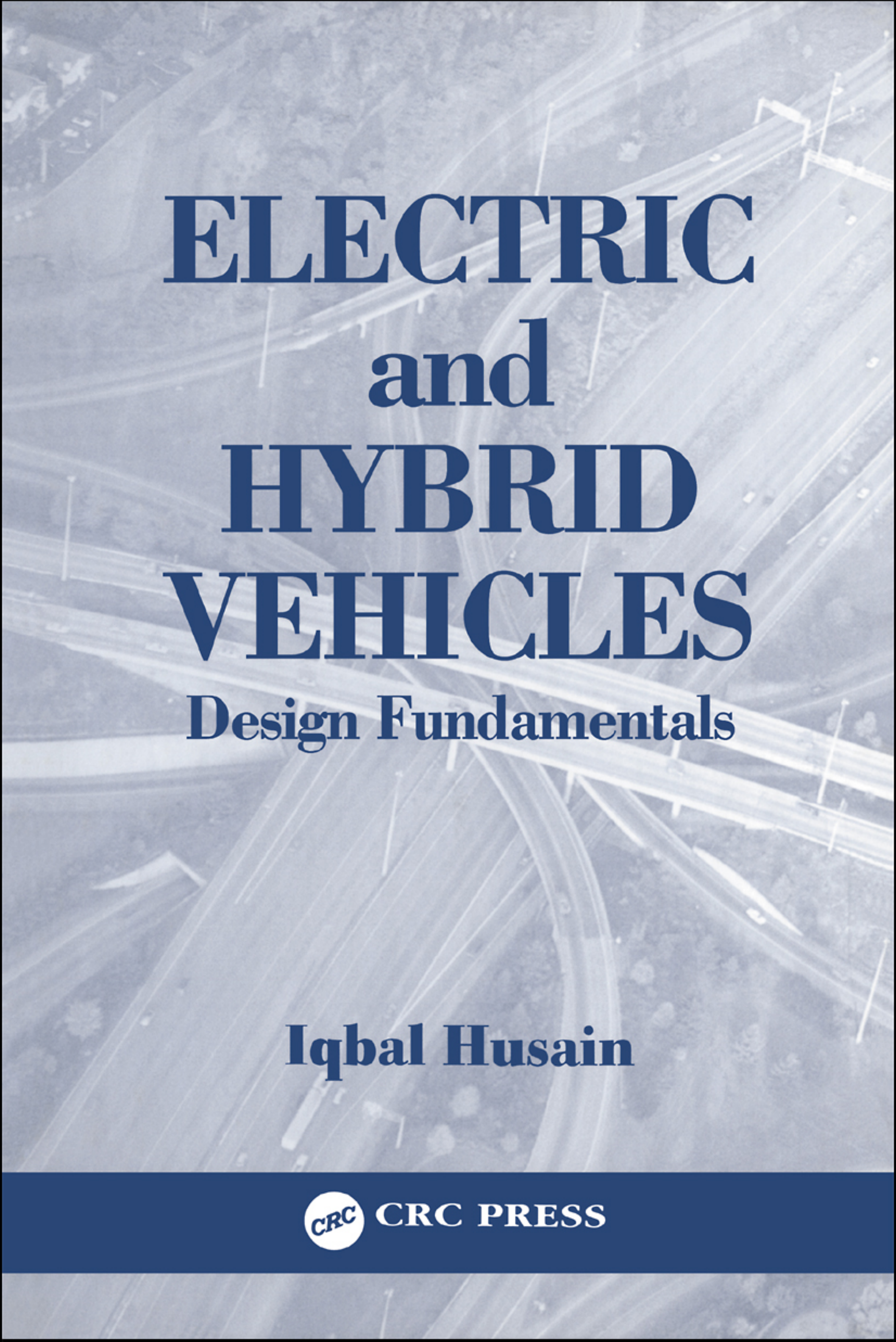

ELECTRIC and HYBRID VEHICLES

Design Fundamentals

Iqbal Husain

CRC PRESS

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Preface

The book presents a comprehensive systems-level perspective of electric and hybrid electric vehicles, with emphasis on technical details, mathematical relationships, and basic design guidelines. The electric vehicle is an excellent example of an electro-mechanical and electrochemical system that is technically challenging as well as highly intriguing to engineering students. With a good balance between technical details, design equations, numerical examples, and case studies, the subject matter presents an ideal platform for educating today's engineers with a systems-level perspective—a concept that served as the primary motivation to develop this textbook on electric and hybrid vehicles.

Automobiles are an integral part of our everyday lives. Yet, conventional automobiles are the major cause of urban pollution in the 21st century. The world will eventually encounter an acute energy crisis if we do not focus on alternative energy sources and transportation modes. Current environmental concerns are driving the international community toward developing low-emission (hybrid electric) and zero-emission (electric) vehicles to replace conventional internal combustion engine vehicles. The subject of electric and hybrid vehicles is becoming increasingly important, with intense drive from the government, environmental activists, and associated industries to advance the technology. Several auto industries have already started marketing electric and hybrid electric vehicles. Furthermore, the next generation of conventional automobiles will experience a gradual replacement of the hydraulically driven actuators by electrically driven actuators. The trend clearly suggests that there is a need to adequately educate the engineers of today and tomorrow with the technical details of electric and hybrid vehicles and the electrical units used within an automobile. While there are ample books on electric and hybrid vehicles available, providing narrative descriptions of the components of vehicles, and numerous technical papers published with research results, none covers the technical aspects and mathematical relationships in a comprehensive way to educate a junior-or senior-level or a beginning graduate-level engineering student.

This book will serve to educate students on aspects of electric vehicles, which will generate interest to support the development and use of electric vehicles. The book will also serve as a reference for a working engineer dealing with design and improvement of electric and hybrid vehicles. Discussion on most topics has been limited to fundamentals only in the book, considering the wide spectrum of technical aspects related to an electric and hybrid vehicle system. Appropriate references are given to direct the readers toward details on topics for further reading. The intent of the book is not to present the wide spectrum of the state of the art in electric and hybrid electric vehicles, but rather to prepare the student with the necessary background to evaluate the technology.

The book, starting with a historical background on electric vehicles, will describe the system components, the laws of physics that govern vehicle motion, the mathematical relationships within a component and between components, the energy sources, and the design of components to meet the specifications for the complete vehicle system. After the introduction of the systems concept in Chapter 1, Chapter 2 focuses on the laws of physics to define the force characteristics of ground vehicles. The design guidelines for the power and energy requirements based on design specifications are established in this chapter.

The flow of the book shifts from mechanical to chemical concepts, when energy sources are introduced in Chapter 3, and the topic is continued in Chapter 4, with alternatives to battery power. The two major contenders for energy sources in road vehicles are batteries and fuel cells, which are described in detail, while other types of energy sources are mentioned briefly.

Chapters 5 through 8 are mostly electrical, where electric motors for propulsion and power electronic drives for the motors are presented. The DC machines and AC induction machines suitable for propulsion are discussed in Chapter 5, while the permanent magnet and switched reluctance machines are presented in Chapter 6. Chapters 7 and 8 are dedicated to the power-electronics-based motor drives for electric propulsion units. Vehicle system control fundamentals are also addressed in these two chapters.

Mechanical and electrical concepts merge in Chapters 9 and 10. Drivetrain components, including the transmission for electric vehicles, are presented in Chapter 9, while Chapter 10 discusses the drivetrain and the design basics of hybrid electric vehicles.

This book is intended to be used as a textbook for an undergraduate or beginning graduate-level course on electric and hybrid electric vehicles. The ten chapters of the book can be comfortably covered in a three-credit, one-semester or a four-credit, one-quarter course. Although the materials in this book are biased toward the electrical units, it is still multidisciplinary enough to teach electrical, mechanical, and chemical engineers all in one course, utilizing the systems approach. In that case, parts of the electrical details appearing in Chapters 5 though 8 should be skipped. This type of course will certainly mimic the real situation existing in many industries, where multidisciplinary engineers work together to devise a system and develop a product. The equations developed can be utilized to develop a system-level modeling and simulation tool for electric and hybrid electric vehicles on a suitable platform, such as MATLAB/SIMULINK. The book has several worked-out problems and many exercises that are suitable to convey the concept to students through numerical examples.

Author

Dr. Iqbal Husain is an Associate Professor in the Department of Electrical and Computer Engineering at the University of Akron, Akron, Ohio, where he is engaged in teaching and research. After earning his Ph.D. degree in Electrical Engineering from Texas A&M University, College Station, in 1993, Dr. Husain worked as a lecturer at Texas A&M University and as a consulting engineer for Delco Chassis at Dayton, Ohio, prior to joining the University of Akron in 1994. He worked as a summer researcher for Wright Patterson AFB Laboratories in 1996 and 1997. More recently, he taught at Oregon State University as a short-term visiting faculty member. His research interests are in the areas of control and modeling of electrical drives, design of electric machines, and development of power conditioning circuits. He has worked extensively in the development of switched reluctance motor drives, including sensorless controllers. He also worked as a consultant for Delphi Automotive Systems, Goodyear Tire and Rubber Industry, ITT Automotive, Delphi Chassis, Graphic Enterprises, and Hy-Tech Inc.

Dr. Husain received the 2000 IEEE Third Millenium Medal, the 1998 IEEE-IAS Outstanding Young Member award, and the NSF CAREER Award in 1997. He is also the recipient of three IEEE Industry Applications Society prize paper awards.

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I am extremely thankful to Dr. Robert Pasch of Oregon State University and Dr. Richard Gross of the University of Akron, both from Mechanical Engineering Departments, who educated and helped me in writing about the mechanical-related topics. I would also like to thank the reviewers who provided extremely useful suggestions that helped enhance the quality of the book. The reviewers included Prof. Alan K.Wallace and Prof. Annette von Jouanne, Department of Electrical and Computer Engineering, Oregon State University; Prof. M. Ehsani, Department of Electrical Engineering, Texas A&M University; Prof. Longya Xu, Department of Electrical and Computer Engineering, Ohio State University; Prof. Pragassen Pillay, Department of Electrical and Computer Engineering, Clarkson University; Dr. Khwaja M.Rahman, General Motors ATV; and Dr. Alexander Yokochi, Department of Chemistry, Oregon State University.

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Iqbal Husain
Akron, Ohio

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1

Introduction to Electric Vehicles

Environmental as well as economical issues provide a compelling impetus to develop clean, efficient, and sustainable vehicles for urban transportation. Automobiles constitute an integral part of our everyday life, yet the exhaust emissions of conventional internal combustion (IC) engine vehicles are to blame for the major source of urban pollution that causes the greenhouse effect leading to global warming.[1] The dependence on oil as the sole source of energy for passenger vehicles has economical and political implications, and the crisis will inevitably become acute as the oil reserve of the world diminishes. The number of automobiles on our planet doubled to about a billion or so in the last 10 years. The increasing number of automobiles being introduced on the road every year is only adding to the pollution problem. There is also an economic factor inherent in the poor energy conversion efficiency of combustion engines. Although the number for alternative electric vehicles is not significantly higher when efficiency is evaluated on the basis of conversion from crude oil to traction effort at the wheels, it makes a difference. Emission due to power generation at localized plants is much easier to regulate than that emanating from IC engine vehicles (ICEV) that are individually maintained and scattered. People dwelling in cities are not exposed to power plant related emissions, because these are mostly located outside urban areas. Electric vehicles (EV) enabled by high-efficiency electric motors and controllers and powered by alternative energy sources provide the means for a clean, efficient, and environmentally friendly urban transportation system. Electric vehicles have no emission, having the potential to curb the pollution problem in an efficient way. Consequently, EVs are the only zero-emission vehicles possible.

Electric vehicles paved their way into public use as early as the middle of the 19th century, even before the introduction of gasoline-powered vehicles.[2] In the year 1900, 4200 automobiles were sold, out of which 40% were steam powered, 38% were electric powered, and 22% were gasoline powered. However, the invention of the starter motor, improvements in mass production technology of gas-powered vehicles, and inconvenience in battery charging led to the disappearance of the EV in the early 1900s. However, environmental issues and the unpleasant dependence on oil led to the resurgence of interest in EVs in the 1960s. Growth in the enabling technologies added to environmental and economic concerns over the next several decades, increasing the demand for investing in research and development for EVs. Interest and research in EVs soared in the 1990s, with the major automobile manufacturers embarking on plans for introducing their own electric or hybrid electric vehicles. The trend increases today, with EVs serving as zero-emission vehicles, and hybrid electric vehicles already filling in for ultralow-emission vehicles.

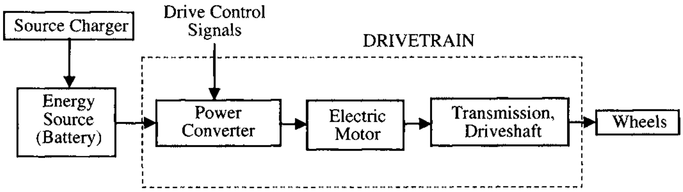

FIGURE 1.1 Top-level perspective of an EV system.

1.1
EV SYSTEM

An EV has the following two features:

1. The energy source is portable and chemical or electromechanical in nature.
2. Traction effort is supplied only by an electric motor.

Figure 1.1 shows an EV system driven by a portable energy source. The electromechanical energy conversion linkage system between the vehicle energy source and the wheels is the drivetrain of the vehicle. The drivetrain has electrical as well as mechanical components.

1.1.1
COMPONENTS OF AN EV

The primary components of an EV system are the motor, controller, power source, and transmission. The detailed structure of an EV system and the interaction among its various components are shown in Figure 1.2. Figure 1.2 also shows the choices available for each of the subsystem level components. Electrochemical batteries have been the traditional source of energy in EVs. Lead-acid batteries have been the primary choice, because of their well-developed technology and lower cost, although promising new battery technologies are being tested in many prototype vehicles. The batteries need a charger to restore the stored energy level once its available energy is near depletion due to usage. Alternative energy sources are also being developed for

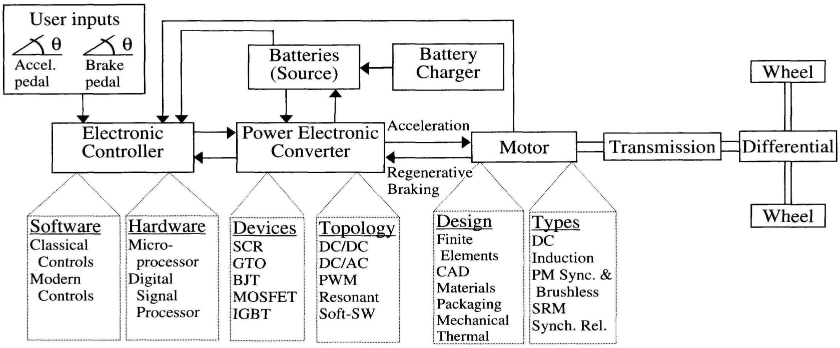

FIGURE 1.2 Major electrical components and choices for an EV system.

zero-emission vehicles. The limited range problem of battery-driven EVs prompted the search for alternative energy sources, such as fuel cells and flywheels. Prototypes have been developed with fuel cells, while production vehicles will emerge in the near future.

The majority of electric vehicles developed so far are based on DC machines, induction machines, or permanent magnet machines. The disadvantages of DC machines pushed EV developers to look into various types of AC machines. The maintenance-free, low-cost induction machines became an attractive alternative to many developers. However, high-speed operation of induction machines is only possible with a penalty in size and weight. Excellent performance together with high-power density features of permanent magnet machines make them an attractive solution for EV applications, although the cost of permanent magnets can become prohibitive. High-power density and a potentially low production cost of switched reluctance machines make them ideally suited for EV applications. However, the acoustic noise problem has so far been a deterrent for the use of switched reluctance machines in EVs. The electric motor design includes not only electromagnetic aspects of the machine but also thermal and mechanical considerations. The motor design tasks of today are supported by finite element studies and various computer-aided design tools, making the design process highly efficient.

The electric motor is driven by a power-electronics-based power-processing unit that converts the fixed DC voltage available from the source into a variable voltage, variable frequency source controlled to maintain the desired operating point of the vehicle. The power electronics circuit comprised of power semiconductor devices saw tremendous development over the past 3 decades. The enabling technology of power electronics is a key driving force in developing efficient and high-performance power-train units for EVs. High-power devices in compact packaging are available today, enabling the development of lightweight and efficient power-processing units known as power electronic motor drives. Advances in power solid state devices and very large-scale integration (VLSI) technology are responsible for the development of efficient and compact power electronics circuits. The developments in high-speed digital signal processors or microprocessors enable complex control algorithm implementation with a high degree of accuracy. The controller includes algorithms for the motor drive in the inner loop as well as system-level control in the outer loop.

1.2
EV HISTORY

The history of EVs is interesting. It includes the insurgence of EVs following the discovery of electricity and the means of electromechanical energy conversion and later being overtaken by gasoline-powered vehicles. People digressed from the environmentally friendly mode of transportation due to lack of technology in the early years, but they are again focused on the correct track today.

1.2.1
THE EARLY YEARS

Prior to the 1830s, the means of transportation was only through steam power, because the laws of electromagnetic induction, and consequently, electric motors and generators, were yet to be discovered. Faraday demonstrated the principle of the electric motor as early as in 1820 through a wire rod carrying electric current and a magnet, but in 1831 he discovered the laws of electromagnetic induction that enabled the development and demonstration of the electric motors and generators essential for electric transportation. The history of EVs in those early years up to its peak period in the early 1900s is summarized below:

- Pre-830—Steam-powered transportation
- 1831—Faraday’s law, and shortly thereafter, invention of DC motor
- 1834—Nonrechargeable battery-powered electric car used on a short track
- 1851—Nonrechargeable 19 mph electric car
- 1859—Development of lead storage battery
- 1874—Battery-powered carriage
- Early 1870s-Electricity produced by dynamo-generators
- 1885—Gasoline-powered tricycle car
- 1900—4200 automobiles sold:
    - 40% steam powered
    - 38% electric powered
    - 22% gasoline powered

The specifications of some of the early EVs are given below:

- 1897—French Krieger Co. EV: weight, 2230 lb; top speed, 15 mph; range, 50 mi/charge
- 1900—French B.G.S. Co. EV: top speed, 40 mph; range, 100 mi/charge
- 1912—34,000 EVs registered; EVs outnumber gas-powered vehicles 2-to-1
- 1915—Woods EV: top speed, 40 mph; range, 100 mi/charge
- 1915—Lansden EV: weight, 2460 Ib, top speed, 93 mi/charge, capacity, 1 ton payload
- 1920s—EVs disappear, and ICEVs become predominant

The factors that led to the disappearance of EV after its short period of success were as follows:

1. Invention of starter motor in 1911 made gas vehicles easier to start.
2. Improvements in mass production of Henry T (gas-powered car) vehicles sold for \$260 in 1925, compared to \$850 in 1909. EVs were more expensive.
3. Rural areas had limited access to electricity to charge batteries, whereas gasoline could be sold in those areas.

1.2.2
1960s

Electric vehicles started to resurge in the 1960s, primarily due to environmental hazards being caused by the emissions of ICEVs. The major ICEV manufacturers, General Motors (GM) and Ford, became involved in EV research and development. General Motors started a \$15 million program that culminated in the vehicles called Electrovair and Electrovan. The components and specifications of two Electrovair vehicles (Electrovair I (1964) and Electrovair II (1966) by GM) are given below.

Systems and characteristics:
Motor—three-phase induction motor, 115 hp, 13,000 rev/m
Battery—silver-zinc (Ag-Zn), 512 V, 680 lb
Motor drive—DC-to-AC inverter using a silicon-controlled rectifier (SCR)
Top speed—80 mi/h
Range—40 to 80 miles
Acceleration—0–60 mi/h in 15.6 s
Vehicle weight—3400 lb

The Electrovair utilized the Chevy Corvair body and chassis. Among the positive features was the acceleration performance that was comparable to the ICEV Corvair. The major disadvantage of the vehicle was the silver-zinc (Ag-Zn) battery pack that was too expensive and heavy, with a short cycle life and a long recharge time.

An additional factor in the 1960s that provided the impetus for EV development included “The Great Electric Car Race” cross-country competition (3300 miles) between an EV from Caltech and an EV from MIT in August 1968. The race generated great public interest in EVs and provided an extensive road test of the EV technology. However, technology of the 1960s was not mature enough to produce a commercially viable EV.

1.2.3
1970s

The scenario turned in favor of EVs in the early 1970s, as gasoline prices increased dramatically due to an energy crisis. The Arab oil embargo of 1973 increased demands for alternate energy sources, which led to immense interest in EVs. It became highly desirable to be less dependent on foreign oil as a nation. In 1975, 352 electric vans were delivered to the U.S. Postal Service for testing. In 1976, Congress enacted Public Law 94–413, the *Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976*. This act authorized a federal program to promote electric and hybrid vehicle technologies and to demonstrate the commercial feasibility of EVs. The Department of Energy (DOE) standardized EV performance, which is summarized in Table 1.1.

The case study of a GM EV of the 1970s is as follows:

System and characteristics:
  Motor—separately excited DC, 34 hp, 2400 rev/m
  Battery pack—Ni-Zn, 120 V, 735 lb
  Auxiliary battery—Ni-Zn, 14 V
  Motor drive—armature DC chopper using SCRs; field DC chopper using bipolar junction transistors (BJTs)
  Top speed—60 mi/h
  Range—60–80 miles
  Acceleration—0–55 mi/h in 27 s

TABLE 1.1
EV Performance Standardization of 1976

Category	Personal Use	Commercial Use
Acceleration from 0 to 50 km/h	<15 s	<15 s
Gradability at 25 km/h	10%	10%
Gradability at 20 km/h	20%	20%
Forward speed for 5 min	80 km/h	70 km/h
Range:		
Electric	50 km, C cycle	50 km, B cycle
Hybrid	200 km, C cycle	200 km, B cycle
Nonelectrical energy consumption in hybrid vehicles (consumption of nonelectrical energy must be less than 75% of the total energy consumed)	<1.3 MJ/km	<9.8 MJ/km
Recharge time from 80% discharge	<10 h	<10 h

The vehicle utilized a modified Chevy Chevette chassis and body. This EV was used mainly as a test bed for Ni-Zn batteries. Over 35,500 miles of on-road testing proved that this EV was sufficiently road worthy.

1.2.4
1980s AND 1990s

In the 1980s and the 1990s, there were tremendous developments of high-power, high-frequency semiconductor switches, along with the microprocessor revolution, which led to improved power converter design to drive the electric motors efficiently. Also in this period, factors contributed to the development of magnetic bearings used in flywheel energy storage systems, although these are not utilized in mainstream EV development projects.

In the last 2 decades, legislative mandates pushed the cause for zero-emission vehicles. Legislation passed by the California Air Resources Board in 1990 stated that by 1998 2% of vehicles should be zero-emission vehicles (ZEV) for each automotive company selling more than 35,000 vehicles. The percentages were to increase to 5% by 2001 and to 10% by 2003. The legislation provided a tremendous impetus to develop EVs by the major automotive manufacturers. The legislation was relaxed somewhat later due to practical limitations and the inability of the manufacturers to meet the 1998 and 2001 requirements. The mandate now stands that 4% of all vehicles sold should be ZEV by 2003, and an additional 6% of the sales must be made up of ZEVs and partial ZEVs, which would require GM to sell about 14,000 EVs in California.

Motivated by the pollution concern and potential energy crisis, government agencies, federal laboratories, and the major automotive manufacturers launched a number of initiatives to push for ZEVs. The partnership for next-generation vehicles (PNGV) is such an initiative (established in 1993), which is a partnership of federal laboratories and automotive industries to promote and develop electric and hybrid electric vehicles. The most recent initiative by the DOE and the automotive industries is the Freedom CAR initiative.

The trends in EV developments in recent years can be attributed to the following:

- High level of activity exists at the major automotive manufacturers.
- New independent manufacturers bring vigor.
- New prototypes are even better.
- High levels of activity overseas exist.
- There are high levels of hybrid vehicle activity.
- A boom in individual ICEV to EV conversions is ongoing.
- The fuel cell shows great promise in solving the battery range problem.

The case studies of two GM EVs of the 1990s are given below:

1. GM Impact 3 (1993 completed):
    a. Based on 1990 Impact displayed at the Los Angeles auto show
    b. Two-passenger, two-door coupe, street legal and safe
    c. Initially, 12 built for testing; 50 built by 1995 to be evaluated by 1000 potential customers
    d. System and characteristics:
        i. Motor—one, three-phase induction motor; 137 hp; 12,000 rev/m
        ii. Battery pack—lead-acid (26), 12 V batteries connected in series (312 V), 869 lb
        iii. Motor drive—DC-to-AC inverter using insulated gate bipolar transistors (IGBTs)
        iv. Top speed—75 mph
        v. Range—90 miles on highway
        vi. Acceleration—0 to 60 miles in 8.5 s
        vii. Vehicle weight—2900 lb
    e. This vehicle was used as a test bed for mass production of EVs.
2. Saturn EVl
    a. Commercially available electric vehicle made by GM in 1995.
    b. Leased in California and Arizona for a total cost of about $30,000.
    c. System and characteristics:
        i. Motor—one, three-phase induction motor
        ii. Battery pack—lead-acid batteries

   iii. Motor drive—DC-to-AC inverter using IGBTs
   iv. Top speed—75 mph
   v. Range—90 miles on highway, 70 miles in city
   vi. Acceleration—0 to 60 mi in 8.5 s

d. Power consumption:

   i. 30 kW-h/100 mi in city, 25 kW-h/100 mi on highway

e. This vehicle was also used as a test bed for mass production of EVs.

1.2.5

RECENT EVs AND HEVs

All of the major automotive manufacturers have production EVs, many of which are available for sale or lease to the general public. The status of these vehicle programs changes rapidly, with manufacturers suspending production frequently due to the small existing market demand of such vehicles. Examples of production EVs which are or until recently have been available are GM EVl, Ford Think City, Toyota RAV4, Nissan Hypermini, and Peugeot 106 Electric. There are also many prototype and experimental EVs being developed by the major automotive manufacturers. Most of these vehicles use AC induction motors or PM synchronous motors. Also, interestingly, almost all of these vehicles use battery technology other than the lead-acid battery pack. The list of EVs in production and under development is extensive, and readers are referred to the literature[3,4] for the details of many of these vehicles.

The manufacturers of EVs in the 1990s realized that their significant research and development efforts on ZEV technologies were hindered by unsuitable battery technologies. A number of auto industries started developing hybrid electric vehicles (HEVs) to overcome the battery and range problem of pure electric vehicles. The Japanese auto industries lead this trend with Toyota, Honda, and Nissan already marketing their Prius, Insight, and Tino model hybrids. The hybrid vehicles use an electric motor and an internal combustion engine and, thus, do not solve the pollution problem, although it does mitigate it. It is perceived by many that the hybrids, with their multiple propulsion units and control complexities, are not economically viable in the long run, although currently a number of commercial, prototype, and experimental hybrid vehicle models are available from almost all of the major automotive industries around the world. Toyota, Honda, and Nissan are marketing the hybrid vehicles well below the production cost, with significant subsidy and incentive from the government. However, the cost of HEVs and EVs are expected to be high until production volume increases significantly.

Fuel cell electric vehicles (FCEV) can be a viable alternative to battery electric vehicles, serving as zero-emission vehicles without the range problem. Toyota is

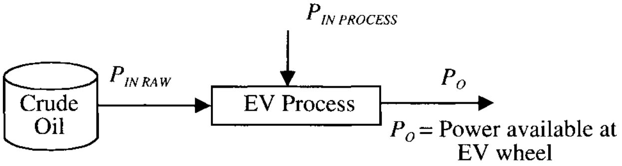

FIGURE 1.3 EV process from crude oil to power at the wheels.

leading the way with FCEV, announcing the availability of its FCEV in 2003. The Toyota FCEV is based on the Toyota RAV4 model.

1.3
EV ADVANTAGES

The relative advantages and disadvantages of an EV over an ICEV can be better appreciated from a comparison of the two on the bases of efficiency, pollution, cost, and dependence on oil. The comparison must be executed with care, ensuring fairness to both systems.

1.3.1
EFFICIENCY COMPARISON

To evaluate the efficiencies of EV and ICEV on level ground, the complete process in both systems starting from crude oil to power available at the wheels must be considered. The EV process starts not at the vehicles, but at the source of raw power whose conversion efficiency must be considered to calculate the overall efficiency of electric vehicles. The power input P_{IN} to the EV comes from two sources—the stored power source and the applied power source. Stored power is available during the process from an energy storage device. The power delivered by a battery through electrochemical reaction on demand or the power extracted from a piece of coal by burning it are examples of stored power. Applied power is obtained indirectly from raw materials. Electricity generated from crude oil and delivered to an electric car for battery charging is an example of applied power. Applied power is labeled as $P_{IN\ AW}$ while stored power is designated as $P_{IN\ PROCESS}$ in Figure 1.3. Therefore, we have the following:

$$P_{IN} = P_{IN\ PROCESS} + P_{IN\ RAW}$$

The complete EV process can be broken down into its constituent stages involving a chain of events responsible for power generation, transmission, and usage, as shown in Figure 1.4. Raw power from the applied source is fed to the system only at the first stage, although stored power can be added in each stage. Each stage has its efficiency based on total input to that stage and output delivered to the following stage. For example, the efficiency of the first stage based on the input and output shown in Figure 1.4 is

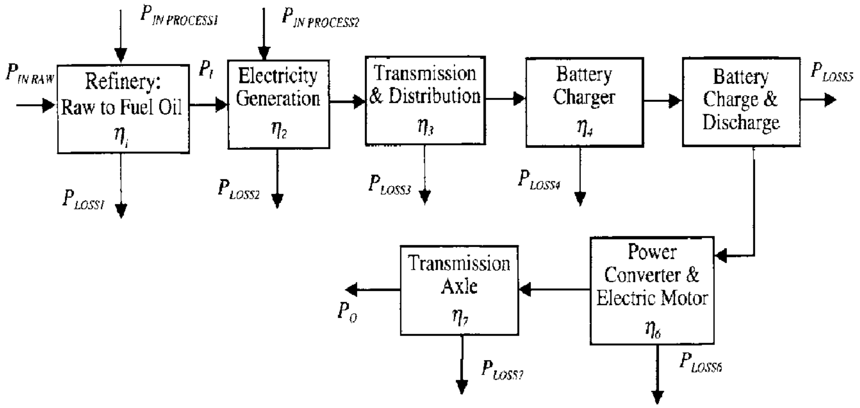

FIGURE 1.4 The complete EV process broken into stages.

$$\eta_1 = \frac{P_1}{P_{IN\,RAW} + P_{IN\,PROCESS1}}$$

The efficiency of each stage must be calculated from input-output power considerations, although the efficiency may vary widely, depending on the technology being used. Finally, overall efficiency can be calculated by multiplying the efficiencies of the individual stages. The overall efficiency of the EV system shown in Figure 1.4 is

$$\eta_{EV} = \frac{P_0}{P_{IN}} = \frac{P_0}{P_0 + \sum_{i=1}^{7} P_{LOSSi}} = \eta_1\eta_2\eta_3\eta_4\eta_5\eta_6\eta_7$$

The overall ICEV process is shown in Figure 1.5, while the process details are illustrated in Figure 1.6. Starting from the conversion of crude oil to fuel oil in the refinery, the ICEV process includes the transmission of fuel oil from refinery to gas stations, power conversion in the internal combustion engine of the vehicle, and power transfer from the engine to the wheels through the transmission before it is available at the wheels. The efficiency of the ICEV process is the product of the efficiencies of the individual stages indicated in Figure 1.6 and is given by

$$\eta_{ICEV} = \eta_1\eta_2\eta_3\eta_4$$

A sample comparison of EV and ICEV process efficiencies based on the diagrams of Figure 1.4 and 1.6 is given in Table 1.2. Representative numbers have been used for the energy conversion stages in each process to convey a general idea of the efficiencies of the two systems. From Table 1.2, it can be claimed that the overall efficiency of an EV is comparable to the overall efficiency of an ICEV.

TABLE 1.2 EV and ICEV Efficiencies from Crude Oil to Traction Effort

	Efficiency (%)			**Efficiency (%)**	
ICEV	**Max.**	**Min.**	**EV**	**Max.**	**Min.**
Crude oil			Crude oil		
Refinery (petroleum)	90	85	Refinery (fuel oil)	97	95
Distribution to fuel tank	99	95	Electricity generation	40	33
Engine	22	20	Transmission to wall outlet	92	90
Transmission/axle	98	95	Battery charger	90	85
Wheels			Battery (lead/acid)	75	75
			Motor/controller	85	80
			Transmission/axle	98	95
			Wheels		
Overall efficiency (crude oil to wheels)	19	15	Overall efficiency (crude oil to wheels)	20	14

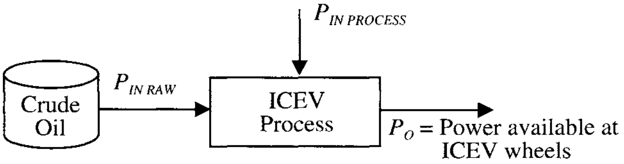

FIGURE 1.5 ICEV process from crude oil to power at the wheels.

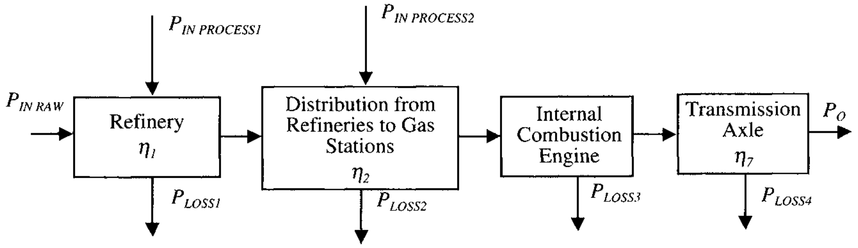

FIGURE 1.6 The complete ICEV process broken into stages.

1.3.2
POLLUTION COMPARISON

Transportation accounts for one third of all energy usage, making it the leading cause of environmental pollution through carbon emissions.[5] The DOE projected that if 10% of automobiles nationwide were zero-emission vehicles, regulated air pollutants would be cut by 1,000,000 tons per year, and 60,000,000 tons of green-house carbon dioxide gas would be eliminated. With 100% electrification, i.e., every ICEV replaced by an EV, the following was claimed:

- Carbon dioxide in air, which is linked to global warming, would be cut in half.
- Nitrogen oxides (a greenhouse gas causing global warming) would be cut slightly, depending on government-regulated utility emission standards.
- Sulfur dioxide, which is linked to acid rain, would increase slightly.
- Waste oil dumping would decrease, because EVs do not require crankcase oil.
- EVs reduce noise pollution, because they are quieter than ICEVs.
- Thermal pollution by large power plants would increase with increased EV usage.

EVs will considerably reduce the major causes of smog, substantially eliminate ozone depletion, and reduce greenhouse gases. With stricter SO_2 power plant emission standards, EVs would have little impact on SO_2 levels. Pollution reduction is the driving force behind EV usage.

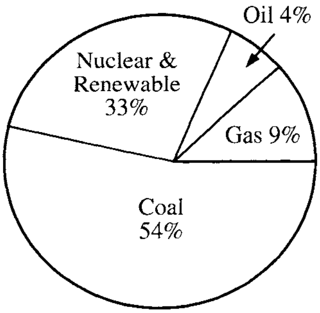

FIGURE 1.7 Electricity generation Piechart

1.3.3
CAPITAL AND OPERATING COST COMPARISON

The initial EV capital costs are higher than ICEV capital costs primarily due to the lack of mass production opportunities. However, EV capital costs are expected to decrease as volume increases. Capital costs of EVs easily exceed capital costs of ICEVs due to the cost of the battery. The power electronics stages are also expensive, although not at the same level as batteries. Total life cycle cost of an EV is projected to be less than that of a comparable ICEV. EVs are more reliable and will require less maintenance, giving a favorable bias over ICEV as far as operating cost is concerned.

1.3.4
U.S. DEPENDENCE ON FOREIGN OIL

The importance of searching for alternative energy sources cannot be overemphasized, and sooner or later, there will be another energy crisis if we, the people of the earth, do not reduce our dependence on oil. Today's industries, particularly the transportation industry, are heavily dependent on oil, the reserve of which will eventually deplete in the not so distant future. Today, about 42% of petroleum used for transportation in the United States is imported. An average ICEV in its lifetime uses 94 barrels of oil, based on 28 mi/gallon fuel consumption. On the other hand, an average EV uses two barrels of oil in its lifetime, based on 4 mi/kWh. The oil is used in the EV process during electricity generation, although only 4% of electricity generated is from oil. The energy sources for electricity generation are shown in the pie chart of Figure 1.7.

1.4

EV MARKET

We normally discuss the use of EVs for passenger and public transportation but tend to forget about their use as off-road vehicles in specialty applications, where range is not an issue. EVs have penetrated the market of off-road vehicles successfully over the years for clean air as well as for cost advantages. Examples of such applications are airport vehicles for passenger and ground support; recreational vehicles as in golf carts and for theme parks, plant operation vehicles like forklifts and loader trucks; vehicles for disabled persons; utility vehicles for ground transportation in closed but large compounds; etc. There are also EVs that run on tracks for material haulage in mines. There is potential for EV use for construction vehicles. The locomotives that run on tracks with electricity supplied from transmission lines are theoretically no different from other EVs, the major difference being in the way energy is fed for the propulsion motors.

Motivated by the growing concern about global pollution and the success of electric motor driven transportation in various areas, the interest is ever increasing for road EVs that can deliver the performance of ICEV counterparts. The major impediments for mass acceptance of EVs by the general public are the limited EV range and the lack of EV infrastructure. The solution of the range problem may come from extensive research and development efforts in batteries, fuel cells, and other alternative energy storage devices. An alternative approach is to create awareness among people on the problems of global warming and the advantages of EVs, while considering the fact that most people drive less than 50 miles a day, a requirement that can be easily met by today’s technology.

The appropriate infrastructure must also be in place for EVs to become more popular. The issues related to infrastructure are as follows:

- Battery charging facilities: residential and public charging facilities and stations
- Standardization of EV plugs, cords, and outlets, and safety issues
- Sales and distribution
- Service and technical support
- Parts supply

The current initial cost of an EV is also a big disadvantage for the EV market. The replacement of the batteries, even for HEVs, is quite expensive, added to which is the limited life problem of these batteries. The cost of EVs will come down as volume goes up, but in the meantime, subsidies and incentives from the government can create momentum.

The increasing use of EVs will improve the job prospects of electrical engineers. The new jobs related to EVs will be in the following areas:

- *Power electronics and motor drives:* Design and development of the electrical systems of an EV
- *Power generation:* Increased utility demand due to EV usage
- *EV infrastructure:* Design and development of battery charging stations and of hydrogen generation, storage and distribution systems

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2. Wakefield, E.H., *History of Electric Automobile,* Society of Automotive Engineers, Warrendale, PA, 1994.
3. Westbrook, M.H., *The Electric Car,* The Institute of Electrical Engineers, London, United Kingdom, and Society of Automotive Engineers, Warrendale, PA, 2001.
4. Hodkinson, R. and Fenton, J., *Lightweight Electric/Hybrid Vehicle Design,* Society of Automotive Engineers, Warrendale, PA, 2001.
5. The Energy Foundation, 2001 annual report.

ASSIGNMENT

Search through reference materials and write a short report on the following topics:

1. Commercial and research EV/HEV programs around the world over the last 5 years, describing the various programs, goals, power range, motor used, type of IC engine, battery source, etc.
2. Case study of a recent EV/HEV
3. State and federal legislations and standardizations

References

1 Introduction to Electric Vehicles

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3. Westbrook, M.H., The Electric Car, The Institute of Electrical Engineers, London, United Kingdom, and Society of Automotive Engineers, Warrendale, PA, 2001.

4. Hodkinson, R. and Fenton, J., Lightweight Electric/Hybrid Vehicle Design, Society of Automotive Engineers, Warrendale, PA, 2001.

5. The Energy Foundation, 2001 annual report. ASSIGNMENT

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3 Energy Source: Battery

1. Rand, D.A.J., Woods, R., and Dell, R.M., Batteries for Electric Vehicles, John Wiley & Sons, New York, 1998.

2. Dhameja, S., Electric Vehicle Battery Systems, Newnes (Elsevier Science), Burlington, MA, 2002.

3. Dell, R.M. and Rand, D.A.J., Understanding Batteries, Royal Society of Chemistry, United Kingdom, 2001. PROBLEMS

3.1

Estimate the weight of a 12 V, 100 Ah lead-acid battery by calculating the reactant masses participating in the overall chemical reaction. Assume that the mass of H_2O in the electrolyte is twice the mass of H_2SO_4. Neglect battery casing mass, electrode grid mass, separator mass, and current bus mass. (Note that $n=2$ for Pb and PbO_2, and $n=1$ for H_2SO_4.)

3.2

In the nickel-cadmium cell, nickel oxyhydroxide NiOOH is the active material in the charged positive plate. During discharge, it reduces to the lower valence state, nickel hydroxide $Ni(OH)_2$, by accepting electrons from the external circuit:

Cadmium metal is the active material in the charged negative plate. During discharge, it oxidizes to cadmium hydroxide $Cd(OH)_2$ and releases electrons to the external circuit:

The net reaction occurring in the potassium hydroxide (KOH) electrolyte is:

Estimate the weight of an 11.7 V, 100 Ah Ni-Cd battery.

Neglect the mass of the

KOH component of the electrolyte.

FIGURE P3.3

3.3

A 12 V battery is connected to a series RL load as shown in Figure P3.3 . The

battery has a rated capacity of 80 Ah. At t=0, the switch is closed, and the battery

begins to discharge. (a) Calculate and plot the battery discharge current, i(t), if the steady state discharge rate is C/2. Neglect battery voltage drop. (b) Calculate and plot SoD(t) in Ah for 0<t<2 h. (c) Calculate and plot SoC(t), assuming that at t=0 the battery is charged to rated capacity. Assume also that the rated capacity is the practical capacity. (d) Calculate the time corresponding to 80% DoD.

3.4

Given below are constant power discharge characteristics of a 12 V lead-acid

battery:

The battery characteristics are to be expressed in terms of Peukert's equation,

which has the following form: (a) Derive the constants n and λ, assuming a linear relationship between log (SP) and log(SE). (b) Find the capacity Q T of the battery if the theoretical energy density is SE T =67.5 Wh/kg, given a battery mass of 15 kg.

3.5

An EV battery pack consists of four parallel sets of six series-connected 12 V,

100 Ah lead-acid batteries. One steady state motoring (discharge) cycle of

battery current is shown in Figure P3.5a. The steady-state regenerative braking (charge) cycle of the battery is shown in Figure P3.5b.

FIGURE P3.5 (a) Suppose no regenerative braking is employed. How much time does it take to reach 80% DoD? (b) If regenerative braking is employed such that for every 50 motoring cycles there is one regenerative braking cycle, how much time does it take to reach 80% DoD?

(Note: In this problem, neglect variation of capacity with discharge rate. Assume

that the practical capacity is equal to the rated capacity.)

3.6

Given a lead-acid battery having the following empirical characteristics:

where SP is specific power, and SE is specific energy. The EV parameters are as

follows:

Also, take (a) Derive and plot F TR (t) vs. t (assume level road). (b) Derive and plot P TR (t) vs. t. (c) Calculate the EV range based on the SAE J227a Schedule B driving cycle using the power density approach of the FDM. The SAE J227a driving cycle and the current profile of the EV are given in Figures P3.6a and P3.6b. (Assume no regenerative braking.)

FIGURE P3.6

4 Alternative Energy Sources

1. Appleby, A.J. and Foulkes, F.R., Fuel Cell Handbook, Van Nostrand Reinhold, New York, 1989.

2. Andrews, N., Poised for growth: DG and ride through power, Power Quality, January/February, 10-15. 2002.

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10. Dhameja, S., Electric Vehicle Battery Systems, Newnes (Elsevier Science), Burlington, MA, 2002.

11. Rand, D.A.J., Woods, R., and Dell, R.M., Batteries for Electric Vehicles, John Wiley & Sons, New York, 1998.

PROBLEM

4.1

The current drawn by an electric motor of a fuel cell EV for a SAE Schedule D

J227A driving cycle is

The fuel flow rate for PEM fuel cell used in the vehicle is (a) Calculate the amount of fuel (hydrogen) needed for one cycle of Schedule D. (b) Calculate the amount of hydrogen needed for a range of 200 mi.

5 DC and AC Electric Machines

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2. Park, R.H., Two-Reaction Theory of Synchronous Machines—Generalized Method of Analysis—Part I, AIEE Transactions, Vol. 48, July, New York, 1929, pp. 716- 727.

3. Vas, P., Electric Machines and Drives: A Space-Vector Theory Approach, Oxford University Press, Oxford, 1992.

4. Novotny, D.W. and Lipo, T.A., Vector Control and Dynamics of AC Drives, Oxford University Press, Oxford, 1996.

5. Mohan, N., Electric Drives—An Integrated Approach, MNPERE, Minneapolis, MN, 2001.

6. Lyon, W.V., Transient Analysis of Alternating Current Machinery, John Wiley & Sons, New York, 1954.

7. Krasue, P.C. and Wasynchuk, O., Analysis of Electric Machinery, McGraw-Hill, New York, 1986. PROBLEMS

5.1

Find the condition of operation that minimizes the losses in a separately excited DC machine. (Start by writing an equation for P loss in terms of the field currents and armature currents. Assuming linearity for all the nonlinear functions, establish the relation between armature current and field current, and then find the condition for minimum P loss .)

5.2

Present an argument why it is impossible to achieve maximum efficiency at every operating point (T*,ω*) for a permanent magnet DC machine. (Start by writing an equation for P loss in terms of T, ω, and machine flux).

5.3

Proceeding as in Problem 5.2, explain why it is impossible to minimize losses at

any operating point (T^*,ω^*) for a series DC motor.

6 PM and SR Machines

1. Miller, T.J.E., Brushless Permanent Magnet and Switched Reluctance Motor Drives, Oxford University Press, Oxford, 1989.

2. Lawrenson, P.J. et al., Variable-speed switched reluctance motors, IEE Proc., Pt. B, Vol. 127, No. 4, July, 1980, pp. 253–265.

3. Miller, T.J.E., Switched Reluctance Motors and Their Control, Magna Physics Publishing, Hillsboro, OH; Oxford Science Publications, Oxford, UK, 1993.

4. Anwar, M.N., Husain, I., and Radun, A.V., A Comprehensive Design Methodology for Switched Reluctance Machines, IEEE-IAS Annual Conf., Italy, October, 2000.

PROBLEMS

6.1 (a) A PM brushless DC has a torque constant of 0.12 N-m/A referred to the DC supply. Estimate its no-load speed in rpm when connected to a 48 V DC supply. (b) If the armature resistance is 0.15 Ω/phase and the total voltage drop in the controller transistors is 2 V, determine the stall current and the stall torque.

6.2

Consider a three-phase 6/8 SRM. The stator phases are excited sequentially

with a total time of 25 ms required to excite all three phases. Find the angular

velocity of the rotor. Express your answer in rad/s and rev/m.

6.3

The following flux equation describes the nonlinear characteristics of a three

phase, 6/4 SRM:

where

and

Here, $j=1, 2, 3$ denotes the phase number, and $m=3$. Also, $a=0.024$ and

$b=0.019$.

Derive the expression for the phase torque $T_j(i,\theta)$.

7 Power Electronics and Motor Drives

1. Baliga, B.J., Power Semiconductor Devices, PWS Publishing Company, Boston, MA, 1995.

2. Kassakian, J.G., Schlecht, M.F., and Verghese, G.C., Principles of Power Electronics, Addison-Wesley, Reading, MA, 1991.

3. Mohan, N., Undeland, T.M., and Robins, W.P., Power Electronics: Converters, Applications and Design, John Wiley & Sons, New York, 1995.

4. Dubey, G.K., Power Semiconductor Controlled Drives, Prentice Hall, New York, 1989. PROBLEMS

Parameters for Problems 7.1 and 7.2 are as follows:

7.1

The time γ(see Figure P7.1) in the discontinuous conduction mode (DCM)

during acceleration of a two-quadrant chopper can be derived as

where

Derive the $\langle\omega\rangle$-$\langle T\rangle$ characteristics for acceleration operation of the two

quadrant chopper operating in the DCM. (Do not substitute numerical values

for parameters yet.) Do not try to solve $\langle\omega\rangle$ in terms of $\langle T\rangle$. Instead, solve for

$\langle T\rangle$ in terms of $\langle\omega\rangle$. Plot $\langle T\rangle$ vs. $\langle\omega\rangle$ for the given parameters, and d_1 =0.9, 0.

5, and 0.1.

7.2

Calculate the worst-case armature current ripple in CCM for the given

parameters. If the worst-case ripple is required to be less than 10 A, what is the value of the filter inductance, or what value should the switching frequency be

changed to?

7.3

Find the regions in the T-ω plane for DCM, CCM, and UNCM acceleration

operation of a two-quadrant chopper-fed DC motor. That is, find the restrictions

on T and ω for each mode. Hint: Start with the condition on E. Solve the

inequality for d_1. Then, use the ω-T characteristics to eliminate d_1. Also,

remember, $0 \le d_1 \le 1$.

Plot these regions for the given parameters, and also plot the safe operating

area given:

aa -100 Nm $\le T \le 100$ Nm -300 rad/s $\le \omega \le 300$ rad/s -30 hp $\le P \le 30$ hp

FIGURE P7.1

7.4

Describe the UNCM of braking operation. Draw waveforms of armature current

and terminal voltage. Calculate the speed-torque characteristics for this mode. In

what quadrant in the ω-T plane is this mode?

7.5

Consider the EV drivetrain driven by a two-quadrant chopper, as shown in

Figure 7.26. The duty ratio for the acceleration operation is d_1, while the duty

ratio for braking operation is d_2. The various parameters are given below:

EV parameters:

aam=1050 kg, M B =150 kg, C D =0.25, A F =2 m 2 , C 0 =0.01, C 1 =0 ρ=1.1614 kg/m 3 , and g=9.81 m/s 2 r wh =radius of wheel=0.28 m

Motor and controller parameters:

aaR a =0.1 Ω, L a =2 mH, K=0.6 V-s, I arated =200 A f s =chopper switching frequency=500 Hz L f =series filter inductance =1.6 mH

In each of the following cases, determine whether steady state operation is in

CCM, DCM, or UNCM. (a) d 1 =0.4, d 2 =0, V=25 m/s (b) d 1 =0.8, d 2 , V=45 m/s (c) d 2 =0, V=25 m/s, T=40 Nm

Note: V is the vehicle steady state velocity, and T is the motor torque. Also,

neglect friction and windage loss, and assume zero power loss between the

motor shaft and the vehicle wheels.

8 AC and SR Motor Drives

1. Trzynadlowski, A.M., Introduction to Modern Power Electronics, John Wiley & Sons, New York, 1998.

2. Dubey, G.K., Power Semiconductor Controlled Drives, Prentice Hall, New York, 1989.

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8.1

A 460 V, 60 Hz, six-pole, 1176 rpm, Y-connected induction motor has the

following parameters referred to the stator at rated condition:

The motor is fed by a six-step inverter. The inverter is fed from a battery pack

through a DC/DC converter.

The battery pack voltage is 72 V. Neglecting all the losses: (a) Determine the output of the DC/DC converter. (b) Mention the type of the converter and its conversion ratio.

8.2

The motor in Problem 8.1 is employed to drive an EV that requires 300 N-m to

propel the vehicle on a level road at constant velocity. The configuration is

shown in Figure P8.2. Determine its operating speed and slip, while the

frequency and voltage are kept constant at rated value.

8.3

The vehicle in Problem 8.1 is moving downwards so that it requires 250 N-m. (a) What will be the input voltage for the motor from the inverter? Hence, determine the conversion ratio of the converter. Frequency is kept constant at rated value, and the motor is running at the rated speed. (b) What should be the operating frequency of the inverter if the input voltage to the motor is kept constant at rated value, and the motor is running at rated speed?

8.4

Find the speed of the motor mentioned in Problem 8.1 for a braking torque of

350 N-m and the inverter frequency of 40 Hz when the motor

is supplied at rated

voltage.

8.5

A three-phase induction machine is operated from a variable voltage, fixed

frequency source. (a) Derive an expression for machine efficiency in terms of slip (not in terms of torque and speed). Include only stator and rotor copper losses and core loss in P loss . Model core loss by a constant resistance in the equivalent circuit. To simplify the analysis, assume that core loss resistance and magnetizing reactance are large compared to the other parameters. Under this assumption, you can use an approximate equivalent circuit, where the core loss resistance and magnetizing reactance are directly across the stator terminals. (b) Does motor efficiency depend on terminal voltage? Calculate the slip that maximizes motor efficiency.

8.6

An AC inverter is operated in a sinusoidal pulse mode. The transistor base

current waveforms are shown in Figure P8.6. Sketch line-to-line voltages v AB ,

v BC , and v CA , and line to neutral voltage v AN in the space provided. Briefly

comment on the voltages. Are they balanced? (i ci for i=1 to 6 are the base

currents for transistors 1 to 6, respectively).

FIGURE P8.2

FIGURE P8.6

9 Electric Vehicle Drivetrain

1. Willis, R.L. and Brandes, J., Ford next generation electric vehicle powertrain, 12th Electric Vehicle Symp., December, 1994, pp. 449–458.

2. Scott, T.E., Power Transmission Mechanical, Hydraulic, Pneumatic, and Electrical, Prentice Hall, New York, 2000.

3. Ehsani, M., Rahman, K.M., and Toliyat, H.A., Propulsion system design for electric and hybrid vehicles, IEEE Transactions on Industrial Electronics, Vol. 44, No. 1, February, 1997, pp. 19–27. PROBLEM

9.1

An EV drivetrain employs a separately excited DC motor that drives the EV

rear axle through a gearbox, as shown below in Figure P9.1. The vehicle is

traveling in fourth gear on a level road at a constant velocity of 60 mi/h. All

necessary parameters are as follows:

Motor parameters are as follows:

In the following calculations, assume no power loss from motor output to

wheels. Also, assume that chopper outputs are pure DC. (a) Calculate the operating speed and torque of the motor. (b) For $0.5 \le I_F \le 4$ A, plot I_A vs. I_F

FIGURE P9.1

10 Hybrid Electric Vehicles

1. Moran, M.J. and Shapiro, H.N., Fundamentals of Engineering Thermodynamcis, 3rd ed., John Wiley & Sons, New York, 1995.

2. Howell, J.R. and Buckius, R.O., Fundamentals of Engineering Thermodynamics, 2nd ed., McGraw-Hill, New York, 1992.

3. Ehsani, M., Rahman, K.M., and Toliyat, H.A., Propulsion system design for electric and hybrid vehicles, IEEE Transactions on Industrial Electronics, Vol. 44, No. 1, February, 1997, pp. 19–27. PROBLEM

10.1

An HEV has the following parameter values: p=1.16 kg/m 3 , m=692 kg, C D =0.2,

A F =2 m 2 , g=9.81 m/s 2 , C 0 =0.009, and C 1 =1.75*10- 6 s 2 /m 2 . The type of IC

engine that will be used for the vehicle has the force (at wheel) vs. velocity

characteristics of FTR=2.0 sin 0.0285x N for 5<x<100, where x is the vehicle

speed in mi/h. Determine the displacement of the ICE for a rated cruising

velocity of 60 mi/h on a 2% slope.