

ANALYSIS OF SERIES-PARALLEL HYBRID ELECTRIC VEHICLE WITH SUITABLE DC-DC CONVERTER FOR A GIVEN DRIVE CYCLE

A Dissertation submitted in fulfillment of the requirements for the Degree

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MASTER OF ENGINEERING

in

Power Systems

Submitted by

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CERTIFICATE

Certified that the dissertation entitled, "**Analysis of Series-Parallel Hybrid Electric Vehicle with Suitable DC-DC Converter for a Given Drive Cycle**", which is being submitted by Jasandeep Singh in partial fulfillment of the requirements for the award of the Master of Engineering in Power Systems, to Thapar University, Patiala, is a bona-fide record of the candidate's own work carried out by him under my supervision and guidance. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other university or institute for award of any degree.

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, “**Analysis of Series-Parallel Hybrid Electric Vehicle with Suitable DC-DC Converter for a Given Drive Cycle**”, in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of Dr. Santosh Sonar. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

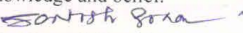
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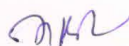
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ABBREVIATIONS

HEV	HYBRID ELECTRIC VEHICLE
SPHEV	SERIES-PARALLEL HYBRID ELECTRIC VEHICLE
EMS	ENERGY MANAGEMENT SYSTEM
PMSM	PERMANENT MAGNET SYNCHRONOUS MACHINE
ICE	INTERNAL COMBUSTION ENGINE
PI	PROPORTIONAL INTEGRAL
BMS	BATTERY MANAGEMENT SYSTEM
SOC	STATE OF CHARGE

NOMENCLATURE

F_T	TOTAL TRACTIVE FORCE
T_M	MOTOR TORQUE
P_D	DRIVE POWER
V_C	CAPACITOR VOLTAGE
V_L	INDUCTOR VOLTAGE
V_D	DIODE VOLTAGE
I_L	INDUCTOR CURRENT
V_O	OUTPUT VOLTAGE
P_M	MECHANICAL POWER
P_E	ELECTRICAL POWER

ABSTRACT

Due to depleting conventional energy resources, ongoing research and development area is focused on finding the alternates which are clean and efficient. In transport sector, as the fuel prices are consistently rising and simultaneously harmful emissions are causing serious environmental impacts, the automotive industry has shifted to the development of Hybrid Electric Vehicle/Electric Vehicle which overcomes the limitations and problems faced by conventional vehicles. Many automotive companies including Maruti, Mahindra, Toyota and Tesla are competing with each other in the field of HEV's. The electrical system in the vehicle comprises mainly of battery source, dc-dc converter and the motor drive. The dc-dc converter is the key element in the Hybrid electric vehicle system which boosts the voltage level of battery to the rated voltage level of the motor drive and also helps in reducing the size of huge battery packs. Also during regenerative action, dc-dc converter is used to buck the generated voltage level to charge the battery bank.

The thesis work started with studying various dc-dc converters including Buck, Boost, Buck-Boost, Push-pull and various others. Merits and demerits of the converters are analysed. Improved dc-dc converters including Z source and Trans z source dc-dc converters are simulated in MATLAB initially for resistance load. The Z source dc-dc converter is mathematically modeled using the State space averaging technique and its step response is plotted. Mathematical modeling using State space averaging technique is also performed for Trans Z source and bi-directional dc-dc converter.

The work aimed at application of bidirectional DC-DC converters in Hybrid electric vehicle. The Bi-directional full bridge dc-dc converter is implemented in Series-Parallel hybrid electric vehicle model in SIMULINK. The closed loop speed controller using PI controller is used for achieving the speed demanded by the driver in terms of acceleration in motor and generator drives. It is also used for deciding the throttle values of ICE according to the power demanded by the drive train. The results include the analysis and discussion of various parameters including voltage, current, power and drive torque. The charging/discharging of battery for acceleration and deceleration modes of operation is also presented and justified.

CHAPTER 1

INTRODUCTION

1.1 Background: -

The concern for preserving the environment and its resources has led to the introduction of alternative green energy resources which should not compromise with the exploitation of environment while contributing in development of the society. The HEV is the most interesting and popular technological advancement of this era. Hybrid electric vehicle is a combination of two or more propulsion systems, one of which is mainly a storage element. Hybrid vehicle are driven by internal combustion engine as well as battery whether separately or simultaneously. Hybrid Electric vehicles are classified according to their architecture and working principle into three main configurations- Series, Parallel and Series-Parallel or power-split. Recently Tesla has announced to launch HEV named Model-3 in India. So competition and popularity in this area is increasing day by day. Although traditional vehicles also have battery but its function is to ignite the fuel and operate the small capacity gadgets and the vehicle is driven by engine alone thus burning the fuel and causing pollution too. But in HEV's, drive cycle rely majorly on clean energy resource i.e. battery banks. To drive the high powered motors connected to wheels of the vehicle, rated voltage has to be supplied through the battery banks. This resulted in use of high capacity battery banks which consumed huge space and made the system bulkier and costly. To limit this problem, dc-dc converters were introduced in Hybrid electric vehicles. These converters play a crucial role in operation of HEV's as these boosts the input battery voltage to the rated motor voltage without having to install huge battery banks in the vehicle system. It reduces size and cost of the vehicle. Some of the common chassis configurations in HEV are discussed as follows: -

Series Hybrid Electric Vehicle Configuration

Series Hybrid vehicle architecture is the simplest one among all. The driving force is only the motor which gets supply from either battery or the gasoline engine. As we can see from the Figure.1, engine is directly coupled to generator set, which drives the generator shaft and electrical power is generated which is further supplied to the motor and thus drives the vehicle.

Both the powers from the battery as well as Generator are fed to the Power Converter .It boosts the voltage and fed to motor terminals. In series hybrid, the main aim is to drive the vehicle through the battery power. Therefore, the limitation encountered in this configuration is that we need to install the battery packs of large capacities. The ICE is installed in this configuration as an backup which only supplies power to the drive train when the battery is completely discharged.

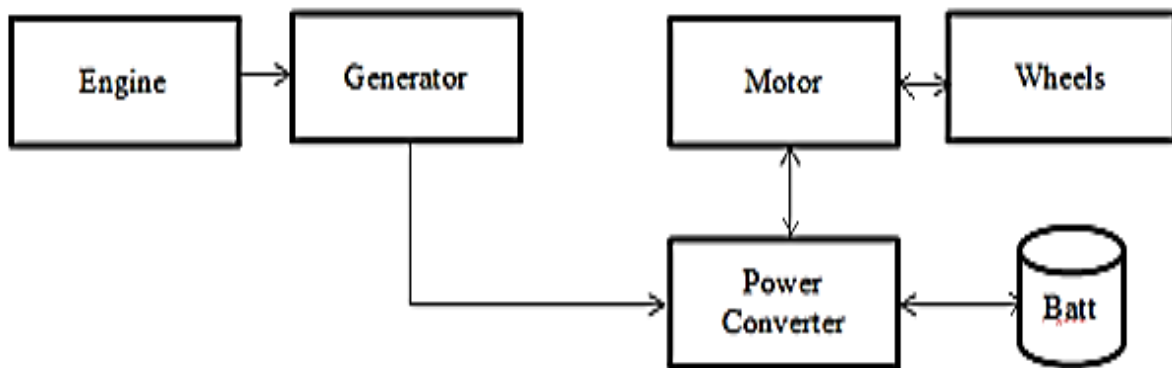


Figure 1: Series Hybrid Electric vehicle

Parallel Hybrid Electric Vehicle

The parallel HEV configuration tries to eradicate the demerits of the Series hybrid configuration. In this system, engine is not isolated from the motor as was in the case of series hybrid. This configuration generally does not need generator though as in earlier case. The engine is coupled to motor through gears and it is directly coupled to the shaft. The charging of the battery is performed by the external circuit or through the regenerative braking. During regenerative braking, motor drive acts as a generator and converts the kinetic energy into the electrical energy. Due to combined efforts by both the sources during drive cycle, there is no need of huge battery banks as we can recharge the battery during braking or deceleration modes.

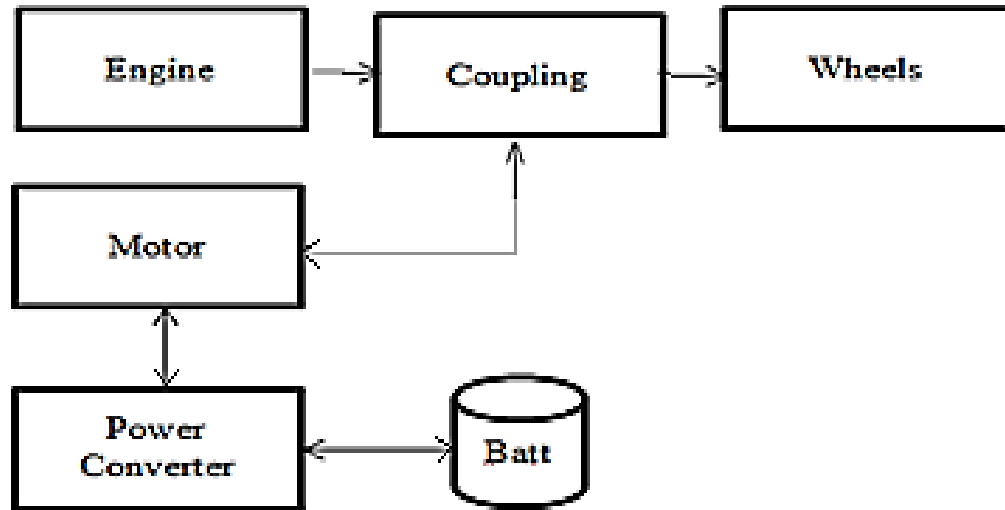


Figure 2: Parallel Hybrid Electric vehicle.

Series-Parallel Hybrid Electric Vehicle

Series-Parallel hybrid configuration, also known as power split configuration is the combination of series and parallel configurations. The merits of both the architectures are blended to enhance the range of performance of the vehicle. These are generally Parallel hybrids but only difference is that the engine, generator and motor are coupled to each other through the planetary gears. The planetary gears include three component gears- Sun gear, Ring gear and Carrier gear. The Sun gear is connected to the generator, Ring gear is connected to the motor and Carrier gear is connected to the Engine shafts. The planetary gears split the engine power between motor and generator drives which depends upon the ratio of ring gear to that of sun gear. The Energy Management System is designed to control the fulfillment of demand power whether through the engine power or through the battery power. The main aim of the EMS is to harness more energy through the battery unless additional energy is required which can be met through the engine. The charging of the battery during the regenerative braking mode is also controlled by EMS.

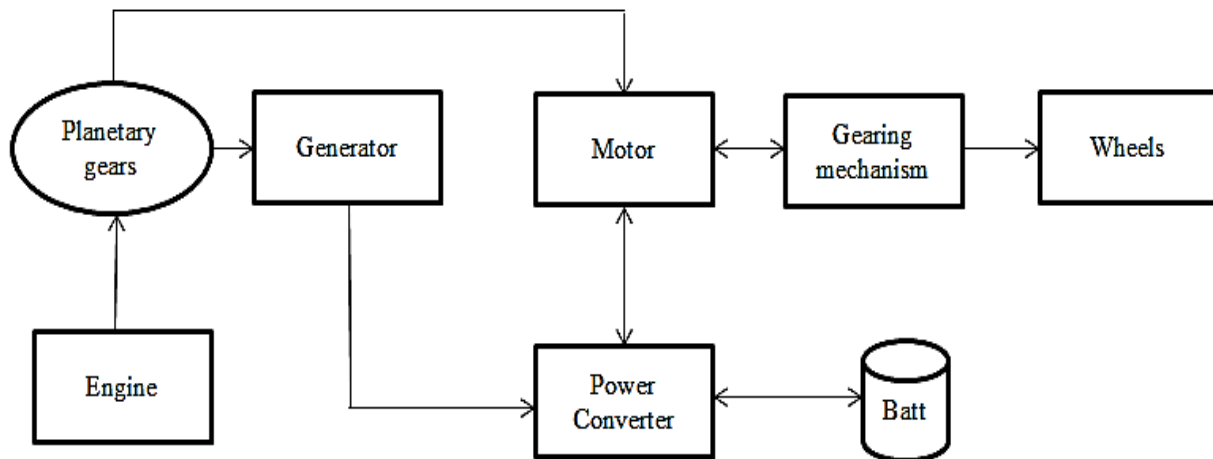


Figure 3: Series Parallel Hybrid Electric Vehicle

The EMS operate according to the accelerator input by the driver so to meet the required driving power, sharing of power is decided and implemented. During acceleration operation, engine supplies power to the generator which drives the motor shaft whereas during braking mode, engine and generator are idle and the motor acts as a generator to charge the battery.

DC-DC Converters

The dc-dc converters are the most important consideration in the field of HEV's which are used to boost the input battery voltage to the rated motor voltage in case of forward acceleration and operates as buck converter during regenerative braking for recharging of batteries. It can be considered as the equivalent circuit consisting of an AC transformer with the variable turn's ratio. Similarly to the working of transformer, it can also step up as well as step down the levels of voltage. The DC converters mostly find its application in traction systems in controlling the motor in automobiles, trucks, cranes etc. DC-DC converters also known as Choppers is the power electronic device which transform the level of DC input voltage to give the desired DC output voltage. It is designed to convert fixed input dc voltage to varying dc output through buck or boost operation. The DC converters has important role to play in case of regenerative braking in which kinetic energy of the vehicle is supplied back to the source and this technique is very important in increasing the efficiency of the vehicular system.

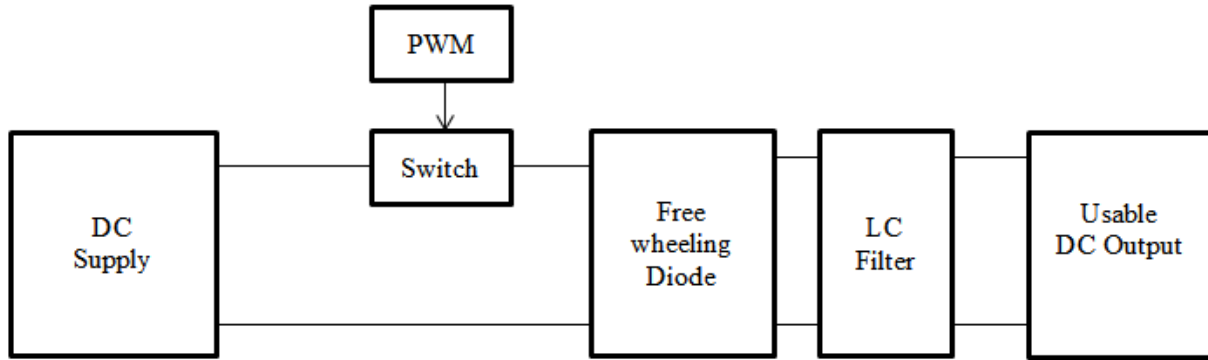


Figure 4: Block diagram of DC-DC Converter

DC-DC converters make use of a high speed switches like MOSFET, IGBT etc. The purpose of the switch is to develop a connection between source side and load side. During on and off operation, load is connected and disconnected from the source respectively. The fixed source voltage at the input is converted to variable dc voltage by varying the switching frequency. During the on period, switch is at ON position and source voltage is directly applied at the load. During the off period, switch is at the OFF position and the load current flows through the free-wheeling diode. The FD during freewheeling operation short circuit the load resulting null voltage across load.

There are two important methods to control the duty cycle are described below:-

1. *Constant frequency operation:* - In this method, switching frequency of the converter or the switch is kept constant and just ON time is varied. As the width of the pulse is varied in this method, therefore it is also known as Pulse width modulation (PWM) control.
2. *Variable frequency operation:* - As the name suggests, switching frequency of the converter or the switch is varied by varying T keeping ON time or OFF time constant . The frequency is varied to the wider range to vary the duty cycle. This method is also known as Frequency modulation.

CHAPTER 2

LITERATURE SURVEY

2.1 Overview of Hybrid Electric Vehicle

With the aim of improving the efficiency of the drive train, HEV's are introduced in the automotive sector. The comparison and analysis of a number of hybrid and battery operated vehicles in different regions is discussed which developed the trend of past few years pointing out the change in technologies depending upon various parameters including machine technology, installation and energy capacity [1]. HEV's are more efficient than the traditional vehicles due to their in-dependency on conventional fuels and causing less emission. The characteristics including fuel consumption and emission are compared between conventional vehicles and HEV's [2]. These vehicles use battery source or fuel cells instead of internal combustion engine for propulsion which encourages the conservation of environment and fuel for future generation. Various battery technologies including Lead-acid, Nickel meta hydride and zinc air fuel cells are analysed in terms of technical performance for utilization in commercial HEV's [3]. The Hybrid electric vehicle is split into three basic configurations- Series, Parallel and Series-Parallel or power split configurations. Series configuration is the basic architecture in which ICE is isolated from the transmission system so to be fuel efficient, large battery banks are to be installed and are presented in [4]. The parallel architecture overcomes the limitations encountered in series architecture by coupling engine and the motor to the wheels in parallel thus allowing the simultaneous flow of energy from engine as well as battery run motor. Modeling of multi-purpose series hybrid is presented [5]. Thirdly, Series-Parallel configuration combines the merits of both series and parallel and is considered more flexible and efficient which is compared with the series and parallel configurations and results are discussed in [6]. It is basically a parallel hybrid in which planetary gears are introduced for coupling between engine, generator and the motor which allows the sharing of power from all the sources simultaneously. The derivation of the model and its experimental analysis are studied in [7]. This configuration combines with certain control systems including energy management, battery management and hybrid management which are designed and discussed to allow better drivability [8]. The HEV's can be partially or fully hybrid depending upon the drive train and demand. The partial hybrid

utilizes only battery energy and is less efficient than fully hybrid which comprises of combination of ICE and battery packs which are compared in [9] in terms of the architecture and performance. Another topology i.e. Plug-in hybrid is also gathering popularity due to their flexibility in external charging mechanism. The Plug-in is the modified HEV which offers friendly user interaction for self-charging whether from home circuits or grid charging [10]. Plug-in hybrids offer external charging circuits so that the battery banks can be recharged through normal home switching circuits or power grids. The vehicle to grid technology is also in discussion for the futuristic approach which could be a major turn over in HEV market. The merits and demerits of V2G technology are discussed in [11].

The ICE power coupled to generator produces electrical energy which is used for recharging the battery in parallel and series-parallel hybrids during regenerative braking mode which is experimentally justified [12]. The ICE is required to maintain the specific speed throughout the drive cycle which can be done using PI controllers which are designed by Zeigler-Nichols method or by trial method [13]. The base speed of ICE has to be maintained because engines cannot be made to run instantly when required as they need time to get into synchronization for feeding the power as discussed in [14]. The HEV's are considered as a part of green and clean energy system which rely mostly on batteries instead of burning of hydrocarbon fuels in ICE thus reducing the level of pollution and is analyzed by the comparison tests based on the drive cycle [15].

In the thesis work, the series-parallel configuration which is mostly found in all the commercial vehicles in the market due to its unparalleled advantage over the other configurations is implemented. This architecture includes the coupling of ICE, generator and motor drives. The ICE is directly coupled to the generator in series whereas battery, motor drive and generator drive are further connected to each other in parallel with a common dc bus [16]. Various control strategies including energy management system (EMS) which is responsible for controlling the flow of power in HEV are analyzed and discussed in [17].

The EMS is the brain center of HEV which develops a relation between accelerator signal and the drive torque. This system controls the demand power and commands the Hybrid system to match the supply with demand by acting on different parameters in order to minimize the fuel consumption [18]. The ICE controller is introduced in EMS in meeting the speed demands of

ICE and controls the throttle output depending upon the hybridization parameters which are discussed in [19] so that fuel consumption is less adding to higher efficiency of the system. The modeling of the controller is presented in [20]. EMS ensures the efficient working of all the components clubbed together so that they work in synchronization. The EMS is huge system comprising of different sub systems including battery management, ICE controller and Hybrid management systems as discussed in [21]. The control center of HEV i.e. EMS consists of Battery management system (BMS) whose sole purpose is to control the state of charge of the battery. The SOC system in the battery model defines the charging capacity status of the battery which is modeled in [22]. BMS also ensure that battery is not discharged below certain limit which is generally 20% in order to avoid sedimentation of the battery so that recharging phenomena is not hindered.

The series-parallel configuration is analyzed and compared with the introduction of electric variable transmission technology and its results are compared in [23]. The power split control in series-parallel configuration is performed by introduction of planetary gears which are coupled in between ICE, motor drive and generator drive as shown in [24]. As the name suggests, these gears resemble the planetary motion in the universe and revolves around each other to vary the speed and direction whose working operation is discussed in [25]. The planetary gears consists of three basic gear teeth's- sun, carrier and ring which are coupled to generator, ICE and the motor drive respectively. The control of the motion of planetary gears depends upon the ratio of ring gear to that to sun gear. The relation between the number of teeth and their rotational speeds including mathematical formulations are presented in [26].

Apart from the Simulink modeling, futuristic approach is discussed. Certain renewable sources of energy are clubbed together with the HEV's to offer more reliability and flexibility. The solar energy roofs of the vehicle or fuel cell technology implemented in the HEV enhances the performance levels [27]. These are implemented to extend the driving range of the vehicle instead of using high capacity battery banks, also ultra-capacitors are being introduced which saves the space and size in HEV as well. A complete overview of the hybrid electric vehicle including its origin, improvements in the HEV technology and future scope is discussed in [28].

2.2 DC-DC Converters

Moving to electrical system of the vehicle, it is the most important part of the HEV which decides the level and degree of hybridization. It comprises of motor drive, generator drive and the dc-dc converter connected to each other. The motor drive is a sub-system including control center for high powered motors. The control parameters of these drives including speed controllers using PI controller are mathematically modeled. [29]. Various motors according to their power ratings, size and speed control are introduced for electric hybrid vehicles but the motors used in the HEV's are mostly BLDC or PMSM motors whose construction and working is presented. These are used for their higher efficiency, power density and robust construction [30]. The generator drive is similar to the motor drive provided the torque is negative to that of the motor drive. To connect these drives to a common bus, a power electronic interface as modeled in [31] is needed i.e. dc-dc converters are designed which act as a bridge between drives and battery source.

One of the key aspects of introduction of HEV's is to enhance the efficiency of the vehicle drive train. The battery banks offer high voltages to drive the motor at low currents which thus limit the losses as discussed in [32]. The rise in voltage can be attained by connecting batteries in series with each other to meet the demand by the motor drive. Although, voltage level can be met by this method but it simultaneously increases the weight and size of the system thus adding to high cost. Another effective alternate is to introduce Bi-directional full bridge dc-dc converter [33]. The utilization of suitable dc-dc converter reduces the size of the hybrid system and increases its efficiency. The merits of using the dc-dc converters in HEV are discussed in [34]. These converters boost the input battery voltage to the rated value of the motor drive without affecting the size of the battery. The important factor of the bi-directional converter for its application in HEV is that it provides flow of power in both the directions as explained in [35]. The power flows from battery to motor drive during forward acceleration mode whereas it reverses in case of braking or regenerative operation. This helps in reducing the size of battery banks as well extend the range of drivability. Various methods and topologies of using dc-dc converters using different configurations of inductors and capacitors in a circuit are compared including the application of bi-directional dc-dc converter feeding the permanent magnet dc motor in battery fed electrical vehicle [36]. The bi-directional dc-dc converters employ the

inductor at battery side which acts as a booster during boost operation while it acts as a filter during buck operation and its working operation is explained in [37]. The four phase multilevel dc-dc converter overcomes the use of inductance thus increasing the efficiency of the system by reduction in ripples and its results are compared with bi-directional converter [38].

Bi-directional dc-dc converters can have isolated or non-isolated configurations. Non-isolated converter is proposed for charging and discharging of battery packs in UPS or HEV's. This configuration is achieved using less number of switches and resulting in high voltage gain. Also zero voltage switching technique is introduced for reducing the conduction losses and current stress on the switches [39]. An isolated bi-directional converter using high frequency transformer is introduced and its control strategies for decoupled flow of power resulting in fast dynamic response are presented. The reduction in delay time and rise time avoids the current spikes and noise. [40]. Further isolated bi-directional full bridge dc- dc converter is proposed with super capacitor represented as the battery pack. It acts as an interface between low voltage, high current operation at battery side and high voltage, low current operation at motor side. The input dc voltage source fed to the dc-dc converter can be electric battery or ultra-capacitors considering the space and size requirement [41]. The ultra-capacitors offer wider range in input voltage which is fed to isolated bi-directional dc-dc converter. The zero voltage switching is introduced for soft switching and reduction in current stress for transformer connected circuits. These configurations are preferred for high power density applications [42]. Another modular isolated dc-dc converter is studied which allows the bi-directional flow of power by phase shifting between the two bridges at regular intervals [43]. The converters are designed and modeled with less number of switches i.e. using at most one switch to control the switching phenomena using PWM in order to reduce the switching losses and cost thus increasing the efficiency [44].

The ongoing research in HEV industry aims at implementing the fuel cells as the source of energy replacing the traditional battery packs which is presented in [45]. The power flow in the bi-directional dc-dc converter is controlled using phase shifting or duty cycle in the fuel cell powered vehicle. The proposed converter encourages minimized use of switches and two high frequency transformers. This current fed converter is energy efficient but at the same time more complex and bulkier [46]. The bi-directional converters have found many applications due to its

flexibility in design and control, are used as an energy buffer with super capacitor. At this point, we know that bi-directional dc-dc converters have high efficiency and wide number of applications including HEV, SMPS, chargers and UPS. Aiming at futuristic approach, Plug-in HEV's are found to be more flexible and environment friendly.

The PHEV's have introduced the concept of vehicle to grid technology which allows the exchange of power between the vehicle and the grid. The converter develops the interface between the grid and the vehicle for ac-dc-ac conversion. The V2G technology and non-inverted bi-directional buck-boost converter is modeled and discussed in [47]. This has reduced the requirements of large size of battery packs and enhanced the performance level. Likewise V2G, to enhance the working performance of HEV, two or more sources of energy including solar panels or wind energy are used in parallel and independently which increases the reliability of operation as described in [48]. The battery pack is supported by super-capacitors or solar panels fitted on roof top of the vehicle so as to extend the range.

The limitation of bi-directional converter includes the appearance voltage and current spikes which affects the performance of the system. The comparison of the converter with and without using Fly-back snubber which is used to minimize the spikes is presented in [49]. The snubber circuit is used for limiting the spikes and EMI noise from the output. The bi-directional topology is compared with two different configurations including cascaded inductor and capacitor in the middle depending upon the ratings, stress and switching losses in [50].

The study has also been carried forward in developing and implementing the various configurations of Z-Source. It employs a distinct circuitry which aims at removing the demerits of current source as well as voltage source inverters and hence improving the voltage profile output. Due to its unique configuration, it focuses on its application in Electric Hybrid Vehicles or Fuel Cell Vehicles [51]. Certain control methods of Z- Source Inverter which includes Simple Boost and Maximum Boost techniques are discussed. Various important factors such as Modulation Index and Shoot through duty ratio are observed. It is found that increasing the values of Modulation index results in reduction of dc link voltage overshoot and rise in power flow capacity of inverter [52]. A general approach towards usage of impedance or Z network in conversion from dc to ac, dc to dc, ac to ac or ac to dc is studied. Various converter topologies are discussed whether bidirectional, buck-boost or high frequency conversions to reduce the

number of levels in conversion. It presents the comprehensive approach to design, modeling and control of various converters which improves its reliability and performance. It gives various parameters including voltage gain, losses and powers rating for the selection of efficient converter for the particular application [53]. The LC coupling is placed between the power source and input of the inverter or converter which is mainly responsible for boosting of voltage to high levels that is not possible in currently available converters. It is learnt that z source configuration is available for ac-dc, ac-ac, dc-dc as well as dc-ac configurations which makes it quite popular technology to replace the present converter circuitry [54].

The Z source converter is operated in different modes such as Shoot through and Non-shoot through states. It is found that shoot through state which is not acceptable in traditional converters but is important factor in boosting the output voltage in Z source converters [55]. The steady state values of the capacitor voltage, dc link voltage and output voltage are observed through Simulation which are verified through the mathematical calculations [56]. Mathematical modeling of Z source converter using State Space Averaging method is performed for continuous conduction mode. In state space averaging model, two models are developed i.e. large signal model and small signal model. The design of controller which drives the dc-dc converter is also discussed [57]. The transient response of the Z source dc-dc converter is studied. The unique feature of the Z source dc-dc converter is that it is not affected by the shoot through state i.e. shorting of the output terminal but in fact utilize it to boost the voltage to higher gain. In shoot through state, transfer of energy takes place from inductor to capacitor. The transient response of the model was obtained by giving the step input [58].

The study of Z source converter is extended to modified and improved circuit known as Trans Z source converter and it is found to be much better than traditional z source configuration. In the circuit, coupled inductors of transformer have led to reducing the size of circuit as well as inductances. Here only one capacitor is used in the circuit [59]. A modular approach to dc-dc converters designed for high power applications is also followed. The dc-dc converter designed is bidirectional for its application in hybrid electric vehicle during regenerative braking. The key factors of this converter are its tolerance towards faults and redundancy [60]. It does not use bulky transformer so the circuit is quite simple. A multi-level dc-dc converter is used for high voltage gain as well as low voltage operation and bidirectional power flow which

ismathematically modeled in [61]. Similarly, dual input dc-dc converters which allows the two sources of energy such as solar panels and battery to be connected in parallel thus increasing the reliability of operation are also designed according to their demand and applications as presented in [62].

1.2 Main Contributions in Thesis work: -

- a) Analysis of Bi-directional full bridge dc-ac-dc converter suitable for HEV.
- b) Modeling and simulation of Series-Parallel Hybrid Electric Vehicle model for particular drive cycle.
- c) Implementation of bi-directional full bridge dc-dc converter in SPHEV for acceleration and regenerative modes of operation.
- d) High voltage gain is obtained with low output currents to reduce I^2R losses.
- e) The charging and discharging of battery during these modes is studied and justified through results.
- f) Modeling of Z source and Trans Z source dc-dc converters using State Space Averaging Technique.
- g) Study of speed controllers using PI controller. The vector control fed PMSM drive operation is also studied.

1.3 Organization of Thesis work: -

The thesis work has been divided as follows: -

- **CHAPTER 3** It provides the State Space Averaging methodology for analysis of Z source and Trans Z source dc-dc converters. Speed control and Vector Control for controlling the operation of PMSM motor drive is explained.
- **CHAPTER 4** deals with the mathematical modeling of Bi-directional dc-dc converter, Z source as well as Trans Z source dc-dc converters. Various DC-DC converters are compared. Mathematical modeling of HEV is presented.
- **CHAPTER 5** presents the Simulation results and discussion.
- **CHAPTER 6** presents the Conclusions and the Future Scope.

CHAPTER 3

METHODOLOGIES

3.1 State Space Averaging Technique: -

Modeling of switching converters is performed by two main methods- one is by the state space modeling and other is by using an averaging technique. The first method strictly focuses towards computation of equations and manipulations, therefore highly dependent on numerical methods and integrations. It has unified description of all the power stages independent of the type of converter i.e. buck, boost or any other by developing the state space equations of two separate switching models. While the other method deals with the processing of equivalent systems and representing them to form a single equivalent circuit of the power stage. This method is used for linearizing the complex switching circuits. This method has unique advantage of imbibing the physical insight behavior of the original equivalent circuit. The circuit averaging technique is bridged with the state space technique to form State space averaging method which offers advantages of both.

The proposed method outlined in the Flowchart of Fig. 16 allows the mathematical modeling of large number of levels in power converter switching circuits as the step of averaging the model is quite simple mathematics and is clearly depicted in the flowchart. It consists of averaging of two state space models for ON period i.e. T and other for the OFF period i.e. T' over a single cycle T where switching frequency is given by $f_s = 1/T$. The averaged model is inclined to a small disturbance or perturbation to include the duty ratio modulation effect. This led to the development of two general models- steady state dc model and other is small signal ac model. The transfer functions of the output variables with respect to small change in duty ratio are available at the end of the procedure. The small signal analysis by adding the disturbance is performed for the dynamic circuits where change in state of operation over the regular intervals is seen. It helps in studying the transient effects in the circuit along with the steady state analysis.

Flowchart depicting the procedure of averaging the state space equations is presented: -

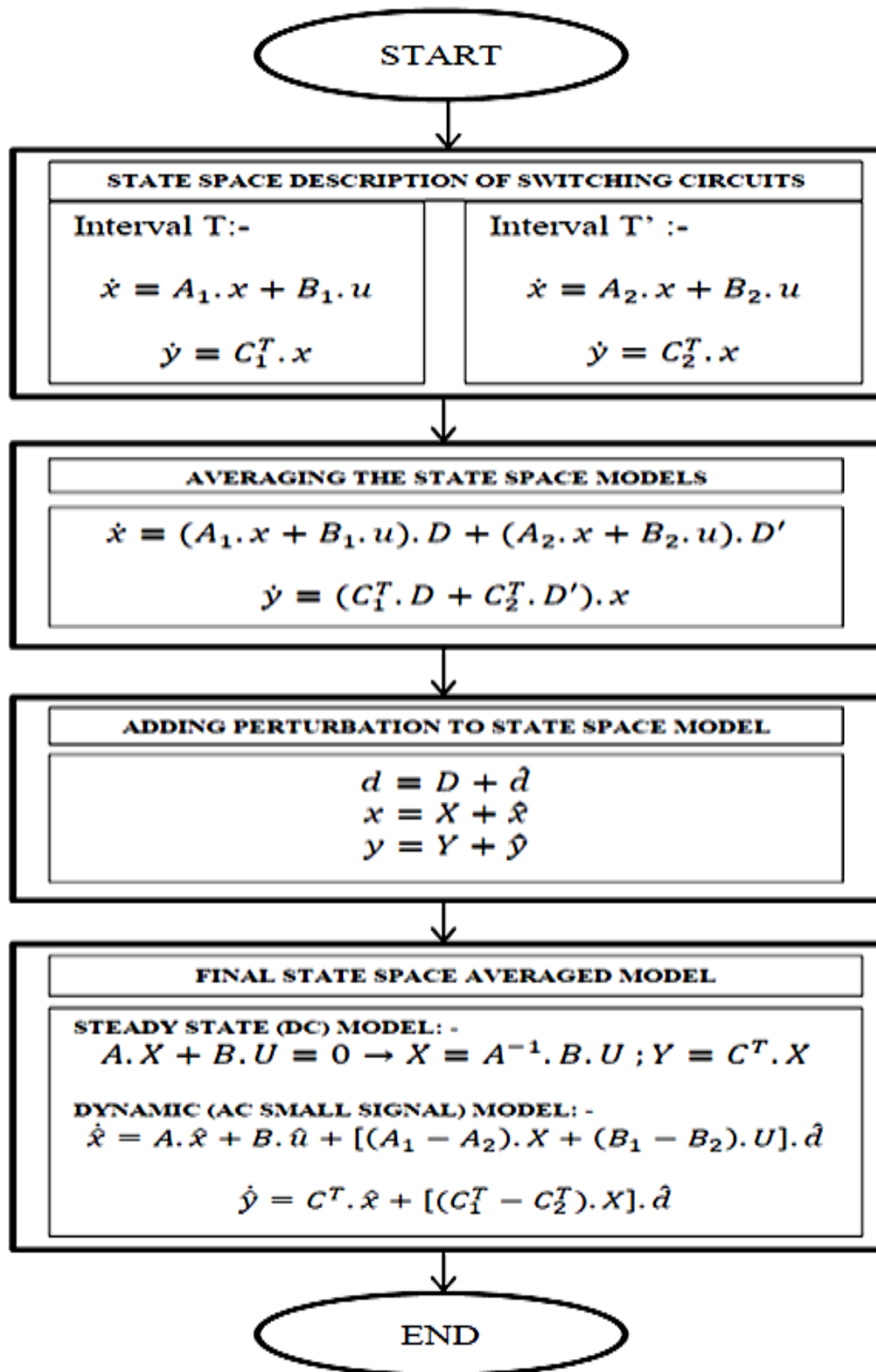


Figure 5: Flowchart of State Space Averaging Technique

where x and y are state variables.

u is the input

A is state transition matrix

B is the input matrix

C is the control matrix

d is the change in duty ratio

T and T' are the ON and OFF switching time intervals

Advantages: -

- a) The mathematical equations are represented in a compact form.
- b) The computation of steady state dc analysis and ac small signal analysis is done by using simple equations.
- c) The method linearizes the circuit and being time invariant, no switching ripples are considered for constant duty cycle.
- d) This technique is used basically for complex circuits involving switching over regular time intervals.

State space averaging technique offers a clear understanding into quantitative approach of basic averaging approximation. Further, the small signal analysis at low frequencies offers the smaller voltage ripple output. Thus it does not pose any limitation or restriction in modeling of dc-dc converter. Finally, it can be said that this technique serves as the efficient mechanism for modeling of general circuit model that describes the input-output control parameters of any dc-dc converter.

3.2 Speed Control of PMSM Drive using PI controller: -

The speed controller is a closed loop operation which controls the speed of the motor by comparing the actual speed with the demand speed. The demand speed is obtained from the driver of the vehicle in terms of the pressure on the accelerator pedal. The accelerator range varies from 0 to 1 which is equivalent to motor speed ranging from 0 to 6000 rpm. This demand speed is fed to the speed controller input. Below is the block diagram depicting the working of speed controller using PI controller.

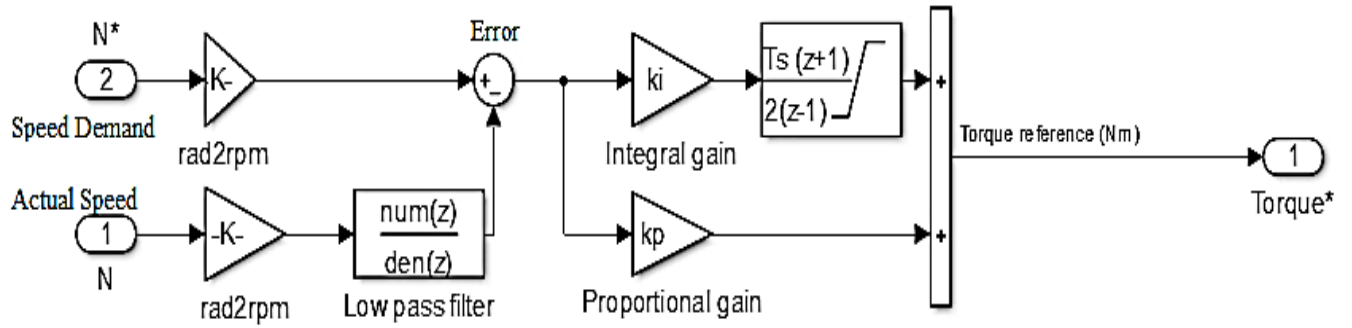


Figure 6: Closed loop Speed Controller

The demand speed and the actual speed of the motor are compared and the difference between them i.e. the error signal is generated. The actual speed is fluctuating signal in practicality which is passed through the Low pass filter which filters out the peaks and harmonics. The error signal is passed through the PI controller. The values of K_p and K_i are set manually through repeated testing on the Simulink model by trial method. The PI controller is used to reduce the steady state error occurred due to difference in demand speed and the actual speed. The output of the PI controller is a signal denoted by Torque* i.e. reference torque which is an input control signal for the vector control analysis.

Transfer function of the PI controller is given as: -

$$G(z) = K_p + \frac{T_s(z+1)}{2(z-1)} K_i \quad (3.1)$$

K_p = Proportional gain

K_i = Integral gain

Transfer function of Low pass filter:-

$$H(s) = \frac{1}{1 - e^{-2\pi f t}} \quad (3.2)$$

f = cut-off frequency = 100Hz

$$N \text{ (rad/s)} = \frac{2\pi N \text{ (rpm)}}{60}, \text{ where N is speed in rpm}$$

Table 1: Speed Controller using PI controller for constant drive cycle

Time	Speed Demand	Gain(rad to rpm)	Actual speed	Gain(rad to rpm)	Filter output	Error	Effect of Kp	Effect of Ki	Torque*
2	628.32	6000.00	619.29	5913.75	5908.62	91.38	31.90	0.173	32.07
2.5	628.32	6000.00	627.13	5999.66	5999.66	0.34	0.12	0.005	0.12
3	628.32	6000.00	627.13	5999.67	5999.67	0.33	0.13	0.005	0.14
3.5	628.32	6000.00	627.13	5999.69	5999.69	0.31	0.14	0.005	0.14
4	628.32	6000.00	627.14	5999.71	5999.71	0.29	0.15	0.005	0.15
4.5	628.32	6000.00	627.14	5999.72	5999.72	0.28	0.16	0.004	0.16
5	628.32	6000.00	627.14	5999.74	5999.74	0.26	0.17	0.004	0.17
5.5	628.32	6000.00	627.14	5999.76	5999.76	0.24	0.18	0.004	0.18
6	628.32	6000.00	627.14	5999.77	5999.77	0.23	0.19	0.004	0.19

Characteristics of PI controller: -

The proportional controller is used in the circuits where there is a lag between the demand and the actual input speed. It reduces the rise time and helps in minimizing the steady state error. On other side, Integral controller not just reduces but try to eliminate the steady state error.

The PI controller has been implemented for the PMSM motor drive, PMSM generator drive and the internal combustion engine. The controllers are designed with different values of parameters for different tasks respectively. Torque* signal which is described earlier is the input for vector control of PMSM drive. The speed control is the inner loop whereas current control is the outer loop for the vector control analysis.

Table 2: Parameters for PI controllers

PI Controller	K _p	K _i	Output
Motor Drive	0.35	0.0015	Torque* (vector control)
Generator Drive	0.002	0.0005	Torque* (vector control)
ICE	0.01	0.1	Throttle

In ICE, demand speed is offered by the Battery management system, which will be explained in later chapter. The BMS controls the state of charge of the battery and whenever it is below 20% (in general), it sends the signal to energy management system to start the internal combustion engine for the vehicle propulsion. These signals are compared to output the Throttle signal to run the vehicle according to the acceleration provided.

Tuning of PI controller: -

The process of selecting the suitable values of parameters for the controller to get the desired controlled output is known as Tuning of the controller. The tuning can be done with the help of basic rules suggested by the Zeigler Nichols for the tuning of PI controller. The rules include setting the integral controller parameter to infinity and computing the proportional control parameter for the resulting sustained oscillations. In other case, shape of the characteristics of output is observed for unit step signal. These are somewhat complex to solve and need large amount of calculation. In our case, tuning of controllers has been performed with few iterations of value substitution to get the required output.

3.3 Vector Control of PMSM Drive: -

The permanent magnet synchronous motor (PMSM) is said to be a cross product between the induction motor and BLDC motor. The rotor of PMSM is similar in construction to BLDC motor but having permanent magnets placed on it. And the stator structure resembles to that of AC induction motor. The windings on the stator are wound in such a way so as to produce the sinusoidal flux density in the air gap of the machine. Unlike BLDC, PMSM motors run with better efficiency with sinusoidal waveform. PMSM drives does not perform well with the open loop scalar V/f control because during transient conditions, there is no rotor coil to provide mechanical damping.

Instead, a more improved technology known as Field oriented control (FOC) or Vector control is used to control the torque and speed of the motor. The principle of operation of FOC is that it transforms the three phase time variant stator currents into the two phase dc equivalents- d and q axis which decouples flux and torque respectively which are independently controlled.

The control signal Torque* generated through speed controller as discussed in previous section is fed to the vector control. The signals Torque* from Speed controller, rotor angle (θ) and actual speed value from the motor sensor are fed to the Torque to current transformation block. The three phase stator currents from the motor terminals are transformed to d-q equivalent in terms of I_d and I_q are also fed to the Torque to current block. The three phase signals are transformed into two phase system i.e. abc to d-q axis by using Park Transformation. The current I_d and I_q are directly proportional and equivalent to the Flux and Torque respectively. So the

optimal values of direct axis current i.e. I_d^* and quadrature axis current I_q^* are generated at the output of Torque to current transformation block. These optimal values are transformed back to three phase equivalents i.e. d-q* to abc* axis.

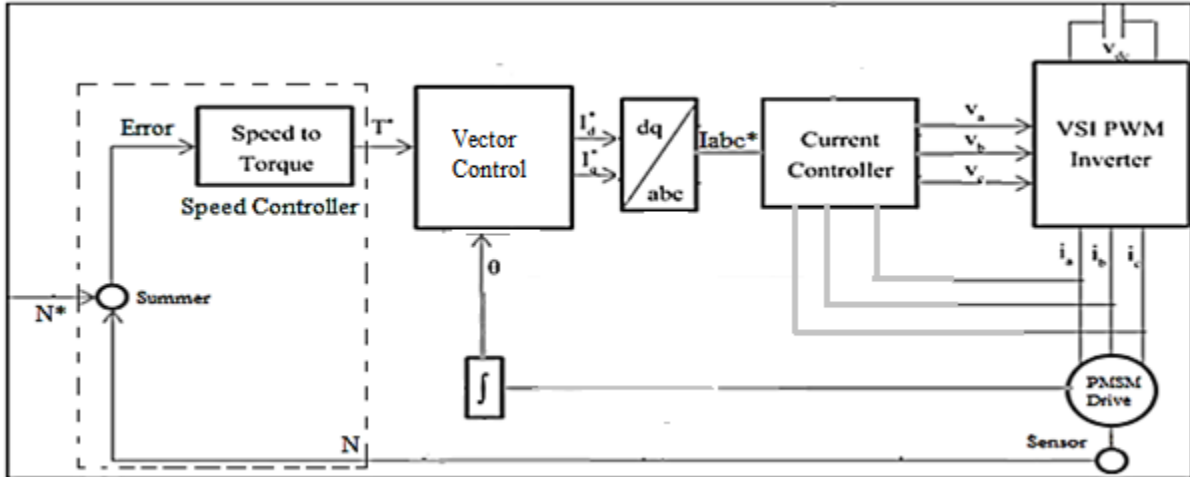


Figure 7: Control mechanism

The reference stator currents I_{abc} are now compared to the transformed currents I_{abc}^* in the current regulator. The current regulator used is basically a Hysteresis band controller in which current is made to follow the reference current in a circle shaped band. Whenever the currents are high or low in magnitude than the reference current, pulse is generated which controls the switching of the inverter. The switching sequence of the PWM voltage source inverter decides the working of the PMSM motor.

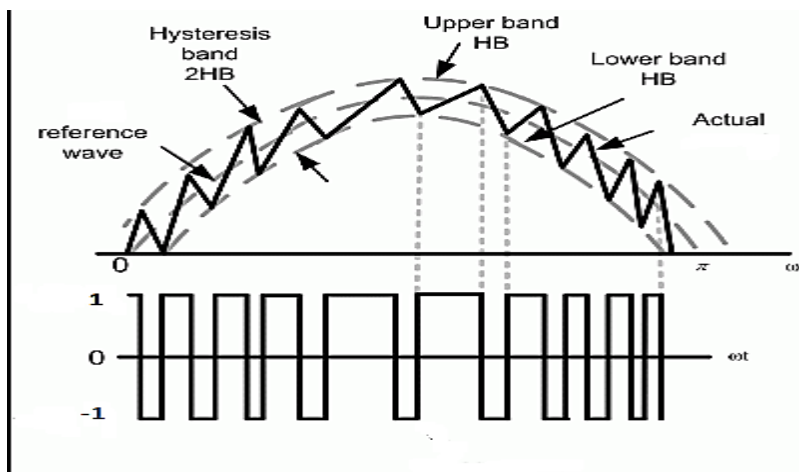


Figure 8: Hysteresis band current controller

In Fig.8, the reference currents I_{abc} is depicted by dotted line in the center. The actual stator currents I_{abc}^* follows a zig-zag path in a band. These two currents are compared and the PWM switching is obtained.

Mathematical equations of PMSM Drive: -

The equations for the flux linkages due to presence of permanent magnets are given as: -

$$\lambda_{ma} = \lambda_{pm} \cos \theta \quad (3.3)$$

$$\lambda_{mb} = \lambda_{pm} \cos\left(\frac{2\pi}{3} - \theta\right) = \lambda_{pm} \cos(\theta - 2\pi/3) \quad (3.4)$$

$$\lambda_{mc} = \lambda_{pm} \cos\left(\frac{4\pi}{3} - \theta\right) = \lambda_{pm} \cos(\theta - 4\pi/3) \quad (3.5)$$

where λ_{ma} , λ_{mb} and λ_{mc} are the amplitude of flux linkages of axis a,b and c.

λ_{pm} is the amplitude of the flux linkage produced by the permanent magnets

and θ is the time varying component of the rotor position which can be given as: -

$$\theta = \int w_e dt + \theta_o \quad (3.6)$$

where w_e is the angular speed of the rotor is magnetic field and θ_o is the initial position of the rotor position.

A PMSM is basically similar to the transformer with its secondary rotating and moreover coupling coefficients between stator and rotor phases are linked to the position of the rotor i.e. change with the change in position. Such models which are time varying are modeled mathematically by forming the differential equations, but developing matrices with the time dependent inductance components is a very complex process.

R.H. Park has given Park Transformations to simplify constructing the machine models including time varying inductance/capacitance parameters by eliminating the cumbersome calculations. In this method, the three phase stationary phase variables are mapped to two phase synchronously rotating frame, also popularly known as d-q reference frame.

So accordingly, voltage transformations from abc to d-q axis are represented as follows: -

$$\begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin \theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3.7)$$

The zero axis component of voltage v_o is neglected due to complexity in the calculations.

According to Park's transformation, equations for stator voltages in d-q frame are given as: -

$$v_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega_e \lambda_q \quad (3.8)$$

$$v_q = R_s i_q + \frac{d\lambda_q}{dt} + \omega_e \lambda_d \quad (3.9)$$

Where, λ_d is the d-axis flux linkage,

λ_q is the q-axis flux linkage.

Flux linkage equations can be represented as follows: -

$$\lambda_d = L_d i_d + \lambda_{pm} \quad (3.10)$$

$$\lambda_q = L_q i_q \quad (3.11)$$

where L_d is the d-axis inductance,

L_q is the q-axis inductance.

λ_{pm} is the amplitude of flux linkage due to permanent magnets

In steady state, when motor runs at constant speed, λ_d and λ_q become time independent.

Therefore we can eliminate the differential factors like $\frac{d\lambda_d}{dt}$ and $\frac{d\lambda_q}{dt}$ from the equations. Also neglecting the stator resistance, the model can be simplified in d-q frame as: -

$$v_d = -\omega_e \lambda_q \quad (3.12)$$

$$v_q = \omega_e \lambda_d \quad (3.13)$$

$$\hat{I}_s = \sqrt{(i_d^2 + i_q^2)} \quad (3.14)$$

$$\hat{V}_s = \sqrt{(v_d^2 + v_q^2)} \quad (3.15)$$

where \hat{I}_s and \hat{V}_s are the magnitude values of space vector current and voltage respectively.

The mathematical computation of i_d^* and i_q^* is performed using above equations. These currents are obtained at the output of Torque to current transformation block and fed to current controller.

We can further expand the equations by substituting the values of $\lambda_d = L_d i_d$ and $\lambda_q = L_q i_q$ in d-q frame.

The input power and output power of PMSM can be given by:-

$$P_{in} = [v_a \quad v_b \quad v_c] \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{3}{2} [v_a \quad v_b] \begin{bmatrix} i_a \\ i_b \end{bmatrix} \quad (3.16)$$

If we assume the system to be ideal and lossless, then input power is equal to output power.

$$P_{out} = \frac{3}{2} (v_d i_d + v_q i_q) \quad (3.17)$$

For that, we need to derive the speed formula depending on number of poles and can be expressed as:-

$$\omega_e = \frac{P}{2} \omega_m \quad (3.18)$$

where P is the number of poles.

The output power is:-

$$P_{out} = \frac{3P}{2} \omega_e (\lambda_{pm} i_q + (L_d - L_q) i_d i_q) \quad (3.19)$$

where,

P is the number of poles

L_d is the inductance referred to direct axis winding.

L_q is the inductance referred to q axis winding.

λ_{pm} is the flux linkage of permanent magnet.

The mathematical equations for computing the currents referred to d-q axis are presented. The input and output power of PMSM drive is mathematically derived which depends upon the flux linkages and inductance values referred to d and q axis respectively.

CHAPTER 4

THEORY AND CALCULATIONS

4.1 Mathematical Modeling of DC-DC Converters: -

4.1.1 Bi-Directional Full Bridge Dc-Dc Converter: -

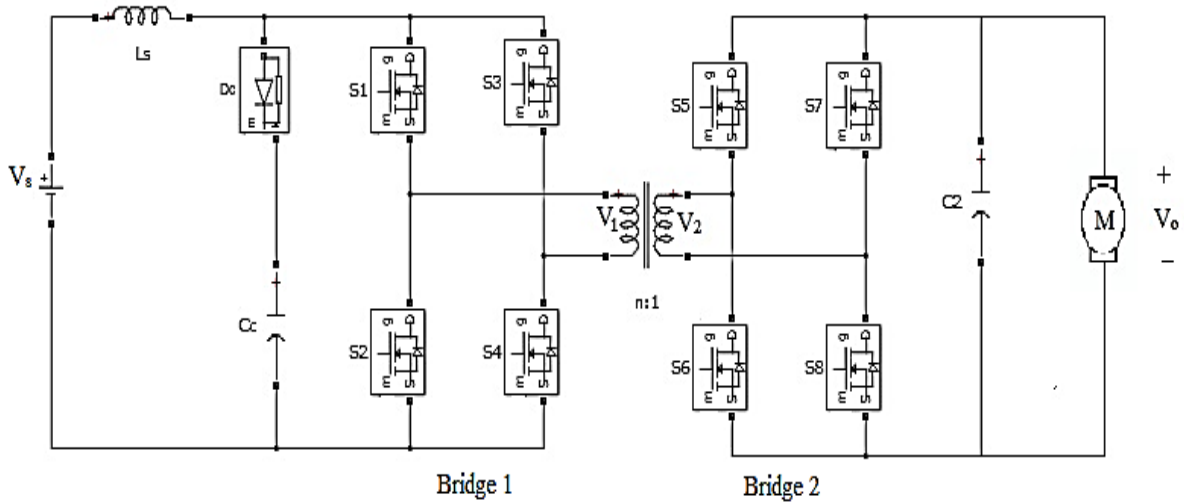


Figure 9: Bi-directional full bridge dc-dc converter

From the Fig.9, turns ratio of transformer is denoted by ‘n’

$$\text{where } n = (V_1/V_2) \tag{4.1}$$

V_1 = voltage across the primary winding of transformer

V_2 = voltage across the secondary winding of transformer

The bidirectional converter circuit is operated in two modes – boost mode and buck mode: -

Boost operation: - During boost mode, switches S1- S4 are controlled through SPWM whereas S5-S8 are uncontrolled. Only the diodes of switches S5-S8 are present in a circuit and act as a rectifier. First of all, at time t_0 switches S1-S4 are turned ON which leads to the short circuiting of primary side of transformer and voltage across it is zero. During this operation, inductor L_s is fully charged by the battery. At time t_1 , only switches S1 and S4 are conducting and this leads to

voltage across the terminals of primary winding of transformer. The diode present in clamping branch continues to conduct till the difference in the current reaches to zero. Also diodes D5 and D8 continue to conduct and allow the flow of power. During this interval, the magnitude of current difference flows through the clamping capacitor till it reduces to zero thus letting the capacitor charge till that time. The boost in level of input voltage depends upon the turn's ratio of isolation transformer and the output voltage appears at the terminals of bridge 2.

Buck operation: - During buck mode, switches S5-S8 are controlled through SPWM whereas S1-S4 are uncontrolled. Only the diodes of switches S1-S4 are present in the circuit which acts as a rectifier. During the interval t_0-t_1 , only switches S5 and S8 are in ON state whereas S6 and S7 are in OFF state. The voltage output of bridge 2 appears across the transformer causing inrush of high current. And to curb the rise in transformer current, switches S1 and S4 are conducting to allow the transfer of power to bridge 1 or current fed bridge at the instant of time. The bridge 1 is acting as a rectifier so it reflects the output voltage across its terminals. During time t_1 , switch S8 remains conducting and S5 is turned OFF whereas leakage current freewheels through the body diode D6. Also there is decrease in transformer current which rose to load current level during time t_1 . Clamping diode D_c conducts during this interval. During time t_2 , as the diode D6 already conducting, switch S6 shall be turned ON with the help of zero voltage switching technique. At time t_3 , switch S6 continues to be in conduction state whereas switch S8 is turned OFF. And diode D7 freewheel the leakage current during this interval. Similarly during time t_4 , as the diode D7 is already conducting, switch S7 can be turned ON with the application of zero voltage switching. On the whole, during this interval, other pair of diagonal switches are turned ON and voltage across the transformer reverses its polarity to balance the flux and thus curb the transient voltage problem.

Mathematical modeling during Boost mode: -

a) Bridge 1 as Inverter & Bridge 2 as Rectifier : -

During single pulse width modulation, only one pulse appears for one half cycle and the output rms voltage depends on variation in width of the pulse. The gating pulse for the switches is generated by comparing the fixed dc voltage of magnitude V_g with the triangular wave of

magnitude V_{carr} . The frequency of the signal defines the fundamental frequency of the ac output voltage.

The modulation index of system is given by: -

$$m_f = \frac{V_s}{V_{carr}} \quad (4.2)$$

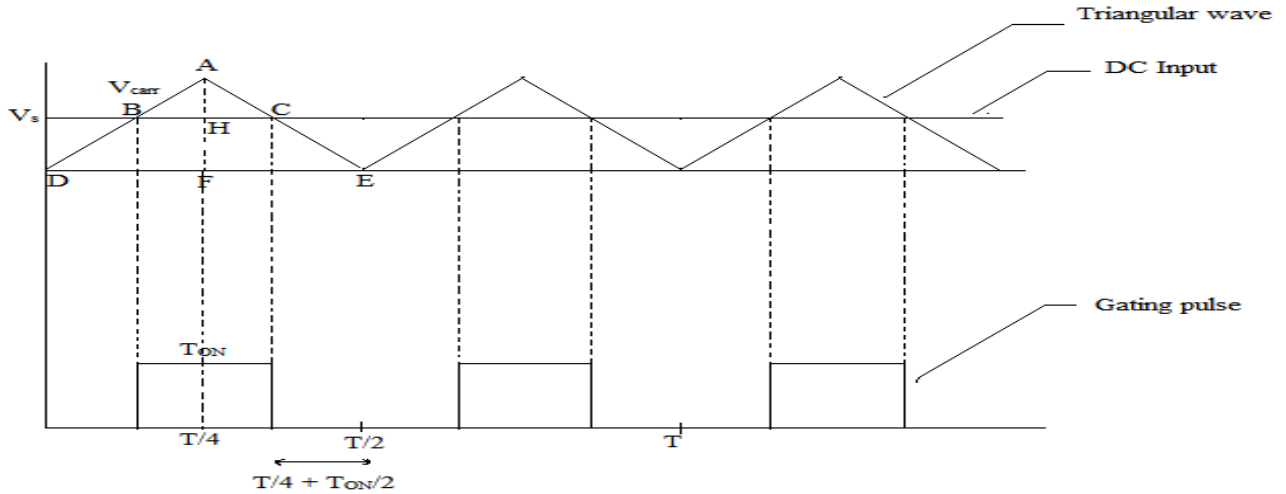


Figure 10: Single pulse width modulation technique

From the Fig.10, by the principle of congruency of two triangles,

$$\Delta ABC \cong \Delta ADE \quad (4.3)$$

Therefore,

$$\frac{V_{carr}}{V_s} = \frac{AF}{AH} = \frac{DE}{BC} = \frac{T}{T_{ON}} \quad (4.4)$$

Therefore, Modulation index = Duty ratio

The rms value of the output voltage can be given by the equations: -

$$V_1 = \left\{ \frac{2}{T} \int_{\left(\frac{T}{4} - \frac{T_{ON}}{2}\right)}^{\left(\frac{T}{4} + \frac{T_{ON}}{2}\right)} V_s^2 dt \right\}^{1/2} \quad (4.5)$$

$$V_1 = V_s \sqrt{2 \frac{T_{ON}}{T}} \quad (4.6)$$

$$V_1 = V_s \sqrt{2D} \quad (4.7)$$

Isolation transformer transforms the ac voltage from the primary side to the secondary side depending upon the turn's ratio and is given by the equation: -

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = n \quad (4.9)$$

$$V_2 = \frac{V_1}{n} = \frac{V_s}{n} \quad (4.10)$$

The transformed output from the secondary of the transformer is fed to the input of the rectifier bridge and its rms value is given by the following equations: -

$$V_p = \sqrt{2}V_2 \quad (4.11)$$

$$V_o = \frac{V_p}{\sqrt{2}} \quad (4.12)$$

Similarly, during Buck operation, power flow reverses and flow from motor turned generator side to the battery. The Bridge 2 at the high voltage side consisting of switches S5-S8 is active during this mode and act as inverter whereas Bridge 1 acts as a Rectifier.

4.1.2 Z source dc-dc converter

The Z source converter came into existence with the direct ac-ac conversion which is now extended to ac-dc, dc-ac and dc-dc converters. It can buck as well boost the input dc voltage to the wider range and with the higher efficiency.

Working operation: -

The Z source dc-dc converter performance is explained in two operating modes- Non shoot through mode and Shootthrough mode. The circuit forshoot through state and non-shoot through

state is shown in Fig.11 and Fig.12 respectively. Equations for these two different modes are as follows: -

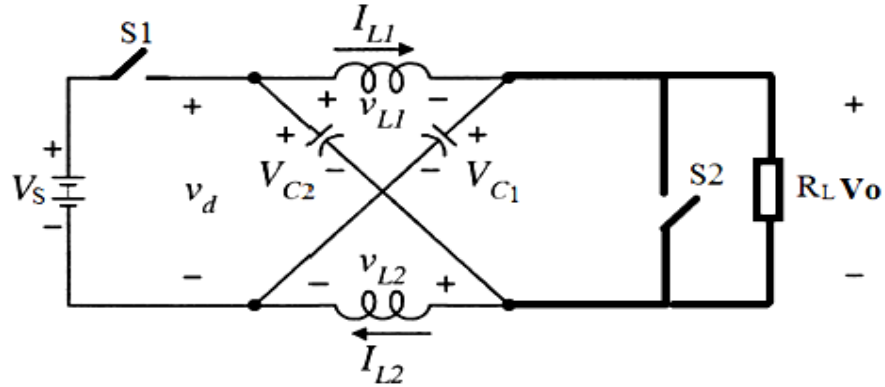


Figure 11: Z source dc-dc converter

Assumptions:-

1. Inductors L_1 and $L_2 = L$ and capacitors C_1 and $C_2 = C$
2. Circuit is assumed to be symmetrical.
3. Due to symmetry, $V_{c1} = V_{c2} = V_c$ and $V_{L1} = V_{L2} = V_L$.

Mode 1: - Shoot through state

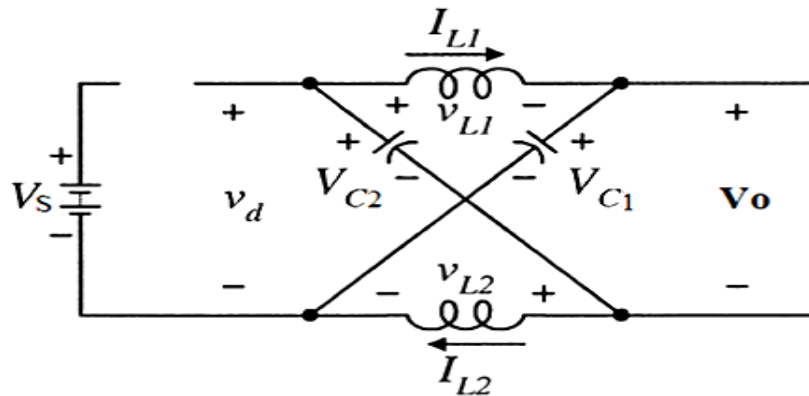


Figure 12: Shoot through state

Applying Kirchhoff's law, we get following relations,

$$V_L = V_c \tag{4.13}$$

$$v_d = 2v_c \tag{4.14}$$

Mode 2: - Non-shoot through state

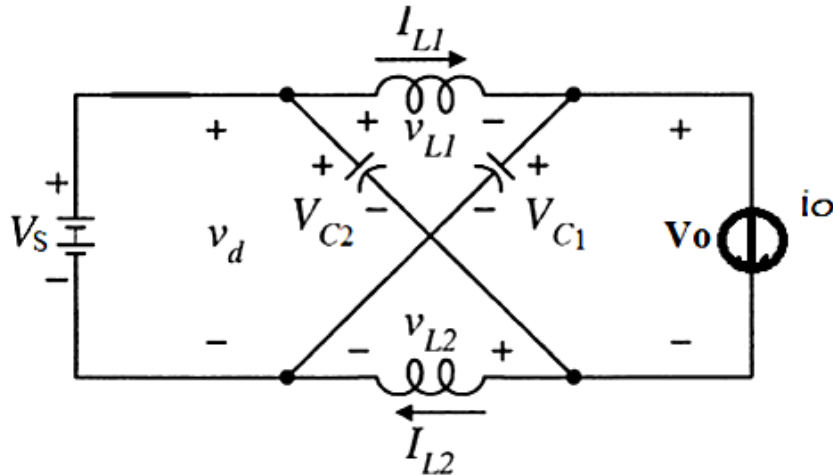


Figure 13: Non- shoot through state

Applying Kirchhoff's law, we get following relations,

$$v_L = V_s - V_c \quad (4.15)$$

$$v_d = V_s \quad (4.16)$$

$$v_i = V_C - V_L = 2V_C - V_s \quad (4.17)$$

The average value of the dc link voltage over a switching period must be zero in the steady state.

The equation is given as follows:-

$$V_L = \frac{T_0 \cdot V_C + T_1 (V_s - V_C)}{T} = 0 \quad (4.18)$$

$$\frac{V_C}{V_s} = \frac{T_1}{(T_1 - T_0)} \quad (4.19)$$

$$V_C = V_0 = \frac{T_1}{(T_1 - T_0)} V_s \quad (4.20)$$

$$V_0 = \frac{1 - D}{1 - 2D} V_s \quad (4.21)$$

Where $T = T_1 + T_0$ is the total switching period with,

$$\text{Shoot through time duty ratio } D = \frac{T_0}{T}, \quad (4.22)$$

It can be stepped up and down by stepping up and down the shoot through time and can be given by the following equation: -

$$V_{dc} = 2V_c - V_s = \frac{T}{(T_1 - T_0)} V_s = \frac{1}{1 - 2D} V_s \quad (4.23)$$

State space modeling: -

The state space modeling of the Z source dc-dc converter is implemented using Circuit averaging technique. The circuit averaging technique performs the average operation where there are two modes of operation- shoot through state and non-shoot through state. The small signal model is used to study the steady state as well dynamic characteristics of the circuit.

Assumptions:-

- a. The circuit is in continuous conduction mode.
- b. The components i.e. L and C including switch are ideal and lossless.
- c. Input voltage is a constant voltage source.
- d. Switching losses and stresses are neglected.

For shoot through state, following equations are developed as given below: -

$$L1 \frac{dIL_1}{dt} - VC_1 = 0 \quad (4.24)$$

$$L2 \frac{dIL_2}{dt} - VC_2 = 0 \quad (4.25)$$

$$C1 \frac{dV_{c1}}{dt} = -IL_1 \quad (4.26)$$

$$C2 \frac{dV_{c2}}{dt} = -IL_2 \quad (4.27)$$

State matrix:

$$\begin{bmatrix} \dot{IL}_1 \\ \dot{IL}_2 \\ \dot{VC}_1 \\ \dot{VC}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1/L1 & 0 \\ 0 & 0 & 0 & 1/L2 \\ -1/C1 & 0 & 0 & 0 \\ 0 & -1/C2 & 0 & 0 \end{bmatrix} \begin{bmatrix} IL_1 \\ IL_2 \\ VC_1 \\ VC_2 \end{bmatrix} \quad (4.28)$$

For non-shoot through state, following equations are developed as given below:

$$L1 \frac{dIL_1}{dt} + VC_2 - V_{DC} = 0 \quad (4.29)$$

$$L2 \frac{dIL_2}{dt} + VC_1 - V_{DC} = 0 \quad (4.30)$$

$$C1 \frac{dVC_1}{dt} - IL_2 + I_{DC} = 0 \quad (4.31)$$

$$-C2 \frac{dVC_2}{dt} + IL_1 - I_{DC} = 0 \quad (4.32)$$

State matrix:-

$$\begin{bmatrix} \dot{IL}_1 \\ \dot{IL}_2 \\ \dot{VC}_1 \\ \dot{VC}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -1/L1 \\ 0 & 0 & -1/L2 & 0 \\ 0 & 1/C1 & 0 & 0 \\ 1/C2 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} IL_1 \\ IL_2 \\ VC_1 \\ VC_2 \end{bmatrix} + \begin{bmatrix} V_{DC}/L1 \\ V_{DC}/L2 \\ -I_{DC}/C1 \\ -I_{DC}/C2 \end{bmatrix} \quad (4.33)$$

The state equations are averaged considering shoot through duty ratio D (i.e. when S1 is on).

Averaging Two Matrices as

$$x(t) = D(A_1x + B_1u) + (1 - D)(A_2x + B_2u) \quad (4.34)$$

The state space model becomes

$$\begin{bmatrix} \dot{IL}_1 \\ \dot{IL}_2 \\ \dot{VC}_1 \\ \dot{VC}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & D/L & -(1-D)/L \\ 0 & 0 & -(1-D)/L & D/L \\ -D/C & (1-D)/C & 0 & 0 \\ (1-D)/C & -D/C & 0 & 0 \end{bmatrix} \begin{bmatrix} IL_1 \\ IL_2 \\ VC_1 \\ VC_2 \end{bmatrix} + \begin{bmatrix} (1-D)V_{DC}/L \\ (1-D)V_{DC}/L \\ -(1-D)I_{DC}/C \\ -(1-D)I_{DC}/C \end{bmatrix}$$

Small Signal Analysis: -

Introducing a small disturbance or perturbation and including load resistance R_L : -

$$L \frac{d(IL_1 + \hat{i}_{L1})}{dt} = (D + \hat{d})(V_{c1} + \hat{V}_{c1}) - (\dot{D} - \hat{d})(V_{c2} + \hat{V}_{c2}) + (\dot{D} - \hat{d})(V_{DC} + \hat{V}_{DC}) \quad (4.25)$$

Where $(1 - D) = \dot{D}$

$$L \frac{d\hat{i}_{L1}}{dt} = (D\hat{V}_{c1} + \hat{d}V_{c1}) - (\dot{D}\hat{V}_{c2} - V_{c2}\hat{d}) + (\dot{D}\hat{V}_{DC} - \hat{d}V_{DC}) \quad (4.35)$$

Considering, $IL_1 = IL_2 = IL$, $V_{c1} = V_{c2} = V_c$

$$L \frac{d\hat{i}_L}{dt} = 2\hat{d}V_c + (2D - 1)\hat{V}_c + \dot{D}\hat{V}_{DC} - \hat{d}V_{DC} \quad (4.36)$$

Similarly,

$$C \frac{d\hat{V}_c}{dt} = -2\hat{d}I_L - \frac{\hat{V}_c}{R_L} + (1 - 2D)\hat{i}_L - \dot{D}\hat{I}_{DC} - \hat{d}I_{DC} \quad (4.37)$$

Taking Laplace transform of

$$sL\hat{i}_L(s) = 2V_c\hat{d}(s) + (2D - 1)\hat{V}_c(s) + \dot{D}\hat{V}_{DC}(s) + V_{DC}\hat{d}(s) \quad (4.38)$$

$$\left(sC + \frac{1}{R_L}\right)\hat{V}_c(s) = -2I_L\hat{d}(s) + (1 - 2D)\hat{i}_L(s) - \dot{D}\hat{I}_{DC}(s) + I_{DC}\hat{d}(s) \quad (4.39)$$

Rearranging above

$$sL\hat{i}_L(s) + (1 - 2D)\hat{V}_c(s) = (2V_c + V_{DC})\hat{d}(s) + \dot{D}\hat{V}_{DC}(s) \quad (4.40)$$

$$(2D - 1)\hat{i}_L(s) + \left(sC + \frac{1}{R_L}\right)\hat{V}_c(s) = (I_{DC} - 2I_L)\hat{d}(s) - \dot{D}\hat{I}_{DC}(s) \quad (4.41)$$

$$\text{Where } A = s^2LC + sL/R_L + (2D - 1)^2 \quad (4.42)$$

$$\begin{bmatrix} \hat{i}_L(s) \\ \hat{V}_c(s) \end{bmatrix} =$$

$$\frac{1}{A} \begin{bmatrix} sC & (2D - 1) \\ -(2D - 1) & sL \end{bmatrix} \begin{bmatrix} 2V_c + V_{DC} \\ (I_{DC} - 2I_L) \end{bmatrix} \cdot \hat{d}(s) + \dot{D}1/A \begin{bmatrix} sC & (2D - 1) \\ -(2D - 1) & sL \end{bmatrix} \begin{bmatrix} \hat{V}_{DC}(s) \\ -\hat{I}_{DC}(s) \end{bmatrix}$$

Transfer functions of the model:

$$\frac{\hat{i}_L(s)}{\hat{d}(s)} = K_1 \frac{(2V_c + V_{DC})sC - (2D - 1)(2I_L - I_{DC})}{s^2LC + sL/R_L + (2D - 1)^2} \quad (4.43)$$

$$\frac{\hat{V}_c(s)}{\hat{d}(s)} = K_2 \frac{(2V_c + V_{DC})(1 - 2D) - sL(2I_L - I_{DC})}{s^2LC + sL/R_L + (4D - 1)^2} \quad (4.44)$$

As the system is non-linear, it is required to develop the small signal model for Z source dc-dc converter. The small signal analysis is performed on the model by adding a small perturbation \hat{d} to the duty ratio, \hat{i}_L to the inductor current and \hat{V}_c to the capacitor voltage. Taking Laplace

transform of the small signal model, we get transfer functions of capacitor voltage and inductor current with respect to small change in duty ratio respectively.

Step Response of the Z source dc-dc converter is presented. The step response is obtained through the open loop analysis of Z source dc-dc circuit. The results of analysis are helpful in designing the controller to minimize the voltage and current spikes.

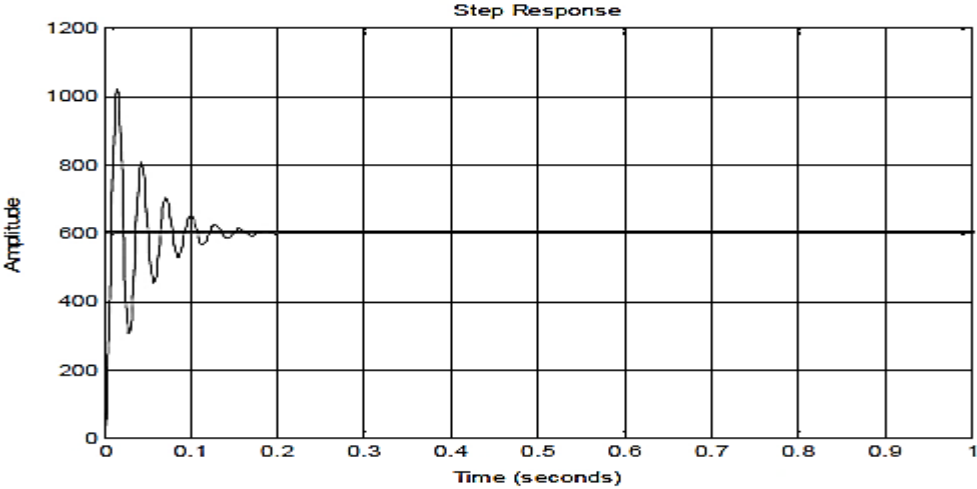


Figure 14: Step response of capacitor voltage

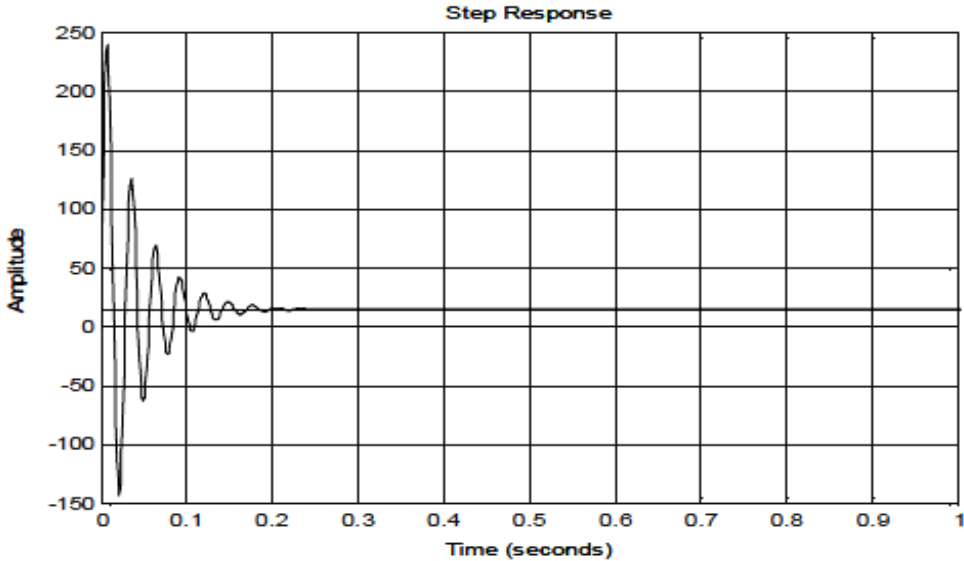


Figure 15: Step response of inductor current

4.1.3 Trans Z source dc-dc converter

The Trans Z source dc-dc converter is derived from the Z source dc-dc converter. It follows the same basic gain boosting principle. It entirely depends upon the principle of magnetic coupling between the two inductors. The reason to look for a dc-dc converter better than Z source dc-dc converter was high efficiency and gain. It also offers less harmonics and stable output.

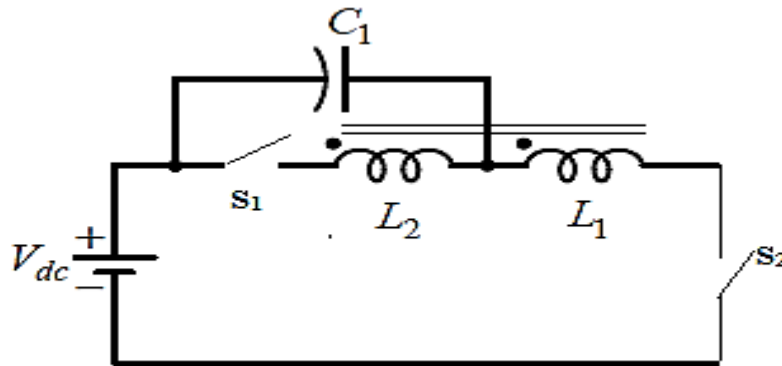


Figure 16: Trans Z source dc-dc converter

Working operation: -

The circuit diagram for the Trans Z source dc-dc converter is shown in the Fig.16. The converter works similarly like Z source dc-dc converter i.e. in two modes- Shoot through state and Non-shoot through state. During Non-shoot through state, switch is open or in OFF state. In non-shoot through state, energy stored by the coupled inductors or transformer is transferred to capacitor and the load. And the Diode is forward biased during Non-shoot through state. During Shoot-through state, switch is in ON state and the load end is shorted out. The coupled inductors are energized by the capacitor. The Diode is reverse biased during the Shoot-through state. The load is connected after allowing the output through the LC filter to eliminate small harmonics.

Assumptions: -

1. Inductors and capacitors are ideal elements i.e. lossless.
2. Switching stresses are neglected.
3. Turns ratio of transformer are set to unity.
4. Input current is continuous.

Mode 1: - Shoot through mode

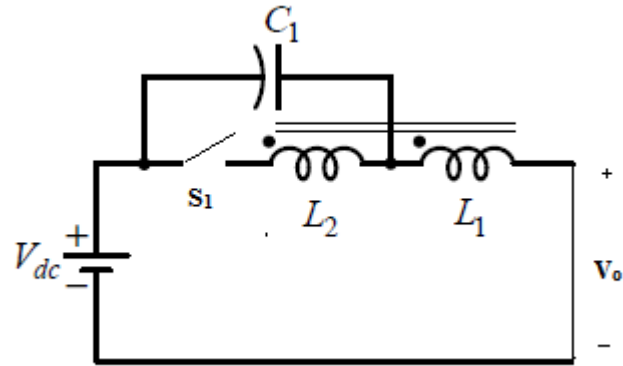


Figure 17: Shoot through mode of Trans Z source

$$V_{L_1} = V_C \tag{4.45}$$

$$V_{L_2} = n \cdot V_{L_1} = n \cdot V_C \tag{4.46}$$

Mode 2: - Non-Shoot through mode

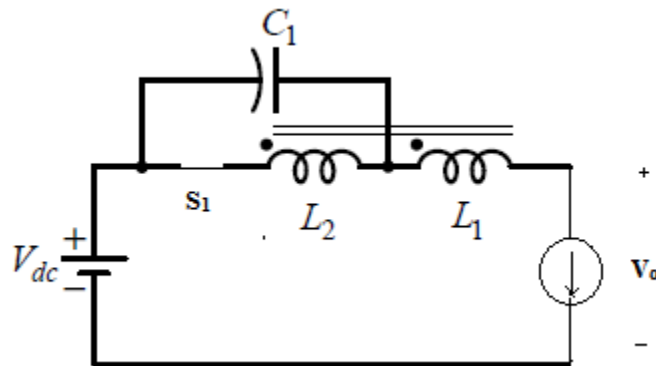


Figure 18: Non- Shoot through mode of Trans Z source

$$V_{dc} = nV_c - V_{L2} \tag{4.47}$$

$$V_o = V_{C1} - V_{L1} \tag{4.48}$$

$$V_{L1} + V_{L2} = -V_{C2} \tag{4.49}$$

During the non-shoot through state, due to presence of transformer, capacitor C gets charged. Similarly, the Diode D gets forward biased which further energize the windings of transformer.

The total power which flows to the output is the sum of the power from transformer and the capacitor C.

On further calculations, we get the following relations of duty cycle with the inductors: -

$$V_{L1} = \frac{-D}{1-D} V_C \quad (4.50)$$

$$V_{L2} = \frac{-nD}{1-D} V_C \quad (4.51)$$

The peak dc link voltage at the output is given by: -

$$V_o = \frac{1}{1-(n+2)D} V_{dc} \quad (4.52)$$

$$B = \frac{1}{1-(n+2)D} \quad (4.53)$$

$$V_o = B.V_{dc} \quad (4.54)$$

Where B is a Boost factor which boosts the fixed input voltage to the variable dc voltage

State Space Modeling: -

The state space modeling of the converter is performed by the Circuit averaging technique. The circuit averaging technique is used where the circuit includes switching operations. There are two conditions during the whole operation- one when the switch is ON and other when the switch is OFF. Here in Trans Z source dc-dc converter as shown in the circuit, it makes use of only one switch. Then circuit averaging technique is applied on both the conditions and a small signal model is developed. The small signal model is useful in studying the dynamic characteristics of the circuit model.

Assumptions:-

1. The circuit is in CCM mode.
2. The elements including switch are ideal and lossless.
3. Input voltage is a constant voltage source and diode used has specific voltage drop.
4. Switching losses are neglected.

The operation of Trans z source converter is similar to the Z source dc-dc converter making use of Shoot through state and Non-shoot through state. The shoot through state is achieved when the ideal switch is closed or we can say when the circuit is shorted out and the Diode is reverse biased. The non- shoot through state is achieved when the switch is open and the Diode is conducting.

Dynamic modeling of Trans z source dc-dc converter:

In Dynamic model of Trans z source dc-dc converter, we take inductor current (i_L), capacitor voltage (V_c) and Load current as state variables for modeling the circuit in continuous conduction mode.

$$\dot{x} = A_1.X + B_1.U \quad (4.55)$$

State matrix:-

$$\frac{d}{dt} \begin{bmatrix} iL1(t) \\ iL2(t) \\ Vc(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1/L2 \\ 0 & -1/C & 0 \end{bmatrix} \begin{bmatrix} iL1(t) \\ iL2(t) \\ Vc(t) \end{bmatrix} \quad (4.56)$$

Where, $A_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1/L2 \\ 0 & -1/C & 0 \end{bmatrix}$; $B1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$

In non-shoot through state, energy transfer takes place between inductors and a capacitor. Following equation is for the Non Shoot through state :-

$$\dot{x} = A_2.X + B_2.U$$

State matrix

$$\frac{d}{dt} \begin{bmatrix} iL1(t) \\ iL2(t) \\ Vc(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 - 1/L1 \\ 0 & -R1/L2(L2 + L1) & -1/L2 \\ 1/C & -1/C & 0 \end{bmatrix} \begin{bmatrix} 1/L1 \\ 0 \\ 0 \end{bmatrix} . (Vdc - VD) \quad (4.57)$$

$$A_2 = \begin{bmatrix} 0 & 0 & -1/L1 \\ 0 & -R1/(L2 + L1) & -1/L2 \\ 1/C & -1/C & 0 \end{bmatrix}$$
; $B2 = \begin{bmatrix} 1/L1 \\ 0 \\ 0 \end{bmatrix}$

Now to find the small signal model of Trans z source dc-dc converter, we need to add a small disturbance which is commonly known as perturbation $\hat{V}d$ to input voltage V_{dc} and $\hat{d}(t)$ to the shoot through duty ratio of the switch. The equations are given as follows: -

$$V_{dc}(t) = V_{dc} + \hat{v}_{dc}(t) \quad (4.58)$$

$$d(t) = D + \hat{d}(t) \quad (4.59)$$

resulting in small signal variation in state space.

$$x = X + \hat{x} \quad (4.60)$$

where D is the shoot through duty ratio.

Now we have two equations for the different conditions, on combining them, we get the equation as follows:-

$$\hat{X} = (D.A_1 + D'.A_2).\hat{X} + (D.B_1 + D'.B_2).\hat{U} + (A_1 - A_2)X + (B_1 - B_2)U \quad (4.61)$$

$$\begin{bmatrix} L1 & 0 & 0 \\ 0 & L2 & 0 \\ 0 & 0 & Vc \end{bmatrix} \frac{d}{dt} \begin{bmatrix} iL1(t) \\ iL2(t) \\ Vc(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & -D' \\ 0 & -D'R1 & -(D + D') \\ D' & -(D + D') & 0 \end{bmatrix} \quad (4.62)$$

$$\begin{bmatrix} iL1(t) \\ iL2(t) \\ Vc(t) \end{bmatrix} = \begin{bmatrix} D' \\ 0 \\ 0 \end{bmatrix} (\hat{V}g(t)) + \begin{bmatrix} Vc - Vg + Vd \\ IL2 * R1 \\ -IL1 \end{bmatrix} \hat{d}(t) \quad (4.63)$$

where $D' = 1 - D$

As we apply State space averaging technique, State matrices A and B become as respectively

$$A = D.A_1 + D'.A_2 \quad (4.64)$$

$$B = D.B_1 + D'.B_2 \quad (4.65)$$

Following the addition of perturbation, DC steady state equations can be written as:-

$$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -D'/L1 \\ 0 & -D'R1/L2(L1 + L2) & (D + D')/L2 \\ D'/C & -(D + D')/C & 0 \end{bmatrix} \begin{bmatrix} \widehat{iL1(t)} \\ \widehat{iL2(t)} \\ \widehat{Vc(t)} \end{bmatrix} + \begin{bmatrix} D'/L1 \\ 0 \\ 0 \end{bmatrix} (Vg - VD)$$

Due to symmetry of inductances in Trans Z source converter, we can also take $iL_1 = iL_2 = iL$

Small signal model is developed using Laplace Transform which is shown as follows:-

$$s\hat{L}1(s) = -\frac{D'}{L1}\hat{V}c(s) + \frac{D'}{L1}\hat{V}g(s) + \left(\frac{Vc}{L1} - \frac{(Vg-VD)}{L1}\right)\hat{d}(s) \quad (4.66)$$

$$s\hat{L}4(s) = -\frac{R1D'}{L2(L1+L2)}\hat{L}2(s) - \frac{D'+D}{L2}\hat{V}c(s) + \left(\frac{R1.LL2}{L4(L1+L2)}\right)\hat{d}(s) \quad (4.67)$$

$$s\hat{V}c(s) = -\frac{D'}{C}\hat{L}1(s) - \frac{D'+D}{L2}\hat{L}2(s) - \frac{iL1}{C}\hat{d}(s) \quad (4.68)$$

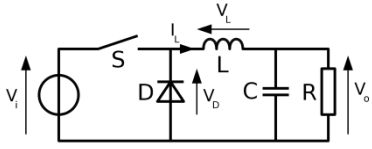
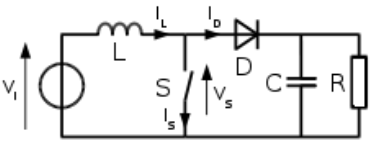
Transfer Functions of the model:-

$$\begin{aligned} &= Hvcd(s) \\ &= \frac{s\{D'^2L2(Vc - Vg + VD) - L1(D + D')(L4R1 - IL1)\} + D'^2R1(Vc - Vg + VD)}{s^2L1L2C + s^2L1CD'R1 + s[D'^2L2 - L1(D + D')^2] + D'^2R1L} \end{aligned} \quad (4.69)$$

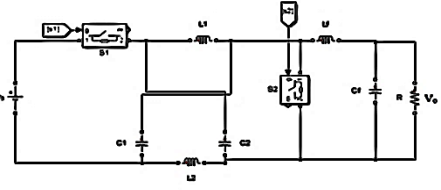
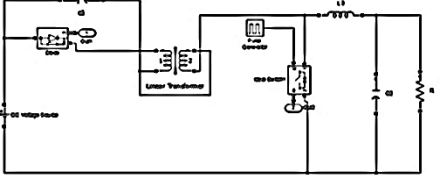
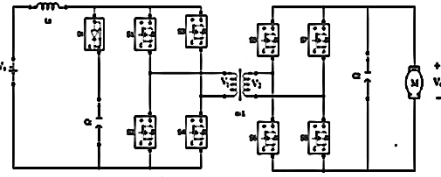
$$HiLd(s) = \frac{sC\{(Vc + VD - Vg) + D'iL\}}{s^2L1C - D'^2} \quad (4.70)$$

4.1.4 Selection of suitable DC-DC converter for HEV

Table 2: Selection of suitable DC-DC Converters for HEV

S No	Converter	Configuration	Practical Duty ratio	Merits	Demerits
1.	Buck		0.9	<ul style="list-style-type: none"> • Simple • Higher efficiency • Regulated output • High power applications • Less cost 	<ul style="list-style-type: none"> • Discontinuous Input current • Only buck operations and not boost.
4.	Boost		0.9	<ul style="list-style-type: none"> • Continuous Input current • Low power applications • High efficiency • Less cost 	<ul style="list-style-type: none"> • Only boost operations and not buck

4.	Buck-Boost		0.9	<ul style="list-style-type: none"> • Low power applications • High efficiency • Both buck and boost Operations • Battery powered Applications 	<ul style="list-style-type: none"> • Complicated • Electro-magnetic • Interference • Inverted output
4.	SEPIC		0.9	<ul style="list-style-type: none"> • Low power Applications • High efficiency • Buck and Boost 	<ul style="list-style-type: none"> • Bulky circuit • High cost
5.	CUK		0.9	<ul style="list-style-type: none"> • Low power Applications • High efficiency • Buck and Boost 	<ul style="list-style-type: none"> • Bulky circuit • High cost • Inverted output
6.	Fly-back		0.9	<ul style="list-style-type: none"> • Low power Applications • High efficiency • Multiple outputs • Buck and Boost 	<ul style="list-style-type: none"> • Bulky circuit due to transformer • High cost
7.	Forward		0.45	<ul style="list-style-type: none"> • Low power • High efficiency • Non-pulsating and • High output currents • Buck and Boost 	<ul style="list-style-type: none"> • Bulky circuit due to Transformer • High cost • Limited to low input voltages
8.	Push-pull		0.45	<ul style="list-style-type: none"> • Need small filter • High power Applications • High efficiency • Buck and Boost 	<ul style="list-style-type: none"> • Bulky circuit due to transformer • High cost • High switching stress
9.	Half-Bridge		0.45	<ul style="list-style-type: none"> • High power Applications • High output currents • Buck and Boost 	<ul style="list-style-type: none"> • Shoot through problem • Limited duty ratio • High cost • Bulky circuit
10.	Resonant		0.45	<ul style="list-style-type: none"> • High power Applications • Reduced switching Stress • Wide range 	<ul style="list-style-type: none"> • Not for stand-by power • Supply • Needs continuous Energization • Complex and costly

11.	Z- source		0.4-0.8	<ul style="list-style-type: none"> • Wide range of duty ratio • High voltage gain • Low I^2R losses • Low switching losses 	<ul style="list-style-type: none"> • Difficulty in maintaining L & C coupling values. • Control circuits are needed for stable output • Unidirectional
12.	Trans Z-source		0.4-0.8	<ul style="list-style-type: none"> • Wide range of duty ratio • Simple and robust circuit • Low switching losses • High voltage gain 	<ul style="list-style-type: none"> • Control circuit is complex • High input current • Unidirectional
13.	Bi-directional Full Bridge		0.5	<ul style="list-style-type: none"> • Controlled Bidirectional flow of power • Stable dc output • Low I^2R losses • Less harmonics • High voltage gain 	<ul style="list-style-type: none"> • Bulky circuit • High switching losses

Various DC-DC converters described in Table.2 are analyzed and discussed for its application in HEV's. The simple buck and boost configurations are unidirectional and have limited voltage gain which is not suitable for HEV's. Other isolated topologies including forward, fly-back, push-pull and half bridge converters have complex circuits owing to high costs. Improved dc-dc converters including Z source and Trans Z source dc-dc converter are introduced for their high voltage gain and low switching losses but flow of power is unidirectional and also control circuit is complex. Comparing the merits and demerits of all these converters, Bi-directional full bridge dc-dc converter is found suitable for the HEV's for its unique configuration allowing bidirectional power flow i.e. key factor in regenerative mode in HEV's. Also the control of this converter is not complex resulting in stable dc output thus minimizing the need of additional filter circuit.

4.2 Modeling of Series-Parallel Hybrid Electric Vehicle

This part deals with the discussion on various control blocks used in developing the Series-Parallel Hybrid electric vehicle.

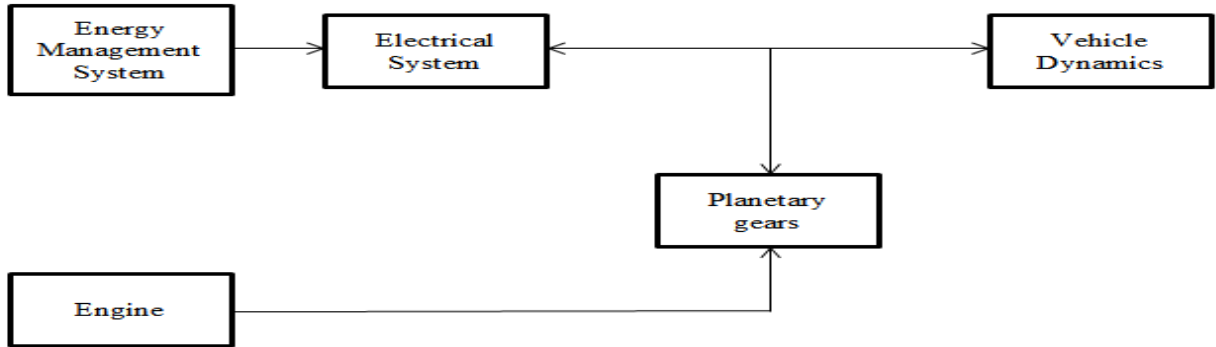


Figure 19: Block diagram of SPHEV

4.2.1 Energy Management System:-

This system deals with the control and management of hybrid electric vehicle. It can be called as the control center of the vehicle model. The EMS is responsible for sending the signals to all other blocks for working in synchronization with each other. The accelerator pedal is connected with the EMS through which its input is processed and accordingly signal is sent to battery to engine for vehicle propulsion. The system also controls the amount of power required by the drive cycle to be shared between battery and engine which is further controlled through BMS. Energy Management System is classified into the following control centers: -

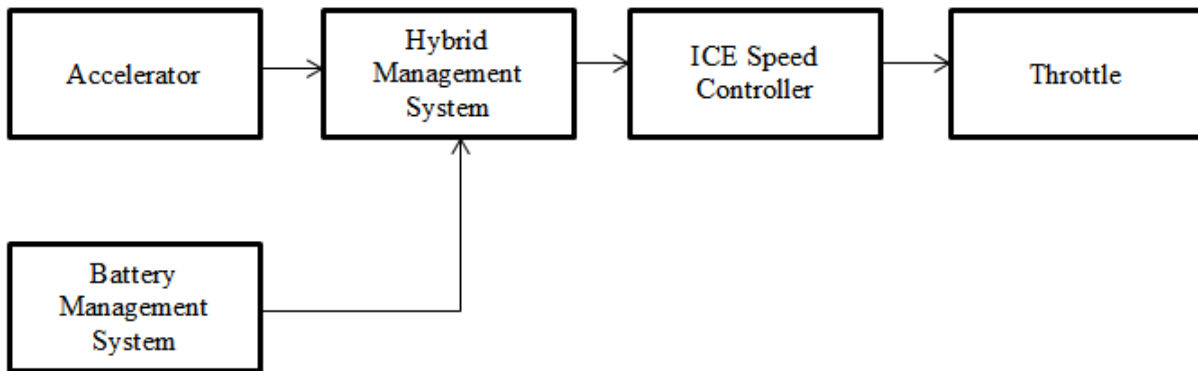


Figure 20: Energy Management System

Battery management system:-

Battery Management System is a part of EMS which controls the charging and discharging of battery according to the required drive cycle. Parameters including voltage, current and SOC of the battery is evaluated in battery management system. The voltage and current of the battery decides the output power of the battery which is utilized to operate the motor drive. State of charge of battery is the key parameter which is managed in BMS and further decides the operation of battery for a particular drive cycle. The State of charge of battery depicts the percentage of charge or current left in battery at a particular interval. The SOC of the battery is maintained at minimum of 20% so that sedimentation of battery is avoided. The BMS controls the SOC of the battery between the safety limits and sends the signal to Hybrid management system for specific operation.

Power of the battery is given by: -

$$P_{batt} = V_{oc} \cdot I_{batt} - I_{batt}^2 \cdot R_{batt} \quad (4.71)$$

where V_{oc} = open circuit voltage

I_{batt} = internal battery current

R_{batt} = internal resistance of the battery

The state of charge (SOC) of the battery is given by: -

$$SOC = \frac{I_{batt}}{Q_{max}} \quad (4.72)$$

where Q_{max} = capacity of the battery in terms of Ah

Hybrid Management System:-

The Battery Power status and the Required Drive power are fed to the Hybrid Management System. This system manages the switching ON and OFF of the Hybrid mode. The Battery power status is referred to as Recharge power which means that if SOC limit goes below certain limit value, the battery is not in a condition to supply the required power to drive a motor so it needs to be recharged. The charging and discharging is controlled through the Battery Management System. In Hybrid Management System, hybrid signal turns ON when battery power is

insufficient to supply the motor. The Required Drive power is the output obtained in terms of speed demand and the feedback torque from the operating motor which varies with drive cycle from acceleration to deceleration period as the Torque and Speed varies at different intervals. The Recharge/Battery power status is compared with the Required Drive power so that the difference in output can decide the speed and torque of engine and generator irrespective of battery. The order of hybridization decides whether only battery would be supplying the power to the drive train or clubbed with the engine power. The turning ON of the hybrid mode starts the engine and throttle is produced to run the vehicle.

ICE Speed Controller:-

The generator speed is taken as a feedback from the generator shaft and fed to this system. The ICE speed and power as explained before is also fed into this system. The shafts of ICE and generator are coupled to each other. This system only comes in operation when Hybrid management system sends the Hybrid ON signal to it. As we know that when Hybrid signal will be enabled, only then engine and generator will work else battery only will supply the power to the motor drive. The clubbed power of generator and engine power which they deliver to motor drive depends upon the speed and torque they develop from the closed loop cycle of required drive power. This system uses the PI controller so that demand engine speed to produce the adequate power by the system matches its actual speed. The throttle signal is generated at the output of PI controller for vehicle propulsion.

4.2.2 IC Engine: -

IC engine is a very important component of SPHEV. It acts as a base component which supports the vehicle drive train as a backup fuel alternative to battery. It has a speed governor which controls the rotational speed according to the throttle provided. The engine ignition depends upon the pressure on the accelerator pedal fed by the driver, accordingly the engine start and EMS sends the signal about the required power needed from the generator and battery respectively. The throttle values lies between 0 and 1 depending upon the drive cycle of the vehicle. The 0 is equivalent to the switching OFF of the engine whereas 1 means that engine is

ON and running. Throttle signal is the output of the ICE speed controller block which analyzes the hybrid enable signal as well as ICE reference speed which depends upon the accelerator signal coming from the drive cycle as explained in ICE speed controller part.

The brake engine power is given by: -

$$\text{Brake power} = \text{Engine Torque} \times N \quad (4.73)$$

$$\text{Fuel consumption} = \frac{\text{Brake power}}{\text{Efficiency} \times \text{Calorific value of fuel}} \quad (4.74)$$

4.2.3 Electrical System: -

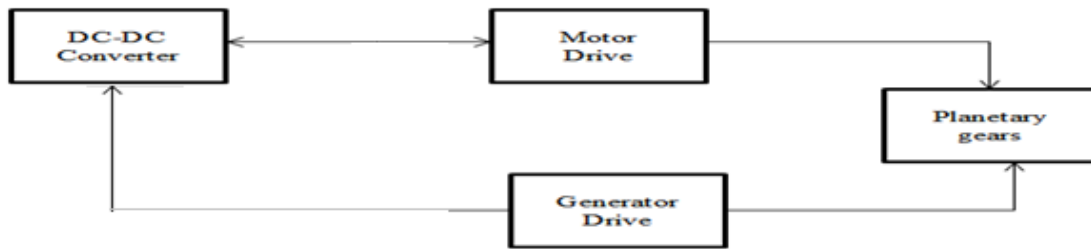


Figure 21: Electrical System of SPHEV

The electrical system of the SPHEV comprises of motor drive, generator drive and dc-dc converter. The dc-dc converters are already explained in previous sections. The motor and generator drive are basically PMSM drives whose control and modeling is discussed in Chapter-3. The electrical system works in synchronization with the energy management system for the efficient working of HEV. From the Fig. 21, we can see that dc-dc converter, motor drive and generator drive are connected to a common dc bus so it is necessary to maintain the fixed dc output voltage. The variations in the electrical supply will generate spikes and lowers the level of performance. The motor drive and generator drives are coupled with IC engine through planetary gears. The motor drive is also directly coupled to axle of wheels through gearing mechanism.

4.2.4 Vehicle Dynamics: -

When a vehicle is moving on the road, certain frictional forces are acting on it which tries to oppose the motion of vehicle. Some frictions are internal like of bearings and shafts. Other kind of frictional forces are external forces which include rolling friction which acts between wheels and road. One more friction which exists is Air friction which is independent of mass of vehicle but depends on its design, shape and velocity with which it is moving considering the direction of flow of wind.

The traction forces generally include the following modes of working:-

1. Accelerating the mass of drive train in horizontal direction with respect to ground.
2. Accelerating the rotational components of the drive train like tires, shafts and gears etc.
3. Overcoming the gravitational forces.
4. Overcoming the resistance offered by air to drive train.

Referring to Table 6 for justification of velocity and acceleration: -

$$v = u + at \quad (4.75)$$

$$a = \frac{v - u}{t} \quad (4.76)$$

The performance of HEV depends upon various frictional forces acting on it which varies with the shape and design of the vehicle. The forces are discussed below using following equations: -

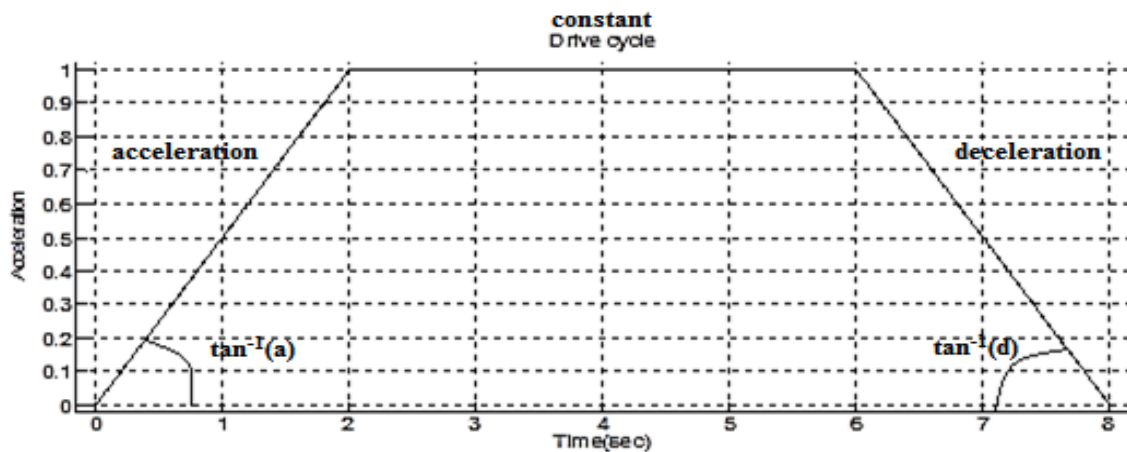


Figure 22: Drive cycle of the HEV

Acceleration and Deceleration angles: -

Angle 'a' denotes acceleration angle whereas angle 'd' denotes deceleration angle. They are represented by the following equations: -

$$\tan^{-1} a = \frac{V_m}{t} \quad (4.77)$$

where V_m is the maximum free running speed of the vehicle. (Refer to Table 6)

t is the time taken by vehicle to reach V_m .

Similarly, we can find the angle for deceleration period for the justification of Drive cycle.

a) **Rolling frictional force:** - It acts due to friction between the tires of the vehicle and the road surface. It is computed by the equation: -

$$F_{rr} = \mu_{rr} mg \cdot \cos(a) \quad (4.78)$$

where μ_{rr} is the rolling resistance. It is generally 0.005-0.015.

A is the frontal area

b) **Angular Friction:** - appears across the rotating parts including tires and hubs, given by: -

$$F_{wa} = \frac{Iag^2}{r^2} = \frac{1}{2} mw^2 \frac{ag^2}{r^2} \quad (4.79)$$

where g is the gear ratio = (wheel speed/motor speed)

I is the moment of inertia

Total Tractive force: -

$$F_t = F_{rr} + F_{wa} \quad (4.80)$$

$$F_t = \mu_{rr} mg \cdot \cos(a) + \frac{Iag^2}{r^2} \quad (4.81)$$

Torque: -

Torque referred to shaft of motor is given as: -

$$T_m = F_t \cdot r \quad (4.82)$$

where η_t is the transmission efficiency.

Power: -

Power developed:-

Power developed by the motor to drive the power train is computed by: -

$$P_d = w \times T_m \quad (4.83)$$

4.2.5 Planetary gears

Planetary gears, also known as epicyclic gears are the power split device which is core component of Series-Parallel hybrid electric vehicle. It is a mechanical coupling between IC engine, generator and motor drives. The power is split between the three of these according to the gear ratio. The planetary gears include two gears mounted and the center of one gear revolves around the axis of the other gear. There are mainly three gears known as Carrier gear, Sun gear and Ring gear (outer gear). The carrier connects the centers of these two gears and rotates to carry one gear, called the planet gear around other gear known as Sun gear.

Three main components of epicyclic gears are explained as follows: -

- Sun gear- the central gear,
- Carrier gear- holds one or more planet gear clubbed with sun gear,
- Ring gear- outer gear with its teeth facing inwards and clubbed with the planet as well as sun gear.

The overall gear ratio of the planetary gears is given by the following equations: -

$$N_S w_S + N_p w_p - (N_s + N_p) w_C = 0 \quad (4.84)$$

$$N_r w_r - N_p w_p - (N_r - N_p) w_C = 0 \quad (4.85)$$

Where w_r , w_c , w_p and w_s are the angular velocities of ring, carrier, planet and sun gears,

and N_r , N_c , N_p and N_s are the number of teeth of ring, carrier, planet and sun gears.

From the above equations, we can reach to the following equation: -

$$N_S w_S + N_r w_r = (N_s + N_r) w_C \quad (4.86)$$

$$\text{Or, } -\frac{N_r}{N_s} = \frac{w_s - w_c}{w_r - w_c} = -K \quad (4.87)$$

Provided, w_c is not equal to the w_r .

$$N_r = N_s + 2N_p \quad (4.88)$$

$$nw_s + (2 + n)w_r - 2(1 + n)w_c = 0 \quad (4.89)$$

Where, $n = N_s/N_p$

For power split ratio K i.e. ring to sun gear ratio must be greater than 1, in our case, we have taken the value of K as 2.61.

Following equations for these laws must satisfy the zero condition in order to verify the energy law.

Power law for planetary gears: -

$$P_{carrier} - P_{sun} - P_{ring} = 0 \quad (4.90)$$

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Simulink results and discussions

The chapter deals with the various blocks or techniques involved in modeling the Series-Parallel Hybrid electric vehicle. The Block diagram for the complete SPHEV is also discussed. Physical components like Motor/Generator drive, Battery and IC engine coupled to planetary gears are explained. The block diagram of SPHEV is modeled in MATLAB SIMULINK. The theory and calculations of the complete model is explained.

Simulink model of SPHEV

Simulink model for the SPHEV is developed to understand the concepts of working and operation of Hybrid vehicle dynamics. HEV and has certain advantages over the series and parallel configurations. The block diagram describes the IC engine, Electrical System including motor/generator drives, battery and converter, Vehicle dynamics and planetary gears.

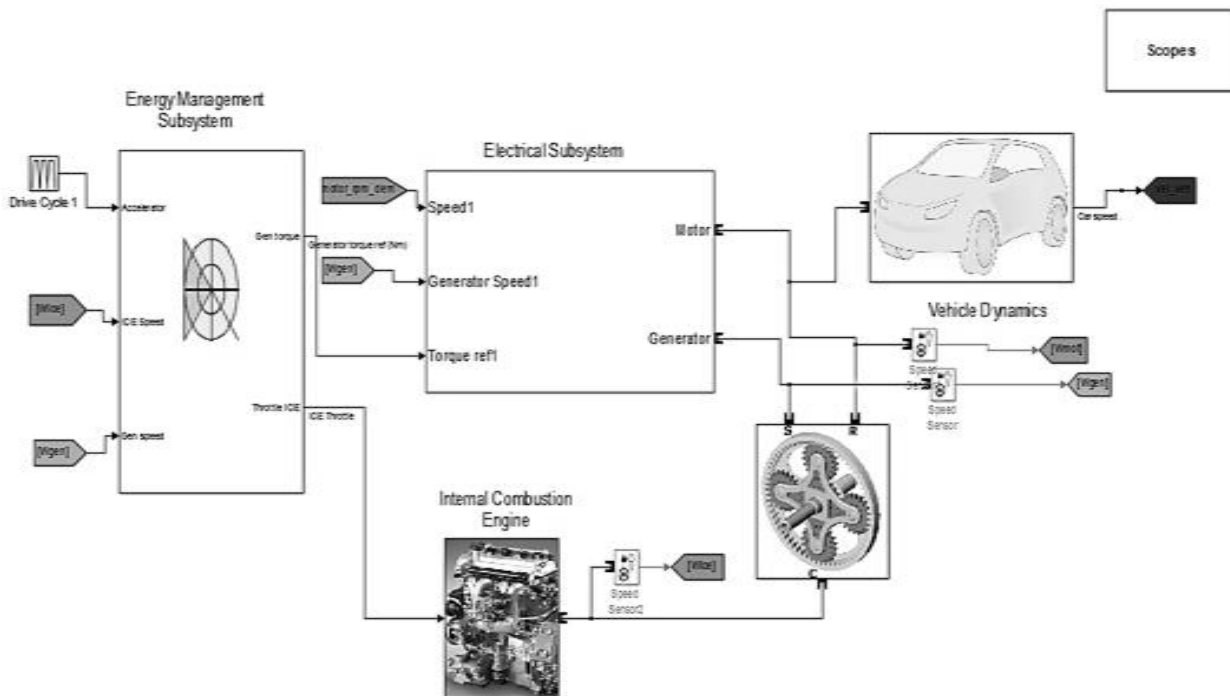


Figure 23: Simulink model for SPHEV

Simulation of Series-Parallel Hybrid Electric Vehicle was performed using Bi-directional full bridge dc-dc converter which is modeled and explained in Chapter 4. Various characteristics including power, torque, output voltage and drive cycle of the vehicle are discussed. The SIMULINK is simulated for the following drive cycle of the vehicle: -

- a) Acceleration period (Time: 0-4 sec)
- b) Constant period (Time: 4-6 sec)
- c) Deceleration period (Time: 6-8 sec)

The results obtained from the SIMULINK are shown in graphs below:

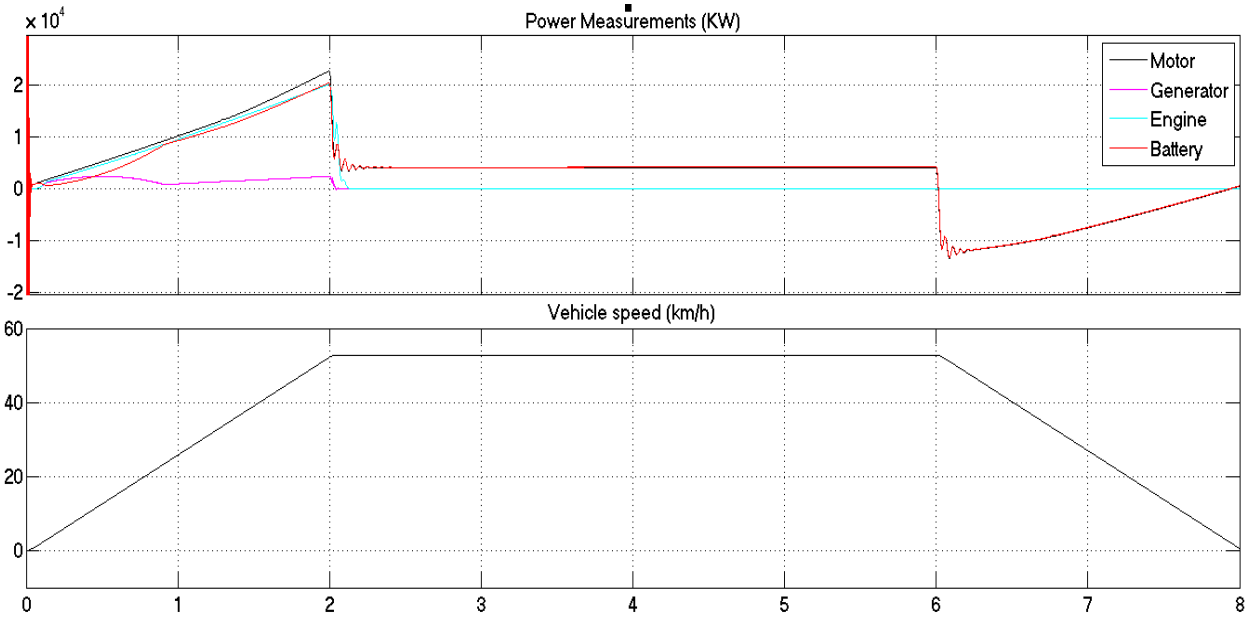


Figure 24: (a) Power flow waveforms (b) Vehicle speed

The Figure.24 (a) depicts the power measurements of motor, generator, engine and battery for a given drive cycle in acceleration, constant and deceleration periods. And the Figure.24 (b) depicts the change in velocity of the vehicle for the entire cycle. In acceleration mode, engine, motor, generator and battery are supplying power combined with each other. During constant operation, only battery supplies the power whereas engine and generator are idle. And during deceleration mode, regenerative action takes place and battery is charging during this phase.

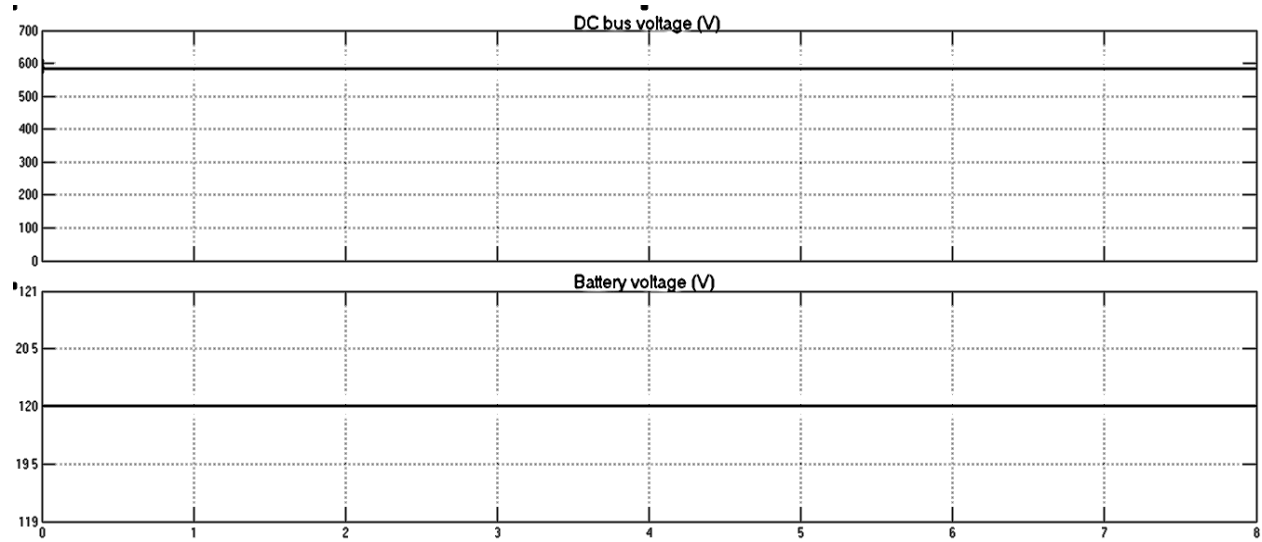


Figure 25: (a) DC bus voltage (b) Battery voltage

The Figure.25 (a) depicts the input dc voltage to the bi-directional dc-dc converter whereas in Figure.25 (b) the output voltage of the converter is presented.

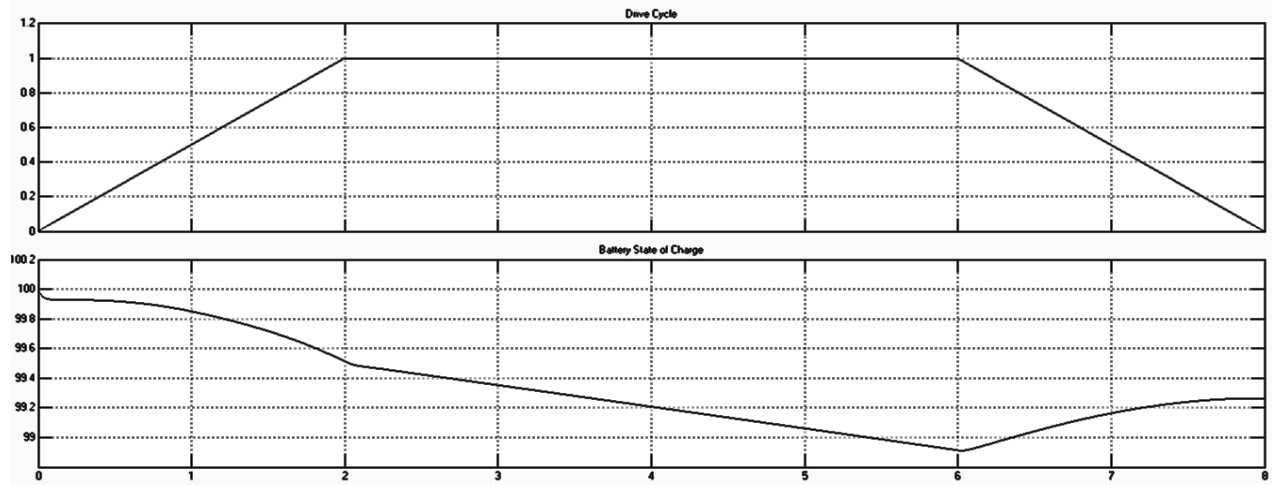


Figure 26: (a) Drive cycle (b) Battery SOC

The Figure.26 (a) shows the drive cycle given to the HEV for different modes including acceleration, constant and deceleration mode. And in Figure.26 (b) change in SOC of battery i.e. charging and discharging is recorded with respect to change in drive cycle.

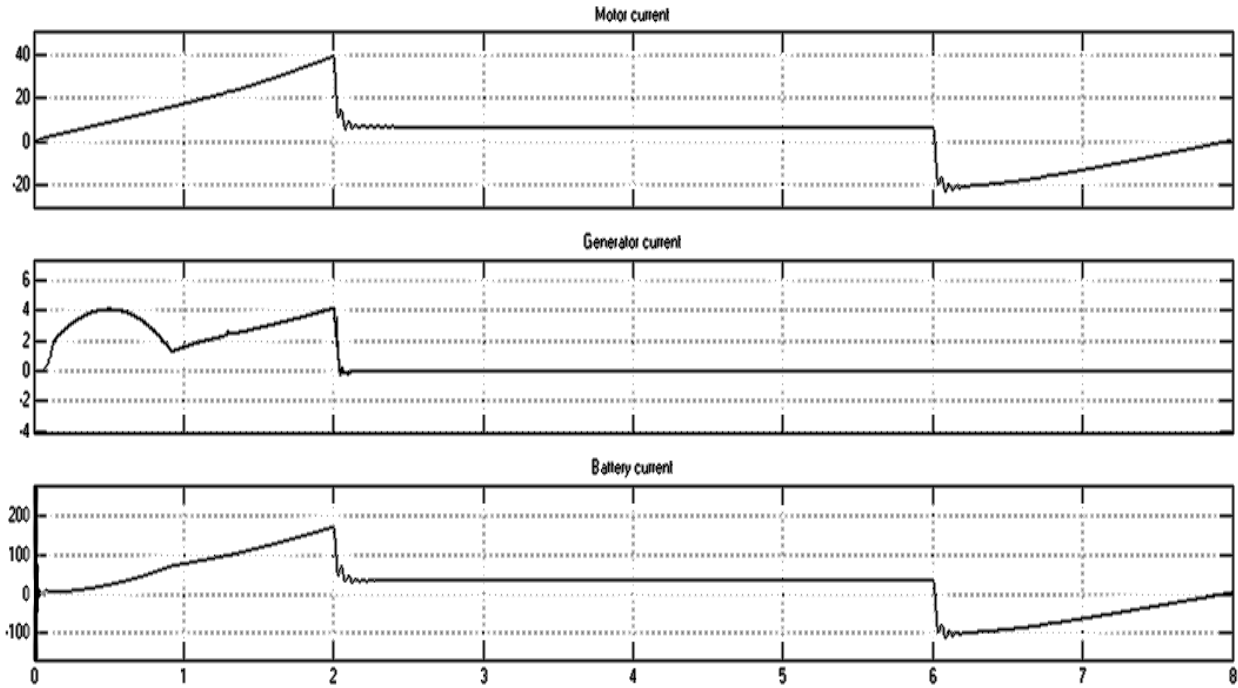


Figure 27: Current waveforms

The Figure.27 shows the input motor, generator and the battery currents varying with the drive cycle. During regenerative action, motor acts as a generator i.e. direction of reversed current is shown as negative. The battery is charging during this mode which is analyzed with the negative current supply to it.

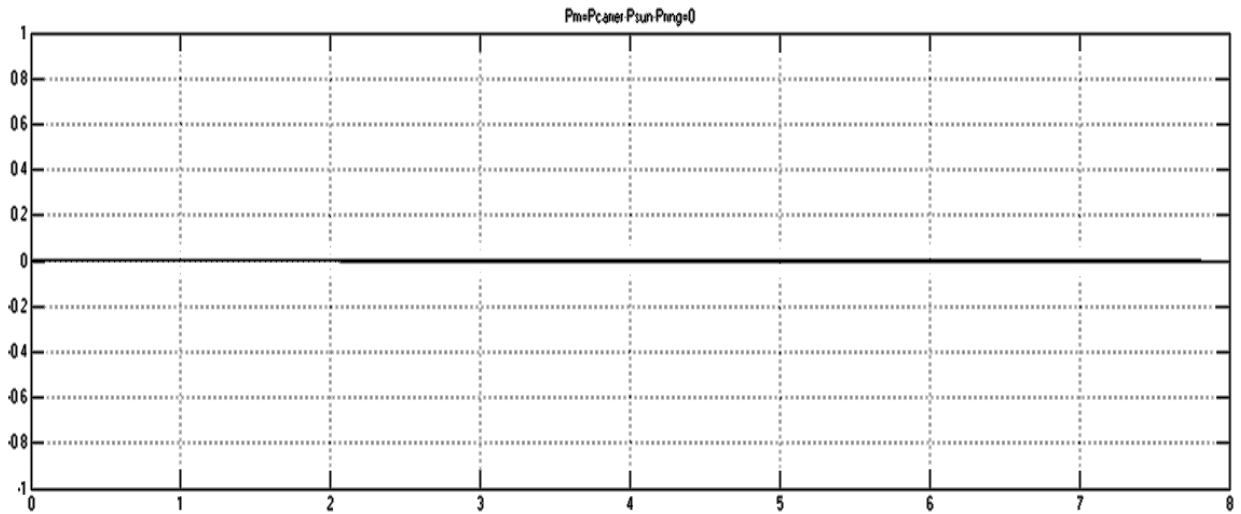


Figure 28: Power Law for Planetary gears

The Figure.28 depicts the power law i.e. $P_{\text{carrier}} - P_{\text{sun}} - P_{\text{ring}} = 0$ for planetary gears.

Table 3: Voltage, Current, Power and Efficiency of Bidirectional Converter

Input voltage(V)	Input current(A)	P_input (KW)	Output voltage(V)	Output current(A)	P_output (KW)	Efficiency(%)
120	34.50	4.14	582.11	6.96	4.05	97.85

Table 4: Characteristics of Converter for anacceleration and constant Drive cycle

Time (sec)	Input voltage (V)	T/F Input (V)	T/F output (V)	Output voltage (V)	Driving Mode
0	120.00	119.85	582.12	0.00	Acceleration
0.5	120.00	119.92	582.98	582.77	Acceleration
1	120.00	119.76	582.62	581.93	Acceleration
1.5	120.00	119.65	582.23	581.41	Acceleration
2	120.00	119.50	581.81	580.60	Acceleration
2.5	120.00	119.84	581.92	582.37	Constant
3	120.00	119.84	582.01	582.38	Constant
3.5	120.00	119.84	582.06	582.36	Constant
4	120.00	119.84	582.11	582.37	Constant
4.5	120.00	119.84	582.14	582.38	Constant
5	120.00	119.84	582.17	582.36	Constant
5.5	120.00	119.84	582.19	582.37	Constant

Table 5: Characteristics of converter for Deceleration mode

Time	Input voltage (V)	T/F Input(V)	T/F output(V)	Output voltage (V)	Driving Mode
6	582.21	582.38	119.84	120	Deceleration
6.5	582.45	585.01	120.35	120	Deceleration
7	582.63	584.47	120.25	120	Deceleration
7.5	582.73	583.84	120.12	120	Deceleration
8	582.78	583.12	119.98	120	Deceleration

Table 6: Justification of Power Law for Planetary gears

Time	P_sun (KW)	P_carrier (KW)	P_ring (KW)	Power law (P _c -P _s -P _r =0)
0	0.0000	0.0000	0.0000	0.0616
0.5	2.6318	4.6094	1.9777	0.0357

1	1.8013	9.4419	7.6405	0.0541
1.5	2.6148	14.7206	12.1058	0.0754
2	3.4215	20.1185	16.6970	0.1111
2.5	0.0005	-0.0011	-0.0016	0.0752
3	0.0000	0.0000	0.0000	0.0802
3.5	0.0000	0.0000	0.0000	0.0857
4	0.0000	0.0000	0.0000	0.0900
4.5	0.0000	0.0000	0.0000	0.0960
5	0.0000	0.0000	0.0000	0.1019
5.5	0.0000	0.0000	0.0000	0.1061
6	0.0000	0.0000	0.0000	0.1124
6.5	-0.0002	0.0002	0.0004	0.0928
7	-0.0002	0.0002	0.0004	0.1025
7.5	-0.0001	0.0002	0.0003	0.1143
8	0.0001	0.0001	0.0000	0.1243

Table 7: Effect of PI controller to get speed demanded by drive cycle

Time	Engine demand speed (rpm)	Engine actual speed (rpm)	Error	Motor demand speed (rpm)	Motor actual speed (rpm)	Error	Gen demand speed (rpm)	Gen actual speed (rpm)	Error	Velocity (Km/h)	Acc/De acc (km/h ²)
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0
0.5	750.0	749.2	0.8	1500.0	1419.0	81.0	800.0	968.7	-168.7	12.5	26.4
1	819.1	818.8	0.3	3000.0	2916.9	83.1	819.1	985.7	-166.6	25.7	26.4
1.5	1212.0	1211.6	0.4	4500.0	4416.1	83.9	1212.0	1380.4	-168.5	38.9	26.4
2	1608.4	1608.0	0.5	6000.0	5914.0	86.0	1608.4	1776.0	-167.6	52.1	1.3
2.5	750.0	788.0	-38.0	6000.0	5999.9	0.1	800.0	798.4	1.6	52.8	0.0
3	750.0	749.8	0.2	6000.0	5999.9	0.1	800.0	799.3	0.7	52.8	0.0
3.5	750.0	749.8	0.2	6000.0	6000.0	0.0	800.0	799.3	0.7	52.8	0.0
4	750.0	749.8	0.2	6000.0	6000.0	0.0	800.0	799.3	0.7	52.8	0.0
4.5	750.0	749.8	0.2	6000.0	5999.6	0.4	800.0	799.6	0.4	52.8	0.0
5	750.0	749.8	0.2	6000.0	5999.6	0.4	800.0	799.8	0.2	52.8	0.0
5.5	750.0	749.8	0.2	6000.0	5999.6	0.4	800.0	799.3	0.7	52.8	0.0
6	750.0	749.8	0.2	6000.0	5989.3	10.7	800.0	798.3	1.7	52.8	-25.1
6.5	973.5	498.9	474.7	4500.0	4566.2	-66.2	973.5	967.1	6.4	40.3	-26.4
7	750.0	329.1	420.9	3000.0	3069.4	-69.4	800.0	796.7	3.3	27.1	-26.4
7.5	750.0	217.1	532.9	1500.0	1571.4	-71.4	800.0	801.2	-1.2	13.9	-26.4
8	750.0	143.2	606.8	0.0	73.5	-73.5	800.0	805.6	-5.6	0.6	-1.3

Table 8: Speed-Torque Characteristics

Time	Motor speed (rpm)	Motor Torque (Nm)	Motor power (KW)	Generator speed (rpm)	Generator Torque (Nm)	Generator Power (KW)	Engine speed (rpm)	Engine Torque (Nm)	Engine Power (KW)
0	0.0	0.0	0.0000	0.0	0.0	0.0000	0.0	0.000	0.0000
0.5	1419.0	29.7	4.4058	968.7	-34.8	-3.5280	749.2	58.980	4.6252
1	2916.9	30.4	9.2960	985.7	-34.1	-3.5223	818.8	110.776	9.4933
1.5	4416.1	31.2	14.4371	1380.4	-34.6	-5.0025	1211.6	115.927	14.7008
2	5914.0	32.0	19.8200	1776.0	-34.5	-6.4159	1608.0	119.397	20.0946
2.5	5999.9	6.4	4.0191	798.4	0.0	0.0000	788.0	0.011	0.0009
3	5999.9	6.4	4.0192	799.3	0.0	0.0000	749.8	0.000	0.0000
3.5	6000.0	6.4	4.0192	799.3	0.0	0.0000	749.8	0.000	0.0000
4	6000.0	6.4	4.0192	799.3	0.0	0.0000	749.8	0.000	0.0000
4.5	5999.6	6.4	4.0189	799.6	0.0	0.0000	749.8	0.000	0.0000
5	5999.6	6.4	4.0189	799.8	0.0	0.0000	749.8	0.000	0.0000
5.5	5999.6	6.4	4.0189	799.3	0.0	0.0000	749.8	0.000	0.0000
6	5989.3	6.4	4.0120	798.3	0.0	0.0000	749.8	0.000	0.0000
6.5	4566.2	-24.5	-11.723	967.1	1.6	0.1609	498.9	0.004	0.0002
7	3069.4	-25.3	-8.1326	796.7	0.8	0.0667	329.1	0.006	0.0002
7.5	1571.4	-26.1	-4.2925	801.2	-0.8	-0.0639	217.1	0.007	0.0002
8	73.5	-26.9	-0.2069	805.6	-2.3	-0.1960	143.2	0.008	0.0001

Table 9: Fuel Consumption comparison for HEV and conventional vehicle

Tabular Data for HEV					Common Data		Tabular Data for Conventional			
Time	Engine speed	Engine Torque	Brake power	Fuel consumption (HEV)	Efficiency	Calorific value(Kg /m3)	Engine speed	Engine Torque	Brake power	Fuel consumption (Conventional)
0.5	749.2	58.980	4625.24	0.114713	0.9	44800	749.2	58.980	4625.24	0.11471
1	818.8	110.776	9493.26	0.235448	0.9	44800	818.8	110.776	9493.26	0.23544
1.5	1211.6	115.927	14700.81	0.364603	0.9	44800	1211.6	115.927	14700.8	0.36460
2	1608.0	119.397	20094.65	0.498379	0.9	44800	1608.0	119.397	20094.5	0.49837
2.5	788.0	0.011	0.94	0.000023	0.9	44800	1608.0	119.397	20094.5	0.49837
3	749.8	0.000	0.00	0.000000	0.9	44800	1608.0	119.397	20094.6	0.49837
3.5	749.8	0.000	0.01	0.000000	0.9	44800	1608.0	119.397	20094.6	0.49837
4	749.8	0.000	0.00	0.000000	0.9	44800	1608.0	119.397	20094.6	0.49837
4.5	749.8	0.000	-0.01	0.000000	0.9	44800	1608.0	119.397	20094.6	0.49837

5	749.8	0.000	0.01	0.000000	0.9	44800	1608.0	119.397	20094.6	0.49837
5.5	749.8	0.000	0.01	0.000000	0.9	44800	1608.0	119.397	20094.6	0.49837
6	749.8	0.000	0.01	0.000000	0.9	44800	1608.0	119.397	20094.6	0.49837
6.5	498.9	0.004	0.19	0.000005	0.9	44800	1189.5	112.524	14009.3	0.34745
7	329.1	0.006	0.20	0.000005	0.9	44800	585.5	109.120	6687.13	0.16585
7.5	217.1	0.007	0.16	0.000004	0.9	44800	217.1	52.240	1187.04	0.02944
8	143.2	0.008	0.12	0.000003	0.9	44800	143.2	0.008	0.12	0.00000

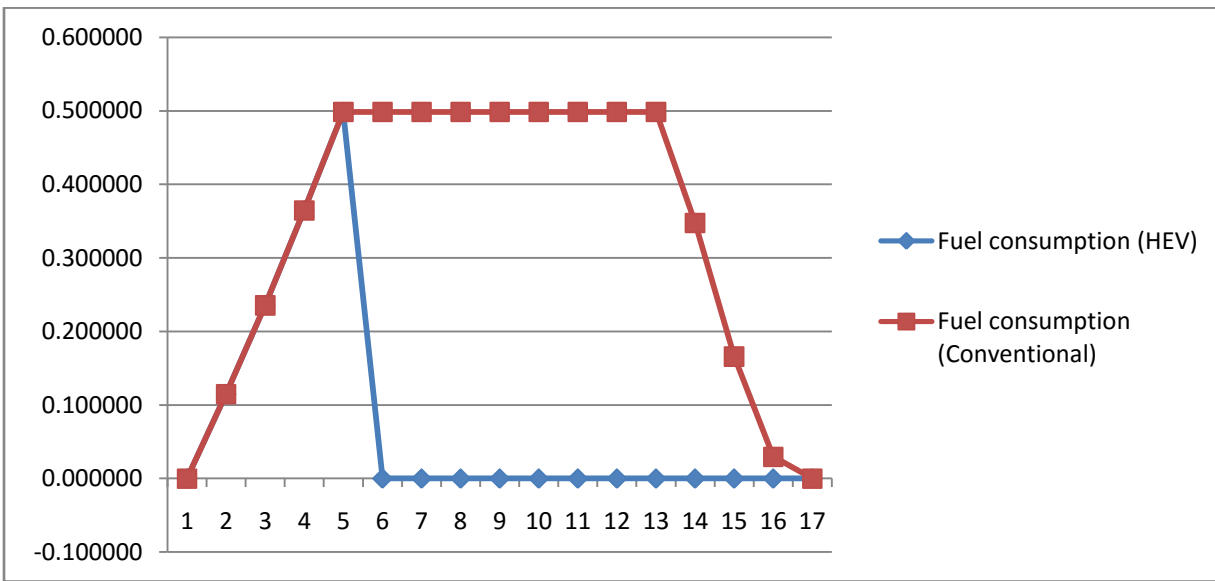


Figure 29: Fuel Consumption comparison

CHAPTER- 6

CONCLUSIONS AND FUTURE SCOPE

6.1 Conclusions: -

This thesis has described the research work on developing a series-parallel Hybrid Electric Vehicle System employing bidirectional DC-DC converter interfacing a variable speed permanent magnet synchronous motor. Main attention is paid on developing flexible, economical and environment friendly electrical vehicle. An AC/DC/AC power electronic conversion system is the most suitable type of interface for the electrical energy conversion system. The following DC/DC converter systems have been investigated in detail by mathematical and simulation analysis.

- Simple z-source converter.
- Trans z-source converter
- Bidirectional DC-DC converter

The operation and control of these systems are addressed in detail; the technical feasibility has been established. These converters having the boosting capabilities, deliver the optimal power captured from the battery, generate the desired power and have satisfactory ripple performance.

The results of analytical, numerical analysis, simulation studies of the above-mentioned z-source converter based systems have demonstrated the performance of many alternative systems.

Chapter 2 of the thesis presents a review of the relevant literature showing the work done previously in the area of proposed research to plan further research effectively. It surveys the continuous developments in the area of Hybrid Electric Vehicle and application of power electronics based converter for that. It presents the literature survey in the area of newly proposed z-source converters along with many existing DC-DC converters.

Chapter 3 provides the State Space Averaging methodology for analysis of Z source and Trans Z source dc-dc converters. Open loop transfer function of the converters is developed and step responses of the converters are presented. Speed control and Vector Control (FOC) for controlling three phase input current of PMSM motor drive is explained in detail.

Chapter 4 deals with the mathematical modeling of Bi-directional dc-dc converter, Z source as well as Trans Z source dc-dc converters. Step responses of the Z source converter are presented. Various DC-DC converters are compared and suitable DC/DC converters are chosen for proposed HEV system. HEV system for acceleration, constant and deceleration period is represented mathematically.

Chapter 5 presents the Simulation results of closed loop HEV system for a particular drive cycle. The model was simulated a particular drive cycle including different modes of driving i.e. acceleration, constant and deceleration modes. During acceleration, Torque is positive and follows a constant relation whereas during constant mode, Torque is reduced as force reduces which further depends upon the acceleration which is nearly zero. During braking or deceleration mode, acceleration is negative so torque is negative too. The speed and torque relationship helps in computing the respective powers outputs of motor, generator and engine. The battery power is computed electrically for the input voltage and current. The velocity of the vehicle is presented which can be justified by computing the slope and angle of acceleration/deceleration of the drive cycle for a given time interval. The nominal voltage of battery is supplied equal to 120V which is boosted to 580V. The currents of motor, generator and battery are varying with respect to drive cycle input. The data values for all the parameters are presented in Table 3-9.

The sharing of the power in power split design is performed by the introduction of planetary gears. The summation of power shared by all the components connected to each other which should be zero and is justified. From the results, it is concluded that battery and motor current is negative during braking mode. The kinetic energy of the wheels turn the motor in reverse direction which justifies that the motor is acting as a generator and regenerative mode is in action. The battery is being recharged. Finally the fuel consumption for the drive cycle has been compared for the HEV's and the conventional vehicles which strongly recommend the future generation cars as HEV/EV cars.

6.2 Future Scope: -

Series-Parallel HEV model was also simulated with Z source dc-dc converter but the results obtained for deceleration mode were not satisfactory (as shown below) because of its unidirectional consideration. A control system and bidirectional power flow requirements is to be designed for its effective implementation.

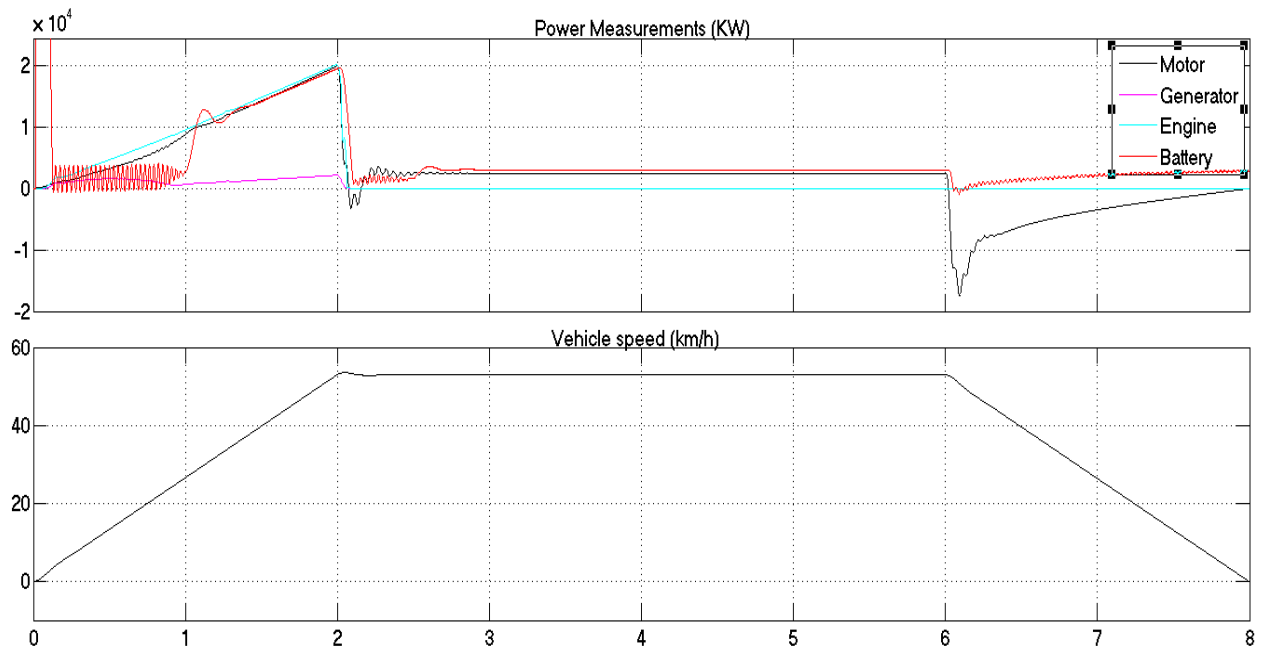


Figure 30: Power measurements of Z source converter in HEV

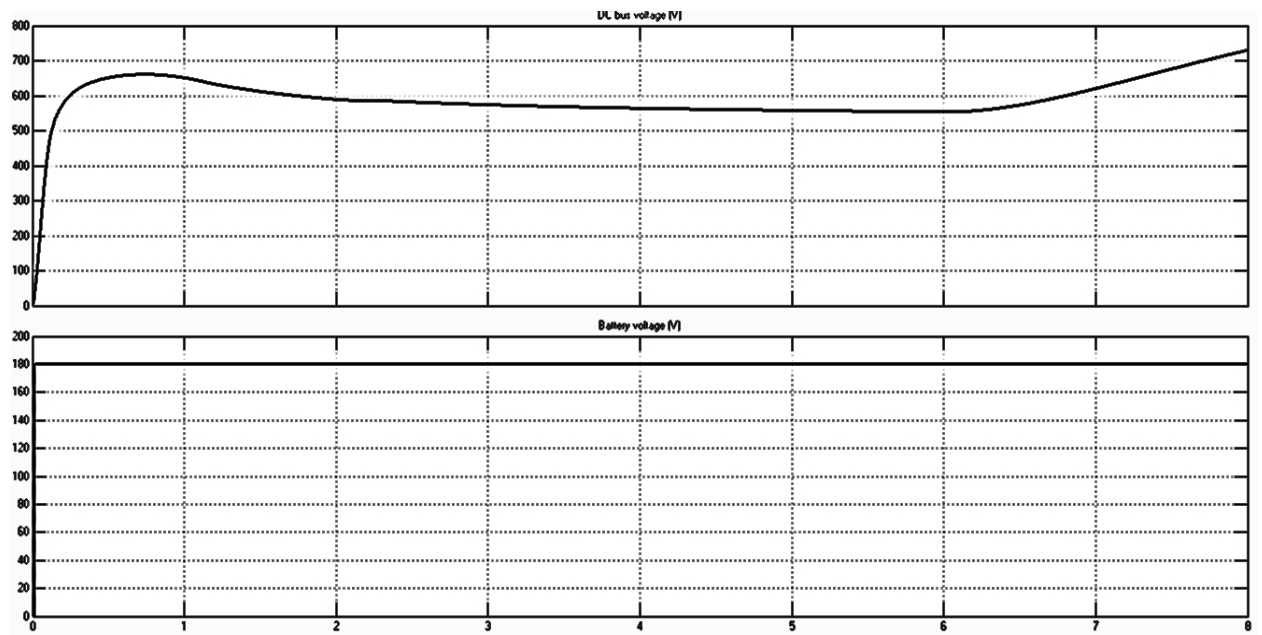


Figure 31: Voltage measurements of Z source converter in HEV

LIST OF PUBLICATIONS: -

- [1] Jasandeep Singh and Santosh Sonar, "Analysis of Z source DC-DC converter using State Space Averaging Technique", *IEEE Seventh India International Conference on Power Electronics (IICPE 2016)*[**COMMUNICATED**]
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APPENDIX- A

Model Specifications

Parameters	Specifications
Input voltage	120 V
Transformer Turns ratio	100/486
Switching Frequency	20 KHz
Duty ratio	0.5
Mass of vehicle	800 Kg
Displacement	1200 cc
Vehicle Power	36 HP, 1700 rpm
Radius of tire	0.3 m
Drag coefficient	0.26
Sun speed	-226 rad/s
Ring speed	195 rad/s
Planet speed	460 rad/s
Carrier speed	78.5rad/s
Number of teeth in sun gear	18
Number of teeth in ring gear	48
Number of teeth in planet gear	15

Planetary gear ratio	1.16
Frontal Area	2.57 m ²
Moment of Inertia	0.5 Kgm ²
Vehicle velocity	52 Km/h
Acceleration angle	26.4 ⁰
Deceleration angle	-26.4 ⁰
Distance travelled	88 m in 8 sec
Rolling frictional force	39.19 N
Angular force	193.149 N
Total Tractive Force	232.339
Average Torque for drive cycle	70 Nm
Average Power for drive cycle	13.95 KW
Motor	25 KW, 600V, 8 pole PMSM, 6000 rpm
Generator	10 KW,600V, 2 pole PMSM, 2000 rpm
Battery	15 KW, 120V, 6.5Ah Nickel meta-hydride
Engine	20 KW, 1700 rpm

CURRICULUM VITAE

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Academic Details

- 2014-16 Masters in Engineering in Power System Engineering from Thapar University, Patiala
- 2009-13 Bachelor of Engineering in Electrical & Electronics Engineering from UIET, Panjab University, Chandigarh
- 2008-09 Senior Secondary education (12th examination) with Non-Medical subjects from GMSSS-33, Chandigarh
- 2006-07 Matric Examination (10th examination) from Kundan Vidya Mandir (CBSE), Ludhiana, Punjab

Association/ Membership

- An active member of SAE (Society of Automotive Engineers), India

Extracurricular Activities

- Participated in ICAER-2011, submitted paper on “Wireless Energy Transfer”.
- Worked as an organizer in ICAER conference, 2011.
- Worked as an organizer in event SAE-Efficycle, 2010.

Publications: -

- [1] Jasandeep Singh and Santosh Sonar, “Analysis of Z source DC-DC converter using State Space Averaging Technique”, *IEEE Seventh India International Conference on Power Electronics (IICPE 2016)* (Communicated)
- [2] Jasandeep Singh and Santosh Sonar, “Bi-Directional DC-DC Converter used for Hybrid Electric Vehicle for a given drive cycle”, *International Journal of Electrical Power and Energy Systems, Elsevier, 2016* (Communicated)

Thesis: -

Analysis of Series-Parallel Hybrid Electric Vehicle with suitable DC-DC converter for a given drive cycle.

PLAGIARISM CERTIFICATE

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