Chapter 1

Introduction

1.1 Motivation

The advancement of technology and standards of living continues to evolve. The ever increasing dependency on electrical energy in many commercial operations such as Uninterrupted power supply (UPS), Electric vehicles (EVs), microgrids, etc. is much manifest. The problem with Internal combustion (IC) engines is air pollution which causes climatic hazards and other environmental issues like depletion of fossil fuels. The need to come up with alternatives IC engines with green energy based vehicles for sustainable development has emerged to provide society with an eco-friendly environment and better life. The Electric vehicles (EVs) have drawn more attention as a substitute for conventional IC engine vehicles in recent years. EVs have seen a resurgence due to technological developments, an increased focus on renewable energy, and the advancement of batteries and motors. In EV, the motor drive and power electronic converter should be capable of bidirectional energy transfer between the battery and motor drive system. It has many benefits when compared to other modes of transport.

- Electric vehicle does not require any fossil fuel.
- Electric vehicle reduces the noise pollution.
- It is powered by electric energy, which is cheaper and more compatible with smart technologies.
- Electric vehicles are highly efficient.

- It requires less maintenance.
- Electric vehicle can be used as emergency power backup (With the help of advanced converter for EV charging and battery as the power back in the home).

A DC-DC converter in an electric vehicle's powertrain converts the DC voltage available from the battery storage or fuel cell into a stable voltage level to maintain the vehicle's desired operating point. In EVs, the DC-DC converter provides required voltage levels and maintains the bus voltage for the electric motor drive-based propulsion system. In EV applications, many types of converters are employed. Isolated and non-isolated converters can be distinguished based on their use. Non-isolated converters are used in powertrain to boost battery voltage to higher levels for propulsion, whereas isolated converters are utilized in high to low voltage conversion to supply the necessary 12 V for auxiliary circuits. Half-bridge and full-bridge converters, cascaded converter, buck-boost converter, Cuk, and SEPIC/Luo converters are examples of non-isolated converters. Additional components are added with the basic converters to improve the efficiency and reliability of the converter. In EVs applications, the converter should have bi-directional power transfer capability so that the battery can be charged during regenerative braking and to provide power to the propulsion system.

The electricity pathway between the EVs energy storage and the utility grid is provided by the electronic interface between the energy storage system and the grid. The bi-directional DC-DC converter used to serve the purpose should be capable of power flow in either direction and with proper voltage regulation. The maximum overall efficiency of the cascaded buck-boost topology [17,18] is lower, and the efficiency reduces drastically for large voltage transfer ratios. Saranga et al. proposed an isolated bidirectional converter topology [19] to control the quantity and direction of power flow in an inductive power transfer system with reversible rectifiers on either side is used. To minimize the voltage stress on the transistors and the requirement for large inductors, a multilevel converter topology was employed.

1.2 Research Background

The Country's dependence on imported oil has been gradually increasing over the years, which has become an important issue in national and global energy considerations. The world's supply of fossil fuels is depleting over time, and the price of fuel is steadily rising. These are crucial concerns that must be considered. Environmental pollution is another important concern where the main source of carbon dioxide emissions is from the transportation sector. Approaches to curb the emissions must be developed and evaluated. Alternative vehicles that eliminate or minimize the size of the IC engines of the conventional vehicles can be used to ease this problem. EVs, Hybrid electric vehicles (HEVs), and Plug-in hybrid electric vehicles (PHEVs) are termed as alternative vehicles use advanced technologies alternative to the conventional IC engine vehicles.

In a hybrid vehicle, there are two or three types of sources that deliver propulsion power. An IC engine and one or two electric machines are used in the powertrain of a hybrid vehicle. Depending on the type of hybrid vehicle architecture, the traction electric motors can operate independently or combined with the IC engine. The arrangement of the hybrid powertrain components classifies the hybrid vehicles as series, parallel and series-parallel hybrids. In a series hybrid, only one converter provides propulsion power and in a parallel hybrid, more than one energy conversion device delivers propulsion power. These vehicles can operate in battery-only mode to provide power for propulsion during the daily commute and IC engine provides additional power and capability for a longer range of driving. EV consists of the following features: (1) the energy source is portable and electrochemical or electromechanical in nature, and (2) traction force is supplied only by an electric motor.

The driving range of an EV is between 70-300 Km per charging. Charging time depends on the size of the battery, the size of the on-board charger, and power levels. Typical charging times for EV with different types of charging stations. In the transportation sector, EVs provides the opportunity to use the grid electricity. The Indian power grid has the potential to deliver sufficient amounts of energy for the daily requirement of light duty vehicles. EVs help to reduce emissions both directly and indirectly. Directly it reduces greenhouse gases emissions and indirectly it can help the environment by using electricity obtained from renewable generation.

The first Electric vehicle (EV) was built by Frenchman Gustave Trouvé in 1881 [20], 140 years back. A similar EV was built by E.H Wakefield in 1883 [21]. In 1884, Thomas Parker built a practical production electric car in Wolverhampton using his own specially designed high-capacity rechargeable batteries. With this development, it was possible to develop EVs as commercial products, by 1886. Some of the popular companies are Electric Carriage and Wagon Company, which came up with its model called, ‘Electroboat’, in 1894. Similarly, there was a model called, ‘Victoria’, in 1897, which, has become a household name, in 1900 since it has a very good design.

The Detroit Electric was an electric car produced by the Anderson Electric Car Company in Detroit, Michigan [22]. The General Motors EV1 was an electric car produced and leased by General Motors from 1996 to 1999. The Tesla Roadster is a Battery electric vehicle (BEV) sports car, based on the Lotus Elise chassis, that was produced by the electric car firm Tesla Motors. The Roadster was the first highway legal serial production all-electric car to use lithium-ion battery cells and the first production all-electric car to travel more than 320 kilometres per charge.

At the beginning of the 21^{st} century, interest in electric and alternative fuel vehicles in private motor vehicles has increased due to growing concern over the problems associated with hydrocarbon-fueled vehicles, including damage to the environment caused by their emissions, and the sustainability of the current hydrocarbon-based transportation infrastructure as well as improvements in electric vehicle technology. The Mitsubishi i-MiEV (MiEV is an acronym for Mitsubishi innovative EV) is a five-door hatchback electric car produced in 2010 by Mitsubishi Motors. The Nissan Leaf styled as LEAF, is a compact five-door hatchback BEV manufactured by Nissan. It was introduced in Japan and the United States in December 2010 and is currently in its second generation, introduced in October 2017.

1.3 Electric Motor for EVs

A typical industrial motor gives a maximum torque equal to twice the rated torque of the machine. But the maximum torque requirement of an EV motor is four to five times the rated torque of the motor at the time of starting, hill climbing, overtaking, etc. Typical performance characteristics of electric motors for traction is shown in Figure 1.1. Similarly, the maximum speed required in an industrial motor is around two times the rated speed and the torque and speed requirement is very high in the case of EV application, it is also around four to five times the rated speed for a high-speed highway cruising. Since the motors directly control the wheel, it is decided that they should have high controllability and good steady-state and dynamic performance. EV motor also needs to

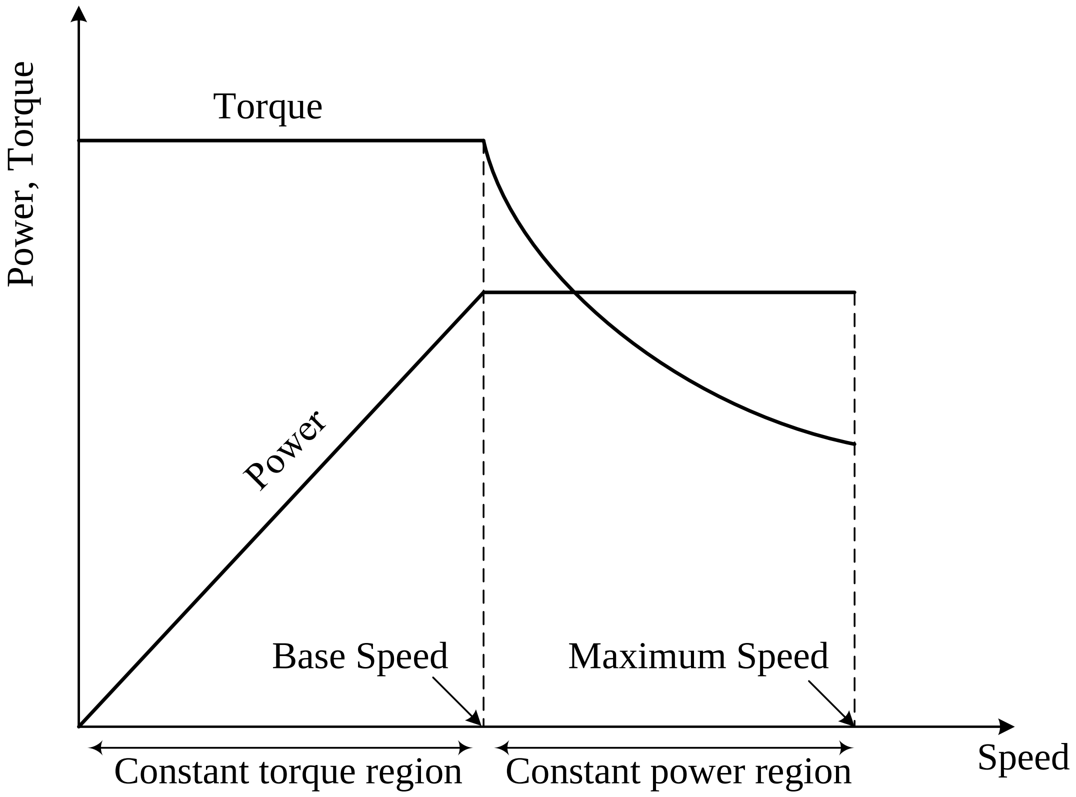


Figure 1.1: Typical performance characteristics of electric motors for traction.

operate in harsh conditions such as bad weather,high temperature and frequent vibrations. Therefore, there is a need to provide thermal, Ingress Protection (IP) protection together with good suspension and Electro magnetic interference (EMI), Electro magnetic compatibility (EMC) compliance. So, an EV motor should be having high torque density and high power density. The electric motor for traction should operate for wide speed range in constant torque region and constant power region. The electric motor for traction should have high efficiency and operate over wide speed range in constant torque as well as constant power region. There are different types of EV motors used for electric vehicle applications. The classification of electric motors for EV application is illustrated in Figure 1.2.

An Alternating current (AC) drive EV of van-type was developed by Ernest H. Wakefield in 1974 [23]. In this EV a three-phase squirrel-cage induction motor of 27 KW with 144 V battery bank was employed. Selection of the type and size of traction motor to be employed in an EV depends on expected conditions of motor operation. These conditions are defined as driving cycle, type of vehicle, and power sources.

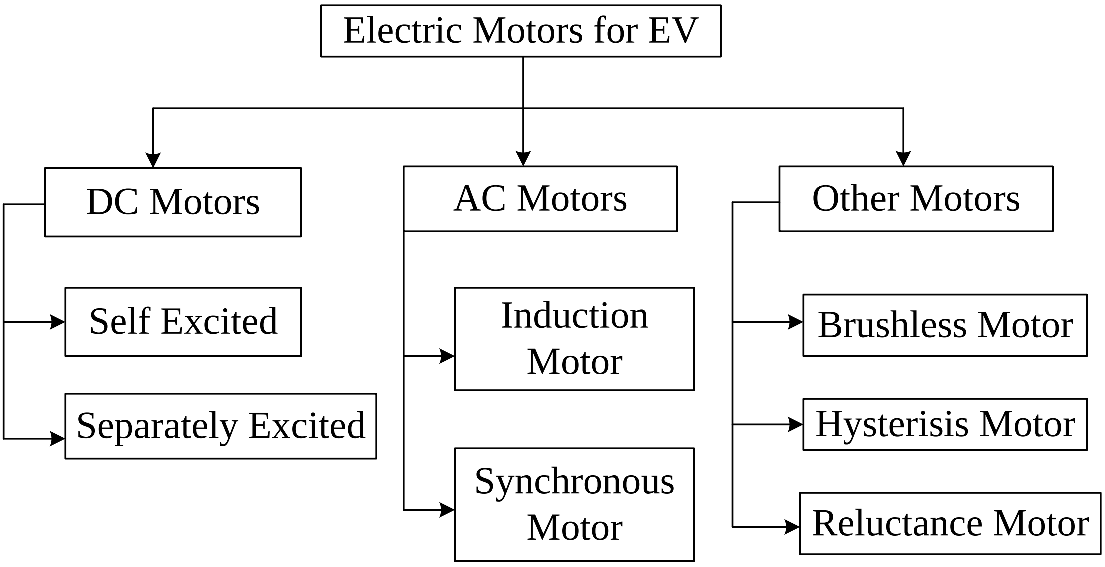


Figure 1.2: Types of motors for EV application

The comparison of five most widely used electric motors for EV application is done in the Table 1.1

Table 1.1: Comparison of five most widely used electric motors for EV application

Properties	Brushless DC	Series Motor	PMSM	Switched Reluctance	Induction Motor
Type	AC	DC	AC	AC	AC
Power to stator	Pulsed DC	DC	AC	Pulsed DC	AC
Weight	Low	Heavy	Medium	Medium	Medium
Overall Cost	High	Low	High	Medium	Medium
Commutation method	Internal electronic	Mechanical commutation	External electronic	External electronic	External electronic
Maintenance	Negligible	Brushes wear	Negligible	Negligible	Negligible
Speed Control Method	Frequency dependent	Field weakening	Frequency dependent	Frequency dependent	Frequency dependent
Starting torque	High	High	Higher than series motor	High	Medium
Efficiency	High	low	High	Medium	High

Other motors which are upcoming in EV domain is synchronous reluctance motor and switched reluctance motor. The special motors are gaining interest for EVs/HEVs electric propulsion for its simple and rugged construction, the ability of extremely high-speed operation, and hazard-free operation [24–26]. A 60 kW switched reluctance motor for traction application in HEV [27] is designed. The motor has been designed for 24 stator poles and 16 rotor poles. High numbers of stator and rotor poles are selected due to the objective of reducing torque ripple and improving output torque quality. The higher number of rotor poles can result in larger phase conduction overlaps and, thus it becomes easier to reduce the torque ripple. The increase of the phase numbers can also lead to the increase of overlap between phase torques, which results in a decrease of torque ripple.

1.4 Permanent Magnet Brushless DC Motor

A Permanent magnet brushless DC (PMBLDC) motor is a rotor position feedback permanent synchronous machine. The PMBLDC motors are generally controlled using a three-phase Voltage source inverter (VSI). The motor requires a rotor position sensor for starting and for providing a proper commutation sequence to turn on the power devices in the VSI. Based on the rotor position, the power devices are commutated sequentially every 60 degrees. Instead of commutating the armature current using brushes, electronic commutation is used for this reason it is an electronic motor. This eliminates the problems associated with the brush and the commutator arrangement, for example, sparking and wearing out of the commutator brush arrangement, thereby, making a PMBLDC more rugged as compared to a dc motor. The modelling, simulation, and analysis of Permanent magnet synchronous motor (PMSM) and PMBLDC drives have been discussed by Krishnan et al. [28, 29].

The rotor position sensors are one of the most notable features of the PMBLDC motor. The control algorithms determine the gate signal to each switch in the power electronic converter based on the rotor position and command signals, which may include torque commands, voltage commands, speed commands, and so on. Basically, it is an electronic motor and requires a three-phase inverter in the front end. The inverter functions as an electrical commutator in self-control mode, receiving the switching logical pulse from the absolute position sensors. The PMBLDC motor drive system and its armature current, back-Electromotive force (EMF) with switching PWM are shown in Figure 1.3 and 1.4 respectively. The inverter switches were controlled to give commutator function only when the devices were sequentially ON, OFF for 120^o angle duration according to rotor position sensor information. It is possible to control the switches in PWM chopping mode for controlling voltage and current continuously at the machine terminal. In PWM chopping mode switches are turned ON and OFF on a duty cycle basis to control the PMBLDC motor average current and average voltage. As the advanced motor concepts, electronically-commutated motors and permanent magnet motors for EVs [30, 31]. The permanent magnet motor drives have been successfully developed to fulfill the special requirements for EVs such as high power density, high efficiency, high starting torque, and high cruising speed [32]. The permanent magnet brushless DC motor is classified

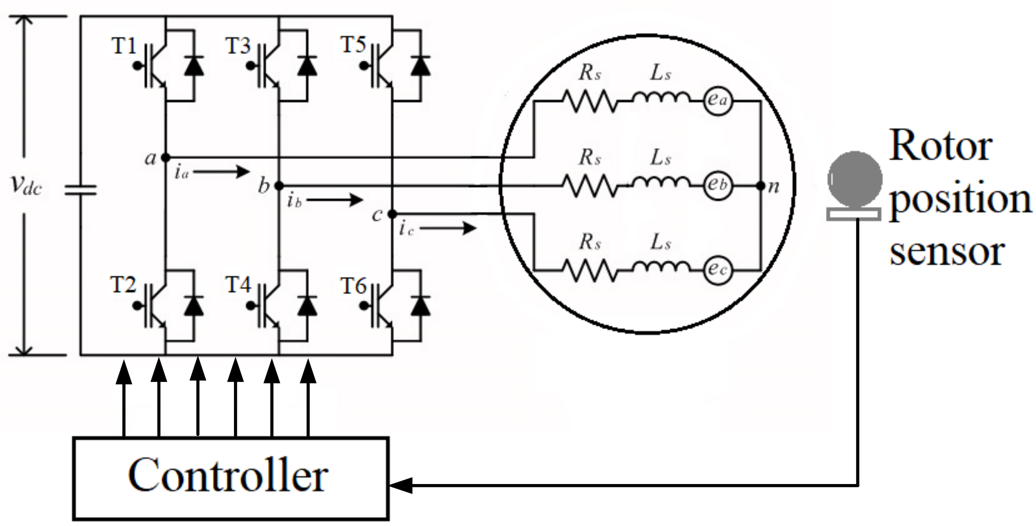


Figure 1.3: PMBLDC motor drive system

as sinusoidal fed and rectangular fed motor. Permanent magnet hysteresis hybrid synchronous motor with features of both conventional hysteresis motor and permanent motor for EVs and HEVs application [33]. The hybrid motor in which the permanent magnets are inserted into the slots at the inner surface of the hysteresis ring is called the hybrid permanent magnet hysteresis synchronous motor. During asynchronous speed, the motor torque consists of the hysteresis torque, eddy current torque, and permanent magnet brake torque. At the synchronous speed, the motor torque is comprised of the hysteresis and permanent magnet torques. The negative effect of the magnet brake torque of a conventional PM motor is ideally compensated by the high eddy current and hysteresis torques, particularly at the initial run-up period. The PMBLDC motor specifications used throughout this thesis work are given in Table 1.2.

Table 1.2: PMBLDC motor specification

Parameter	Value
Power	1.1 hp
Per Phase Resistance (R_a)	1.09 Ω
Per phase Inductance (L_a)	3.37 mH
Voltage Constant (K)	51.3 V/krpm
Inetia(J)	0.00014 kg-m^2
Pole Pair (P)	2

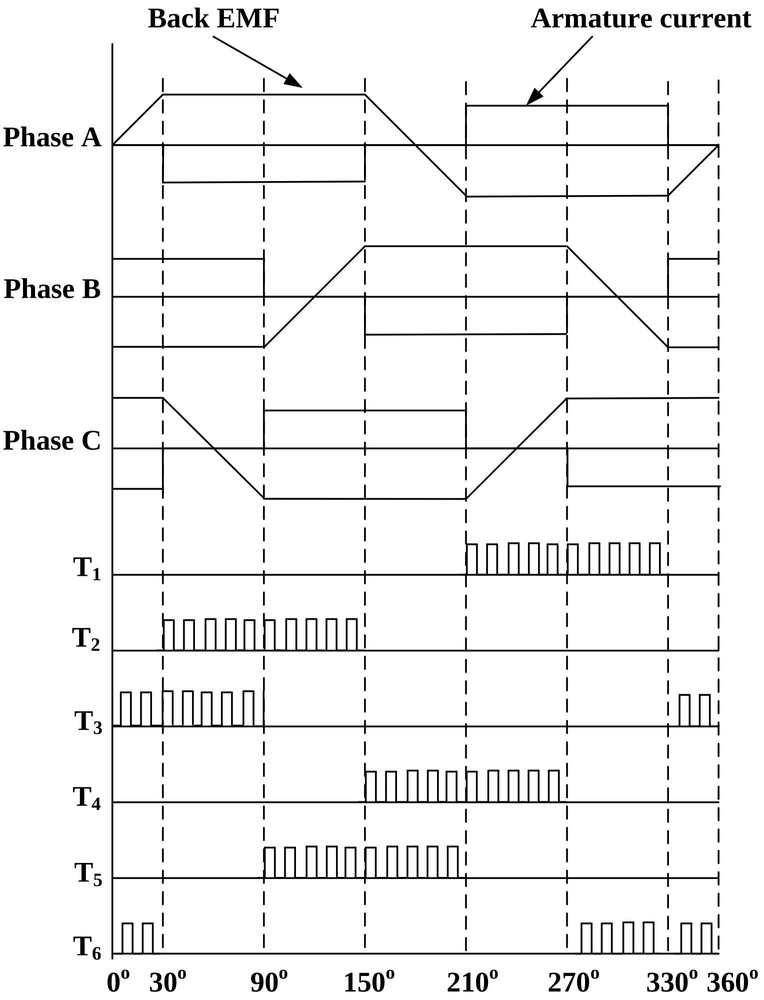


Figure 1.4: PMBLDC motor armature current, back-EMF waveform and switching PWM.

1.5 Traction effort for vehicle movement

Figure 1.5 shows the forces acting on a vehicle moving up a grade. The tractive effort is required to move an EV from standstill to certain speed. There are different types of forces acting on the vehicle: (1) Rolling resistance force (F_{rr}) (2) Grade resistance force (F_{gr}) (3) Aerodynamic drag force (F_{ar}) (4) Acceleration force (F_{ac}). The tractive force (f_t) is calculated as

$$F_t = F_{rr} + F_{gr} + F_{ar} + F_{ac} \tag{1.1}$$

$$= mgC_{rr}\cos\alpha + mg\sin\alpha + 0.5\rho C_w A(V + V_w)^2 + ma \tag{1.2}$$

where C_{rr} is rolling resistance coefficient, m is mass of the vehicle, g is acceleration due to gravity (9.81 m/s^2), C_w is air drag coefficient, ρ is air density, A is frontal area of the vehicle, V is speed of vehicle (m/s), V_w air velocity (m/s) and a is required acceleration.

The torque that is required on the drive wheel will be the one that the driving motor requires to produce to obtained desired speed characteristics. The torque is calculated as

$$T = F_t \times r \tag{1.3}$$

where r is the radius of the wheel. This torque can be obtained by directly mounting a motor with the torque value on the differential of the vehicle or by using a gearbox. The vehicular type of the load on PMBLDC motor is emulated using a belt-drum system and inertial flywheel. In the steady-state operation of the vehicle, the inertial load disappears as the speed is constant. Thus, to emulate the steady-state operation of the motor, the frictional load is applied on the PMBLDC motor through the belt-drum assembly. The load torque on PMBLDC motor is applied through the belt-drum arrangement as shown in Figure 1.6. The torque on drum which is coupled to shaft of the PMBLDC motor is calculated as

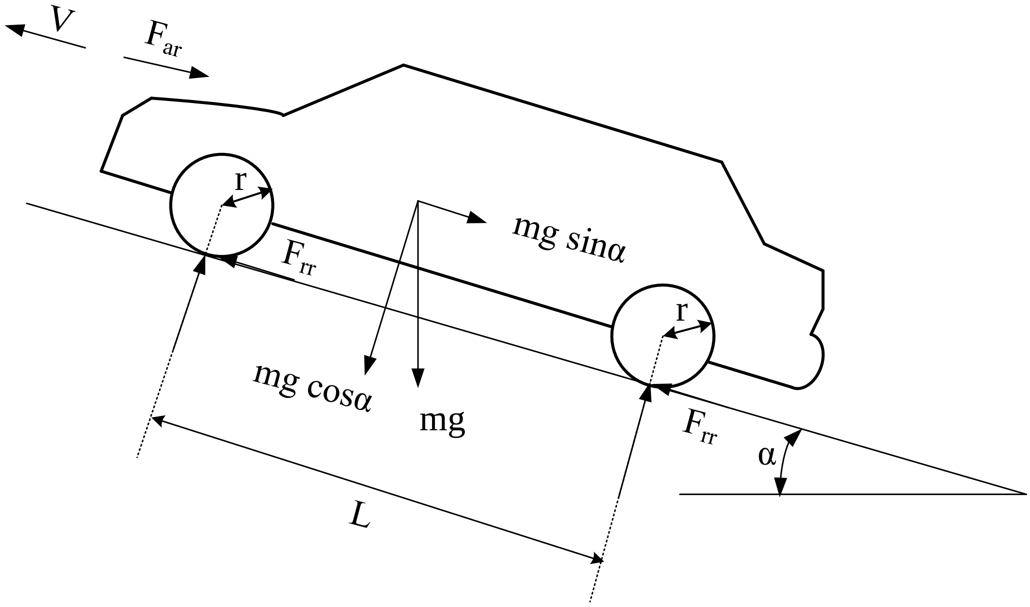


Figure 1.5: Forces acting on a vehicle.

$$T = |W_1 - W_2| \times g \times R \tag{1.4}$$

where W_1, W_2 are readings of weighing instrument in kg, R is radius of drum.

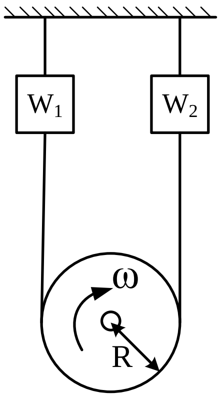
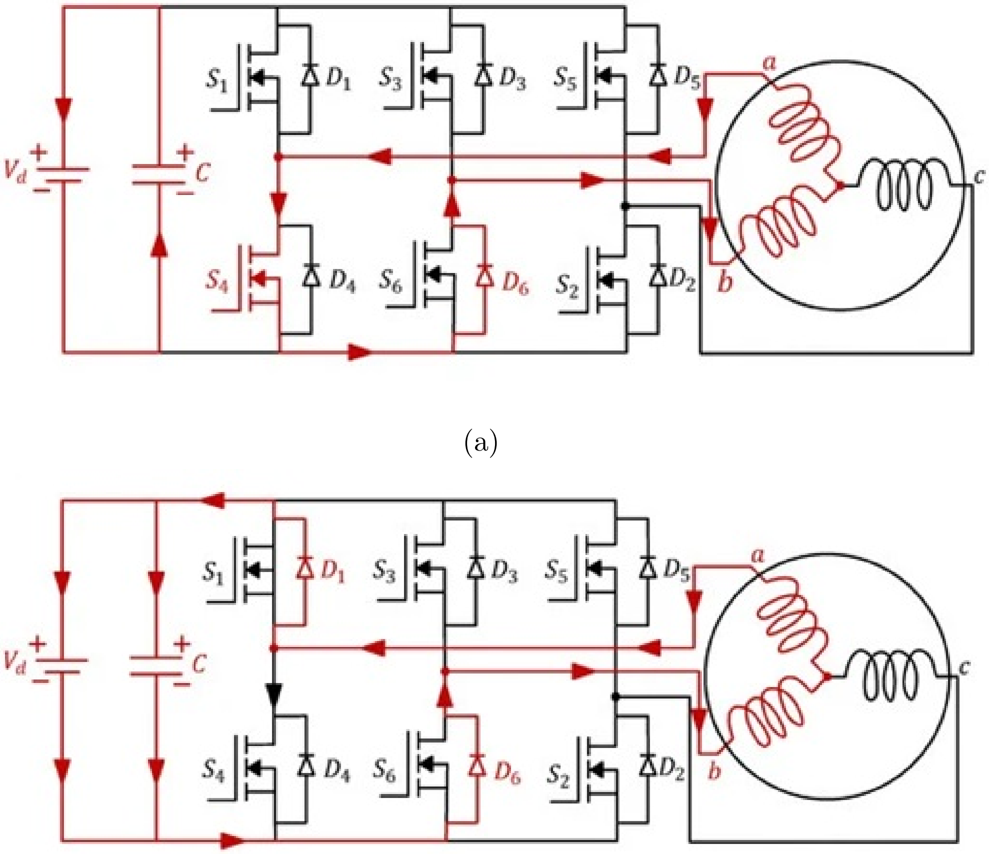


Figure 1.6: Belt-drum arrangement system.

1.6 Regenerative braking of electric vehicle

Conventionally, EVs uses a mechanical brake to increase the friction of the wheel for the deceleration purpose. However, from the viewpoint of saving energy, the mechanical brake dissipates much energy since the EV's kinetic energy is converted into the thermal one. The fact that a motor driving an electric vehicle may, under certain conditions, be converted into a generator and that it will as such exert a braking effect upon the vehicle instead of propelling it, was known very soon after the electric propulsion of vehicles was introduced. The Regenerative braking (RB) of electric vehicle was discuss by R.E. Hellmund in 1917 [34]. This braking effect may be utilized under two conditions: first, when the vehicle is going downhill, for the purpose of avoiding undesirable acceleration, due to gravity, and consequent high speeds; second, after a vehicle has reached a certain speed and it is desirable to reduce this speed to a lower or a standstill. The electric energy generated while braking the vehicle in this manner may be disposed of in two ways: first, it may be used up in resistances mounted on the vehicle, in which case it is customary to speak of dynamic braking; second, it may be returned to the power supply system, in which case it is customary to speak of regenerative braking. With regenerative braking on electric vehicles, this vehicle kinetic energy can be converted back into electrical energy that can be stored in batteries for reuse to propel the vehicle during the driving cycle.

The RB of PMBLDC can be done by only changing the control strategy of VSI. One simple and efficient method is to independently switch the conjunction with PWM to implement an effective braking control. However, with the low speed of the PMBLDC motor, the back-EMF cannot reach the voltage across the battery. Due to the presence



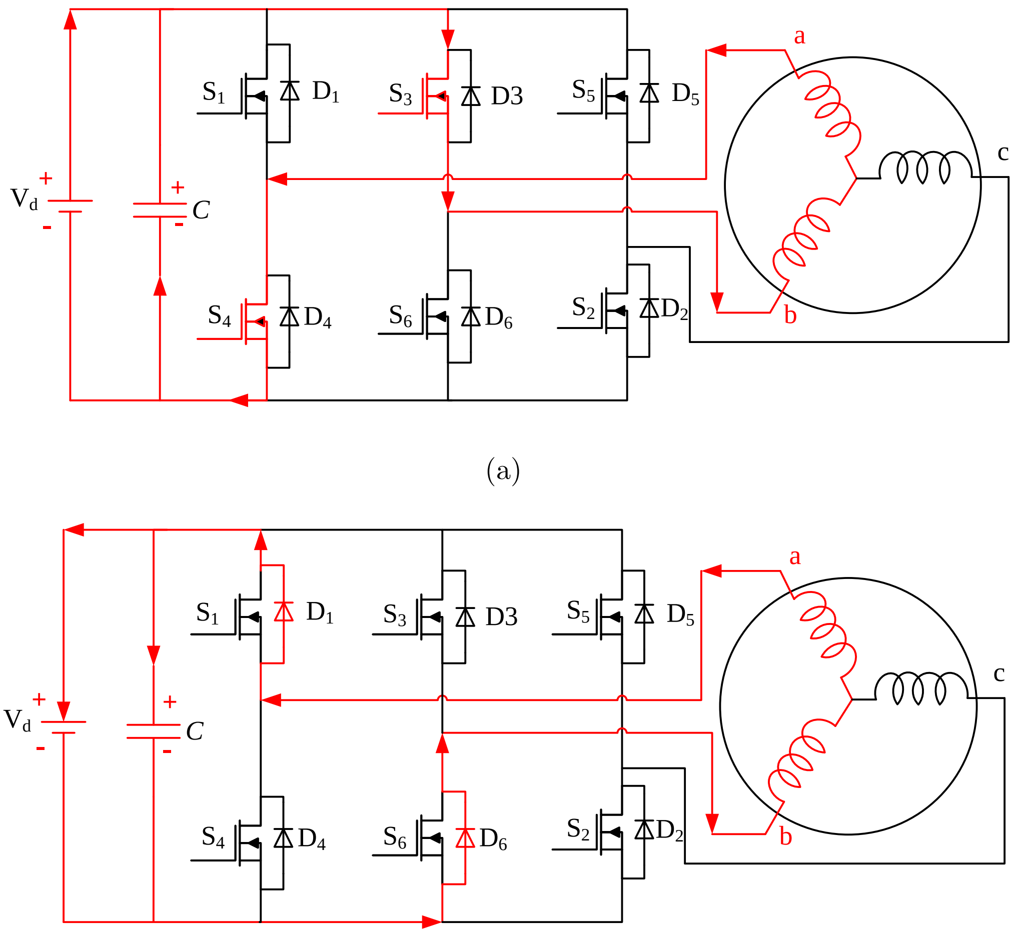
(a)

(b)

Figure 1.7: Current flowing path single-switch control strategy when (a) switch S_4 ON (b) switch S_4 OFF during RB of PMBLDC motor.

of self inductances in motor windings, these inductances in the motor can constitute the boost circuit. To achieve the recovery of energy, we have to boost the voltage on the dc bus through the inductor accumulator. We turn off all switches on the upper side of VSI and control the lower side of VSI with PWM. There are three types of switching strategy of VSI for RB of PMBLDC motor: (a) single-switch (b) two-switch and (c) three-switch control strategy. The current conduction path of the single-switch, two-switch and three-switch control strategy are shown in Figure 1.7, 1.8 and 1.9 respectively.

The braking device is one of the most important subsystems of a light electric vehicle in terms of safety. If the Hall-effect sensors malfunction during a braking event, an accident may occur and result in grave consequences. To cope with the aforementioned problems, in this work employs a cost-effective and simple sensorless-braking commutation method to improve braking commutation reliability. The proposed method has the following



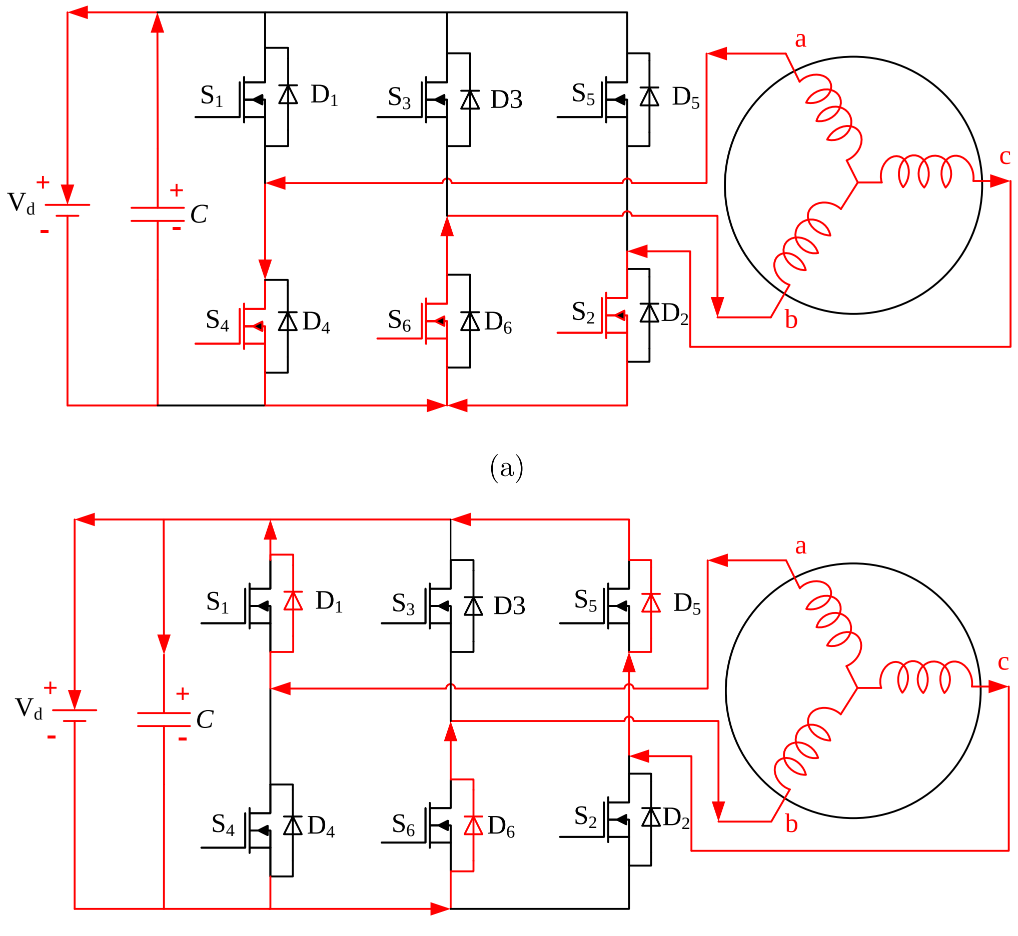
(a)

(b)

Figure 1.8: Current flowing path of two-switch control strategy when (a) switch S_4 and S_3 ON (b) switch S_4 and S_3OFF during RB of PMBLDC motor.

attractive features:

- Additional power switches and inductors are not essential in the proposed approach.
- Only a general six-switch full-bridge inverter is needed to realise braking commutation. Namely, there is no need to change the circuit structure of the motor driver at all.
- Theoretical analysis of important performance indices such as boost ratio is performed in the chapter 3 and chapter 5.
- Two out of three proposed braking commutation strategies are implemented using a cost-effective, position-sensorless method.



(a)

(b)

Figure 1.9: Current flowing path of three-switch control strategy when (a) switch S_4, S_6 and S_3 ON (b) switch S_4, S_6 and S_2 OFF during RB of PMBLDC motor.

In [35], discuss the cost-effective method of regenerative braking in an electric vehicle. During the braking period, the proposed method only changes the switching sequence of the inverter to control the inverse torque so that the braking energy will return to the battery. The experimental results show that the driving range of the EV could be increased to about 16.2% [35]. Regenerative Braking Systems (RBS) provide an efficient method to assist hybrid electric buses to achieve better fuel economy while lowering exhaust emissions. A fuzzy-logic-based regenerative braking strategy integrated with series regenerative braking on an “LF620” prototype EV to advance the level of energy-savings [36]. The driving range of the ”LF620” EV was increased by 27.1 % when compared with the non-regenerative braking strategy condition. Regenerative braking control of BLDC motor drive electric vehicle is designed and implemented in [37]. During the braking period, the switching sequence of the power converter is controlled to inverse the output torque of the three-phase BLDC motor, so that the braking energy can be returned to the battery. Sliding mode voltage and the current controller are used to control the switching sequence of the voltage source inverter in regenerative braking mode. The driving range of the EVs can be improved by about 17 % using the proposed controller with regenerative braking. The distribution of braking force adopts fuzzy logic control of a brushless DC motor is described in [38–40]. Three cost-effective braking commutation strategies based on a general full-bridge DC/AC inverter without using position sensors for BLDC motor [41]. The braking commutation strategies investigated are named according to the number of power switches in action over each commutation state; designated as single-switch, two-switch, and three-switch, respectively. At present, the control methods for regenerative braking of electric vehicles are proposed such as the predictive control method integrating adaptive cubic exponential prediction and dynamic programming in [42].

1.7 Organization of the Thesis

This thesis presents a variety of topics including various key challenges of an electric vehicle. There are different types of dc-dc converters for high voltage and high power for an electric vehicle. The selection of the type and size of traction motor to be employed in an electric vehicle. The thesis consists of six chapters.

Chapter 1 gives an introduction of DC-DC converters for EVs application, different types of electric motors for EVs, working of PMBLDC motor, traction effort for vehicle movement, and regenerative braking of EV.

Chapter 2 presents the literature review of the high gain bidirectional DC-DC converters. Classification of bidirectional DC-DC converter, isolated, non-isolated, multi-port bidirectional DC-DC converter for EVs application.

Chapter 3 presents Quadratic gain bidirectional converter (QGBC) based PMBLDC motor drive for EV application. The converter working principle is in step-up or motoring mode and step-down or regenerative braking mode. Converter design and small signal analysis are done. Simulation and experimental results are provided to validate the fabricated prototype.

Chapter 4 presents a modified QGBC forPMBLDC motor drive in EV application.

This converter has eliminated the two power diodes presented converter in chapter 3. The converter working principle in boost or motoring mode and buck or regenerative braking mode is explained. The converter design and stability analysis are described. Finally, the experimental validation with motoring and regenerative braking of PMBLDC motor.

Chapter 5 presents coupled inductor-based QGBC for high gain and low ripple for PMBLDC motor in EV application. The converter operation in step-up or motoring and step-down or regenerative braking for continuous conduction mode and discontinuous mode. The small signal model has been developed and the controller parameter is selected. Finally, simulation and experimental have been provided to support the developed prototype.

Chapter 6 presents the conclusion and future scope of the work in the area of converters, PMBLDC motor for EV application.