negative. It decreases from $iS2$ to $iS1$ in the switch's off period. The energy stored in the inductance L and the energy supplied by the low-voltage source are given to the load. The capacitor C serves two purposes. At the instant of opening of switch S, the source current, iS, and load current, ia, are not the same. In the absence of C, the turn off of S will force the two currents to have the same values. This will cause high induced voltage in the inductance $L$and the load inductance. Another reason for using capacitor C is to reduce the load voltage ripple. The purpose of the diode D is to prevent any flow of current from the load into switch S or source V.

For understanding the step-up operation, capacitor C is assumed to be large enough to maintain aconstant voltage Va across the load. The average voltage across the terminal a, b is given as

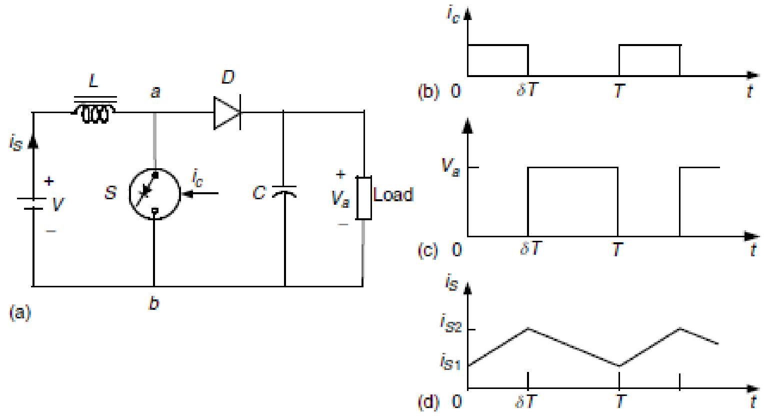


Figure 4.7: Principle of operation of a step-up (or class B) chopper: (a) basic chopper circuit; (b) to(d)waveforms

$$V_{ab} = \frac{1}{T}\int_0^T v_{ab}\, dt = V_a(1-\delta$$ ……………..eq8

The average voltage across the inductance L is

$$V_L = \frac{1}{T}\int_0^T \left(L\frac{di}{dt}\right) dt = \frac{1}{T}\int_{i_{s1}}^{i_{s2}} L\, di = 0.$$ …………………eq9

The source voltage is

$$V = V_L + V_{ab}.$$ ………………….eq10

Substituting from equations (8) and (9) into (10) gives

$$V = V_a(1-\delta) \text{ or } V_a = \frac{V}{1-\delta}$$ ………..eq11

According to (11), theoretically the output voltage *Va* can be changed from *V* to ∞ by controlling δ from 0 to 1. In practice, *Va* can be controlled from *V* to a higher voltage, which depends on the capacitor *C*, and the parameters of the load and chopper.

The main advantage of a step-up chopper is the low ripple in the source current. While most applications require a step-down chopper, the step-up chopper finds application in low-power battery-driven vehicles. The principle of the step-up chopper is also used in the regenerative braking of DC motor drives.

MULTIQUADRANT CONTROL OF CHOPPER-FED DC MOTOR DRIVES:

The application of DC motors on EVs and HEVs requires the motors to operate in Multiquadarant, including forward motoring, forward braking, backward motoring, and backward braking, as shown in Figure 4.8. For vehicles with reverse mechanical gears, two-quadrant operation (forward motoring and forward braking, or quadrant I and quadrant IV) is required. However, for vehicles without reverse mechanical gears, four-quadrant operation is needed. Multiquadarant operation of a separately excited DC motor is implemented by controlling the voltage poles and magnitude through power electronics-based choppers.

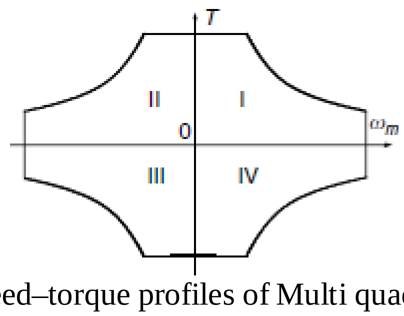


Figure 4.8: Speed–torque profiles of Multi quadarant operation

TWO-QUADRANT CONTROL OF FORWARD MOTORING AND REGENERATIVE BRAKING:

A two-quadrant operation consisting of forward motoring and forward regenerative braking requires a chopper capable of giving a positive voltage and current in either direction. This two-quadrant operation can be realizedin the following two schemes.

Single Chopper with a Reverse Switch:

The chopper circuit used for forward motoring and forward regenerative braking is shown in Figure 4.9, where *S* is a self-commutated semiconductor switch, operated periodically such that it remains closed for a duration of $\delta T$and remains open for a duration of (1-δ) *T*.*C* is the manual switch.

When *C* is closed and *S* is in operation, the circuit is similar to that of+

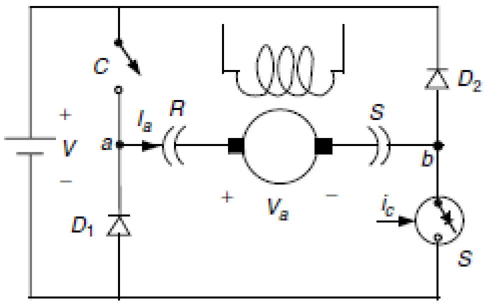


Figure4.9: Forward motoring and regenerative braking control with a single chopper

Under these conditions, terminal *a* is positive and terminal *b* is negative. Regenerative braking in the forward direction is obtained when *C* is opened and the armature connection is reversed with the help of the reversing switch *RS*, making terminal *b* positive and terminal *a* negative. During the on- period of the switch *S*, the motor current flows through a path consisting of the motor armature, switch *S*, and diode *D*1, and increases the energy stored in the armature circuit inductance. When *S* is opened, the current flows through the armature diode *D*2, source *V*, diode *D*1 and back to the armature, thus feeding energy into the source. During motoring, the changeover to regeneration is done in the following steps. Switch *S* is deactivated and switch *C* is opened. This forces the armature current to flow through diode *D*2, source *V*, and diode *D*1. The energy stored in the armature circuit is fed back to the source and the armature current falls to zero. After an adequate delay to ensure thatthe current has indeed become zero, the armature connection is reversed and switch *S* is reactivated with a suitable value of *d* to start regeneration.

Class C Two-Quadrant Chopper:

In some applications, a smooth transition from motoring to braking and vice versa is required. For such applications, the class C chopper is used as shown in Figure 4.10.

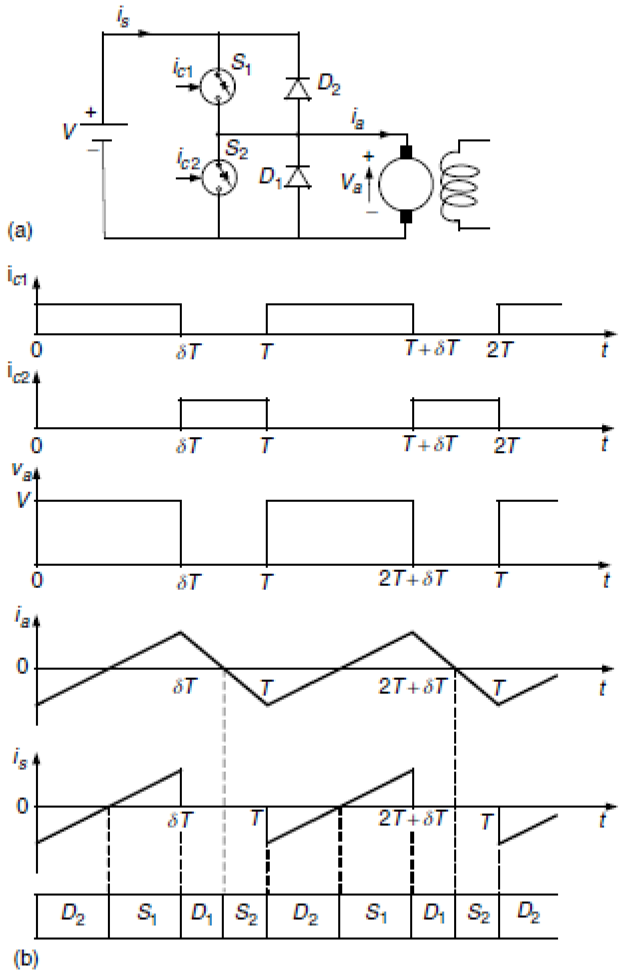


Figure 4 .10 Forward motoring and regenerative braking control using class C two-quadrant chopper: (a) chopper circuit and (b) waveforms

The self-commutated semiconductor switch $S1$ and diode$D1$ constitute one chopper and the self-commutator switch $S2$ and diode$D2$ form another chopper. Both the choppers are controlled simultaneously, both for motoring and regenerative braking. The switches $S1$ and $S2$are closed alternately. In the chopping period T, $S1$ is kept on for duration δT, and $S2$ is kept on from $\delta T$to$T$.To avoid a direct, short-circuit across the source, care is taken to ensure that $S1$ and $S2$ do not conduct at the same time. This is generally achieved by providing some delay between the turn offof one switch and the turn on of another switch.

The waveforms of the control signals *vaia*, and *are* in Figure 4.10(b). In drawing these waveforms, the delay between the turn off of one switch and the turn on of another switch has been ignored because it is usually very small. The control signals for the switches $S1$ and $S2$ are denoted by $ic1$ and $ic2$, respectively. It is assumed that a switch conductsonly when the control signal is present and the switch is forward biased.

The following points are helpful in understanding the operation of this two-quadrant circuit:

1. In this circuit, discontinuous conduction does not occur, irrespective of its frequency of operation. Discontinuous conduction occurs interval of time. The current may become zero either during the freewheeling interval or in the energy transfer interval. In this circuit, freewheeling will occur when $S1$ is off and the current is flowing through $D1$. This will happen in interval $\delta T \leq t \leq T$, which is also the interval for which $S2$ receives the control signal. If ia falls to zero in the freewheeling interval, the back EMF will immediately drive a current through $S2$ in the reverse direction, thus preventing

the armature current from remaining zero for a finite interval of time. Similarly, energy transfer will be present when $S2$ is off and $D2$is conducting — that is, during the interval 0_t_δT. If the current falls to zero during this interval, $S1$ will conduct immediately because ic is present and V_E. The armature current will flow, preventing discontinuous conduction.

2. Since discontinuous conditions are absent, the motor current will be flowing all the time. Thus, during the interval $0 \le t \le \delta T$, the motor armature will be connected either through $S1$ or $D2$. Consequently, the motor terminal voltage will be V and the rate of change of ia will be positive because $V>E$. Similarly, during the interval $\delta T \le t \le T$, the motor armature will be shorted either through $D1$ or $S2$. Consequently, the motor voltage will be zero and the rate of change of ia will be negative.

3. During the interval $0 \le t \le \delta T$, the positive armature current is carried by$S1$ and the negative armature current is carried by $D2$. The source current flows only during this interval and it is equal to ia. During the interval $\delta T \le t \le T$, the positive current is carried by $D1$and the negative current is carried by $S2$.

4. From the motor terminal voltage waveform of Figure 3.10 $V_a = \delta V$. Hence,

$$I_a = \frac{\delta V - E}{R_a}.$$

……………eq12

Equation (12) suggests that the motoring operation takes place when$\delta = E/V$, and that regenerative braking occurs when $\delta = E/V$. The no-loadoperation is obtained when $\delta = E/V$.

FOUR-QUADRANT OPERATION:

The four-quadrant operation can be obtained by combining two class C choppers (Figure 4.10) as shown in Figure 4.11,

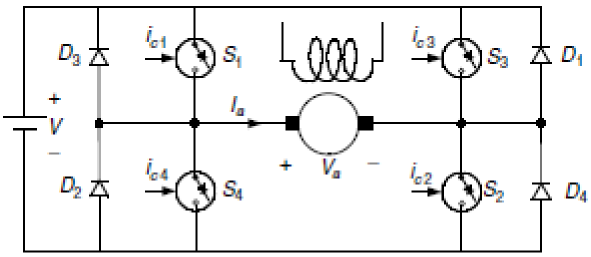


Figure 4.11: Class E four-quadrant chopper

which is referred to as a class Echopper. In this chopper, if $S2$ is kept closed continuously and $S1$ and $S4$ are controlled, a two-quadrant chopper is obtained, which provides positive terminal voltage (positive speed) and the armature current in either direction (positive or negative torque), giving a motor control in quadrants I and IV. Now if $S3$ is kept closed continuously and $S1$ and $S4$ are controlled are controlled a two quadrant chopper which can supply a variable negative terminal voltage (negative speed) and the armature current can be in either direction (positive or negative torque), giving a motor control in quadrants II and III.This control method has the following features:

the utilization factor of the switches is low due to the asymmetry in the circuit operation. Switches $S3$ and$S2$ should remain on for a long period. This can create commutation problems when the switches use thyristors. The minimum output voltage depends directly on the minimum time for which the switch can be closed, since there is always a restriction on the minimum time for which the switch can be closed, particularly in thyristor choppers.The minimum available output voltage, and therefore the minimum available motor speed, is restricted. To ensure that switches $S1$ and $S4$, or $S2$ and $S3$ are not on at the same time, some fixed time interval must elapse between the turn off for one switch and the turn on of another switch. This restricts the maximum permissible frequency of operation. It also requires two switching operations during a cycle of the output voltage.

PERMANENT MAGNET MOTORS:

By using high energy magnets such as rare earth-based magnets, a PM machine drive can be designed with high power density, high speed and high operation efficiency. These advantages are attractive for their application in EVs and HEVs. The major advantages of PM machines are:

- ***High efficiency***: The PM machines have a very high efficiency due to the use of PMs for excitation which consume no power. Moreover, the absence of mechanical commutators and brushes results in low mechanical friction losses.
- ***High Power density***: The use of high energy density magnets has allowed achieving very high flux densities in the PM machines. As a result of high flux densities, high torque can be produced from a given volume of motor compared to other motors of same volume.
- ***Ease of Control***: THE PM motors can be controlled as easily as DC motors because the control variables are easily accessible and constant throughout the operation of the motor.

  However, the PM machines also suffer from some disadvantages such as:
- ***Cost***: Rare-earth magnets commonly used in PM machines are very expensive.
- ***Magnet Demagnetization***: The magnets can be demagnetized by large opposing magneto motive force and high temperatures.
- ***Inverter Failure***: Due to magnets on the rotor, PM motors present major risks in the case of short circuit failures of the inverters. The rotor is always energized and constantly induces EMF in the short-circuited windings. A very large current circulates in those windings and an accordingly large torque tends to block the rotor. The dangers of blocking one or several wheels of a vehicle are non-negligible.

Based on the shape of the back e.m.f induced in the stator windings, the PM motors can be classified into two types:

- Permanent Magnet Synchronous Machine with sinusoidal back e.m.f (**Figure 1a**)
- Brushless Permanent Magnet DC Machines (BLDC) with trapezoidal back e.m.f(**Figure 1b**)

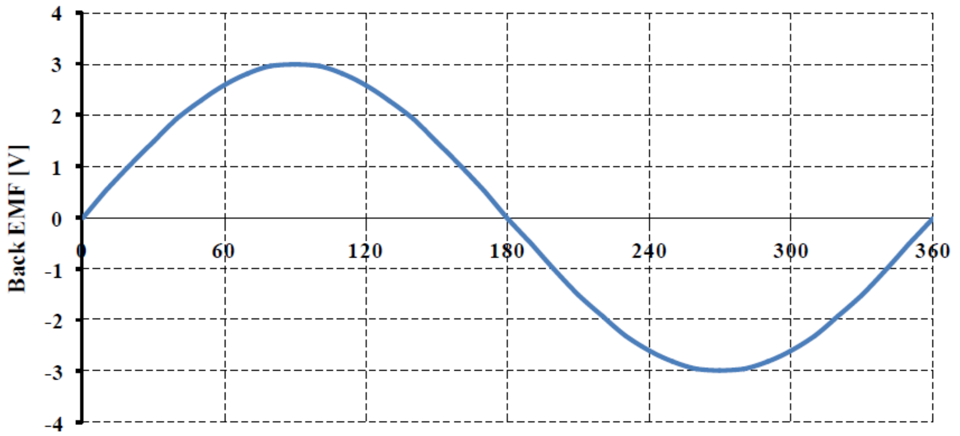


Figure 1a: Sinusoidal back emf

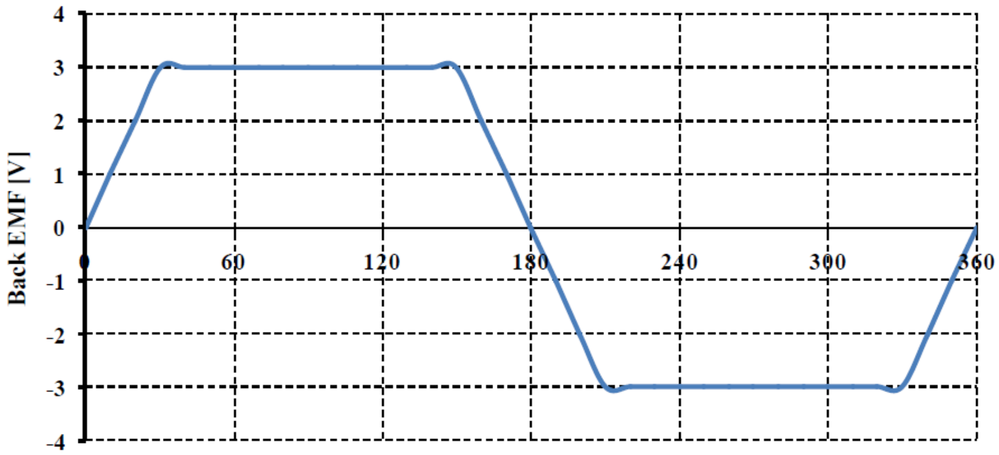


Figure 1b: Trapezoidal back emf

PRINCIPLE OF OPERATION OF PM MACHINE:

To produce torque, in general, a rotor flux and a stator mmf has to be present that are stationary with respect to each other but having a nonzero phase shift between them. In PM machines, the necessary rotor flux is present due to rotor PMs. Currents in the stator windings generate the stator mmf. The zero-relative speed between the stator mmf and the rotor flux is achieved if the stator mmf is revolving at the same speed as the rotor flux, that is, rotor speed and also in the same direction. The revolving stator mmf is the result of injecting a set of polyphase currents phase shifted from each other by the same amount of phase shift between the polyphase windings. For example, a three phase machine with three windings shifted in space by electrical 120o between them produces a rotating magnetic field constant in magnitude and travelling at an angular frequency of the currents (just as in case of Induction machines). The rotor has permanent magnets on it, hence the flux produced by the rotor magnets start to chase the stator mmf and as a result torque is produced. Since the relative speed between the stator mmf and rotor flux has to be zero, the rotor moves at the same speed as the speed of the stator m.m.f. Hence, the PM machines are inherently synchronous machines. As the coils in the stator experience a change of flux linkages caused by the moving magnets, there is an induced e.m.f in the windings. The shape of the induced e.m.f is very dependent on the shape of the flux linkage. If the rotational electrical speed of the machine and the air gap flux is sinusoidal then it can be expressed as (**Figure 3**)

$$\phi = \phi_m \sin(\omega_r t)$$

$$\omega_r = \frac{N_p}{2}\omega_{mech}$$

…………………eq1

where ϕ_m is the peak flux produced
ω_r is the electrical speed of the rotation
ω_{mech} is the mechanical speed of the rotor
N_p is the no of poles of motor

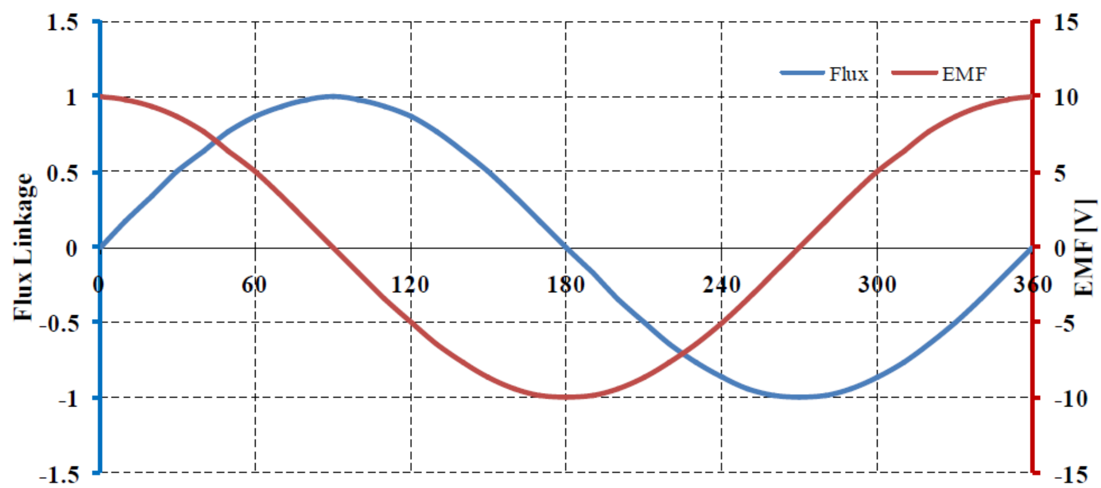


Figure 3: The flux linkage and back emf.

Given the number of turns (N_{turns}), then the flux linkages (λ) are equal to the product $N_{turns}\phi$. The induced emf is equal to the rate of flux linkages and is given by (**Figure 3**):

$$e = -\frac{d\lambda}{dt} = -N_{turns}\phi_m\omega_r\cos(\omega_r t) = -\lambda_m\omega_r\cos(\omega_r t) = -\lambda_m\omega_r\cos(\theta_r)$$

where

$$\lambda_m = N_{turns}\phi_m$$

$$\theta_r = \omega_r t$$

……….eq2

The –ve sign in **equation 2** indicates that the induced e.m.f opposes the applied voltage. Some observations based on **equation 2** are:

- The emf is proportional to the product of the rotational frequency and air gap for a constant number of turns.
- Assuming that air gap flux is constant, it can be seen that the e.m.f is influenced only by the rotational speed of rotor which is same as the stator current frequency.
- By changing the frequency of stator current, the speed of the motor can be changed and a speed control of the motor can be achieved. However, beyond a certain speed known as base speed, an increase in stator frequency will result in voltage demand exceeding the supply capability. During that operation, keeping the voltage constant and increasing the excitation frequency reduces the airgap flux and thus allowing the excitation frequency reduces the air gap flux, thus allowing going to higher speed over and above the base speed. This operation isknown as ***flux weakening***.

The PM machines are fed by DC-AC converter. By changing the frequency at which the gates are turned on, the frequency of the output wave can be varied. In the next sections the operation of a three phase PM machines with 120o and 180o conduction modes are explained. The following assumptions are made in the following analysis:

- The phases of the machines are **Y** connected.
- The current entering the neutral point (n) is considered to be positive and leaving it is considered to be negative. n
- The back e.m.f induced in the phases is sinusoidal.
- All the phases of the machine are balanced, that is, the inductances and resistances of the phases are equal.

STEADY STATE CHARACTERISTICS OF PERMANENT MAGNET MOTORS:

STEADY STATE MODELLING OF PERMANENT MAGNET MACHINES:

The PM machines are driven by the inverter and the triggering of the DC-AC converter switches is symmetric, the waveforms of the applied stator voltage exhibit the followingrelationships

$$V_{an}\left(\omega_r t+\frac{\pi}{3}\right)=-V_{bn}\left(\omega_r t\right);\ V_{bn}\left(\omega_r t+\frac{\pi}{3}\right)=-V_{cn}\left(\omega_r t\right);\ V_{cn}\left(\omega_r t+\frac{\pi}{3}\right)=-V_{an}\left(\omega_r t\right) \qquad (1)$$

The voltage and current relations given in

$$p\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & 0 & 0 \\ 0 & -\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} & 0 & 0 \\ 0 & \frac{1}{L_s} & 0 \\ 0 & 0 & \frac{1}{L_s} \end{bmatrix} + \begin{bmatrix} V_{an} - e_a \\ V_{bn} - e_b \\ V_{cn} - e_c \end{bmatrix}$$

…………………………….....................................eq2(a)

$$e_a = \lambda_m \omega_r \cos(\omega_r t); e_b = \lambda_m \omega_r \cos\left(\omega_r t - \frac{2\pi}{3}\right); e_c = \lambda_m \omega_r \cos\left(\omega_r t + \frac{2\pi}{3}\right)$$

…………………………………………………eq2(b)

The differential equations given in **equation 2** are time-invariant. Hence, the stator currents which form the response of the system, obey the same symmetry relations as the input voltage and can be

$$i_a\left(\omega_r t + \frac{\pi}{3}\right) = -i_b(\omega_r t);\ i_b\left(\omega_r t + \frac{\pi}{3}\right) = -i_c(\omega_r t);\ i_c\left(\omega_r t + \frac{\pi}{3}\right) = -i_a(\omega_r t)$$

………………………………………………………………………………….eq3

STEADY STATE SOLUTION FOR 120° CONDUCTION OF THE DC-ACCONVERTER

Due to the symmetries for the voltages and currents given by **equations 1** and **3**, if the solution is known for one basic switching interval, it can be used to generate the solution for the remaining intervals. **120**°In conduction mode of DC-AC inverter, each switch conducts for **60**°. The analysis starts when switch $S_2$is turned ***on*** and $S_6$is turned ***off*** Due to the inductance of the stator windings, the current in phase **B** does not become zero instantaneously and continues to flow through the freewheeling diodesD_3orD_6depending on the direction of the current. Once the current through the phase **B** becomes zero, the diode stops conducting and only phase **A** and **C** conduct and the equivalent circuit. The duration for which the freewheeling diodes conduct is known as ***commutation period*** and the duration when only two phases conduct is known as ***conduction period***. At the start of the commutation period (when switch $S_6$is turned off), the rotor angle is defined to be

$$\theta_r = -\phi + \frac{\pi}{6}$$

……………………eq4

Where ∅ is the advance firing angle,

The duration of the ***commutation period*** is given by the commutation angleθ_c and is a function of∅ , the winding inductances and resistances and rotor speed ω_r making it difficult to estimate. The determination of current is achieved in two steps:

- **Step 1:** In this step the general solution of the currents is obtained
- **Step 2:** In this step the angle θ_c is determined using the symmetries given in

equations 1 and **3**.

Step 1: General Solution:

At time t=0 the switch S_2 is turned ***on*** and S_2 is turned ***off***. As discussed in the previous section, the current i_b does not become zero immediately and remains nonzero till the time t= . Hence, the commutation period lasts for 0≤t≤ t_c .In this period all the three phases are connected to the DC-AC converter and the stator voltages for $i_b < 0$ are

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} \frac{V_{in}}{3} \\ \frac{V_{in}}{3} \\ -\frac{2V_{in}}{3} \end{bmatrix} \quad \text{..................eq5}$$

In case $i_b > 0$, the stator phase voltages are

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} \frac{2V_{in}}{3} \\ -\frac{V_{in}}{3} \\ -\frac{V_{in}}{3} \end{bmatrix} \quad \text{.......................eq6}$$

Substituting e e e from **equation 2b** and replacing θ with θ -∅ + π in **equation 2a** gives,

$, \; b, b, \qquad r \qquad r \qquad 6$

$$p\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & 0 & 0 \\ 0 & -\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} & 0 & 0 \\ 0 & \frac{1}{L_s} & 0 \\ 0 & 0 & \frac{1}{L_s} \end{bmatrix} \begin{bmatrix} V_{an} - \omega_r \lambda_m \cos\left(\theta_r - \phi + \frac{\pi}{6}\right) \\ V_{bn} - \omega_r \lambda_m \sin(\theta_r - \phi) \\ V_{cn} - \omega_r \lambda_m \cos\left(\theta_r - \phi + \frac{5\pi}{6}\right) \end{bmatrix}$$

………………………………. eq7

The system of first order differential **equation 7** can be expressed in standard state variable form as

$$p i_{abc}(t) = A i_{abc}(t) + B u(t)$$

$$i_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, A = \begin{bmatrix} -\frac{R_s}{L_s} & 0 & 0 \\ 0 & -\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_s}{L_s} \end{bmatrix}$$ ……………………eq8

$$B = \begin{bmatrix} \frac{1}{L_s} & 0 & 0 \\ 0 & \frac{1}{L_s} & 0 \\ 0 & 0 & \frac{1}{L_s} \end{bmatrix}, u(t) = \begin{bmatrix} V_{an} - \omega_r \lambda_m \cos\left(\theta_r - \phi + \frac{\pi}{6}\right) \\ V_{bn} - \omega_r \lambda_m \sin(\theta_r - \phi) \\ V_{cn} - \omega_r \lambda_m \cos\left(\theta_r - \phi + \frac{5\pi}{6}\right) \end{bmatrix}$$

The solution of **equation 8** is

$$i_{abc}(t) = e^{At} i_o + \int_0^{t_c} e^{A(-\tau)} B u(\tau) d\tau$$

……………...eq9

where the initial conditions vector is

$$i_o = \begin{bmatrix} i_a(0) \\ i_b(0) \\ i_c(0) \end{bmatrix} = \begin{bmatrix} i_a(0) \\ i_b(0) \\ -\left(i_a(0)+i_b(0)\right) \end{bmatrix}$$

……………. eq10

The solution of **equation 9** for the time interval $0 \le t \le$, using the initial conditions givenin **equation 10**, is

$$i_a(t) = i_a(0)e^{-\frac{R_s}{L_s}t} + \frac{V_{an}}{R_s}\left(1-e^{-\frac{R_s}{L_s}t}\right) + \frac{\omega_r\lambda_m}{2\left(R_s^2+\omega_r^2L_s^2\right)}\left[\left(\omega_rL_s+\sqrt{3}R_s\right)\cos\phi+\left(R_s-\sqrt{3}\omega_rL_s\right)\sin\phi\right]e^{-\frac{R_s}{L_s}t}$$

$$-\frac{\omega_r\lambda_m}{2\left(R_s^2+\omega_r^2L_s^2\right)}\left[\left(\omega_rL_s+\sqrt{3}R_s\right)\cos\left(\theta_r-\phi\right)-\left(R_s-\sqrt{3}\omega_rL_s\right)\sin\left(\theta_r-\phi\right)\right]$$

………………eq11

$$i_b(t) = i_b(0)e^{-\frac{R_s}{L_s}t} + \frac{V_{bn}}{R_s}\left(1-e^{-\frac{R_s}{L_s}t}\right) - \frac{\omega_r\lambda_m}{\left(R_s^2+\omega_r^2L_s^2\right)}\left[\omega_rL_s\cos\phi+R_s\sin\phi\right]e^{-\frac{R_s}{L_s}t}$$

$$+\frac{\omega_r\lambda_m}{\left(R_s^2+\omega_r^2L_s^2\right)}\left[\omega_rL_s\cos\left(\theta_r-\phi\right)-R_s\sin\left(\theta_r-\phi\right)\right]$$

…………………eq12

Since the three phases are connected in Y, the phase **C** current is given by

$$i_c(t) = -\left(i_a(t)+i_b(t)\right)$$

………………...eq13

When theib becomes zero at t = , the commutation period ends and the conduction period $_{\pi}$starts with just phases **A** and **C** conducting. The duration of conduction period is$t \le t \le$____.

The differential equation given in **equation 11** holds for the conduction period and th only cange is in u(t) and initial values of current given by

$$u(t) = \begin{bmatrix} \frac{V_{in}}{2} - \frac{\omega_r\lambda_m}{2}\cos\left(\theta_r-\phi+\frac{\pi}{6}\right) \\ \omega_r\lambda_m\sin\left(\theta_r-\phi\right) \\ -\frac{V_{in}}{2} - \frac{\omega_r\lambda_m}{2}\cos\left(\theta_r-\phi+\frac{5\pi}{6}\right) \end{bmatrix};\ i_o = \begin{bmatrix} i_a(t_c) \\ i_b(t_c) \\ i_c(t_c) \end{bmatrix} = \begin{bmatrix} i_a(t_c) \\ 0 \\ -i_a(t_c) \end{bmatrix}$$

………………………………eq14

The solution of **equation 9** for conduction period is

$$i_{abc}(t) = e^{A(t-t_c)}i_o + \int_0^{\frac{\pi}{3\omega_r}} e^{A(t-\tau)}Bu(\tau)d\tau$$

……………eq15

The evaluation of the integration given in **equation 15**gives

$$i_a(t)=i_a(t_c)e^{-\frac{R_s}{L_s}(t-t_c)}+\frac{V_{in}}{2R_s}\left(1-e^{-\frac{R_s}{L_s}(t-t_c)}\right)+\frac{\sqrt{3}\omega_r\lambda_m}{2\left(R_s^2+\omega_r^2L_s^2\right)}\left[R_s\cos(\phi-\theta_c)-\omega_rL_s\sin(\phi-\theta_c)\right]e^{-\frac{R_s}{L_s}(t-t_c)}$$

$$-\frac{\sqrt{3}\omega_r\lambda_m}{2\left(R_s^2+\omega_r^2L_s^2\right)}\left[R_s\cos(\theta_r-\phi)+\omega_rL_s\sin(\theta_r-\phi)\right]$$

……………………………………………………………………..eq16

The phase **C** current is same as phase **A** current (i_a(t) = $-i_c(t)$) and phase **B** current is zero ($i_b\, t=0$)

Step 2: Determination of Commutation Angle:

At time $t=0$, the switch $S_6$is turned off and $S_2$is turned on. Hence, at $t=0$ the current in phase **C** is zero and the phase **A** and **B** currents are equal in magnitude. Therefore, the initial conditions are given by

$$i_o=\begin{bmatrix} i_a(0)\\ i_b(0)\\ i_c(0)\end{bmatrix}=\begin{bmatrix} I_o\\ -I_o\\ 0\end{bmatrix}$$

…………………...eq17

At the end of the conduction period, the currents are

$$\begin{bmatrix} i_a\left(\frac{\pi}{3\omega_r}\right)\\ i_b\left(\frac{\pi}{3\omega_r}\right)\\ i_c\left(\frac{\pi}{3\omega_r}\right)\end{bmatrix}=\begin{bmatrix} I_o\\ 0\\ -I_o\end{bmatrix}$$

…………………………. eq18

The commutation period ends when phase **B** current becomes zero, that isi_b ( )=0. Using this condition and initial conditions given by **equation 17**in **equation 18** gives

$$0=-I_oe^{-\frac{R_s}{L_s}t_c}+\frac{V_{in}}{R_s}\left(1-e^{-\frac{R_s}{L_s}t_c}\right)-\frac{\omega_r\lambda_m}{\left(R_s^2+\omega_r^2L_s^2\right)}\left[\omega_rL_s\cos\phi+R_s\sin\phi\right]e^{-\frac{R_s}{L_s}t_c}$$

$$+\frac{\omega_r\lambda_m}{\left(R_s^2+\omega_r^2L_s^2\right)}\left[\omega_rL_s\cos(\theta_c-\phi)-R_s\sin(\theta_c-\phi)\right]$$

………………………………………………………...eq19

Using the boundary condition given by

$$I_o = i_a(t_c)e^{-\frac{R_s}{L_s}\left(\frac{\pi}{3\omega_r}-t_c\right)} + \frac{V_{in}}{2R_s}\left(1-e^{-\frac{R_s}{L_s}\left(\frac{\pi}{3\omega_r}-t_c\right)}\right) + \frac{\sqrt{3}\omega_r\lambda_m}{2\left(R_s^2+\omega_r^2L_s^2\right)}\left[R_s\cos\left(\phi-\theta_c\right)-\omega_rL_s\sin\left(\phi-\theta_c\right)\right]e^{-\frac{R_s}{L_s}\left(\frac{\pi}{3\omega_r}-t_c\right)}$$

$$-\frac{\sqrt{3}\omega_r\lambda_m}{2\left(R_s^2+\omega_r^2L_s^2\right)}\left[R_s\cos\left(\frac{\pi}{3}-\phi\right)+\omega_rL_s\sin\left(\frac{\pi}{3}-\phi\right)\right]$$

…………………………………………………………………eq20

Using the boundary condition given by

CONTROL STRATEGIES OF PM MACHINES:

There are various control strategies and depending on the application a suitable strategy can bechosen. For example, a mutual flux air gap linkages control gives a smooth transition to flux weakening above the base speed. Similarly, a maximum efficiency control is suitable forapplications where energy saving is important such as hybrid and electric vehicles. The most commonly used control strategies are:

- Constant torque angle control
- Unity power factor control
- Constant mutual air gap flux linkages control
- Angle control of air gap flux and current phasors
- Optimum torque per ampere control
- Constant loss based maximum torque speed boundary control
- Minim loss or maximum efficiency control.

The control strategies marked in bold are discussed in the following sections.

Constant Torque Angle Control:

Consider that the PM motor is supplied three phase currents given as follows:

$$i_{as} = I_m \sin\left(\omega_r t + \delta\right)$$

$$i_{bs} = I_m \sin\left(\omega_r t + \delta - \frac{2\pi}{3}\right)$$

$$i_{cs} = I_m \sin\left(\omega_r t + \delta - \frac{4\pi}{3}\right)$$

……………………...eq1

The q and d axes stator currents in the rotor reference frames are obtained through the transformation matrix as

$$\begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\omega_r t & \cos\left(\omega_r t - \frac{2\pi}{3}\right) & \cos\left(\omega_r t - \frac{4\pi}{3}\right) \\ \sin\omega_r t & \sin\left(\omega_r t - \frac{2\pi}{3}\right) & \sin\left(\omega_r t - \frac{4\pi}{3}\right) \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix}$$

$$= \frac{2}{3}\begin{bmatrix} \cos\omega_r t & \cos\left(\omega_r t - \frac{2\pi}{3}\right) & \cos\left(\omega_r t - \frac{4\pi}{3}\right) \\ \sin\omega_r t & \sin\left(\omega_r t - \frac{2\pi}{3}\right) & \sin\left(\omega_r t - \frac{4\pi}{3}\right) \end{bmatrix}\begin{bmatrix} I_m \sin(\omega_r t + \delta) \\ I_m \sin\left(\omega_r t + \delta - \frac{2\pi}{3}\right) \\ I_m \sin\left(\omega_r t + \delta - \frac{4\pi}{3}\right) \end{bmatrix}$$

$$= I_m \begin{bmatrix} \sin\delta \\ \cos\delta \end{bmatrix}$$

……………………………………………………………………….eq2

$$T_e = \frac{3}{2}\frac{N_p}{2}\left[\lambda_{af} i_{qs}^r + \left(L_d - L_q\right) i_{qs}^r i_{ds}^r\right]$$

………………. eq3

Substituting the values of $i^q{}_{sr}$ and $i^q{}_{dr}$ from **equation 2** into **equation 3a** gives

$$T_e = \frac{3}{2}\frac{N_p}{2}\left[\lambda_{af} I_m \sin\delta + \frac{1}{2}\left(L_d - L_q\right) I_m^2 \sin(2\delta)\right]$$

…………………………………………………………….eq4

Having developed the basic equations, we now focus on the ***Constant Torque Angle Control***. In this strategy the torque angle δ is maintained at 90°. Hence, the above torque equation becomes:

$$T_e = \frac{3}{2}\frac{N_p}{2}\lambda_{af} I_m$$

……………………. eq5

The *q* and *d* axis voltage for the PM machine is given by

$$\begin{bmatrix} v_{qs}^r \\ v_{ds}^r \end{bmatrix} = \begin{bmatrix} R_s + L_q p & \omega_r L_d \\ -\omega_r L_q & R_s + L_d p \end{bmatrix}\begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_{af} \\ 0 \end{bmatrix}$$

……………………………eq6

Since the load angle $\delta = 90^\circ$, from **equation 2,**, $i^r{}_{ds} = I_m$ and **equation 5** can be written as:

$$\begin{bmatrix} v_{qs}^r \\ v_{ds}^r \end{bmatrix} = \begin{bmatrix} R_s + L_q p & \omega_r L_d \\ -\omega_r L_q & R_s + L_d p \end{bmatrix} \begin{bmatrix} I_m \\ 0 \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_{af} \\ 0 \end{bmatrix}$$

$$v_{qs}^r = \left(R_s + L_q p\right) I_m + \omega_r \lambda_{af}$$

………………. eq7

$$v_{ds}^r = -\omega_r L_q I_m$$

For the analysis of the control strategy, it is convenient to convert **equation 4** and **equation 6** into per unit (p.u) values. The base values chosen are:

I_b base value of stator current

λ_{af} base value of magnet flux

ω_b base speed

V_b base voltage = $\lambda_{af}\,\omega_b$

R_b base Resistance

L_b base Inductance

T_b base value of torque = $\frac{3}{2}\frac{N_p}{2}\lambda_{af}\,\omega_b$

X_b base value of reactance = $\omega_b\, L_b$

Using the base values given in **equation 7** the normalized can be written as

$$T_{en} = \frac{T_e}{T_b} = \frac{\frac{3}{2}\frac{N_p}{2}\lambda_{af} I_m}{\frac{3}{2}\frac{N_p}{2}\lambda_{af} I_b} = I_{mn}$$

……………………….eq8

From **equation 8** it can be seen that the normalized torque (T) is equal to the normalized stator current I_{sn} . The voltage equation for steady state analysis can be obtained by making P=0 (because in steady state the time variation is zero) in **equation 6** and is written as

$$v_{qs}^r = R_s I_m + \omega_r \lambda_{af}; \quad v_{ds}^r = -\omega_r L_q I_m$$

$$v_{qs}^r = R_s I_m + \omega_r \lambda_{af}; \quad v_{ds}^r = -\omega_r L_q I_m$$

…………………….eq9

The magnitude of the stator voltage is given by

$$V_s = \sqrt{\left(v_{qs}^r\right)^2 + \left(v_{ds}^r\right)^2}$$

……………………….eq10

The normalized stator voltage is obtained as

$$V_{sn} = \frac{V_s}{V_b} = \frac{V_s}{\omega_b \lambda_{af}} = \sqrt{\left(R_{sn} I_{mn} + \omega_{rn}\right)^2 + \left(\omega_{rn} L_{qn} I_{mn}\right)^2}$$

…………………eq11

The phasor diagram for this control strategy is shown in **Figure 1**. From this figure the power factor is obtained as

$$\cos\phi = \frac{v_{qs}^{r}}{V_{s}} = \frac{v_{qs}^{r}}{\sqrt{\left(v_{qs}^{r}\right)^{2} + \left(v_{ds}^{r}\right)^{2}}} = \frac{1}{\sqrt{1 + \left(\frac{v_{ds}^{r}}{v_{qs}^{r}}\right)^{2}}} = \frac{1}{\sqrt{1 + \left(\frac{L_{qn} I_{sn}}{1 + \frac{R_{sn} I_{sn}}{\omega_{rn}}}\right)^{2}}}$$ ……………..eq12

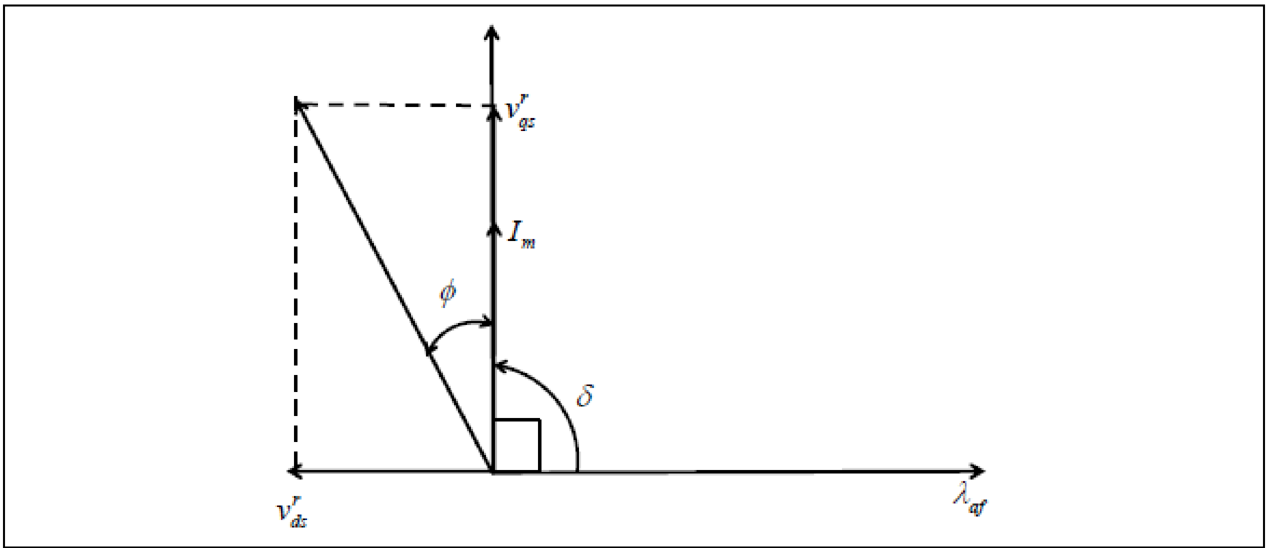


Fig 1: The Phasor Diagram of PM machine with Constant Torque Angle Control

The **equation 12** shows that the power factor deteriorates as the rotor speed goes up. The maximum rotor speed with this control strategy can be obtained by solving **equation 11** for , neglecting the stator resistive drop ($R_{sn} I_{mn} \backsim 0$), and is given as

$$\omega_{rn(\max)} = \frac{V_{sn(\max)}}{\sqrt{1 + \left(L_{qn} I_{sn}\right)^{2}}}$$ ………………..eq13

Assuming that the motor is driven by a three phase DC-AC converter, the maximum voltage is given by:

$$V_{sn(\max)} = \frac{\sqrt{2} \times 0.45 V_{dc}}{V_{b}}$$ ……………………eq14

The performance characteristics of the PM machine are shown in **Figure 2**. The parameters of the machine for a speed of 1p.u. ($_{n}$=1) used to plot the curves are given in **Table 1**. From the **Figure 2** the following can be observed:

- The power factor falls as the current rises.
- The torque is proportional to the current as is evident from **equation 8**.
- The normalized increases with the increase in current. The impedance of the machine remains constant because its speed is constant at 1p.u. hence, when the current through the machine has to increase the applied voltage also has to increase (**equation 11**).

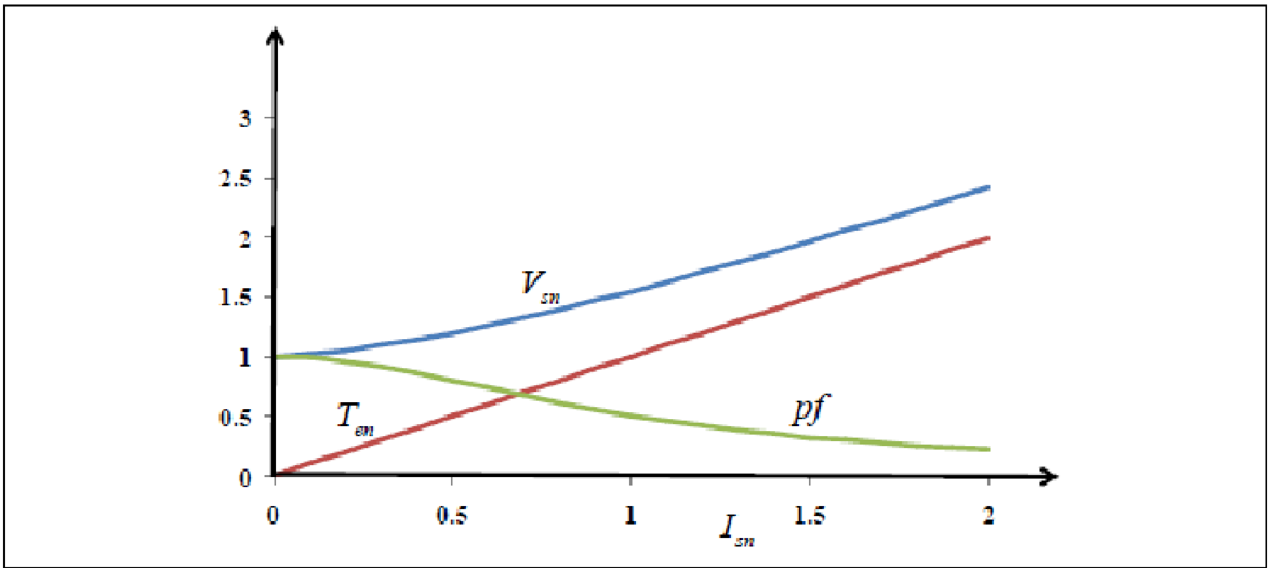


Fig 2: The characteristics curves of PM machine with Constant Torque Angle Control

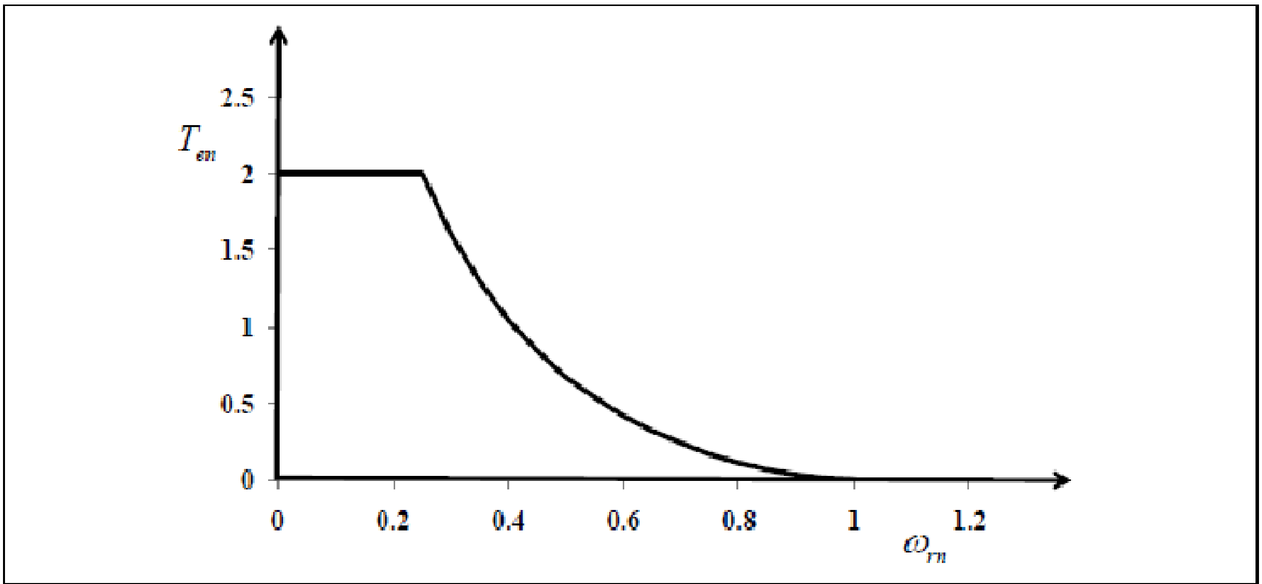


Fig 3: The torque vs. speed characteristic curves of PM machine with Constant Torque Angle Control

Table 1: The parameters of a salient pole PM machine

Base Voltage (V_b)	Base Current (I_b)	Base Inductance (L_b)	Base Speed (ω_b)	Base Flux Linkage (λ_b)	Resistance (R)	d-axis inductance (L_d)	q-axis inductance (L_q)
100 V	10 A	0.02 H	600 rad/s	0.167 Vs/rad	1.8 Ω	0.011 H	0.022 H

The torque vs. speed curve for the machine, whose parameters are given in **Table 1**, is shown in **Figure 3**. In determining the curve it has been assumed that the magnitude of the normalized stator voltage (V) is 1 p.u. and the maximum value of normalized stator current (I_{sn}) is fixed to 2 p.u. From the **Figure 3** the following can be observed:

- Through this control strategy, the PM machine is able to produce 2 p.u. torques up to a speed of 0.25 p.u.
- The machine is able to produce 1 p.u. torque up to a speed of 0.4 p.u.

Constant Mutual Flux Linkage Control:

In this control strategy, the resultant flux linkage of the stator *q* and *d* axis and rotor is Maintained constant. The main advantage of this control strategy is that it keeps the stator Voltage requirement is kept low. To start with the analyses consider the flux linkage Expressionfor the *q* and *d* axis:

$$\lambda_{qs}^r = L_q i_{qs}^r \qquad \text{............eq15}$$

$$\lambda_{ds}^r = L_d i_{ds}^r + \lambda_{af} \qquad \text{...............eq16}$$

The magnitude of the flux linkage is given by

$$\lambda_m = \sqrt{\left(\lambda_{qs}^r\right)^2 + \left(\lambda_{ds}^r\right)^2} = \sqrt{\left(L_q i_{qs}^r\right)^2 + \left(L_d i_{ds}^r + \lambda_{af}\right)^2} \qquad \text{............eq17}$$

In this strategy, the mutual flux linkage given by **equation 17** is held constant and its magnitude is made equal to λ. Substituting the values of i^r , $i^r{}_{qs}$ and from **equation 2** into **equation 17** gives

$$\lambda_m = \lambda_{af} = \sqrt{\left(L_q I_m \sin\delta\right)^2 + \left(L_d I_m \cos\delta + \lambda_{af}\right)^2} \qquad \text{........................eq18}$$

Solving **equation 18** for I_m gives

$$I_m = -\frac{2\lambda_{af}}{L_d}\left(\frac{\cos\delta}{\cos^2\delta + \rho^2\sin^2\delta}\right) \qquad \text{............................eq19}$$

Where

$$\rho = \frac{L_q}{L_d}$$

The normalized current is given bu

$$I_{mn} = \frac{I_m}{I_b} = -\frac{2}{L_{dn}}\left(\frac{\cos\delta}{\cos^2\delta + \rho^2\sin^2\delta}\right) \qquad \text{.....................eq20}$$

The stator voltage is given

$$V_s = \sqrt{\left(v_{qs}^r\right)^2 + \left(v_{ds}^r\right)^2} = \sqrt{\left(R_s i_{qs}^r + \omega_r L_d i_{ds}^r + \omega_r \lambda_{af}\right)^2 + \left(-\omega_r L_q i_{qs}^r + R_s i_{ds}^r\right)^2} \qquad \text{.........eq21}$$

The normalized values of the stator voltage is

$$V_{sn} = \frac{V_s}{V_b} = \frac{\sqrt{\left(R_s i_{qs}^r + \omega_r L_d i_{ds}^r + \omega_r \lambda_{af}\right)^2 + \left(-\omega_r L_q i_{qs}^r + R_s i_{ds}^r\right)^2}}{\omega_b \lambda_{af}}$$

$$= \sqrt{\left(R_{sn} i_{qsn}^r + \omega_{rn} L_{dn} i_{dsn}^r + \omega_{rn}\right)^2 + \left(-\omega_{rn} L_{qn} i_{qsn}^r + R_{sn} i_{dsn}^r\right)^2} \qquad \text{.............eq22}$$

The normalized voltage given by **can** be written as

$$V_{sn} = \sqrt{\left(R_{sn} I_{mn}\sin\delta + \omega_{rn} L_{dn} I_{mn}\cos\delta + \omega_{rn}\right)^2 + \left(\omega_{rn} L_{qn} I_{mn}\sin\delta + R_{sn} I_{mn}\cos\delta\right)^2} \qquad \text{......eq23}$$

In order to determine the value of angle δ, two distinct cases have to be considered:

When ρ =1and ρ ≠1. Once the angle δ is known, the torque can be obtained from equation **3**. Each of these cases are explained in the following subsections.

Case when ρ =1

Substituting ρ =1into **equation 20** and solving for δ gives

$$\delta = \cos^{-1}\left(\frac{-L_{dn}I_{mn}}{2}\right) \quad \text{.............eq24}$$

The torque produced by the machine is given by

$$T_e = \frac{3}{2}\frac{N_p}{2}\left[\lambda_{af} I_m \sin\delta\right] \quad \text{.....................eq25}$$

The normalized torque is given by

$$T_{en} = \frac{T_e}{T_b} = I_{mn}\sin\delta \quad \text{..................eq26}$$

The performance characteristics of a PM machine at a speed of 1 p.u. are shown in **Figure 4a** and the parameters of this machine are given in **Table 2**. The torque versus the speed characteristics of the PM Machine are shown in **Figure 4b**.

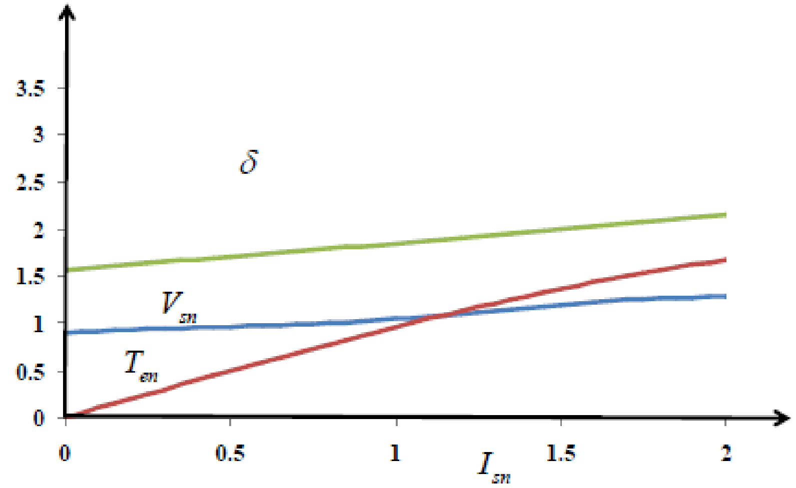


Fig 4a: The characteristics curves of PM machine ($\rho = 1$) with Constant Mutual Flux Linkage Control

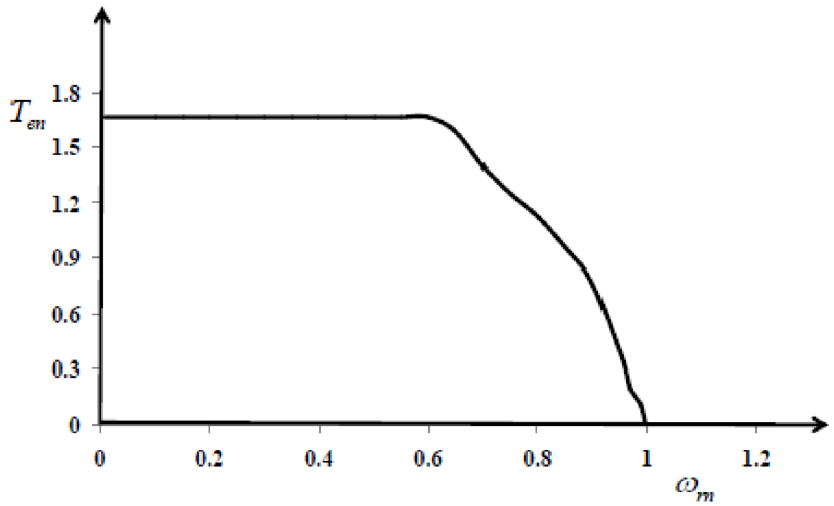


Fig 4b: The torque vs. speed characteristic curves of PM machine ($\rho = 1$) with Constant Mutual Flux Linkage Control

Table 2: The parameters of a non salient pole PM machine

Base Voltage (V_b)	Base Current (I_b)	Base Inductance (L_b)	Base Speed (ω_b)	Base Flux Linkage (λ_b)	Resistance (R)	d-axis inductance (L_d)	q-axis inductance (L_q)
100 V	10 A	0.02 H	600 rad/s	0.167 Vs/rad	1.8 Ω	0.011 H	0.011 H

Case when **ρ ≠1**

When ρ ≠1 , using **equation 20** the expression for is obtained as

$$\delta = \cos^{-1}\left[\frac{-1}{L_{dn} I_{mn} (1-\rho)^2} \pm \sqrt{\left\{ \frac{1}{L_{dn}\left(1-\rho^2\right) I_{sn}} \right\}^2 - \frac{\rho^2}{\left(1-\rho^2\right)}} \right]$$

…………eq27

The performance characteristics of the machine, whose parameters are given in **Table 1**, are shown in **Figure 5a** and the torque versus speed characteristics is shown in **Figure 5b**.

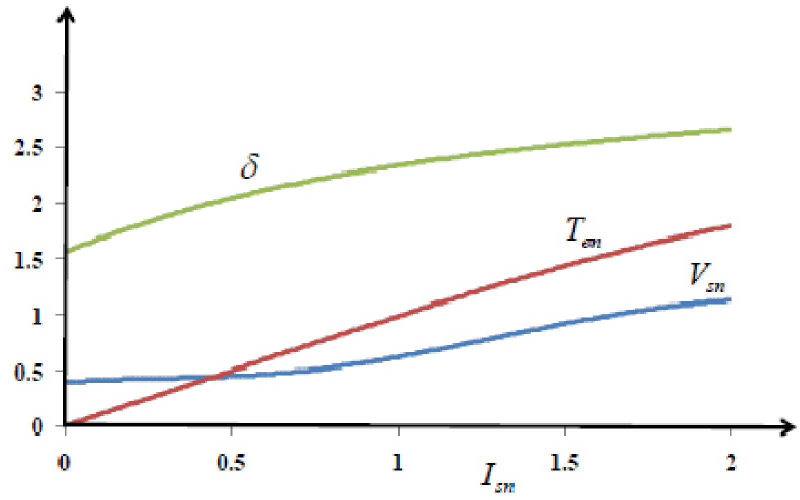


Fig 5a: The characteristics curves of PM machine ($\rho \neq 1$) with Constant Mutual Flux Linkage Control

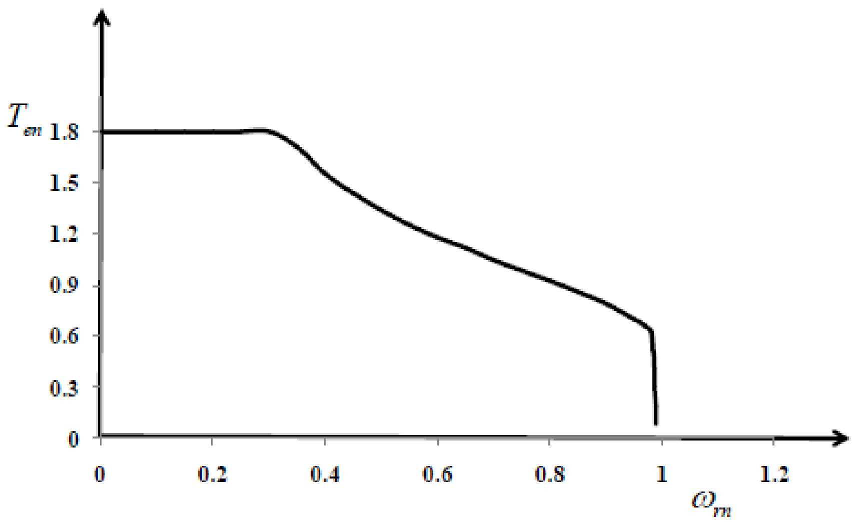


Fig 5b: The torque vs. speed characteristic curves of PM machine ($\rho \neq 1$) with Constant Mutual Flux Linkage Control

Optimum Torque per Unit Current Control:

The aim of this control strategy is to maximize electromagnetic torque for a unit stator current. By using this strategy the PM machine will produce maximum torque for a given magnitude of current. To develop the mathematical models of this strategy, consider the torque equation of the PM machine given in **equation 3** and normalize it into p.u. system. The normalized torque expression is

$$T_{en} = \frac{T_e}{T_b} = I_{mn}\left[\sin(\delta) + \frac{1}{2}\left(L_{dn} - L_{qn}\right) I_{mn} \sin(2\delta)\right] \quad \text{.............eq28}$$

The torque per unit stator current is defined as

$$\frac{T_{en}}{I_{mn}} = \left[\sin(\delta) + \frac{1}{2}\left(L_{dn} - L_{qn}\right) I_{mn} \sin(2\delta)\right] \quad \text{............eq29}$$

The condition under which the machine produces maximum torque per unit stator current is obtained by differentiating **equation 29** with respect to and equating it to zero, that is

$$\frac{d\left[\sin(\delta) + \frac{1}{2}\left(L_{dn} - L_{qn}\right) I_{mn} \sin(2\delta)\right]}{d\delta} = 0$$

$$\Rightarrow \cos(\delta) + \left(L_{dn} - L_{qn}\right) I_{mn} \cos(2\delta) = 0 \quad \text{..................eq30}$$

Using the trigonometric identity 2cos(2δ) =2cos^2 (δ)-1 in **equation 30** gives

$$\cos(\delta) + \left(L_{dn} - L_{qn}\right) I_{mn}\left[2\cos^2(\delta) - 1\right] = 0 \quad \text{.....................eq31}$$

The solution of **equation 31** gives

$$\delta = \cos^{-1}\left[-\frac{1}{4K} \pm \sqrt{\left(\frac{1}{4K}\right)^2 + \frac{1}{2}}\right] \quad \text{.............................eq32}$$

$$\text{where } K = \frac{1}{\left(L_{dn} - L_{qn}\right) I_{mn}}$$

In **equation 32**, only the value of greater than 90o is considered so as to reducethe field in the air gap. The performance characteristics of the PM machine (parameters of the machine are given in **Table 1**) for this control strategy are shown in **Figure 6a** and the torque versus speed characteristics are shown in **Figure 6b**.

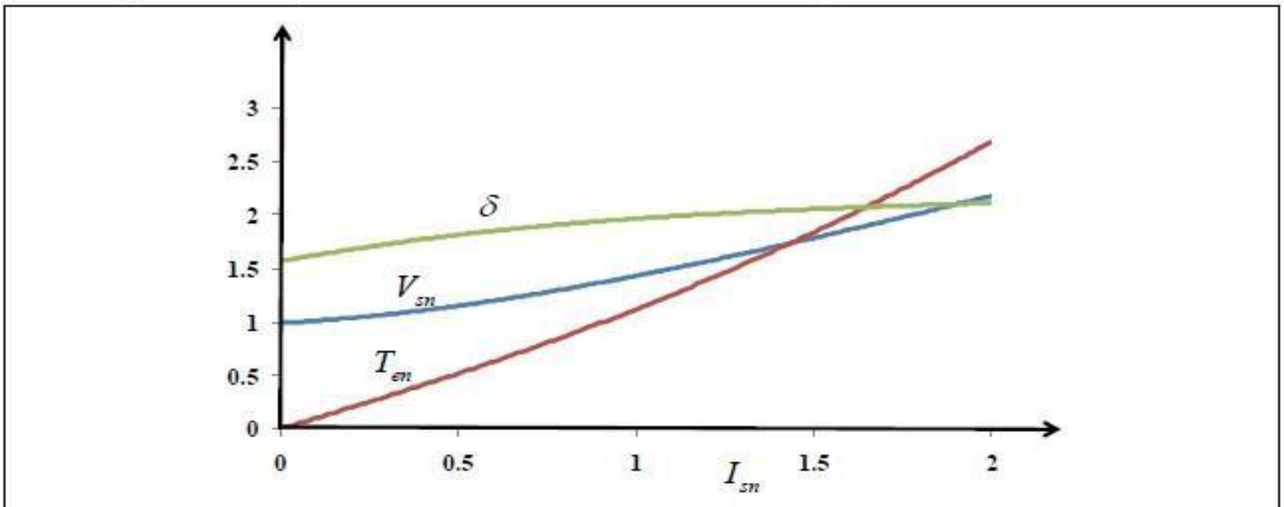


Fig 6a: The characteristics curves of PM machine with Optimum Torque per Unit Current Control

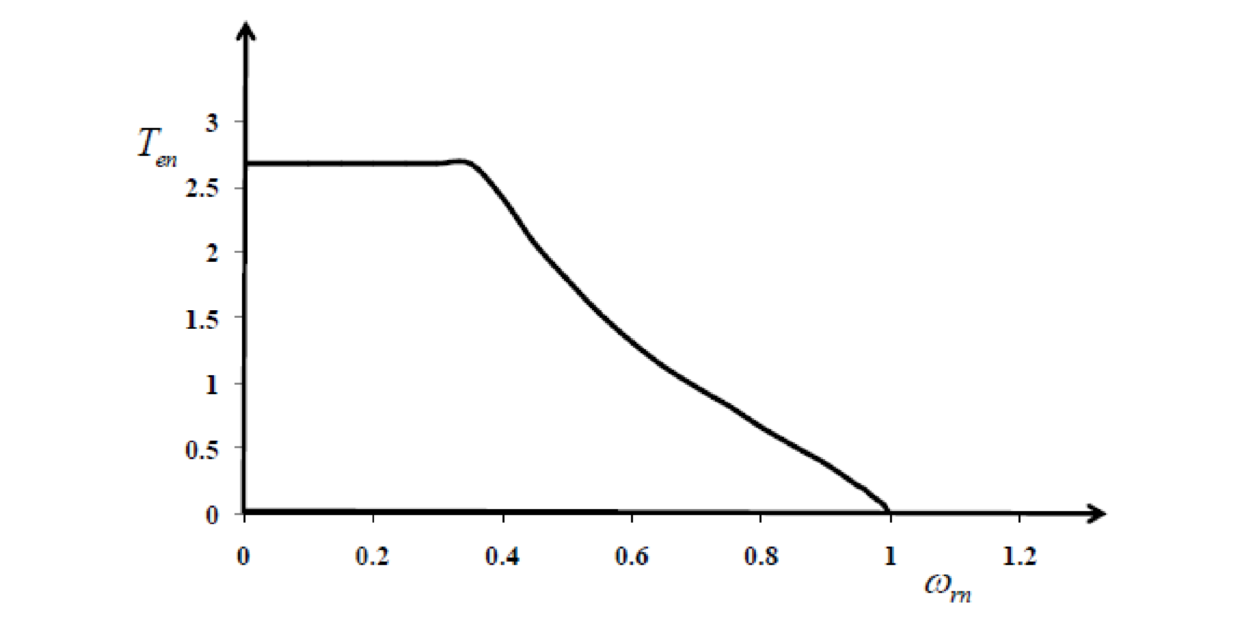


Fig 6b: The torque vs. speed characteristic of PM machine with Optimum Torque per Unit Current Control

SWITCHED RELUCTANCE MOTOR DRIVES:

The switched reluctance motor (SRM) drive is considered to be an attractive candidate for variable speed motor drives due to its low cost, rugged structure, reliable converter topology, high efficiency over a wide speed range, and simplicity in control.43,44 These drives are suitable for EVs, electric traction applications, automotive applications, aircraft starter/generator systems, mining drives, washing machines, door actuators, etc.48,50,51The SRM has a simple, rugged, and low-cost structure. It has no PM or winding on the rotor. This structure not only reduces the cost of the SRM butalso offers high-speed operation capability for this motor. Unlike the induction and PM machines, the SRM is capable of high-speed operation without the concern of mechanical failures that result from the high-level centrifugal force. In addition, the inverter of the SRM drive has a reliable topology. The stator windings are connected in series with the upper and lower switches of the inverter. This topology can prevent the shoot-through fault that exists in the induction and permanent motor drive inverter. Moreover, high efficiency over a wide speed range and control simplicity are known merits of the SRM drive.43,47A conventional SRM drive system consists of the switched reluctance motor, power inverter, sensors such as voltage, currentandpositionsensors, and controlcircuitry such as the DSP controller and its peripherals, as shownin Figure 6.54. Through proper control, high performance can be achieved in the SRM drive system.43,44The SRM drive inverter is connected to a DC power supply, which can be derived from the utility lines through a front-end diode rectifier or from batteries. The phase windings of the SRM are connected to the power inverter, as shown in Figure 6.55. The control circuit provides a gating signal to the switches of the inverter according to particular control strategies and the signals from various sensors.

FIELD ORIENTED CONTROL (FOC):

In an Electric Vehicle, it is required that the traction motor is able to deliver the required torque almost instantaneously. In an induction motor (IM) drive, such performance can be achieved using a class of algorithms known as Field Oriented Control (FOC). There are varieties of FOC such as:

- Stator flux oriented
- Rotor flux oriented
- Air gap flux oriented

The basic premise of FOC may be understood by considering the current loop in a uniform magnetic field as shown in Figure 1a. From Lorenz force equation, it can be seen that the torque acting on the current loop is given by

$$T_e = -2BiNLr\sin\theta \quad \text{.............eq1}$$

Where
B is the flux density
I is the current
N is the no of turns
L is the length of the coil
r is the radius of the coil

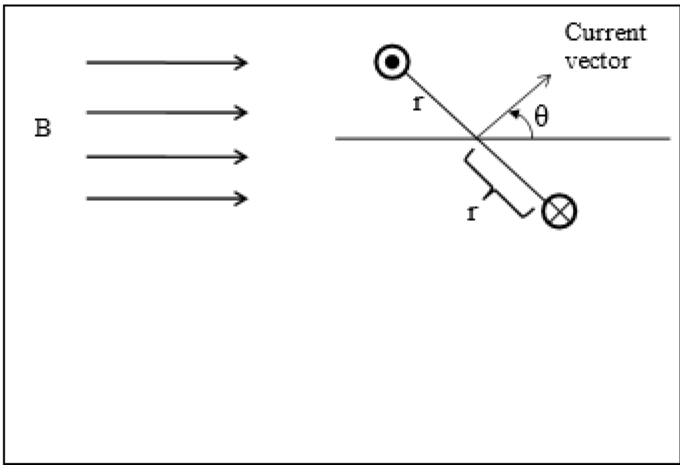


Figure 1a: A coil in a magnetic field

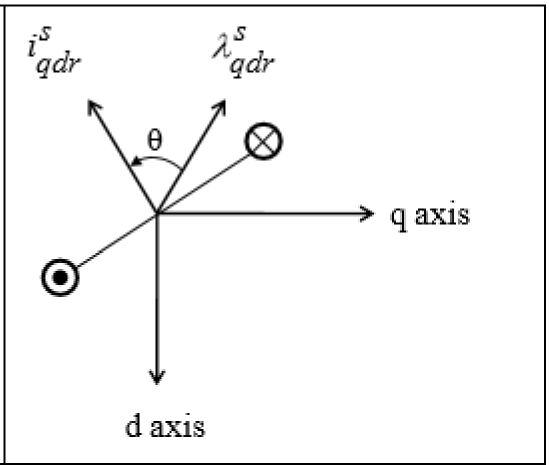


Figure 1b: Orientation of magnetic field in IM

From equation 1 it is evident that the torque is maximized when the current vector is perpendicular to the magnetic field. The same conclusion can be applied to an IM. In Figure 1b orientations of magnetic fields and currents in an IM are shown. The rotor current and flux linkage vectors are shown in Figure 1 at some instant of time. Hence, the torque produced by the motor is given by

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda'_{qr} i'_{dr} - \lambda'_{dr} i'_{qr}\right) \quad \text{……………..eq2}$$

The equation 2 can be re-written as

$$T_e = -\frac{3}{2}\frac{P}{2}\left|\lambda'_{qdr}\right|\left|i'_{qdr}\right|\sin\theta \quad \text{…………….eq3}$$

The equation 3 is analogous to equation 1. Hence, for a given magnitude of flux linkage, torque is maximized when the flux linkage and current vectors are perpendicular. Therefore, it is desirable to keep the rotor flux linkage perpendicular to rotor current vector.

In the analysis of FOC the following convention will be used: □The parameters with a superscript –s‖ are in stator frame of reference.

- The parameters with a superscript –e‖ are in synchronous frame of reference.
- The parameters with subscript –r‖ indicate rotor parameters.
- The parameters with subscript –s‖ indicate stator parameters.
- All rotor quantities are referred to stator using the turns ratio of the windings

In case of singly excited IMs (in singly excited IM, the rotor winding is not fed by any external voltage source. In case of wound rotor machines, they are short circuited using slip rings. For cage IMs, the rotor bars are short circuited at the terminals), the rotor flux linkage vector and rotor current vector are always perpendicular. The voltage equations for the IM (refer to Lecture 19) in synchronous frame of reference are

$$v_{qs}^e = r_s i_{qs}^e + \omega_e \lambda_{ds}^e + p\lambda_{qs}^e$$
$$v_{ds}^e = r_s i_{ds}^e - \omega_e \lambda_{qs}^e + p\lambda_{ds}^e$$
$$v_{os}^e = r_s i_{os}^e + p\lambda_{os}^e$$
$$v_{qr}^e = r_r i_{qr}^e + (\omega_e - \omega_r)\lambda_{dr}^e + p\lambda_{qr}^e$$
$$v_{dr}^e = r_r i_{dr}^e - (\omega_e - \omega_r)\lambda_{qr}^e + p\lambda_{dr}^e$$
$$v_{or}^e = r_r i_{or}^e + p\lambda_{or}^e$$

…………………………eq4

Where ω_ε is the rotational speed of Synchronous frame of reference

In case of singly excited IM, the rotor voltages are zero, that is $V^e{}_{qr}$ =0, ${}_{dr}$ =0,$V^e{}_{or}$ =0. Hence, the rotor currents can be obtained as

$$0 = r_r i_{qr}^e + (\omega_e - \omega_r)\lambda_{dr}^e + p\lambda_{qr}^e \Rightarrow i_{qr}^e = -\frac{1}{r_r}(\omega_e - \omega_r)\lambda_{dr}^e - p\lambda_{qr}^e$$

$$0 = r_r i_{dr}^e - (\omega_e - \omega_r)\lambda_{qr}^e + p\lambda_{dr}^e \Rightarrow i_{dr}'^e = \frac{1}{r_r}(\omega_e - \omega_r)\lambda_{qr}^e - p\lambda_{dr}^e$$

$$0 = r_r i_{or}^e + p\lambda_{or}^e \Rightarrow i_{or}^e = -\frac{p\lambda_{or}^e}{r_r}$$

…….eq5

Since steady state operation of IM is considered, the time derivative term of flux linkage in equation 2 will vanish. Hence, the rotor currents are:

$$i_{qr}^e = -\frac{1}{r_r}(\omega_e - \omega_r)\lambda_{dr}^e$$

$$i_{dr}^e = \frac{1}{r_r}(\omega_e - \omega_r)\lambda_{qr}^e$$

$$i_{or}^e = 0$$

…………………eq6

The dot product of the rotor flux linkage and rotor current vectors may be expressed as

$$\lambda_{qdr}^e . i_{qdr}^e = \lambda_{qr}^e . i_{qr}^e + \lambda_{dr}^e . i_{dr}^e$$

……………………eq7

Substituting the values of$i^e{}_{dr}$ and$i^e{}_{qr}$ from equation 6 into equation 7gives

$$\lambda_{qdr}^e . i_{qdr}^e = -\frac{\lambda_{qr}^e}{r_r}(\omega_e - \omega_r)\lambda_{dr}^e + \frac{\lambda_{dr}^e}{r_r}(\omega_e - \omega_r)\lambda_{qr}^e = 0$$

………eq8

Form equation 5 it can be seen that the dot product between the rotor flux and rotor current vectors is zero in case of singly excited IM. Hence, it can be concluded that the rotor flux and rotor current vectors are perpendicular to each other in steady state operation. The defining feature of FOC is that this characteristic (that the rotor flux and rotor current vectors are perpendicular to each other) is maintained during transient conditions as well. In both direct and indirect FOC, the 90o shift between the rotor flux and rotor current vector can be achieved in two steps:

- The first step is to ensure that

$$\lambda_{qr}^e = 0$$

……………………………………eq8

- The second step is to ensure that

$$i^e_{dr} = 0$$ ……………………………….eq9

By suitable choice of $\theta_s$on an instantaneous basis, equation 6 can be achieved. Satisfying equation 7 can be accomplished by forcing d -axis stator current to remain constant. To see this, consider the d -axis rotor voltage equation

$$0 = r_r i^e_{dr} + (\omega_e - \omega_r)\lambda^e_{qr} + p\lambda^e_{dr}$$ ……………….eq10

Since $\lambda^e{}_{qr} = 0$, eq10 can be written as

$$0 = r_r i^e_{dr} + p\lambda^e_{dr}$$ ……………………eq11

The d -axis rotor flux linkage is given by :

$$\lambda^e_{dr} = L_{lr} i^e_{dr} + L_m\left(i^e_{ds} + i^e_{dR}\right)$$ ………………….eq12

Substituting the value of $\lambda^e{}_{dr}$ from equation 10 into equation 11 gives

$$pi^e_{dr} = -\frac{r_r}{L_{lr}} i^e_{dr} - \frac{L_m}{L_{lr}} pi^e_{ds}$$ ……………………eq13

Is $i^s{}_{ds}$ is held constant, then p$i^e{}_{ds}$ =0 and the solutions of equations 13 becomes

$$i^e_{dr} = Ce^{-\left(\frac{r_r'}{L_{lr}}\right)t}$$ ……………………eq14

Where C is Constant of integration

It is evident from equation 12 that the rotor current $i^e{}_{dr}$ will decay to zero and stay at zero regardless of other transients that may be taking place. Hence, the torque is given by

$$T_e = \frac{3}{2}\frac{P}{2}\lambda^e_{dr} i^e_{qr}$$ ………………..eq15

The q-axis rotor flux is given by

$$\lambda^e_{qr} = L_{lr} i^e_{qr} + L_m\left(i^e_{qs} + i^e_{qr}\right)$$ ………………eq16

The above equation can be rewritten as

$$\lambda^e_{dr} = L_m i^e_{ds}$$ ……………...eq17

The generic rotor flux-oriented control shown in Figure 2.

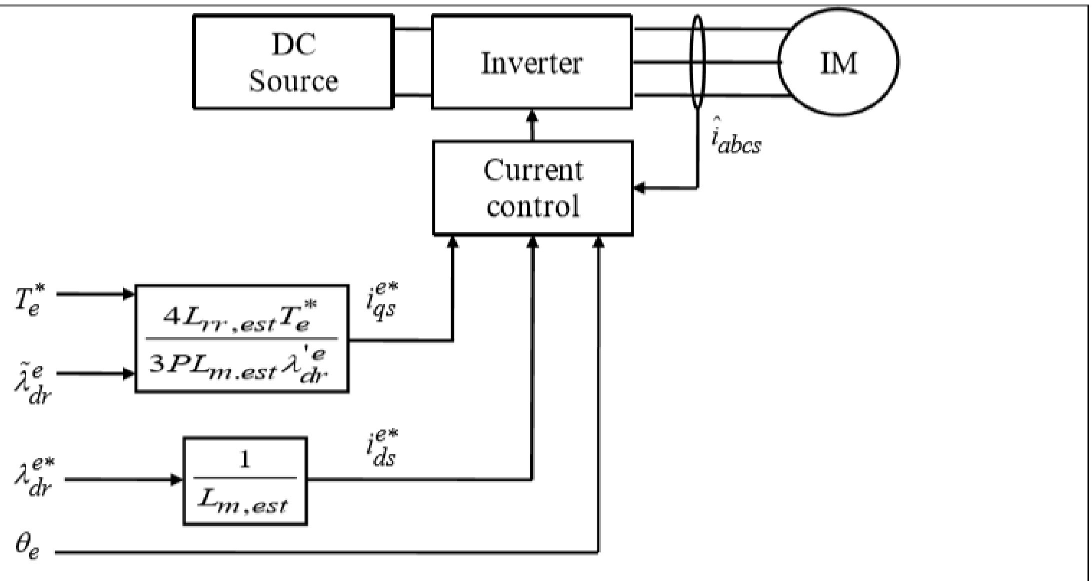


Figure 2: Generic Field Oriented Control (FOC) [1]

In Figure 2 the variables of the form, andx^*,$\hat{}$, $x\tilde{}$denote command, measured and estimated values respectively. In case of parameters that are estimated, a subscript‖ est‖ is used. The working of the controller is as follows:

i. Based on the torque command (T_e *), the assumed values of the parameters and the estimated value of d -axis rotor flux $\lambda\hat{}_{dr}{}^s$is used to formulate a q- axis stator current command$i_{qs}{}^*$
ii. The d -axis stator current command is$i_{ds}{}^*$ calculated such as to achieve a rotor flux command$\lambda\hat{}_{dr}{}^s$.
iii. The q-axis and d -axis stator current command is then achieved using a current source control.

The above description of rotor flux oriented FOC is incomplete with determination of $\lambda\hat{}_{dr}{}^s$and θ_s. The difference between direct and indirect FOC is in how these two variables are determined.

DIRECT ROTOR ORIENTED FOC:

In direct FOC, the position of the synchronous reference frame ( ) is determined based on the values ofq-axis and d-axis rotor flux linkages in the stationary reference frame. The relation of flux linkages in synchronous reference frame and stationary reference frame is

$$\begin{bmatrix} \lambda_{qr}^e \\ \lambda_{dr}^e \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} \lambda_{qr}^s \\ \lambda_{dr}^s \end{bmatrix}$$

……………………...eq18

where

$\lambda_{dr}{}^s$ =is the rotor d -axis flux linkage in stationary frame of reference

$\lambda_{qr}{}^s$= is the rotor q -axis flux linkage in stationary frame of reference

In order to achieve λ_q , it is sufficient to define the position of the synchronous reference frame as

$$\theta_e = \tan^{-1}\left(\frac{\lambda_{qr}^s}{\lambda_{dr}^s}\right) + \frac{\pi}{2}$$

……………………………. eq19

The difficulty with this approach is that$\lambda_{dr}{}^s$and$\lambda_{dr}{}^s$ are not directly measurable quantities.flux, hall-effect sensors are placed in the air gap and used to measure the air-gap flux in q-axis and d-axis. Since the hall-effect sensors are stationary, the flux measured by them is in stationary reference frame. The flux measured by the sensors is the net flux in the air gap (combination of stator and rotor flux). The net flux in the air gap is given by:

$$\lambda_{qm}^{s} = L_{m}\left(i_{qs}^{s} + i_{qr}^{s}\right) \quad \text{.................................eq20}$$

where

L_m is the magnetization inductance

From **equation 20**, the rotor q -axis current is obtained as

$$i_{qr}^{s} = \frac{\lambda_{qm}^{s} - L_{m} i_{qs}^{s}}{L_{m}} \quad \text{.. eq21}$$

The q -axis rotor flux linkage is given by

$$\lambda_{qr}^{s} = L_{lr} i_{qr}^{s} + L_{m}\left(i_{qs}^{s} + i_{qr}^{s}\right) \quad \text{.....................................eq22}$$

Substituting the rotor q -axis current from **equation 21**into **equation 22**gives

$$\lambda_{qr}^{s} = \frac{L_{lr}}{L_{m}} \lambda_{qm}^{s} - L_{lr} i_{qs}^{s} \quad \text{....................................... eq23}$$

An identical derivation for d-axis gives

$$\lambda_{dr}^{s} = \frac{L_{lr}}{L_{m}} \lambda_{dm}^{s} - L_{lr} i_{ds}^{s} \quad \text{......................................eq24}$$

The implementation of this control strategy is shown in **Figure 3a** and **b**

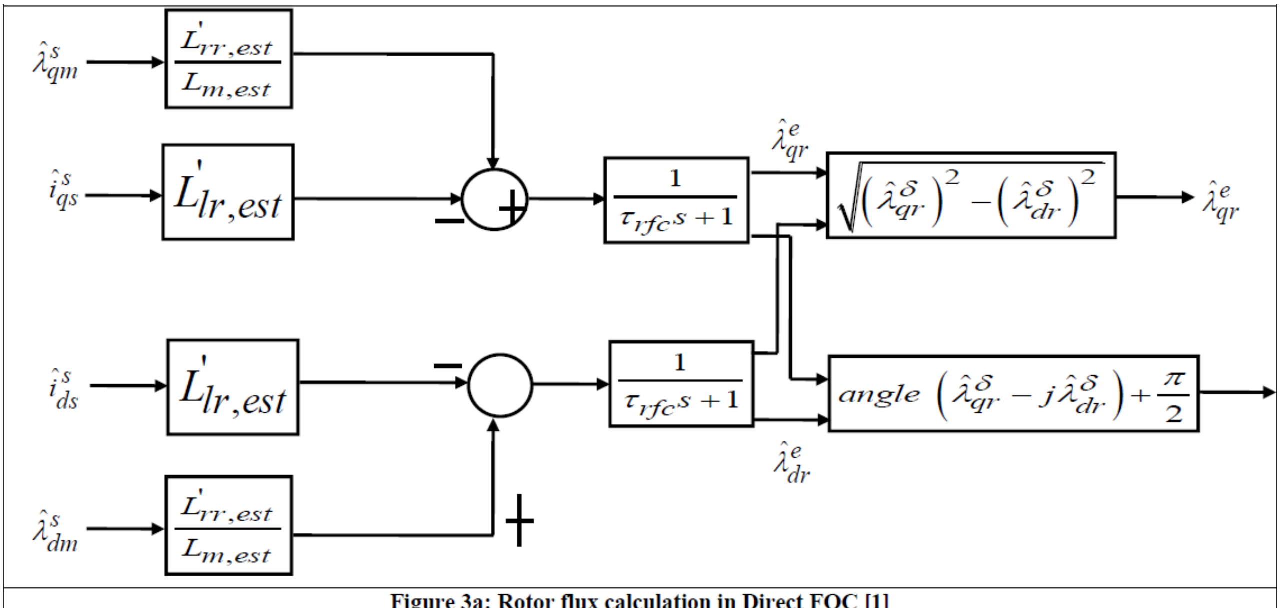


Figure 3a: Rotor flux calculation in Direct FOC [1]

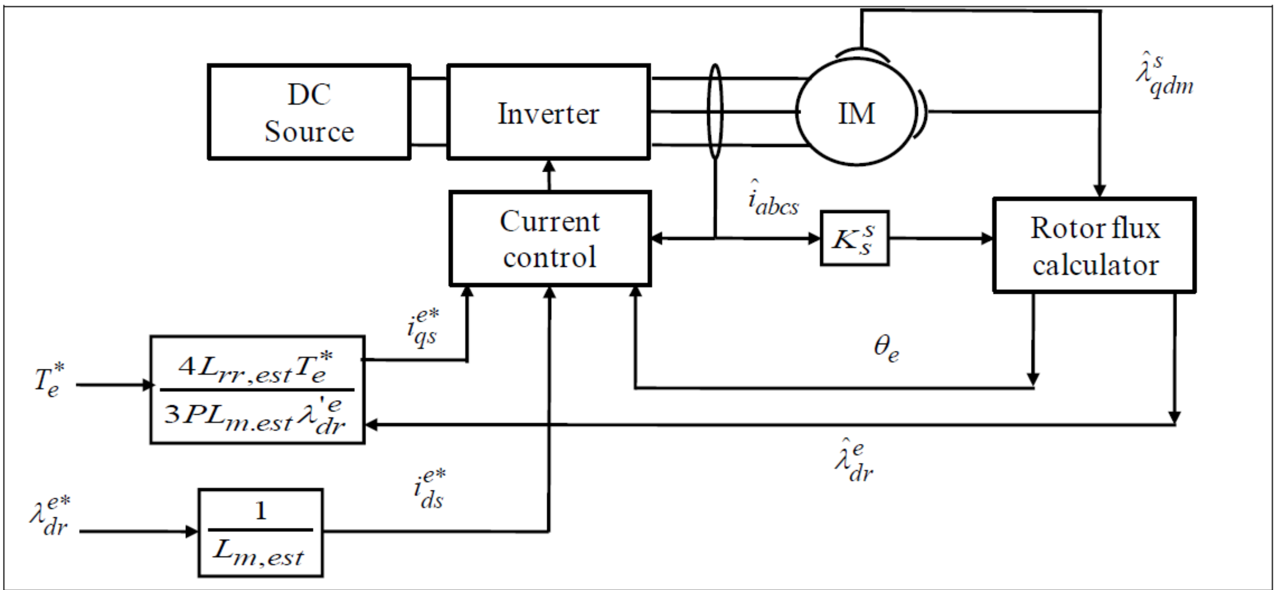


Figure 3b: Control strategy for Direct FOC [1]

INDIRECT ROTOR ORIENTED FOC:

The direct FOC is problematic and expensive due to use of hall-effect sensors. Hence, indirect FOC methods are gaining considerable interest. The indirect FOC methods are more sensitive to knowledge of the machine parameters but do not require direct sensing of the rotor flux linkages. The q-axis rotor voltage equation in synchronous frame is.

$$0 = r_r i_{qr}^{e} + \left(\omega_e - \omega_r\right)\lambda_{dr}^{e} + p\lambda_{qr}^{e}$$

…………………………… eq25

Since for direct field-oriented control, **equation 25**becomes

$$0 = r_r i_{qr}^e + (\omega_e - \omega_r)\lambda_{dr}^e$$

$$\Rightarrow \omega_e = \omega_r - r_r \frac{i_{qr}^e}{\lambda_{dr}^e}$$ ………………………………………… eq26

Substituting the values of $i_{qr}{}^{e}$ and $\lambda_{dr}{}^{e}$ substitute in above equations

$$\omega_e = \omega_r + \frac{r_r}{L_{lr}} \frac{i_{qs}^e}{\lambda_{ds}^e}$$ …………………………………………eq27

From **equation 27** it can be observed that instead of establishing θ_e using the rotor fluxas shown in **Figure 3**, it can be determined by integrating ω_e given by **equation 27** where ω_e is given as:

$$\omega_e = \omega_r + \frac{r_r}{L_{lr}} \frac{i_{qs}^{e*}}{\lambda_{ds}^{e*}}$$ ………………………………eq28

The **equation 28** does satisfy the conditions of FOC. In order to check it, consider the rotor voltage equations for the q -axis and d -axis:

$$0 = r_r i_{qr}^e + (\omega_e - \omega_r)\lambda_{dr}^e + p\lambda_{qr}^e$$ ……………………………………eq29

$$0 = r_r i_{dr}^e + (\omega_e - \omega_r)\lambda_{qr}^e + p\lambda_{dr}^e$$ …………………………………………eq30

Substituting from **equation 28** into **equations 29** and **30** gives

$$0 = r_r i_{qr}^e + \frac{r_r}{L_{lr}} \frac{i_{qs}^{e*}}{i_{ds}^{e*}} \lambda_{dr}^e + p\lambda_{qr}^e$$ ……………………………………...eq31

$$0 = r_r i_{dr}^e + \frac{r_r}{L_{lr}} \frac{i_{qs}^{e*}}{i_{ds}^{e*}} \lambda_{qr}^e + p\lambda_{dr}^e$$ ………………………………………… eq32

Substituting the value of from *d*-axis rotor flux **into equation 32** gives

$$0 = r_r \left(\frac{\lambda_{qr}^e - L_m i_{qs}^{e*}}{L_{lr}} \right) i_{qr}^e + \frac{r_r}{L_{lr}} \frac{i_{qs}^{e*}}{i_{ds}^{e*}} \left(L_{lr} i_{dr}^{e*} + L_m i_{ds}^{e*} \right) + p\lambda_{qr}^e$$

……eq33

$$0 = r_r i_{dr}^e - \frac{r_r}{L_{lr}} \frac{i_{qs}^{e*}}{i_{ds}^{e*}} \lambda_{qr}^e + p\left(L_{lr} i_{qr}^e + L_m i_{ds}^{e*}\right)$$

……………………...eq34

If the d -axis rotor current is held constant, then $Pi_{dr}{}^{e*}$and rearranging **equations 33**and **34**gives

$$p\lambda_{qr}^e = -\frac{r_r}{L_{lr}} \lambda_{qr}^e - r_r \frac{i_{qs}^{e*}}{i_{ds}^{e*}} i_{dr}^e$$

…………………………………………eq35

In **Figure 4** the implementation of ***indirect FOC*** is shown and it is much simpler than the ***direct FOC***.

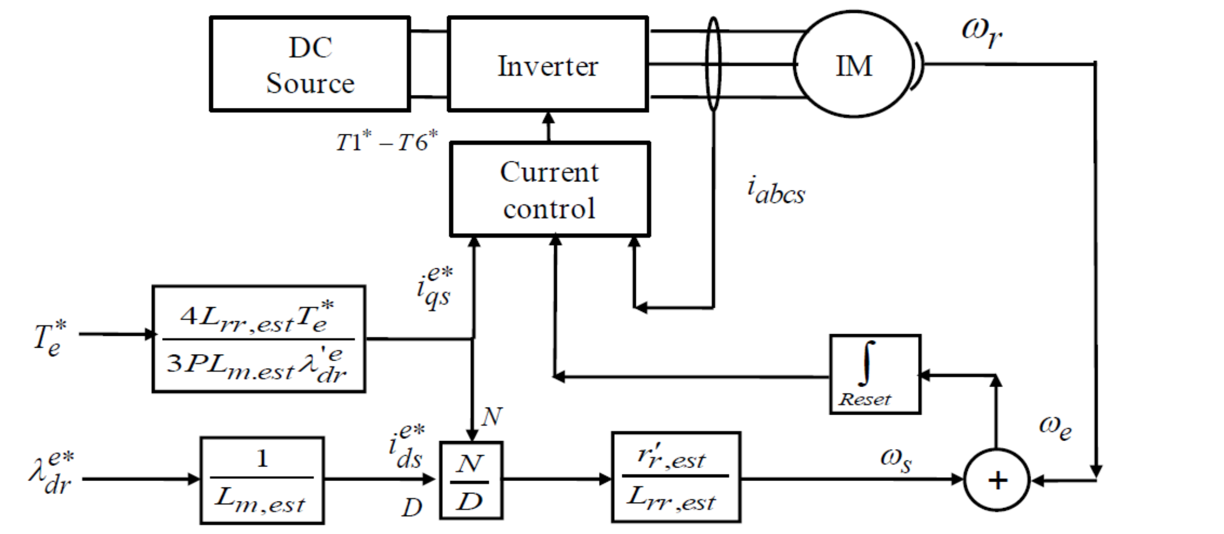


Figure 4: Indirect FOC [1]

UNIT –V

ENERGY STORAGE

Energy storages are defined as the devices that store energy, deliver energy outside (discharge), and accept energy from outside (charge). There are several types of energy storages that have been proposed for electric vehicle (EV) and hybrid electric vehicle (HEV) applications. These energy storages, so far, mainly include chemical batteries, ultra capacitors or super capacitors, and ultrahigh-speed flywheels. The fuel cell, which essentially is a kind of energy converter, will be discussed in this Chapter.There are a number of requirements for energy storage applied in an automotive application, such as specific energy, specific power, efficiency, maintenance management, cost, environmental adaptation and friendliness, and safety. For allocation on an EV, specific energy is the first consideration since it limits the vehicle range. On the other hand, for HEV applications specific energy becomes less important and specific power is the first consideration, because all the energy is from the energy source (engine or fuel cell) and sufficient power is needed to ensure vehicle performance, particularly during acceleration, hill climbing, and regenerative braking. Of course, other requirements should be fully considered in vehicle drive train development.

ELECTROCHEMICAL BATTERIES:

Electrochemical batteries, more commonly referred to as –batteries,‖ are electrochemical devices that convert electrical energy into potential chemical energy during charging, and convert chemical energy into electric energy during discharging. A –battery‖ is composed of several cells stacked together. A cell is an independent and complete unit that possesses all the electrochemical properties. Basically, a battery cell consists of three primary elements: two electrodes (positive and negative) immersed into an electrolyte shown in Figure 5.1.

Battery manufacturers usually specify the battery with coulometric capacity (amp-hours), which is defined as the number of amp-hours gained when discharging the battery from a fully charged state until the terminal voltage drops to its cut-off voltage, as shown in Figure 5.2. It should be noted that the same battery usually has a different number of amp-hours at different discharging current rates. Generally, the capacity will become smaller with a large discharge current rate, as shown in Figure 5.3.

Battery manufacturers usually specify a battery with a number of amp-hours along with a current rate. For example, a battery labeled 100 Ah at C5 rate has a 100 amp-hour capacity at 5 hours discharge rate (discharging current_100/5_20 A).Another important parameter of a battery is the state-of-charge (SOC).SOC is defined as the ratio of the remaining capacity to the fully charged capacity. With this definition, a fully charged battery has an SOC of100% and a fully discharged battery has an SOC of 0%. However, the term –fully discharged‖ sometimes causes confusion because of the different capacity at different discharge rates and different cut-off voltage (refer to Figure 5.3).

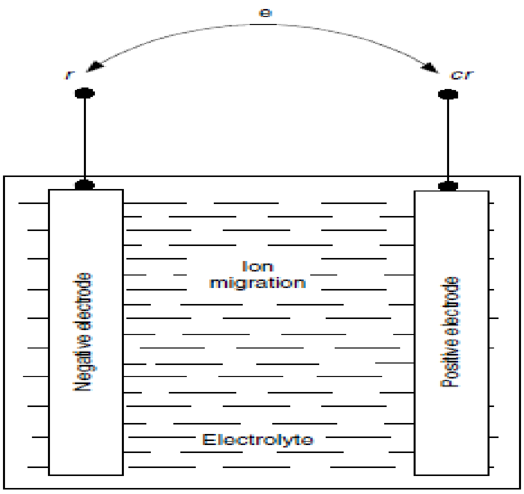


FIGURE 5.1.A typical electrochemical battery cell

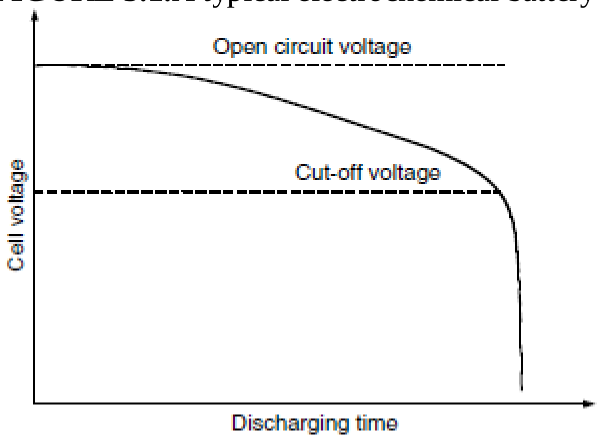


FIGURE 5.2 Cut-off voltage of a typical battery

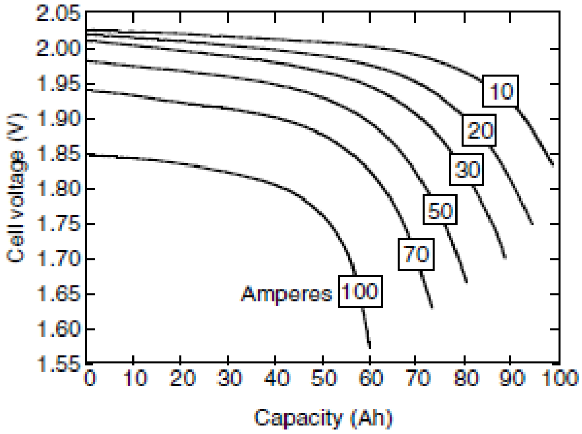


Figure 5.3. Discharge characteristics of a lead-acid battery

The change in SOC in a time interval, *dt*, with discharging or charging current *i* may be expressed as

$$\Delta SOC = \frac{i\,dt}{Q(i)}, \qquad \text{……………………….eq1}$$

Where*Q(i)* is amp-hour capacity of the battery at current rate *i*. For discharging, ***i*is** positive, and for charging, *i* is negative. Thus, the SOC of the battery can be expressed as

$$SOC = SOC_0 - \int \frac{i\,dt}{Q(i)},$$ …………………eq2

where *SOC*0 is the initial value of the SOC.

For EVs and HEVs, the energy capacity is considered to be more important than the coulometric capacity (Ahs), because it is directly associated with the vehicle operation. The energy delivered from the battery can be expressed as

$$EC = \int_0^t V(i, SOC)\, i(t)\, dt,$$ ………………… eq3

Where V (i, SOC*)* is the voltage at the battery terminals, which is a function of the battery current and SOC.

ELECTROCHEMICAL REACTIONS:

For simplicity, and because it is the most widespread battery technology in today's automotive applications, the lead-acid battery case is used as an example to explain the operating principletheory of electrochemical batteries. Lead-acid battery uses an aqueous solution of sulfuric acid(2H SO2_4)as the electrolyte.

The electrodes are made of porous lead (Pb, anode, electrically negative) and porous lead oxide

Figure 4.4(a), where lead is consumed and lead sulfate is formed. The chemical reaction on theanode can be written as

$$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$ …………………eq1

This reaction releases two electrons and, thereby, gives rise to an excess negative charge on the electrode that is relieved by a flow of electrons through the external circuit to the positive (cathode) electrode. At the positive electrode, the lead of PbO2 is also converted to PbSO4 and, at the same time, water is formed. The reaction can be expressed as

$$PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$ ………………..eq2

During charging, the reactions on the anode and cathode are reversed as shown in Figure 4.4(b) that can be expressed by

Anode:

$$PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-}$$ …………………..eq3 and

Cathode:

$$PbSO_4 + 2H_2O \rightarrow PbO_2 + 4H^+ + SO_4^{2-} + 2e^-$$ ……………………eq4

The overall reaction in a lead-acid battery cell can be expressed as

Overall:

$$Pb + PbO_2 + 2H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O.$$

……………………eq5

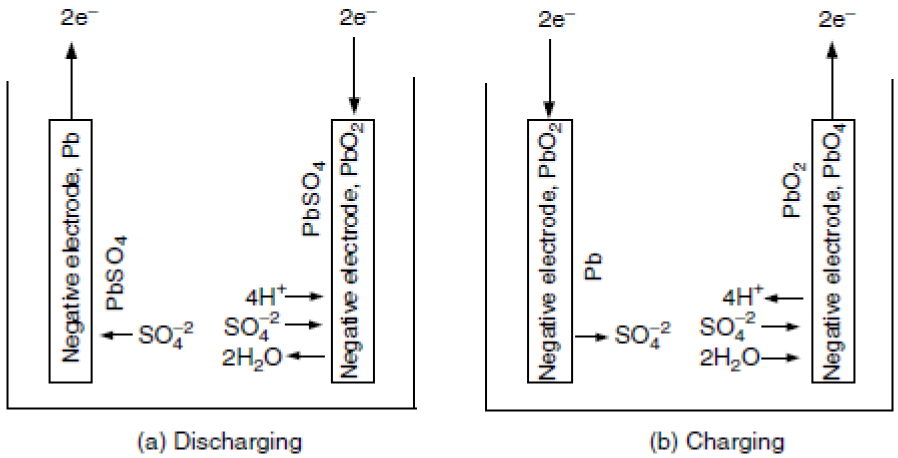


FIGURE 5.4. Electrochemical processes during the discharge and charge of a lead-acid battery cell

The lead-acid battery has a cell voltage of about 2.03 V at standard condition, which is affected by the concentration of the electrolyte.

THERMODYNAMIC VOLTAGE:

The thermodynamic voltage of a battery cell is closely associated with the energy released and the number of electrons transferred in the reaction. The energy released by the battery cell reaction is given by the change in Gibbs free energy, ΔG, usually expressed in per mole quantities. The change in Gibbs free energy in a chemical reaction can be expressed as

$$\Delta G = \sum_{Products} G_i - \sum_{Reactants} G_j,$$

…………………eq6

Where *Gi* and *Gj*are the free energy in species *i* of products and species *j* of reactants. In a reversible process, ΔG is completely converted into electric energy, that is,

$$\Delta G = -nFV_r,$$

……………..eq7

where n is the no of electrons transferred in the reaction , *F*_96,495 is the Faraday constant in coulombs per mole, and *Vr*is the reversible voltage of the cell. At standard condition (25°C temperature and 1 atm pressure), the open circuit (reversible) voltage of a battery cell can be expressed as

$$V_r^0 = -\frac{\Delta G^0}{nF},$$

………………eq8

Where$\Delta G0$ is the change in Gibbs free energy at standard conditions.

The change of free energy, and thus the cell voltage, in a chemical reaction is a function of the activities of the solution species. From equation (7)and the dependence of ΔG on the reactant activities, the *Nernst relationship* is derived as

$$V_r = V_r^0 - \frac{RT}{nF}\ln\left[\frac{\Pi(activities\ of\ products)}{\Pi(activities\ of\ reactants)}\right],$$

………………eq9

Where*R* is the universal gas constant, 8.31J/mol K, and *T* is absolute temperature in K.

SPECIFIC ENERGY:

Specific energy is defined as the energy capacity per unit battery weight (Wh/kg). The theoretical specific energy is the maximum energy that can be generated per unit total mass of the cell reactant. As discussed above, the energy in a battery cell can be expressed by the Gibbs free energy ΔG. With respect to theoretical specific energy, only the effective weights (molecular weight of reactants and products) are involved; then

$$E_{spe,theo} = -\frac{\Delta G}{3.6\sum M_i} = \frac{nFV_r}{3.6\sum M_i}(\text{Wh/kg}),$$

………………eq10

Where$\Sigma Mi$is the sum of the molecular weight of the individual species involved in the battery reaction. Taking the lead-acid battery as an example,Vr_2.03 V, n_2, and ΣMi_642 g; then $Espe,the$_170 Wh/kg. From (10), it is clear that the ―ideal‖ couple would be derived from a highly electronegative element and a highly electropositive element, both of low atomic weight. Hydrogen, lithium, or sodium would be the best choice for the negative reactants, and the lighter halogens, oxygen, or sulfur would be the best choice for the positive. To put such couples together in a battery requires electrode designs for effective utilization of the contained active materials, as well as electrolytes of high conductivity compatible with the materials in both electrodes. These constraints result in oxygen and sulfur being used in some systems as oxides and sulfides rather than as the elements themselves. For operation at ambient temperature, aqueous electrolytes are advantageous because of their high conductivities. Here, alkali-group metals cannot be used as electrodes since these elements react with water. It is necessary to choose other metals, which have a reasonable degree of electro positivity, such as zinc, iron, or aluminum. When considering electrode couples, it is preferable to exclude those elements that have a low abundance in the earth's crust, are expensive to produce, or are unacceptable from a health or environmental point of view.

Examination of possible electrode couples has resulted in the study of more than 30 different battery systems with a view of developing a reliable, high-performance, inexpensive high-power energy source for electric traction. The theoretical specific energies of the systems championed for EVs and HEVs are presented in Table 4.6. Practical specific energies, however, are well below the theoretical maxima. Apart from electrode kinetic and other restrictions that serve to reduce the cell voltage and prevent full utilization of the reactants, there is a need for construction materials which add to the battery weight but which are not involved in the energy-producing reaction.

In order to appreciate the extent to which the practical value of the specific energy is likely to differ from the theoretical values, it is instructive to consider the situation of the well-established lead-acid battery. A breakdown of the various components of a lead-acid battery designed to give a practical specific energy of 45 Wh/kg is shown in Figure 5.5.It shows that only about 26% of the total weight of the battery is directly involved in producing electrical energy. The remainder is made up of (1) potential call reactants that are not discharged at the rates required for EV operation, (2) water used as the solvent for the electrolyte (sulfuric acid alone is not suitable), (3) lead grids for current collection, (4) –top lead‖, that is, terminals, straps and intercellconnectors, and (5) cover, connector and separators. A similar ratio of practical-to-theoretical specific energy is expected for each of thecandidate systems listed in Table 5.6.

Theoretical Specific Energies of Candidate Batteries for EVs and HEVs[1]

Battery ⊕	⊖	Cell Reaction: Charge ⇐	Discharge ⇒	Specific Energy (Wh/kg)
Acidic aqueous solution				
PbO_2	Pb	$PbO_2+2H_2SO_4+Pb$	$\Leftrightarrow 2PbSO_4+2H_2O$	170
Alkaline aqueous solution				
NiOOH	Cd	$2NiOOH+2H_2O+Cd$	$\Leftrightarrow 2Ni(OH)_2+Cd(OH)_2$	217
NiOOH	Fe	$2NiOOH+2H_2O+Fe$	$\Leftrightarrow 2Ni(OH)_2+Fe(OH)_2$	267
NiOOH	Zn	$2NiOOH+2H_2O+Zn$	$\Leftrightarrow 2Ni(OH)_2+Zn(OH)_2$	341
NiOOH	H_2	$2NiOOH+H_2$	$\Leftrightarrow 2Ni(OH)_2$	387
MnO_2	Zn	$2MnO2+H_2O+Zn$	$\Leftrightarrow 2MnOOH+ZnO$	317
O_2	Al	$4Al+6H_2O+3O_2$	$\Leftrightarrow 4Al(OH)_3$	2815
O_2	Fe	$2Fe+2H_2O+O_2$	$\Leftrightarrow 2Fe(OH)_2$	764
O_2	Zn	$2Zn+2H_2O+O_2$	$\Leftrightarrow 2Zn(OH)_2$	888
Flow				
Br_2	Zn	$Zn+Br_2$	$\Leftrightarrow ZnBr_2$	436
Cl_2	Zn	$Zn+Cl_2$	$\Leftrightarrow ZnCl_2$	833
$(VO_2)_2SO_4$	VSO_4	$(VO_2)_2SO_4+2HVSO_4 +2H_2SO_4$	$\Leftrightarrow 2VOSO_4+V_2(SO_4)_3 +2H_2O$	114
Molten salt				
S	Na	$2Na+3S$	$\Leftrightarrow Na_2S_3$	760
$NiCl_2$	Na	$2Na+NiCl_2$	$\Leftrightarrow 2NaCl$	790
FeS_2	LiA1	$4LiA1+FeS_2$	$\Leftrightarrow 2Li_2S+4Al+Fe$	650
Organic lithium				
$LiCoO_2$	Li-C	$Li_{(y+x)}C_6+Li_{(1-(y-x))}CoO_2$	$\Leftrightarrow Li_yC6+Li_{(1-y)}CoO_2$	320[a]

[a]For a maximum value of $x-0.5$ and $y=0$.

TABLE 5.6. Theoretical Specific Energies of Candidate Batteries for EVs and HEVs1

SPECIFIC POWER:

Specific power is defined as the maximum power of per unit battery weight that the battery can produce in a short period. Specific power is important in the reduction of battery weight, especially in high power demand applications, such as HEVs. The specific power of a chemical battery depends mostly on the battery's internal resistance. With the battery model as shown in Figure 10.6, the maximum power that the battery can supply to the load is

$$P_{peak}=\frac{V_0^2}{4(R_c+R_{int})},$$ ……………………….eq11

Where*Rohm* is the conductor resistance (ohmic resistance) and *Rint*is the internalresistance caused by chemical reaction.

Internal resistance, *Rint*, represents the voltage drop, Δ*V*, which is associatedwith the battery current. The voltage dropΔ*V*, termed over potential in

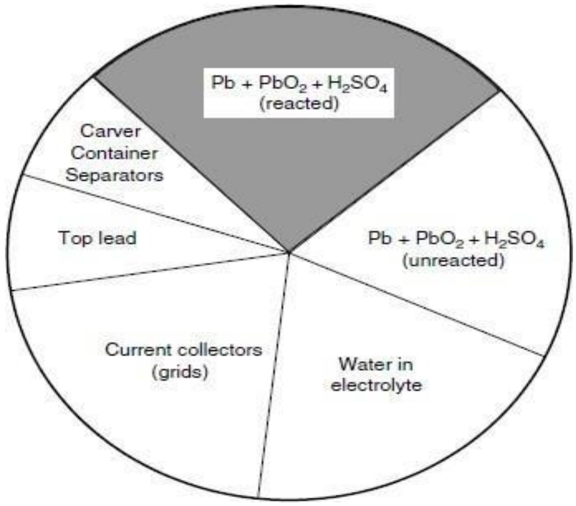


FIGURE 5.7: Weight distribution of the components of a lead-acid EV battery with a specific energy of 45Wh/kg at the C5/5 rate1

Battery terminology includes two components: one is caused by reaction activity Δ*VA*, and the other by electrolyte concentration Δ*VC*. General expressions of Δ*VA* and Δ*VC* are

$$\Delta V_A = a + b \log I$$ …………………eq12

And

$$\Delta V_C = -\frac{RT}{nF}\ln\left(1-\frac{I}{I_L}\right),$$ ……………eq13

where *a* and *b* are constants, *R* is the gas constant, 8.314 J/K mol, *T* is the absolute temperature, *n* is the number of electrons transferred in the reaction,*F* is the Faraday constant — 96,495 ampere-seconds per mole — and *IL*is the limit current. Accurate determination of battery resistance or voltagedrop by analysis is difficult and is usually obtained by measurement.1 Thevoltage drop increases with increasing discharging current, decreasing thestored energy in it (refer to Figure 4.3).Table 4.8 also shows the status of battery systems potentially availablefor EV. It can be seen that although specific energies are high in advancedbatteries, the specific powers have to improve. About 300 W/kg might be

System	Specific Energy (Wh/kg)	Peak Power (W/kg)	Energy Efficiency (%)	Cycle Life	Self-Discharge (% per 48 h)	Cost (US$/kWh)
Acidic aqueous solution						
Lead/acid	35–50	150–400	>80	500–1000	0.6	120–150
Alkaline aqueous solution						
Nickel/cadmium	50–60	80–150	75	800	1	250–350
Nickel/iron	50–60	80–150	75	1500–2000	3	200–400
Nickel/zinc	55–75	170–260	65	300	1.6	100–300
Nickel/metal hydride	70–95	200–300	70	750–1200+	6	200–350
Aluminum/air	200–300	160	<50	?	?	?
Iron/air	80–120	90	60	500+	?	50
Zinc/air	100–220	30–80	60	600+	?	90–120
Flow						
Zinc/bromine	70–85	90–110	65–70	500–2000	?	200–250
Vanadium redox	20–30	110	75–85	—	—	400–450
Molten salt						
Sodium/sulfur	150–240	230	80	800+	0[a]	250–450
Sodium/nickel chloride	90–120	130–160	80	1200+	0[a]	230–345
Lithium/iron sulfide (FeS)	100–130	150–250	80	1000+	?	110
Organic/lithium						
Lithium-ion	80–130	200–300	>95	1000+	0.7	200

[a]No self-discharge, but some energy loss by cooling.

TABLE 5.8: Status of Battery Systems for Automotive Applications

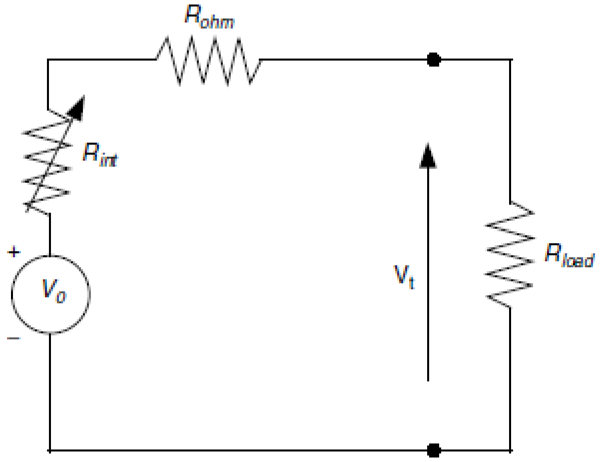


FIGURE 5.9. Battery circuit model

The optimistic estimate. However, SAFT has reported their Li-ion highpower for HEV application with a specific energy of 85 Wh/kg and aspecific power of 1350 W/kg and their high-energy batteries for EV applicationwith about 150 Wh/kg and 420 W/kg (at 80% SOC, 150A current and30sec), respectively.

ENERGY EFFICIENCY:

The energy or power losses during battery discharging and charging appear in the form of voltage loss. Thus, the efficiency of the battery during discharging and charging can be defined at any operating point as the ratio of the cell operating voltage to the thermodynamic voltage, that is:

During Discharging:

$$\eta = \frac{V}{V_0} \quad \text{.....................eq14}$$

And

During charging:

$$\eta = \frac{V_0}{V}. \quad \text{.....................................eq15}$$

The terminal voltage, as a function of battery current and energy stored in itor SOC, is lower in discharging and higher in charging than the electrical potential produced by a chemical reaction. Figure 5.10 shows the efficiency of the lead-acid battery during discharging and charging. The battery has ahigh discharging efficiency with high SOC and a high charging efficiency with low SOC. The net cycle efficiency has a maximum in the middle range of the SOC. Therefore, the battery operation control unit of an HEV should control the battery SOC in its middle range so as to enhance the operating efficiency and depress the temperature rise caused by energy loss. High temperature would damage the battery.

BATTERY TECHNOLOGIES:

The viable EV and HEV batteries consist of the lead-acid battery, nickel based batteries such as nickel/iron, nickel/cadmium, and nickel–metal hydride batteries, and lithium-based batteries such as lithium polymer and lithium-ion batteries.3 In the near term, it seems that lead-acid batteries will still be the major type due to its many advantages. However, in the middle and long term, it seems that cadmium- and lithium-based batteries will be major candidates for EVs and HEVs.

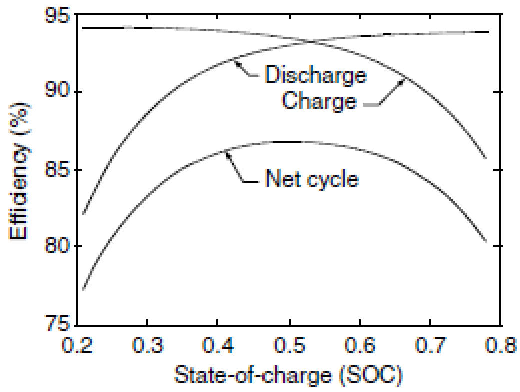


FIGURE 5.10 Typical battery charge and discharge efficiency

LEAD-ACID BATTERIES:

The lead-acid battery has been a successful commercial product for over a century and is still widely used as electrical energy storage in the automotive field and other applications. Its advantages are its low cost, mature technology, relative high-power capability, and good cycle. These advantagesare attractive for its application in HEVs where high power is the firstconsideration. The materials involved (lead, lead oxide, sulfuric acid) are rather low in cost when compared to their more advanced counterparts. Lead-acid batteries also have several disadvantages. The energy density of lead-acid batteries is low, mostly because of the high molecular weight of lead. The temperature characteristics are poor.2 Below 10°C, its specific power and specific energy are greatly reduced. This aspect severely limits the application of lead-acid batteries for the traction of vehicles operating in cold climates.

The presence of highly corrosive sulfuric acid is a potential safety hazard for vehicle occupants. Hydrogen released by the self-discharge reactions is another potential danger, since this gas is extremely flammable even intiny concentrations. Hydrogen emission is also a problem for hermetically sealed batteries. Indeed, in order to provide a good level of protection against acid spills, it is necessary to seal the battery, thus trapping the parasitic gases in the casing. As a result, pressure may build up in the battery, causing swelling and mechanical constraints on the casing and sealing. The lead in the electrodes is an environmental problem because of its toxicity. The emission of lead consecutive to the use of lead-acid batteriesmay occur during the fabrication of the batteries, in case of vehicle wreck (spill of electrolyte through cracks), or during their disposal at the end of battery life.

Different lead-acid batteries with improved performance are beingdeveloped for EVs and HEVs. Improvements of the sealed lead-acid batteries in specific energy over 40 Wh/kg, with the possibility of rapid charge, have been attained. One of these advanced sealed lead-acid batteries isElectro source’s Horizon battery. It adopts the lead wire woven horizontalplate and hence offers long cycle life (over 600 cycles for on-road EV application), rapid recharge capability (50% capacity in 8 minand 100% in less than 30 min), low cost (US$2000–3000 an EV), mechanicalruggedness (robust structure of horizontal plate), maintenance-free conditions(sealedbatterytechnology), and environmental friendliness. Otheradvanced lead-acid batterytechnologies include bipolar designs and microtubular griddesigns. Advanced lead-acid batteries have been developed to remedy these disadvantages. The specific energy has been increased through the reductionof inactive materials such as the casing, current collector, separators, etc. The lifetime has been increased by over 50% — at the expense of cost, however. The safety issue has been addressed and improved, with electrochemical processes designed to absorb the parasitic releases ofhydrogen and oxygen.

NICKEL-BASED BATTERIES:

Nickel is a lighter metal than lead and has very good electrochemical properties desirable for battery applications. There are four different nickel-based battery technologies: nickel–iron, nickel–zinc, nickel–cadmium, and nickel–metal hydride.

NICKEL/IRON SYSTEM:

The nickel/iron system was commercialized during the early years of the20th century. Applications included fork-lift trucks, mine locomotives, shuttle vehicles, railway locomotives, and motorized hand-trucks.1 The system comprises a nickel (III) hydroxy-oxide (NiO OH) positive electrode and a metallic iron negative electrode. The electrolyte is a concentrated solution of potassium hydroxide (typically 240 g/l) containing lithium hydroxide (50 g/l). The cell reaction is given in Table 4.6 and its nominal open-circuit voltage is1.37v

NICKEL-BASED BATTERIES:

Nickel is a lighter metal than lead and has very good electrochemical properties desirable for battery applications. There are four different nickel-based battery technologies: nickel–iron, nickel–zinc, nickel–cadmium, andnickel–metal hydride.

NICKEL/IRON SYSTEM:

The nickel/iron system was commercialized during the early years of the20th century. Applications included fork-lift trucks, mine locomotives, shuttle vehicles, railway locomotives, and motorized hand-trucks.1 The system comprises a nickel (III) hydroxy-oxide (NiOOH) positive electrode and a metallic iron negative electrode. The electrolyte is a concentrated solution of potassium hydroxide (typically 240 g/l) containing lithium hydroxide (50 g/l). The cell reaction is given in Table 10.1 and its nominal open-circuit

voltage is 1.37 V.Nickel/iron batteries suffer from gassing, corrosion, and self-discharge problems. These problems have been partially or totally solved in prototypes that have yet to reach the market. These batteries are complex due to the need to maintain the water level and the safe disposal of the hydrogen and oxygen released during the discharge process. Nickel–iron batteries also suffer from low temperatures, although less than lead-acid batteries. Finally, the cost of nickel is significantly higher than that of lead. Their greatest advantages are high power density compared with lead-acid batteries, and a capability of withstanding 2000 deep discharges.

NICKEL/CADMIUM SYSTEM:

The nickel/cadmium system uses the same positive electrodes and electrolyteas the nickel/iron system, in combination with metallic cadmiumnegative electrodes. The cell reaction is given in Table 10.1 and its nominal open-circuit voltage is 1.3 V. Historically, the development of the battery hascoincided with that ofnickel/iron and they have a similar performance. Nickel/cadmium technology has seen enormous technical improvementbecause of the advantages of high specific power (over 220 W/kg), longcycle life (up to 2000 cycles), a high tolerance of electric and mechanical abuse, a small voltage drop over a wide range of discharge currents, rapid charge capability (about 40 to 80% in 18 min), wide operating temperature(_40 to 85°C), low self-discharge rate (_0.5% per day), excellent long-termstorage due to negligible corrosion, and availability in a variety of sizedesigns. However, the nickel/cadmium battery has some disadvantages, including high initial cost, relatively low cell voltage, and the carcinogenicityand environmental hazard of cadmium. Nickel/iron batteries suffer from gassing, corrosion, and self-discharge problems. These problems complex due to the need to maintain the water level and the safe disposal of the hydrogen and oxygen released during the discharge process. Nickel–iron batteries also suffer from low temperatures, although less than lead-acid batteries. Finally, the cost of nickel is significantly higher than that of lead. Their greatest advantages are high power density compared with lead-acid batteries, and a capability of withstanding 2000 deep discharges.

NICKEL/CADMIUM SYSTEM:

The nickel/cadmium system uses the same positive electrodes and electrolyte as the nickel/iron system, in combination with metallic cadmium negative electrodes. The cell reaction is given in Table 10.1 and its nominal open-circuit voltage is 1.3 V. Historically, the development of the battery has coincided with that of nickel/iron and they have a similar performance. Nickel/cadmium technology has seen enormous technical improvement because of the advantages of high specific power (over 220 W/kg), long cycle life (up to 2000 cycles), a high tolerance of electric and mechanicalabuse, a small voltage drop over a wide range of discharge currents, rapidcharge capability (about 40 to 80% in 18 min), wide operating temperature(_40 to 85°C), low self-discharge rate (_0.5% per day), excellent long-termstorage due to negligible corrosion, and availability in a variety of size designs. However, the nickel/cadmium battery has some disadvantages, including high initial cost, relatively low cell voltage, and the carcinogenicity and environmental hazard of cadmium.

The nickel/cadmium battery can be generally divided into two major categories, namely the vented and sealed types. The vented type consists of many alternatives. The vented sintered-plate is a more recent development, which has a high specific energy but is more expensive. It is characterized by a flat discharge voltage profile, and superior high current rate and low-temperature performance. A sealed nickel/cadmium battery incorporates a specific cell design feature to prevent a build-up of pressure in the cell caused by gassing during overcharge. As a result, the battery requires no maintenance.

The major manufacturers of the nickel/cadmium battery for EV and HEVallocation are SAFT and VARTA. Recent EVs powered by the nickel/cadmium battery have included the Chrysler TE Van, Citroën AX, Mazda Roadster, Mitsubishi EV, Peugeot 106, and Renault Clio.3,6

NICKEL–METAL HYDRIDE (NI–MH) BATTERY

The Nickel-metal hydride battery has been on the market since 1992. Its characteristics are similar to those of the nickel/cadmium battery. The principal difference between them is the use of hydrogen, absorbed in a metal hydride, for the active negative electrode material in place of cadmium. Because of its superior specific energy when compared to the Ni–Cd and its freedom from toxicity or carcinogenicity, the Ni–MH battery is superseding the Ni–Cd battery. The overall reaction in a Ni–MH battery is

$$MH + NiOOH \leftrightarrow M + Ni(OH)_2.$$
………………...eq1

When the battery is discharged, the metal hydride in the negative electrode is oxidized to form metal alloy, and nickel oxyhydroxide in the positive electrode is reduced to nickel hydroxide. During charging, the reverse reaction occurs.

At present, Ni–MH battery technology has a nominal voltage of 1.2 V and attains a specific energy of 65 Wh/kg and a specific power of 200 W/kg. Akey component of the Ni–MH battery is the hydrogen storage metal alloy, which is formulated to obtain a material that is stable over a large number of cycles. There are two major types of these metal alloys being used. These are the rare-earth alloys based around lanthanum nickel, known as AB5, and alloys consisting of titanium and zirconium, known as AB2. The AB2 alloys have a higher capacity than the AB5 alloys. However, the trend is to use AB5alloys because of better charge retention and stability characteristics. Since the Ni–MH battery is still under development, its advantages based on present technology are summarized as follows: it has the highest specific energy (70 to 95 Wh/kg) and highest specific power (200 to 300 W/kg) of nickel-based batteries, environmental friendliness (cadmium free), a flat discharge profile (smaller voltage drop), and rapid recharge capability. However, this battery still suffers from its high initial cost. Also, it may havea memory effect and may be exothermic on charge.

The Ni–MH battery has been considered as an important near-term choice for EV and HEV applications. A number of battery manufacturers, such asGM Ovonic, GP, GS, Panasonic, SAFT, VARTA, and YUASA, have activelyengaged in the development of this battery technology, especially for poweringEVs and HEVs. Since1993, Ovonic battery has installed its Ni–MH batteryin the Solectron GT Force EV for testing and demonstration. A 19-kWhbattery has delivered over 65 Wh kg, 134 km/h, acceleration from zero to 80km/h in 14 sec, and a city driving range of 206 km. Toyota and Honda haveused the Ni–MH battery in their HEVs — Prius and Insight, respectively.

LITHIUM-BASED BATTERIES

Lithium is the lightest of all metals and presents very interesting characteristics from an electrochemical point of view. Indeed, it allows a very highthermodynamic voltage, which results in a very high specific energy and specific power. There are two major technologies of lithium-based batteries: lithium–polymer and lithium-ion.

LITHIUM–POLYMER (LI–P) BATTERY:

Lithium–polymer batteries use lithium metal and a transition metal intercalation oxide (M_yO_z) for the negative and positive electrodes, respectively. This M_yO_z possesses a layered structure into which lithium ions can be inserted, or from where they can be removed on discharge and charge, respectively. A thin solid polymer electrolyte (SPE) is used, which offers themerits of improved safety and flexibility in design. The general electrochemical reactions are

$$x\mathrm{Li}+\mathrm{M}_y\mathrm{O}_z \leftrightarrow \mathrm{Li}_x\mathrm{M}_y\mathrm{O}_z. \quad \text{………. eq2}$$

On discharge, lithium ions formed at the negative electrode migrate through the SPE, and are inserted into the crystal structure at the positive electrode. On charge, the process is reversed. By using a lithium foil negative electrode and vanadium oxide (V6O13) positive electrode, the Li/SPE/V6O13 cell is the most attractive one within the family of Li–polymer. It operates at a nominal voltage of 3 V and has a specific energy of 155 Wh/kg and a specific power of 315 W/kg. The corresponding advantages are a very low self-discharge rate (about 0.5% per month), capability of fabrication in a variety of shapes and sizes, and safe design (reduced activity of lithium with solid electrolyte). However, it has the drawback of a relatively weak low-temperature performance due to the temperature dependence of ionic conductivity.

LITHIUM-ION (LI-ION) BATTERY:

Since the first announcement of the Li-ion battery in 1991, Li-ion battery technology has seenanunprecedented rise to what is now considered to bethe most promising rechargeable battery of thefuture. Although still atthedevelopment stage, the Li-ion battery has already gained acceptance for EVand HEV applications.

The Li-ion battery uses a lithiated carbon intercalation material (Li*x*C) forthe negative electrode instead of metallic lithium, a lithiated transitionmetal intercalation oxide (Li1_*x* M*y*O*z*) for the positive electrode, and a liquidorganic solution or a solid polymer for the electrolyte. Lithium ions swing through the electrolyte between the positive and negative electrodesduring discharge and charge. The general electrochemical reaction is described as

$$\mathrm{Li}_x\mathrm{C}+\mathrm{Li}_{1-x}\mathrm{M}_y\mathrm{O}_z \leftrightarrow \mathrm{C}+\mathrm{LiM}_y\mathrm{O}_z. \quad \text{……. eq3}$$

On discharge, lithium ions are released from the negative electrode, migrate via the electrolyte, and are taken up by the positive electrode. On charge, themprocess is reversed. Possible positive electrode materials include Li1_*x*CoO2, Li1_*x*NiO2, and Li1_*x*Mn2O4, which have the advantages of stability in air, high voltage, andreversibility for the lithium intercalation reaction. The Li*x*C/Li1_*x*NiO2 type, loosely written as C/LiNiO2 or simply calledthe nickel-based Li-ion battery, has a nominal voltage of 4 V, a specificenergy of 120 Wh/kg, an energy density of 200 Wh/l, and a specific powerof 260 W/kg. The cobalt-based type has a higher specific energy and energydensity, but at a higher cost and significant increase in the self-discharge rate. The manganese-based type has the lowest cost and its specific energyand energy density lie betweenthose of the cobalt- and nickel-based types. It is anticipated that the development of the Li- ion battery will ultimately move to the manganese-based type because of the low cost, abundance, and environmental friendliness of the manganese-based materials. Many battery manufacturers, suchas SAFT, GS Hitachi, Panasonic, SONY, and VARTA, have actively engaged in the development of the Li-ion battery. Starting in 1993, SAFT focused on the nickel-based Li-ion battery. Recently, SAFT reported the development of Li-ion high-power batteries forHEV applications with a specific energy of 85 Wh/kg and a specific powerof 1350 W/kg. They also announced high-energy batteries for EV applicationswith about 150 Wh/kg and 420 W/kg (at 80% SOC, 150 A current, and30 sec), respectively.

ULTRACAPACITORS OR SUPER CAPACITORS:

Because of the frequent stop/go operation of EVs and HEVs, the discharging and charging profile of the energy storage is highly varied. The average power required from the energy storage is much lower than the peak power of relatively short duration required for acceleration and hill climbing. In fact, the energy involved in the acceleration and deceleration transients is roughly two thirds of the total amount of energy over the entire vehicle mission in urban driving (Chapters 8 and 9). In HEV design, the peak power capacity of the energy storage is more important than its energy capacity, and usually constrains its size reduction. Based on present battery technology, battery design has to carry out the trade-off among the specific energy and specific power and cycle life. The difficulty in simultaneously obtaining high values of specific energy, specific power, and cycle life has led to some suggestions that the energy storage system of EV and HEV should be a hybridization of an energy source and a power source. The energy source, mainly batteries and fuelcells, has high specific energy whereas the power source has high specific power. The power sources can be recharged from the energy source during less demanding driving or regenerative braking. The power source that has received wide attention is the ultracapacitor

4.7.1. FEATURES OF ULTRACAPACITORS:

The ultracapacitor is characterized by much higher specific power, but much lower specific energy compared to the chemical batteries. Its specific energy is in the range of a few watt-hours per kilogram. However, its specific power can reach up to 3 kW/kg, much higher than any type of battery. Due to their low specific energy density and the dependence of voltage onthe SOC, it is difficult to use ultracapacitors alone as an energy storage forEVs and HEVs. Nevertheless, there are a number of advantages that can result from using the ultracapacitor as an auxiliary power source. One promising application is the so-called battery and ultracapacitor hybrid energy storage system for EVs and HEVs. Specific energy and specificpower requirements can be decoupled, thus affording an opportunity todesign a battery that is optimized for the specific energy and cycle life withlittle attention being paid to the specific power. Due to the load levelling effect of the ultracapacitor, the high-current discharging from the batteryand the high-current charging to the battery by regenerative braking is minimized so that the available energy, endurance, and life of the battery can besignificantly increased.

BASIC PRINCIPLES OF ULTRACAPACITORS

Double-layer capacitor technology is the major approach to achieving theultracapacitor concept. The basic principle of a double-layer capacitor isillustrated in Figure 10.8. When two carbon rods are immersed in a thin sulfuric acid solution, separated from each other and charged with voltage increasing from zero to 1.5 V, almost nothing happens up to 1 V; then at alittle over 1.2 V, a small bubble will appear on the surface of both the electrodes. Those bubbles at a voltage above 1 V indicate electrical decompositionof water. Below the decomposition voltage, while the current does not flow, an –electric double layer‖ then occurs at the boundary of electrode and electrolyte. The electrons are charged across the double layer and for a capacitor.

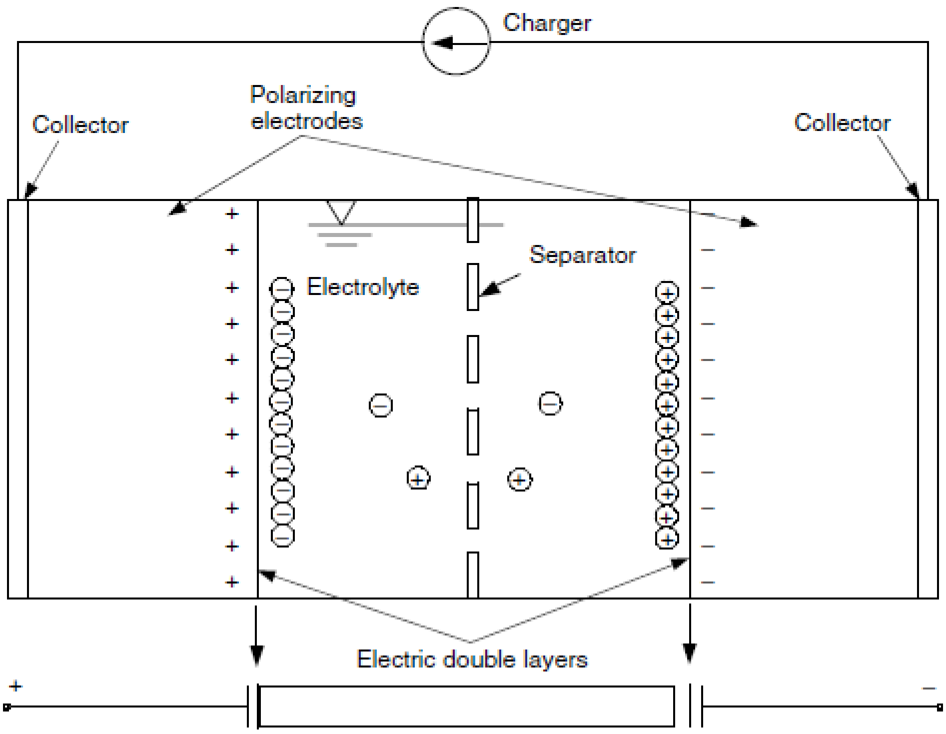


FIGURE 5.11: Basic principles of a typical electric double-layer capacitor

.

An electrical double layer works as an insulator only below the decomposing voltage. The stored energy, *Ecap*, is expressed as

$$E_{cap} = \frac{1}{2} C V^2, \qquad \text{………… eq4}$$

where *C* is the capacitance in Faraday and *V* is the usable voltage in volt.This equation indicates that the higher rated voltage *V* is desirable for larger energy density capacitors. Up to now, capacitors' rated voltage with an aqueous electrolyte has been about 0.9 V per cell, and 2.3 to 3.3 V for each cell with a nonaqueous electrolyte. There is great merit in using an electric double layer in place of plastic oraluminium oxide films in a capacitor, since the double layer is very thin — as thin as one molecule with no pin holes — and the capacity per area is quite large, at 2.5 to 5 µF/cm2.Even if a few µF/cm2 are obtainable, the energy density of capacitors is not large when using aluminium foil. For increasing capacitance, electrodes aremade from specific materials that have a very large area, such as activated carbons, which are famous for their surface areas of 1,000 to 3,000 m2/g. To those surfaces, ions are adsorbed andresult in 50 F/g (1,000 m2/g_5F/cm2_10,000 cm2/m2_50 F/g). Assuming that the same weight of electrolyteis added, 25 F/g is quite a large capacity density. Nevertheless, theenergy density of these capacitors is far smaller than secondary batteries; the typical specific energy of ultracapacitors at present is about 2 Wh/kg, only1/20 of 40 Wh/kg, which is the available value of typical lead-acid batteries.

PERFORMANCE OF ULTRACAPACITORS:

The performance of an ultra capacitor may be represented by terminal voltages during discharge and charge with different current rates. There are three parameters in a capacitor: the capacitance itself (its electric potential), the series resistance *RS*, and the dielectric leakage resistance, *RL*, as shown in Figure 4.12. The terminal voltage of the ultra capacitor during discharge can be expressed as

$$V_t = V_C - iR_S. \quad \text{……………eq5}$$

$$\frac{dV_C}{dt} = -\left(\frac{i+i_L}{C}\right), \quad \text{…………eq6}$$

where *C* is the capacitance of the ultracapacitor. On the other hand, the leakagecurrent *iL*can be expressed as

$$i_L = \frac{V_c}{R_L}. \quad \text{……….....eq7}$$

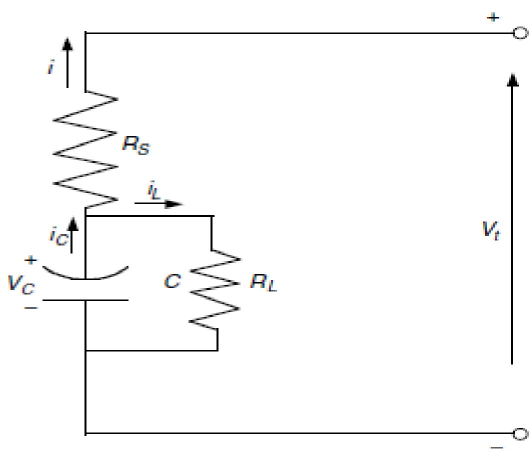


FIGURE 5.12: Ultracapacitor equivalent circuit

$$\frac{dV_C}{dt} = \frac{V_c}{CR_L} - \frac{i}{C}.$$

……….........eq8

The terminal voltage of the ultracapacitor cell can be represented by the diagramas shown in Figure. The analytical solution of (eq8) is

$$V_C = \left[V_{C0} \int_0^t \frac{i}{C} e^{t/CR_L}\, dt \right] e^{t/CR_L},$$

............eq9

where i is the discharge current, which is a function of time in real operation. The discharge characteristics of the Maxwell 2600 F ultracapacitor are shown in Figure 5.14. At different discharge current rates, the voltage decreases linearlywith discharge time. At a large discharge current rate, the voltage decreases much faster than at a small current rate.

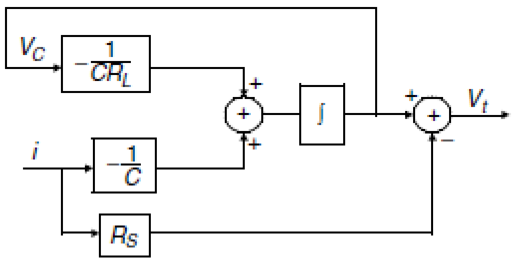


FIGURE 5.13: Block diagram of the ultra capacitor model

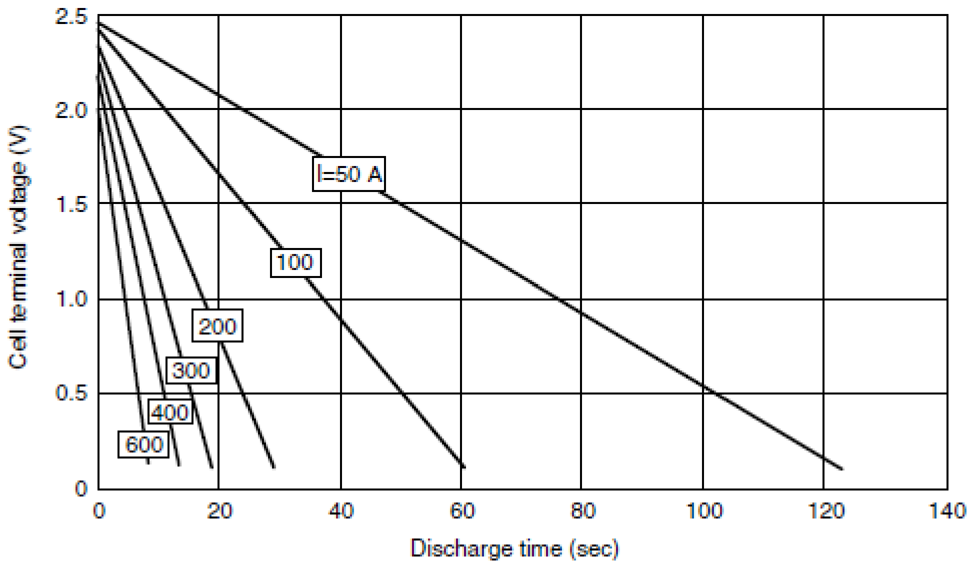


FIGURE 5.14: Discharge characteristics of the 2600 F Maxwell Technologies ultracapacitor

A similar model can be used to describe the charging characteristics of anultracapacitor, and readers who are interested may do their own analysisand simulation.

The operation efficiency in discharging and charging can be expressed as:

discharging:

$$\eta_d = \frac{V_t I_t}{V_C I_C} = \frac{(V_C - I_t R_S) I_t}{V_C (I_t + I_L)}$$

charging:

and

.......eq10

$$\eta_c = \frac{V_C I_C}{V_t I_t} = \frac{V_C(I_t - I_L)}{(V_C + I_t R_s) I_t},$$

..............eq11

where *Vt* is the terminal voltage and *It* is the current input to or output fromthe terminal. In actual operation, the leakage current *IL* is usually very small(few mA) and can be ignored. Thus, equations (10) and (11) can berewritten as:

discharging:

$$\eta_d = \frac{V_C - R_S I_t}{V_C} = \frac{V_t}{V_C}$$

.................eq12

And

charging:

$$\eta_c = \frac{V_C}{V_C + R_s I_t} = \frac{V_C}{V_t}.$$

....................eq13

The above equations indicate that the energy loss in an ultracapacitor iscaused by the presence of seriesresistance. The efficiency decreases at a highcurrent rate and low cell voltage, as shown in Figure 5.15. Thus, in actual operation, the ultracapacitor should be maintained at its high voltage region, for more than 60% ofits rated voltage.

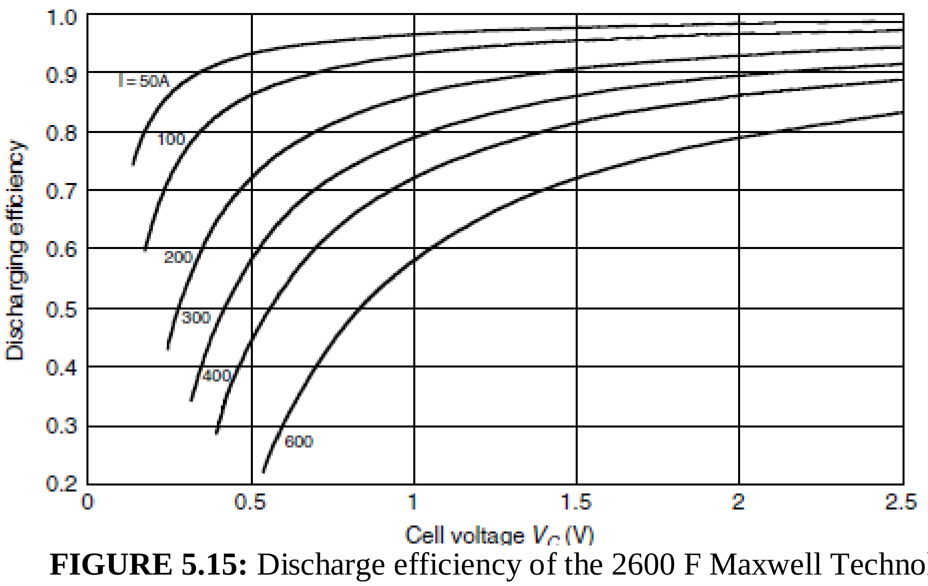


FIGURE 5.15: Discharge efficiency of the 2600 F Maxwell Technologies ultracapacitor

The energy stored in an ultracapacitor can be obtained through the energyneeded to charge it to a certain voltage level, that is,

$$E_C = \int_0^t V_C I_C \, dt = \int_0^v C V_C \, dV_C = \frac{1}{2} C V_C^2,$$

......................eq14

where *VC* is the cell voltage in volts. At its rated voltage, the energy stored in the ultracapacitor reaches its maxima. Equation (10.31) indicates that increasing the rated voltage can significantly increase the stored energy since the energy increases with the voltage squared. In real operation, itis impossible to utilize the stored energy completely because of the low power in the low SOC (low

voltage). Thus, an ultracapacitor is usually given a bottom voltage, *VCb*, below which the ultracapacitor will stop delivering energy. Consequently, the available or useful energy for use is less than its fully charged energy, which can be expressed as $E_u = \frac{1}{2}C\left(V_{CR}^2 - V_{Cb}^2\right),$ eq15
where *VCR* is the rated voltage of the ultracapacitor. At its bottom voltage, theSOC can be written as

$$SOC = \frac{0.5\,CV_{Cb}^2}{0.5\,CV_{CR}^2} = \frac{V_{Cb}^2}{V_{CR}^2}.$$

...........................eq16

For example, when the cell voltage drops from rated voltage to 60% of therated voltage, 64% of the total energy is available for use, as shown inFigure 5.15.

ULTRACAPACITOR TECHNOLOGIES:

According to the goals set by the U.S. Department of Energy for the inclusionof ultracapacitors in EVs and HEVs, the near-term specific energyand specific power should be better than 5 Wh/kg and 500 W/kg, respectively, while the advanced performance values should be over 15 Wh/kgand 1600 W/kg. So far, none of the available ultracapacitors can fully satisfy these goals. Nevertheless, some companies are actively engaged in the research and development of ultracapacitors for EV and EHV applications. Maxwell Technologies hasclaimed that its power BOOSTCAP ultracapacitor cells (2600 F at 2.5 V) and integrated modules (145 F at 42 Vand435 F at 14 V) are in production. The technical specifications are listedin Table 5.9.

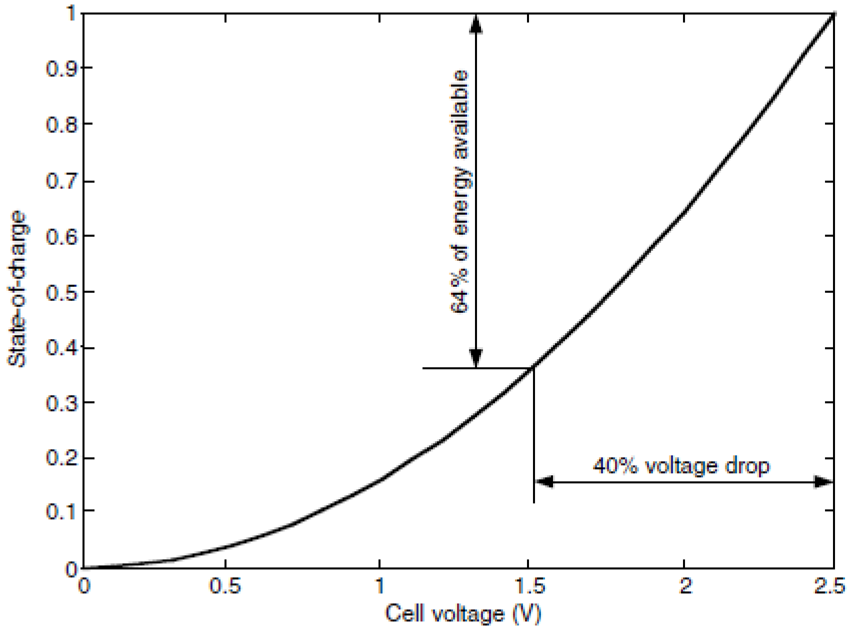


FIGURE 5.16: SOC vs. cell voltage

TABLE 5.9: Technical Specifications of the Maxwell Technologies Ultracapacitor Cell andIntegrated Modules5

	BCAP0010 (Cell)	BMOD0115 (Module)	BMOD0117 (Module)
Capacitance (farads, −20%/+20%)	2600	145	435
maximum series resistance ESR at 25°C (mΩ)	0.7	10	4
Voltage (V), continuous (peak)	2.5 (2.8)	42 (50)	14 (17)
Specific power at rated voltage (W/kg)	4300	2900	1900
Specific energy at rated voltage (Wh/kg)	4.3	2.22	1.82
Maximum current (A)	600	600	600
Dimensions (mm) (reference only)	60 × 172 (Cylinder)	195 × 165 × 415 (Box)	195 × 265 × 145 (Box)
Weight (kg)	0.525	16	6.5
Volume (l)	0.42	22	7.5
Operating temperature[a] (°C)	−35 to +65	−35 to +65	−35 to +65
Storage temperature (°C)	−35 to +65	−35 to +65	−35 to +65
Leakage current (mA) 12 h, 25°C	5	10	10

[a]Steady-state case temperature.

ULTRAHIGH-SPEED FLYWHEELS:

The use of flywheels for storing energy in mechanical form is not a new concept. More than 25 years ago, the Oerlikon Engineering Company inSwitzerland made the first passenger bus solely powered by a massive flywheel. This flywheel, which weighed 1500 kg and operated at 3000 rpm, wasrecharged by electricity at each bus stop. The traditional flywheel is a massive steel rotor with hundreds of kilograms that spins on the order of ten hundreds of rpm. On the contrary, the advanced flywheel is a lightweight composite rotor with tens of kilograms and rotates on the order of 10,000rpm; it is the so-called ultrahigh-speed flywheel. The concept of ultrahigh-speed flywheels appears to be a feasible means for fulfilling the stringent energy storage requirements for EV and HEVapplications, namely high specific energy, high specific power, long cycle life, high-energy efficiency quick recharge maintance free characteristics, cost effectiveness and environmental.

OPERATION PRINCIPLES OF FLYWHEELS:

A rotating flywheel stores energy in the kinetic form as

$$E_f = \frac{1}{2} J_f \omega_{fr}^2$$ eq1

where J_f is the moment of inertia of the flywheel in kgm2/sec and ω_f is the angular velocity of the flywheel in rad/sec. Equation (10.32) indicates that enhancing the angular velocity of the flywheel is the key method of increasing its energy capacity and reducing its weight and volume. At present, a speed of over 60,000 rpm has been achieved in some prototypes. With current technology, it is difficult to directly use the mechanical energy stored in a flywheel to propel a vehicle, due to the need for continuous variation transmission (CVT) with a wide gear ratio variation range. The commonly used approach is to couple an electric machine to the flywheel directly or through a transmission to constitute a so-called mechanical battery. The electric machine, functioning as the energy input and output port, converts the mechanical energy into electric energy or vice versa, as shown in Figure 5.17. Equation (1) indicates that the energy stored in a flywheel is proportional to the moment of inertia of the flywheel and flywheel rotating speed squared. A lightweight flywheel should be designed to achieve moment of inertia per unit mass and per unit volume by properly designing its geometric shape.

The moment of inertia of a flywheel can be calculated by

$$J_f = 2\pi\rho\int_{R_1}^{R_2} W(r)r^3\,dr,$$

................eq2

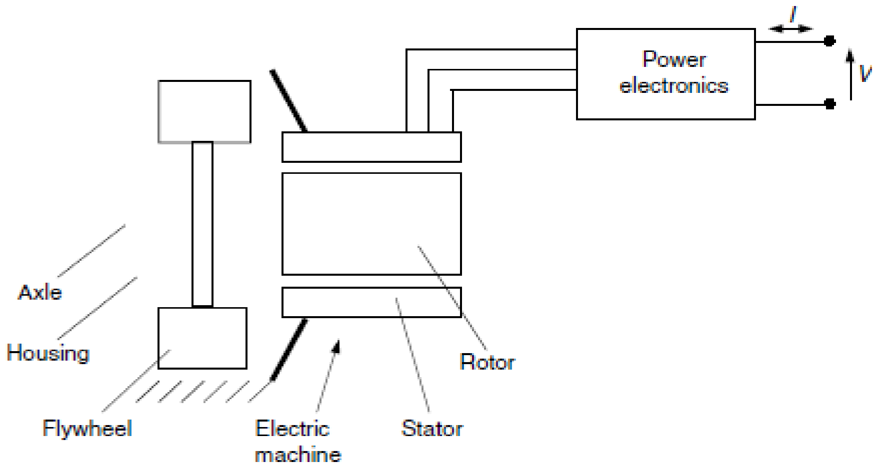
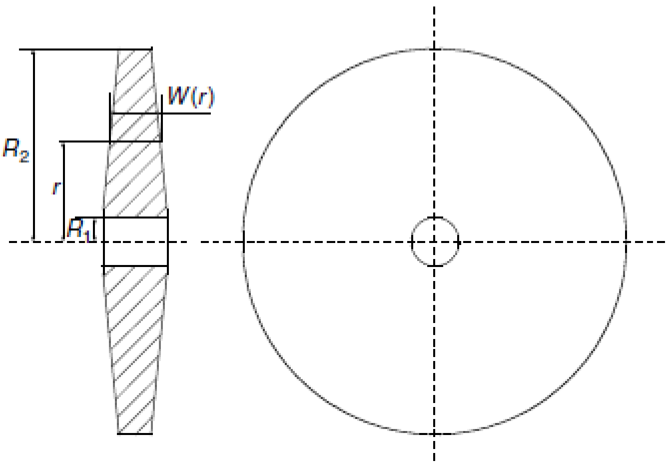


FIGURE 5.17: Basic structure of a typical flywheel system (mechanical battery)



where ρ is the material mass density and *W*(*r*) is the width of the flywheelcorresponding to theradius *r*, as shown in Figure 4.18. The mass of the flywheelcan be calculated by

$$M_f = 2\pi\rho\int_{R_1}^{R_2} W(r)r\,dr.$$

.............eq3

Thus, the specific moment of inertia of a flywheel, defined as the moment ofinertia per unit mass, can be expressed as

$$J_{fs} = \frac{\int_{R_1}^{R_2} W(r)r^3\,dr}{\int_{R_1}^{R_2} W(r)r\,dr}.$$

...........................eq4

Equation (1) indicates that the specific moment of inertia of a flywheel isindependent of its material mass density and dependent solely on its geometricshape $W(r)$.

For a flywheel with equal width, the moment of inertia is

$$J_f = 2\pi\rho\left(R_2^4 - R_1^4\right) = 2\pi\rho\left(R_2^2 + R_1^2\right)\left(R_2^2 - R_1^2\right).$$

............................eq5

The specific moment of inertia is

$$J_{fs} = R_2^2 + R_1^2.$$

.........................eq6

The volume density of the moment of inertia, defined as the moment of inertiaper unit volume, is, indeed, associated with the mass density of the material.

The volume of the flywheel can be obtained by

$$V_f = 2\pi \int_{R_2}^{R_2} W(r) r \, dr.$$

........................eq7

The volume density of the moment of inertia can be expressed as

$$J_{fV} = \frac{\rho \int_{R_1}^{R_2} W(r) r^3 \, dr}{\int_{R_1}^{R_2} W(r) r \, dr}.$$

...............................eq8

For a flywheel with equal width, the volume density of the moment of inertiaIs

$$J_{fV} = \rho\left(R_2^2 + R_1^2\right).$$

........................eq9

Equations (8) and (9) indicate that heavy material can, indeed, reduce the volume of the flywheel with a given moment of inertia.

POWER CAPACITY OF FLYWHEEL SYSTEMS:

The power that a flywheel delivers or obtains can be obtained by differentiatingequation (1) with respect totime, that is,

$$P_f = \frac{dE_f}{dt} = J_f \omega_f \frac{d\omega_f}{dt} = \omega_f T_f,$$

....................eq10

where Tf is the torque acting on the flywheel by the electric machine. When the flywheel discharges its energy, the electric machine acts as a generator and converts the mechanical energy of the flywheel into electric energy. On the other hand, when the flywheel is charged, the electric machine acts as a motor and converts electric energy into mechanical energy stored in the flywheel. Equation (10.44) indicates that the power capacity of a flywheel system depends completely on the power capacity of the electric machine. An electric machine usually has the characteristics as shown in — constant torque and cregion.

In the constant torque region, the voltage of the electric machine is proportional to its angular velocity, and the magnetic flux in the air gap isconstant. However, in the constant power region, the voltage is constant and the magnetic field is weakened with increasing machine angular velocity. In charge of the flywheel, that is, accelerating the flywheel from a low speed, ω0, to a high speed, maximum speed, ω*max*, for example, the torque delivered from the electric machine is

$$T_m = J_f \frac{d\omega_f}{dt},$$

.....................eq11

where it is supposed that the electric machine is directly connected to the flywheel.

$$t = \int_{\omega_0}^{\omega_{max}} \frac{J_f}{T_m} d\omega = \int_{\omega_0}^{\omega_b} \frac{J_f}{p_m/\omega_b} \omega + \int_{\omega_b}^{\omega_{max}} \frac{J_f}{p_m/\omega} d\omega.$$

The time, *t*, needed can be expressed as

.........................eq12

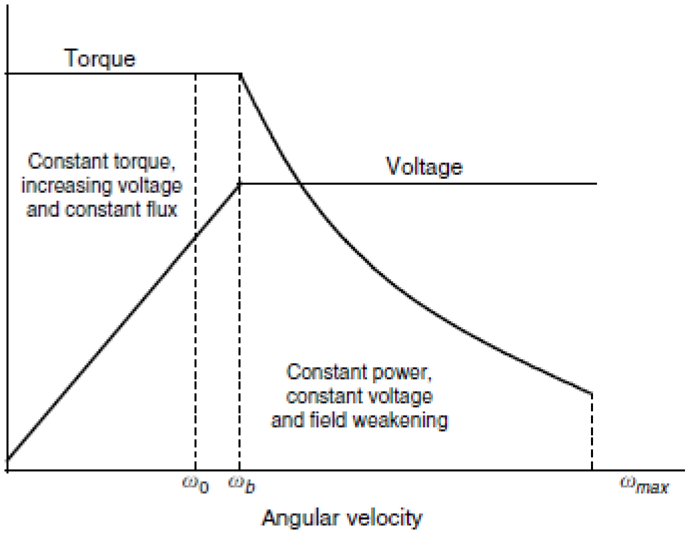


FIGURE 5.19. Typical torque and voltage profile vs. rotational speed

With the given accelerating time, *t*, the maximum power of the electricmachine can be obtained from (12) as

$$P_m = \frac{J_f}{2_t}\left(\omega_b^2 - 2\omega_0\omega_b + \omega_{max}^2\right).$$

.....................eq13

Equation (13) indicates that the power of the electric machine can be minimized by the design of its corner speed or base speed, ω*b*, equal to the bottom speed of the flywheel, ω0. This conclusion implies that the effective operating speed range of the flywheel should coincide with the constant speed region of the electric machine. The power of the electric machine can be minimized as

$$P_m = \frac{J_f}{2_t}\left(\omega_0^2 + \omega_{max}^2\right).$$

.....................eq14

Another advantage achieved by coinciding the operating speed range of the flywheel with the constant power speed range is that the voltage of the electric machine is always constant (refer to

Figure 5.19), therefore significantly simplifying the power management system, such as DC/DC converters and their controls.

FLYWHEEL TECHNOLOGIES:

Although higher rotational speed can significantly increase the stored energy (equation [10.35]), there is a limit to which the tensile strength σ ofthe material constituting the flywheel cannot withstand the stress resulting from the centrifugal force. The maximum stress acting on the flywheeldepends on its geometry, specific density ρ, and rotational speed. The maximum benefit can be obtained by adopting flywheel materials that have a maximum ratio of σ/ρ. Notice that if the speed energy is proportional to the ratio of σ/ρ. Table 10.4 summarizes thecharacteristics of some composite materials for ultrahigh-speed flywheels. A constant-stress principle maybe employed for the design of ultrahigh speedflywheels. To achieve the maximum energy storage, every element inthe rotor should be stressed equally to its maximum limit.

Due to the extremely high rotating speed and in order to reduce the aerodynamic loss and frictional loss, the housing inside the flywheel in spinning is always highly vacuumed, and noncontact, magnetic bearings are employed. The electric machine is one of the most important components in the flywheel system, since it has critical impact on the performance of the system. At present, permanent magnet (PM) brushless DC motors are usually accepted in the flywheel system. Apart from possessing high power density and high efficiency, the PM brushless DC motor has a unique advantage that no heat is generated inside the PM rotor, which is particularly essential for the rotor to work in a vacuum environment to minimize the windage loss A switched reluctance machine (SRM) is also a very promising candidate for the application in a flywheel system. SRM has a very simple structure and can operate efficiently at very high speed. In addition, SRM presents a large extended constant power speed region, which allows more energy in the flywheel that can be delivered. In this extended speed region, only the machine excitation flux is varied, and is easily realized. On the contrary, the PM brushless motor shows some difficulty in weakening the field flux induced by the PM. In contrast to applying the ultrahigh-speed flywheel for energy storage in stationary plants, its application to EVs and HEVs suffers from two specific problems. First, gyroscopic forces occur whenever a vehicle departs from its straight-line course, such as in turning and in pitching upward or downward

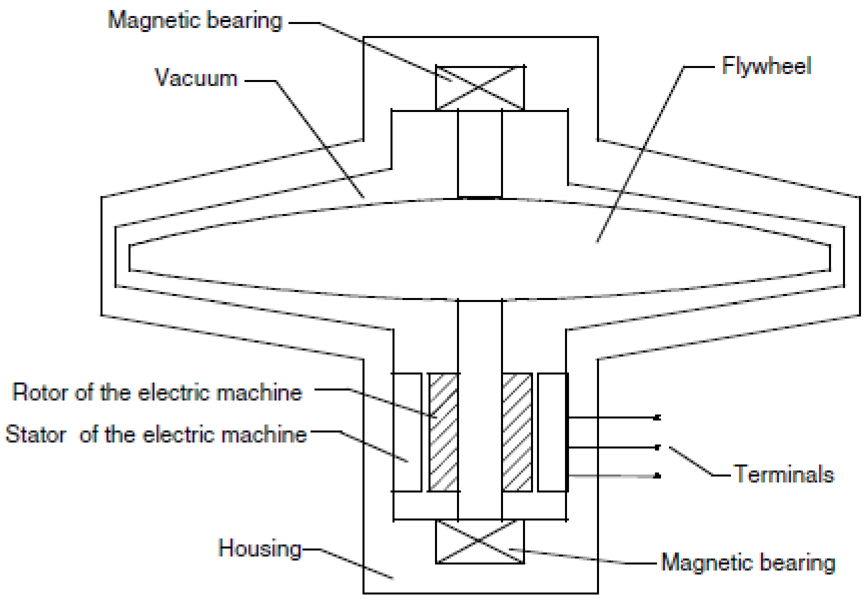


FIGURE 5.20. Basic structure of a typical flywheel system

from road grades. These forces essentially reduce the manoeuvrability of the vehicle. Secondly, if the flywheel is damaged, its stored energy in mechanical form will be released in a very short period of time. The corresponding power released will be very high, which can cause severe damage to the vehicle. For example, if a 1-kWh flywheel breaks apart in 1 to 5 sec, it will generate a huge power output of 720 to 3600 kW. Thus, containment in case of failure is presently the most significant obstacle to implementing the ultra-high speed flywheel in EVs and HEVs.

The simplest way to reduce the gyroscopic forces is to use multiple smaller flywheels. By operating them in apair (one half spinning in one direction and another in the opposite direction), the net gyroscopic effect becomes theoretically zero. Practically, it still has some problems related to the distribution and coordination of these flywheels. Also, the overall specific energy and specific power of all flywheels may be smaller than a single one. Similarly, the simplest way to minimize the damage due to the breakage ofthe ultrahigh-speed flywheel is to adopt multiple small modules, but

specific power. Recently, a new failure containment has beenproposed. Instead of diminishing the thickness of the rotor's rim to zerobased on the maximum stress principle, the rim thickness is purposely enlarged. Hence, the neck area just before the rim (virtually a mechanical fuse) will break first at the instant that the rotor suffers from a failure. Dueto the use of this mechanical fuse, only the mechanical energy stored in therim needs to be released or dissipated in the casing upon failure.6Many companies and research agencies have engaged in the development ofultrahigh-speedflywheels as the energy storages of EVs and HEVs, such as Lawrence Livermore National Laboratory (LLNL) in the U.S., Ashman Technology, AVCON, Northrop Grumman, Power R&D, Rocketdyne/Rockwell Trinity Flywheel US Flywheel Systems, Power Centre at UT Austin, etc. However, technologies of ultrahigh-speed flywheel are still in their infancy. Typically, the whole ultrahigh-speed flywheel system can achieve a specific energy of 10 to 150 Wh/kg and a specific power of 2 to 10 kW. LLIL has built prototype (20 cm diameter and 30 cm height) that can achieve 60,000 rpm,1 kWh, and 100 kW.

HYBRIDIZATION OF ENERGY STORAGES:

The hybridization of energy storage is to combine two or more energy storages together so that the advantages of each one can be brought out and the disadvantages can be compensated by others. For instance, the hybridization of a chemical battery with an ultracapacitor can overcome such problems as low specific power of electrochemical batteries and low specific energy of ultracapacitors, thereforeachieving high specific energy and high specific power Basically, the hybridized energy storage consists of two basic energy storages: one with high specific energy and the other with high specific power. The basic operation of this system is illustrated in Figure 10.18. In high power demand operations, such as acceleration and hill climbing, both basic energy storages deliver their power to the load as shown in Figure (a). On the other hand, in low power demand operation, such as constant speed cruising operations, the high specific energy storage will deliver its power to the load and charge the high specific power storage to recover its charge lost during high power demand operation, as shown in Figure (b). In regenerative braking operations, the peak power willbe absorbed by the high specific power storage, and only a limited part is absorbed by the high specific energy storage. In this way,the whole system would be much smaller in weight and size than if any one of them alone was theenergy storage.

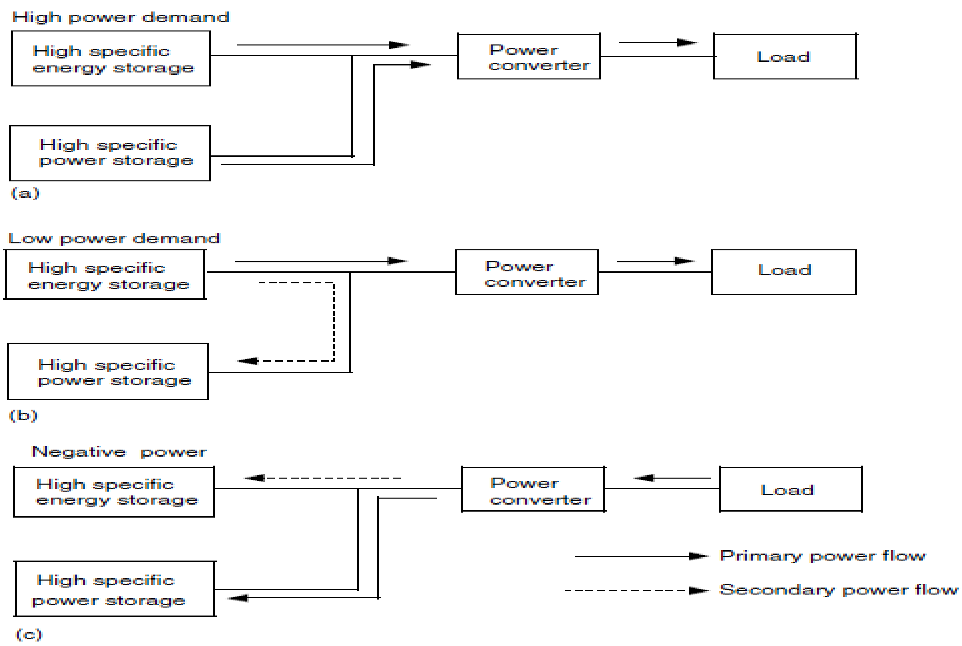


FIGURE 5.21. Concept of a hybrid energy storage operation

Based on the available technologies of various energy storages, there are several viable hybridization schemes for EVs and HEVs, typically, battery and battery hybrids, and battery and ultracapacitor hybrids. The latter is more natural since the ultracapacitor can offer much higher power than batteries, and it collaborates with various batteries to form the battery and ultracapacitor hybrids. During hybridization, the simplest way is to connect the ultracapacitors to the batteries directly and in parallel, as shown in Figure 5.22

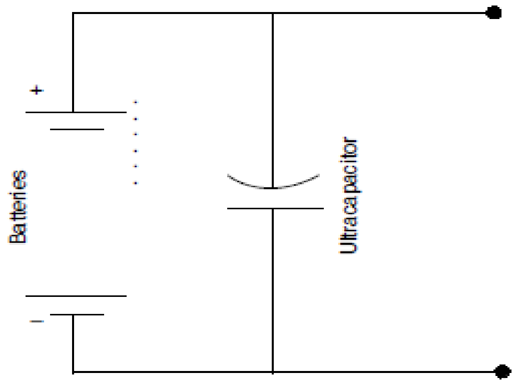


FIGURE 5.22. Direct and parallel connection of batteries and ultra capacitors

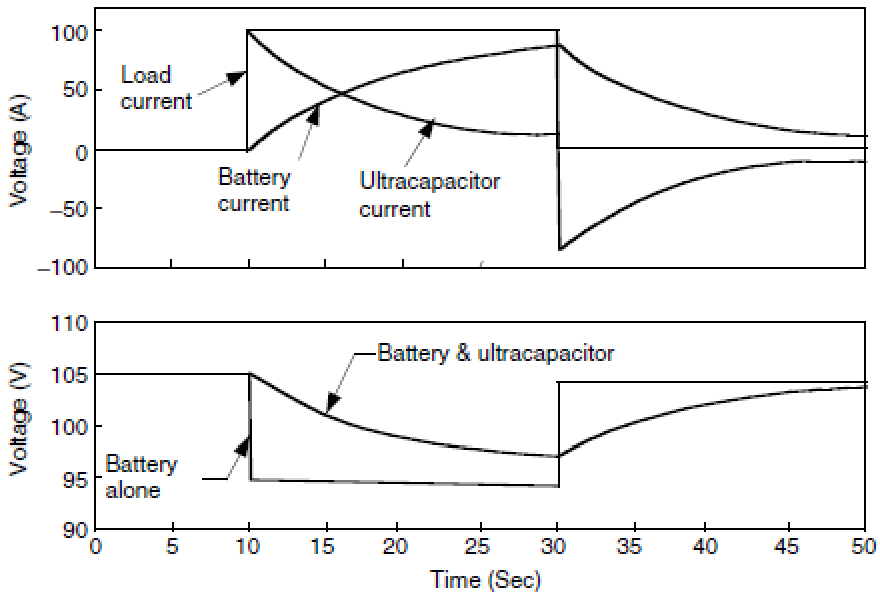


FIGURE 5.23. Variation of battery and ultra capacitor currents and voltages with a step current output change

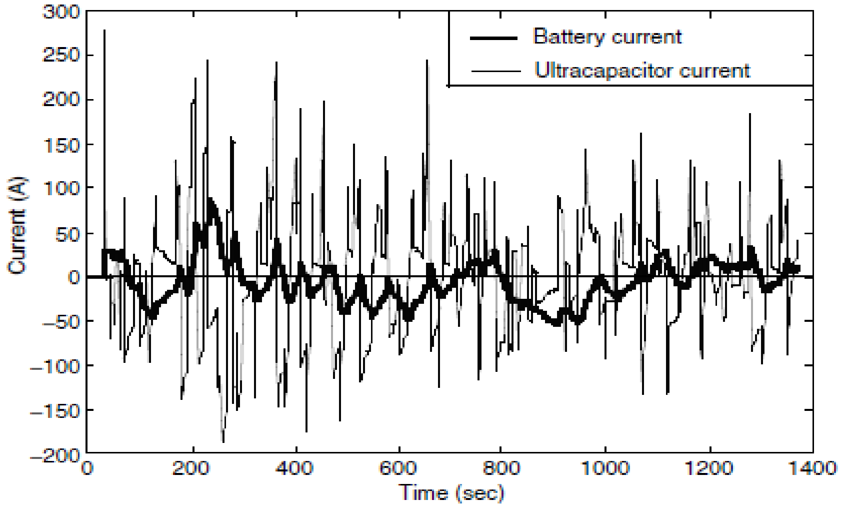


FIGURE5.24: Battery and ultra capacitor currents during operation of HEV in an FTP 75 urban

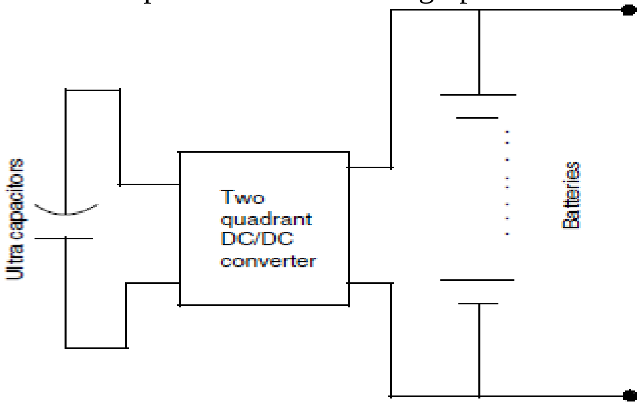


FIGURE 5.25. Actively controlled hybrid battery/ultracapacitor energy storage

In this configuration, the ultracapacitors simply act as a current filter, which can significantly level the peak current of the batteries and reduce the battery voltage drop as shown in Figure 10.20 and Figure 4.25. The major disadvantages of this configuration are that the power flow cannot be actively controlled andthe ultracapacitor energy cannot be fully used. Figure4.25 shows a configuration in which a two-quadrant DC/DC converter is placed between the batteries and ultracapacitors. This design allows the batteries and the ultracapacitors to have a different voltage, the power flow between them can be actively controlled, and the energy in the ultracapacitors can be fully used. In the long term, an ultrahigh-speed flywheel would replace the batteries in hybrid energy storage to obtain a highefficiency,compact, and long-life storage system for EVs and HEVs.