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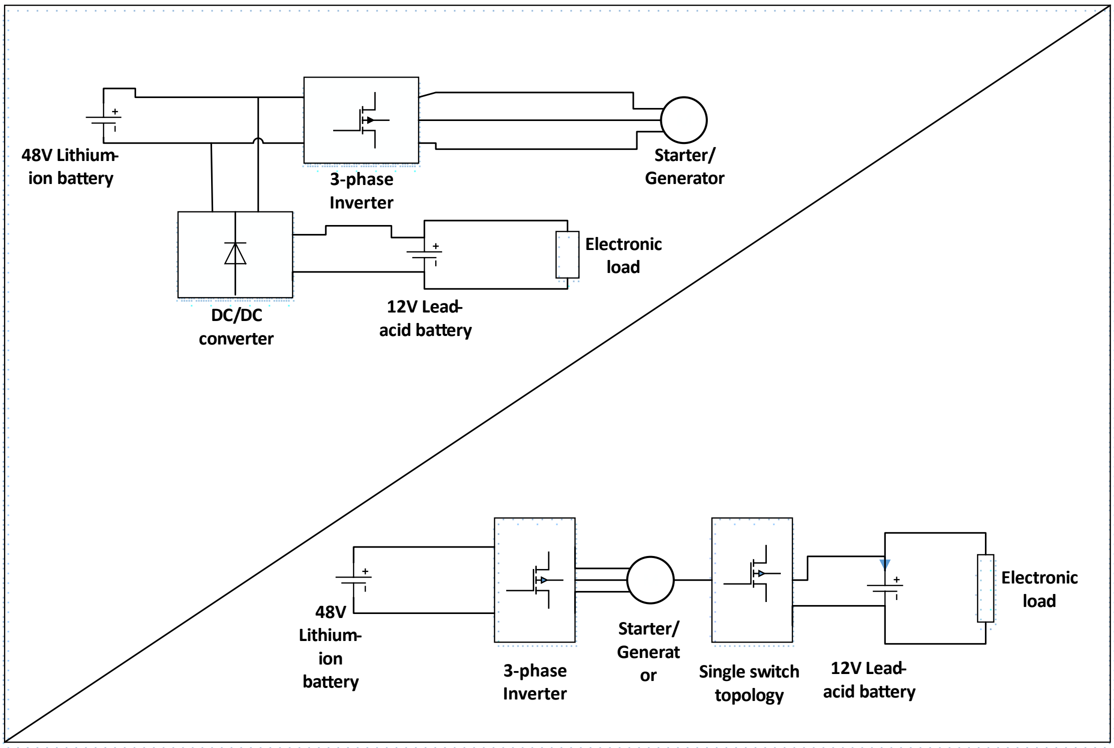

Simulating & Evaluating feasibility to integrate charging of 12V battery with 48V drivetrain for Dual Voltage 48V/12V Mild Hybrid vehicles

Master's thesis in Electrical Power Engineering

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Department of Electrical Power Engineering at Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Cover: Electrical schematic showing Mild hybrid Dual voltage system with separate DC/DC converter for charging 12V battery & Integrated charging for 12V battery

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Abstract

Dual voltage energy storage systems have become common in mild hybrid vehicles due to their advantages such as increased stability and reliability of the system. They serve a viable solution for increasing demand of power for Mild hybrid vehicles. The dual voltage in mild hybrids contains two level of voltages; 48V battery is used for electrical drivetrain and 12V battery is used to power auxiliary system of the vehicles. The demand for power for these auxiliary systems is increasing due to additional safety systems implemented in the car and hence, it is crucial to have required level of SOC for 12V battery. In current system, this is achieved by a separate dc/dc converter unit to charge the 12V battery pack. But, this unit is quite bulky and costly and hence, it is required to find an alternate solution to charge the 12V battery without using a separate dc/dc converter.
This thesis focuses on investigating on an integrated charger topology suitable to charge 12V battery for Mild hybrid Dual voltage 48V/12V system. It also checks the feasibility of the topology to charge the 12V battery continuously under three modes of motor operation; Motoring mode, Regeneration mode and idle mode. The work mainly focuses on developing a simulation model which can simulate different modes of motor for mild hybrid vehicle for charging the 12V. The motivation behind the thesis is to integrate the 12V charging with 48V drivetrain which will reduce the overall size and cost of the drivetrain system. The analysis is done based on charger efficiency and generation of ripple for the three modes of motor operation.

Keywords: Mild Hybrid vehicles, Dual voltage energy storage systems, Integrated Charger topology, Common mode voltage

Acknowledgements

I would like to thank Chalmers University of Technology & VOLVO cars corporation for giving me the opportunity to perform this Master's thesis. I am also thankful to my examiner Prof. Yujing Liu at Chalmers University of Technology & my supervisers at VOLVO cars; Jonas Forsell, Sören Erikson and Peter Almhagen for guiding me in my thesis and giving complete freedom in this thesis. I am also extending my gratitude towards Nima Sadat, Tarik Abdulhovic and Daniel Peherman for helping me with software issues.
I also thank Junfei Tang & Yashovardah Rastogi for giving me support throughout the thesis. Last but not least, I would like to thank my family for believing in me and supporting me throughout my masters at Chalmers University of Technology.

Tanmay Shukla, Gothenburg, February 2018

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1
Introduction

1.1 Regulations on CO_2 emissions in Europe

Although, the first electric car was manufactured in 18th century [2], the ICE (Internal Combustion Engine) took over the global market due to their high availability, cheap and simple design. But, recently there has been great hustle in the automotive industry since, CO_2 emitted from these vehicles is too high and hence, there are strict regulations regarding CO_2 emissions such as by 2015, the average CO_2 emissions for all light duty vehicles from a company should emit 130g/Km and by 2020, this number should reduce up to 95g/Km. [3]

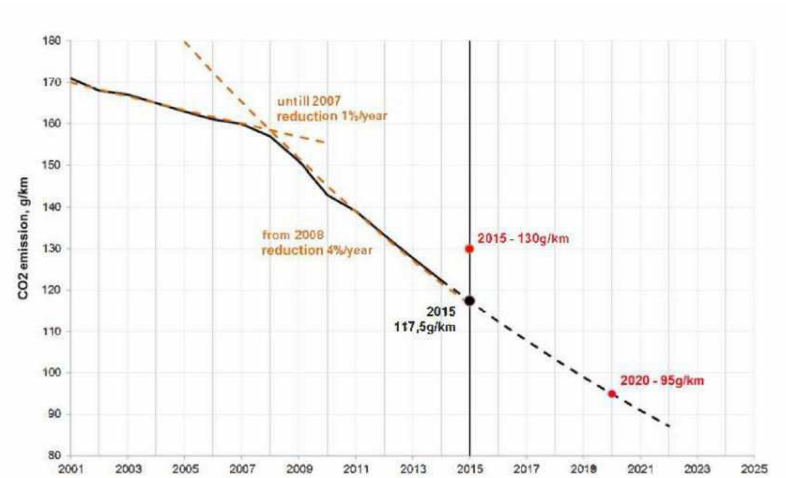


Figure 1.1: EU regulations for CO2 emission over the years [3]

Figure 1.1 shows the average CO_2 emissions that vehicles should have over the years and to meet these regulations, lot of development was done in ICE engines to increase the efficiency so as to reduce the emission. But, this development has a limit and to improve further some other eco-friendly sources need to be developed. Since then, different sources have been investigated to propel the vehicle such as bio-diesel, air technology develop by Volkswagen, CNG, Electrification. Among all these sources, electrification of vehicles seems to be a promising alternative as, electricity is very cheap source of energy and latest development in automation and AI (Artificial intelligence) increases its reliability due to easy control of the devices, fast response and very high efficiency.
The main components in the electrical drive system are the electric motor which drives the vehicle, a battery pack which supplies energy to the motor and other

electronic system in the vehicle. The goal of all OEMs(Original Equipment Manufacturers) is to implement 100% electrification of the vehicles which is also known as BEVs (Battery electric vehicles). The main challenges for complete electrification of vehicles are, the battery technology is very costly compared to diesel or petrol, the vehicles are still limited in range, the time required to charge full battery pack is too long and the charging infrastructure is lacking in development [1][2]. Currently, hybrid vehicles which contains both conventional ICE and electric drive system to drive the cars is growing and based on the amount of electrification and hence the power requirements the hybrid vehicles are divided into following categories, PHEVs (Plug in hybrid vehicles) , Mild hybrid vehicles and Micro hybrid vehicles.

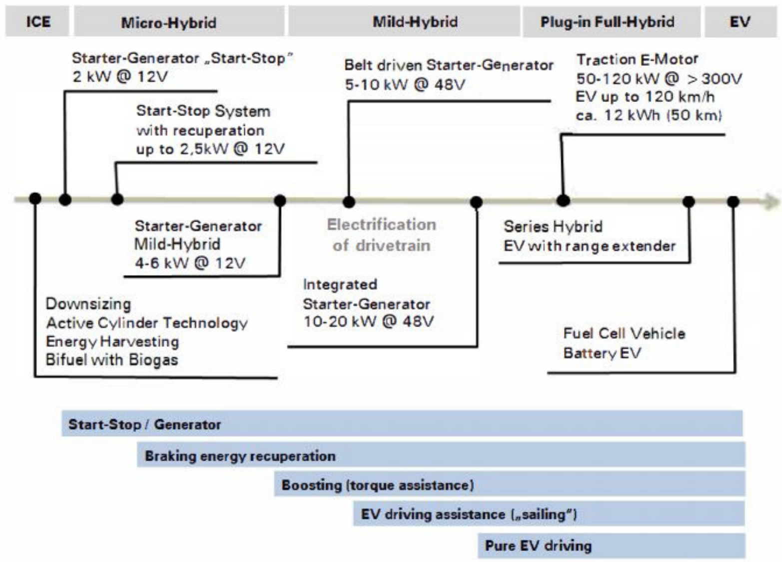


Figure 1.2: Power demand for various Hybrid electric vehicles [3]

Figure1.2 shows the requirement of power for each class of hybrid vehicle. Although, Plug-in hybrid gives significant reduction in CO_2 emission, they are still limited to the range of 50Km and are very costly to buy and hence, cheaper solution is required on commercial and global level. Micro-hybrid is cheapest hybrid class, but it is limited in functions and not sufficient to meet the requirement of increasing power demands because of the low voltage of 12V, the current is very high and to design cable harness for such a high current is impractical. Hence, Mild hybrid is being considered which provides 15% reduction in CO2 emission and still is very cheap with more function such as start/stop, Recuperation and boosting the torque[3]. Mild hybrid vehicles will be discussed in more detail in next chapter.

1.2 Scope of the thesis

The thesis is limited to developing working strategy of Integrated 12V charger for Recuperation, Motoring and Idle mode of motor operation. The study is topology based and hence, simulation model is developed to study the effect of integrated charging on the system. This effect is quantified by measuring the efficiency and also the ripple content in the charging system for different modes of motor operation.

1.3 Methods and tools used in this thesis:

The objective of this thesis is to check the feasibility to integrate charging of 12V battery with 48V drivetrain. Hence, it was decided to use simulation method to analyze the three modes of motor operation as required by VOLVO cars. Different modes of operation were simulated by developing an equivalent electrical circuit model of different components for example, battery pack in the model is represented by a dc voltage source and a series internal resistance, ISG (Integrated Starter/Generator) machine is represented by a generic simplified RLE electrical machine model etc. The ratings of these components were based on input from VOLVO cars, Design project on ‘Design of 48V 3-phase Inverter’ and PHD thesis on Developing 48V EESM (Electrically Excited Synchronous Machine) at Chalmers university of technology. The specifications of rating for various components are provided in 3.1
LTspice is used as a simulation tool for this thesis; the reason is that, it’s a free licensed software, easy to use, availability of big library of various components available freely on respective website of component company; the data can be easily exported to MATLAB for post-processing. It is also easy to form a whole system (in this case mild hybrid system) by integrating other small sub-systems (like inverter, electric machine etc.), Transitioning between different modes of operation of motor is quick and easy. The conclusions drawn are strictly based on simulation results.

1.4 Organization of Thesis

Chapter 1 consists of Introduction explaining the need to implement electrical drivetrain considering the demand to reduce the CO_2 emission for coming years, it also describes the scope of the thesis and methods used to achieve the objective of the thesis. Chapter 2 includes Description of 48V Mild hybrid system with different modes of operation it also describe the need to implement dual voltage energy storage system for hybrid vehicles and the need to integrate 12V charging which is the main objective of this thesis. Chapter 3 describes the different topologies which are considered for this thesis and also introduces the new topology developed for this thesis with simulated model description and defining all the parameters used to simulate the model. Chapter 4 is divided into three parts, each shows the simulation results obtained for different modes of operation for new integrated 12V charging topology and also discuss the results. Chapter 5 contains the conclusion based upon the results obtained and the future work for the thesis.

2
Mild Hybrid vehicle systems

After the huge commercial success of Toyota Prius all major OEM companies in automobile started developing mild hybrid cars[2]. The major reasons for this transition were the strict rules by the governments on reducing carbon emission, underdeveloped battery technologies which resulted in costly Plug in hybrids (PHEVs) and Battery electric vehicles (BEVs) and also insufficient availability of charging infrastructure. Mild hybrid technology reduces carbon emission by 15% and also very cheap compared to PHEVs and BEVs due to less number of components in the powertrain. It operates at a voltage of 48V dc which is four times more than 12V systems that allows higher power and less thick cable harnesses. Furthermore, the voltage is less than 60V dc which is considered as threshold for the dc voltage value for automotive application that prevents any need of additional isolation thus, saving space and cost of the system. Figure 2.1 shows the main components of a

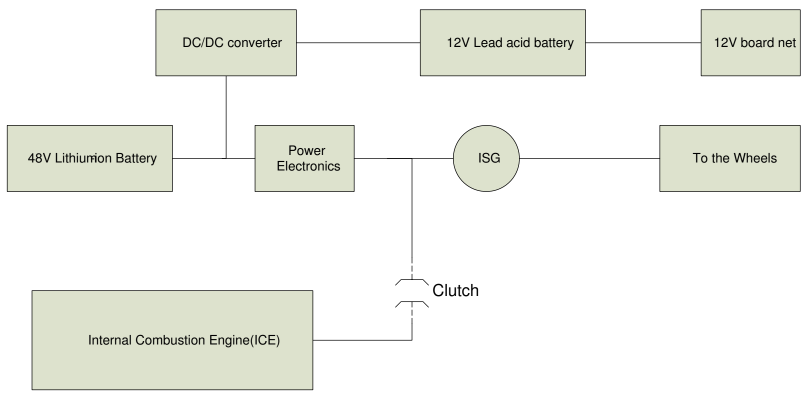


Figure 2.1: Mild hybrid dual voltage system architecture

power train in a typical mild hybrid car. The wheels can be propelled by both ICE and electric machine and hence, the CO_2 emission can be reduced by sharing the load. The Electric motor and ICE are coupled to each other directly and hence this arrangement is called Integrated Starter/Generator(ISG). The name indicates that, the machine is capable of starting the engine as well as recuperating brake energy to charge the lithium ion battery pack thus saving the space from alternator. Power electronics is required to convert the dc power of battery into suitable ac power for the ISG and also a control unit to constantly monitor the requested torque input and control accordingly the torque output by using torque encoder or by converting requested torque into equivalent current and voltage by power control unit of the vehicle.

2.1 Different modes of motor operation in Mild hybrid vehicles

2.1.1 Start/Stop and Torque assistance mode

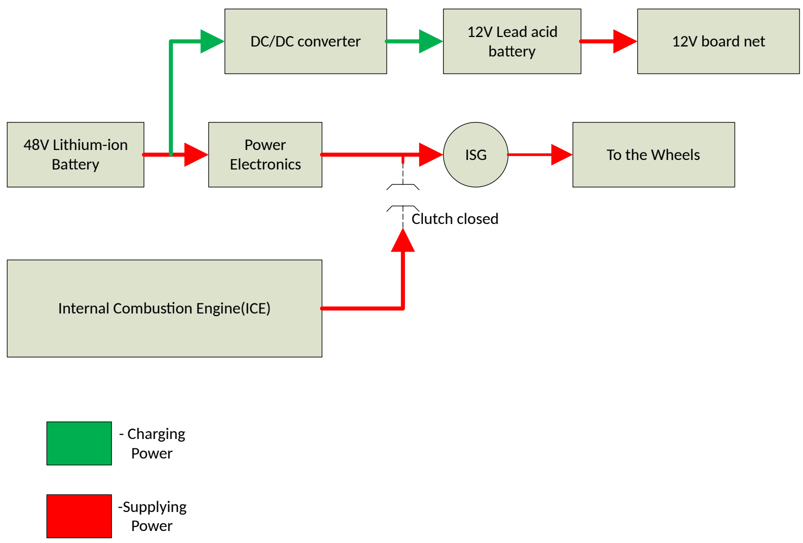


Figure 2.2: Schematic of operation in start/stop and torque assisting for Mild hybrid system

The significant reduction of CO_2 emission for a mild hybrid systems can be achieved in these two operation because, during these two operations, engine needs a very high torque at low speeds and ICE has a drawback of having very low efficiency at lower speed therefore, to achieve required amount of torque, it consumes very high quantity of fuel causing higher CO_2 emissions. This can be achieved by using an electric motor supplied by a lithium ion battery which can generate very high torques at much higher efficiency than ICE. So, the engine is started by using an electrical system and so as shown in the Figure 2.2, battery will supply the required amount of energy.The torque assistance is required when the car is climbing a slope. In this case, there is a limit on torque provided by ICE and the excess torque is supplied by the electrical system reducing the consumption of fuel and reducing the carbon emission. Figure 2.2 shows that, during torque assistance the load is shared by ICE and electrical system. ISGs operate at higher power of 15kW-20kW, refer to figure 1.2 and hence, it is also possible to have electrical steering for very short range which further reduces the carbon emission when driving in the cities[3]. In a electrical simulation model, this mode can be simulated by using 48V battery as a dc source supplying a RLE load which represents electrical machine and an inverter model which converts dc voltage of 48V battery into ac voltage input for the motor.

2.1.2 Recuperation mode(Regenerative Braking)

This mode is used to charge the 48V battery by using ISG, this can be done by using electrical braking to brake the wheels at high speeds by applying negative

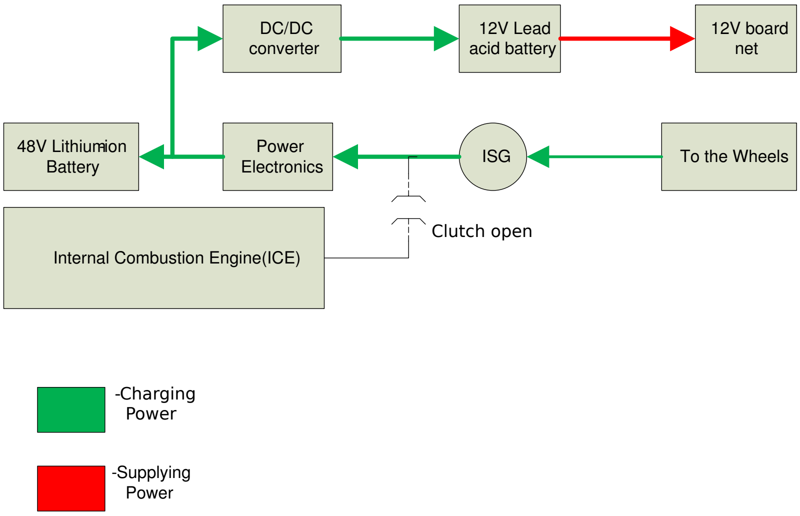


Figure 2.3: Schematic for recuperation mode in mild hybrid system

torque to the ISG, but this is very limited operation since, electrical braking is used only to reduce speed up to certain level and then conventional hydraulics brakes are used to completely stop the vehicle if required. Due to the limited speed range of operation, it may not be sufficient to gain 100% SOC level and hence, when the 48V battery does not have sufficient energy, ICE is used to rotate the ISG and drive the vehicle thereby charging the 48V battery. Figure 2.3 shows regeneration operation in mild hybrid vehicles, as it can be seen the power is flowing from ISG to 48V battery. Regeneration also improves overall efficiency of the system. This mode can be electrically simulated by setting voltage amplitude of RLE high enough so that, the RLE model can be used as source which supplies power to the dc source having series resistance through a rectifier model.

2.1.3 Idle mode:

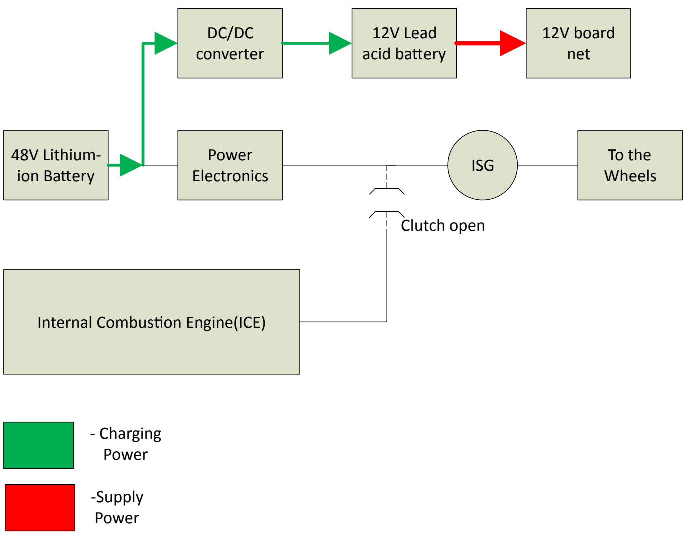


Figure 2.4: Schematic for idle mode in mild hybrid system

In this mode, the ISG in mild hybrid vehicle is not rotating. In other words, it can be viewed that the vehicles is at standstill condition or the vehicle is being propelled by only IC engine. Hence, the 48V battery is said to be idle not supplying any power nor charging due to regeneration. Although the electric drivetrain is not functional in this mode, the auxiliary system such as safety systems, infotainment and A/C systems could be working and hence, the 12V battery is constantly under the load even in this mode and hence, if it is required to charge the 12V battery, the 48V battery is used to charge the 12V battery through a DC/DC converter.

2.2 Dual Energy storage systems in Mild hybrid vehicles (Problem Description):

Mild hybrid vehicles consist of partial electrification of powertrain which helps in reducing CO_2 emissions. These amounts of electrification enable major three modes of operation in mild hybrids as discussed in section 2.1. The power demand during start/stop and torque assistance is very high and the voltage level of mild hybrid is 48V, hence current demand from an energy source is also very high. There are also other auxiliary systems such as safety circuits, Infotainment, heating system, AC (Air condition) which requires low voltage source [12]. If, all these systems are supplied by single energy source, then it will experience a very high stress because of so many loads and due to constant charging/discharging cycles, the life span of this source will be less and hence, change of energy source is required after every few years which is expensive in the long run. Also, the conventional regeneration system will not be sufficient to maintain the required amount of SOC level of this energy storage system. The energy storage system would be a bulky and costly unit which could supply this high power demand and also there would be lot of dc/dc converters in the vehicle to supply the auxiliary system which will make the overall electrical system big and costly. Hence, using single energy source in mild hybrid vehicle for increasing power demand is impractical and hence, Hybrid energy source is considered for such application which reduces the stress and improves the life cycle [1][12].
In this thesis, Lithium-ion battery pack and lead acid battery is considered as a dual voltage storage system for mild hybrid vehicle. Lithium ion battery pack is supplying power to the 48V ISG machine and lead acid battery pack is supplying power to low voltage auxiliary systems. The power demand from auxiliary systems is increasing currently 3kW to 5kW because, additional systems are added such as Electrical power steering (EPS), Fuel injection control in engine, park assistance etc. In order to meet the rising power demand, lead acid battery should maintain the higher SOC level and hence, currently, separate dc/dc converter is used to charge 12V battery by stepping down the voltage from 48V battery. But, this dc/dc converter unit is a bulky and costly unit and hence, alternative method needs to be investigated to charge the 12V battery to further reduce the size and cost of the system. Because, the development cost of 48V system is very high and also the cost of lithium ion battery pack is still very high and hence, it is important to cut the cost in auxiliary distribution systems by reducing the number of components as possible. Hence, the

objective of this thesis is to investigate the feasibility of integrating charging of 12V battery with 48V drivetrain which will make the overall system compact and cost effective. In the next chapter various topologies are discussed and a new topology is adapted to meet the required power increasing demand of the auxiliary system.

3

Integrated Charger topologies

The following conditions were set by VOLVO cars to design the integrated charging topology:

- The topology should be designed for mild hybrid dual voltage vehicle applications.
- The topology should be able to charge the 12V battery continuously, during idle mode, regeneration mode and motoring mode.
- The topology should consist of minimum number of components so that, the overall packaging of drivetrain should be compact and cost effective than the present separate dc/dc architecture.
- The peak power for charging the 12V battery is 3kW.
- The 12V battery in this application is only used to supply the auxiliary loads in the vehicle and hence, it should not be possible to supply the ISG from 12V battery.

Based upon the conditions set for the development of the topology, the major challenge is to find the topology which will fulfill the requirement on continuous operation of charging and at the same time it is compact and have less number of components. Hence, it is decided to develop a single circuit which can have the possibility to charge the 12V battery in all three modes of operation to keep the less number of components and to keep the circuit simple. To simplify the development, it is decided to first incorporate the charging for motor mode and regeneration mode since, lot of papers are found which developed charging strategy for these modes of motor operation for dual voltage vehicle applications.
Various topologies were investigated for integrated charging concept; such as Dual Alternator topology based on a Master thesis done on Dual Alternator topology and Alternator topology with center tap connection is based on PHD thesis. Dual alternator topology consisted of an alternator with two voltage winding, one for the high voltage and other for the low voltage. And because of this arrangement, only a half bridge rectifier was needed to charge the 12V battery along with the full wave conventional rectifier for 36V battery [6].
The other topology which is considered was the ‘Star point alternator topology with center tap connection’; It consists of connecting 12V battery between the star point of alternator and common ground of the electrical drivetrain system. The advantage

of this system is that, the charging of either batteries is dependent on the alternator speed and hence, a control unit was placed which measures the voltage at star point of the alternator and when the voltage amplitude is sufficient to charge the 12V battery i.e. at low speed by 4.1, it will enable the charging of 12V battery by controlling the MOSFET switches. When the voltage is higher i.e. at high speeds, the controller will disable the charging of 12V battery and then the 36V battery will be charged by conventional full wave rectifier circuit [4].
The final topology which is considered for the thesis is 'The Novel Star point inverter topology' for Dual voltage 48V/12V Mild hybrid application. This topology is used to integrate the charging of 12V battery during motoring mode of ISG operation. The charging of 12V battery is achieved by using the common mode voltage of the inverter. Also, in this topology, the 12V battery is connected between the star point of the machine and the negative terminal of the 48V battery, the common neutral point for inverter and the 48V battery and the charging is done by the implementing a half bridge chopper circuit which is used to chop off the excess common mode voltage[5].

3.1 Challenges in developing the new integrated dual voltage charging topology:

Dual Alternator concept was not considered further because, it requires having an additional stator winding in the motor housing which would result in increased in size of electric machine and VOLVO cars, did not want to increase the size of motor due to space constraints. To simplify the development, it was decided to first incorporate the charging for motor mode and regeneration mode since, Star point alternator topology and The novel star point inverter topology discussed about the integrated charging of 12V battery for regeneration mode and motoring mode respectively and hence, these two topologies were considered as a base for this thesis. The thesis work started with developing a simulation model in LTspice based on novel star point inverter topology which is based on common mode voltage, Hence, the model consisted of 48V dc source, 3-phase inverter and a RLE machine model. Initially, the feasibility of model is checked for regeneration mode and then it is checked for for motoring mode. The inverter in motoring mode is operated by using SINE triangle modulation (STM) because, it is quick and simple to implement this pwm techinique and since, the topology is based on using common mode voltage of the motor. It is important to understand the basics of common mode voltage and how it can be controlled by using SINE triangle modulation.

3.2 Common Mode Voltage:

Common mode voltage (Vcm) is voltage which is measured in between the star point of the 3-phase rotating machine with respect to the ground of the traction system. Although, the ground point is not present in the practical system, since electrical drive system is kept floating for safety reasons, But, for mild hybrid vehicles, there is no requirement on galvanic isolation; since, the traction voltage is less than the high voltage ($< 60Vdc$) for automotive application. This point is referred as the point which is connected to the negative terminal of the traction battery. This voltage varies between 0V to maximum dc voltage in the system and has frequency equal to switching frequency of the inverter switches[8]. Ideally, in a 3 phase balanced inverter, the average voltage should be zero, but since modern day electric drives implement high switching frequencies, the sinusoidal output of these inverters in not a pure sine wave and hence, there is presence of voltage at the neutral point of the electric motor and the inverter neutral point which is commonly referred to as Common mode voltage. Although, this voltage is measured at the electric machine, it is inherent property of an inverter [9]. Consider a simple electrical schematic of the 3-phase inverter supplied by 48V dc as shown in figure 1. Figure 3.1 shows Elec-

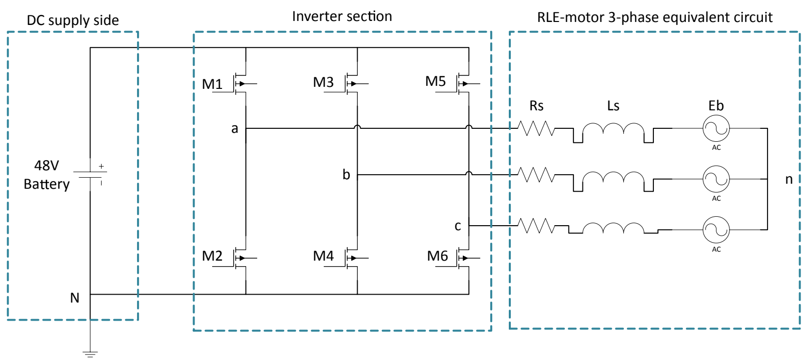


Figure 3.1: Electrical schematic for generating common mode voltage

trical schematic of a 3-phase inverter system. The inverter consists of 6 MOSFET switches referred as M1-M6 and the motor is represented by equivalent circuit having stator resistance(R_s), stator inductance(L_s) and back emf(E_b) connected in star point denoted by 'n' in 3 phases 'a', 'b' and 'c'. The point 'N' denotes the reference point of the system which is connected to the negative terminal of the 48V battery. The instantaneous value of the voltage is given by [5],

$$V_{nN} = \frac{V_{aN} \times V_{bN} \times V_{cN}}{3} \tag{3.1}$$

Where, V_{aN}, V_{bN}, V_{cN}= Phase to ground voltage [V]
V_{nN}=Common mode voltage [V]

3.2.1 Effects of common mode voltage on the machine:

The effect of this voltage is mainly observed on shafts and bearings of the motor. The zero switching currents causes breakdown in shafts switching at higher frequency thrice than that of inverter and hence, it is also called the third harmonic component of inverter current. This current causes insulation breakdown in the shaft and bearings of the motor because very high currents are developed in these components due to this high frequency voltages, This due to the fact that, the insulation forms a capacitance which breaks down at very high amplitude of currents. Although, high frequencies are preferred for the inverter to reduce the size and cost of the components, it causes formation of high currents because [10],

$$i_c = C \times \frac{dV}{dt} \tag{3.2}$$

There are various methods to mitigate the effect of common mode voltage, but, the main objective of this thesis is to utilize this common mode voltage to charge 12V battery and hence, it is important to control the amplitude of this voltage to the required constant value. One such method involves controlling the instantaneous value of common mode voltage which is discussed in next section.

3.2.2 Controlling instantaneous value of common mode voltage by using sine triangle pwm technique:

In STM technique of pwm,the pwm signal for EM is generated by comparing reference sine wave with the triangle waveform, and the switching of MOSFETs is decided by the instant at which the reference sine wave crosses the triangular waveform and the condition is set such that, the amplitude is compared of the two waveforms and the command is send depending upon the condition. For example, if the voltage amplitude of sine wave is greater than triangular wave then the, mosfet should turn ON or Turn off. This is the basic logic behind the generation of sinusoidal output for a inverter. [11] In this method, reference sine wave is compared with two triangular waveforms and the condition is set in LTspice such that, when the amplitude of sine wave is greater than the amplitude of both the triangular waves then the switches in upper leg of the inverter should turn ON and the Switch in lower leg of same phase should turn off and the dead time between these two mosfets is decided by the delay between these two triangular waveforms. Now, it is proved in the paper[7] that the instantaneous value of the common mode voltage is dependent on the point of intersection of two triangle waveforms and the point at which the sine wave intersect the triangular waveform, This control is divided into two levels;

- When point of intersection of sine wave with triangular waves is far lower than point of intersection of triangular waves as shown in figure 3.3a
- When point of intersection of sine wave is higher than point of intersection of triangular waves as shown in figure 3.3b

The interesting thing about this is that, the spikes which are observed in the common mode voltage waveform refer Figure 3.2completely disappears during the case 1 refer figure3.3a, the output common mode voltage waveform looks like a square waveform, without any spikes and this result from the paper[7] can be used to control the common mode voltage amplitude in the system. It should be noted that, only instantaneous value is affected due to this technique while the average value of common mode voltage remains the same and for STM it is half of the value of traction voltage [5]. In our case, it will be 24V, since, the value of traction voltage is 48V.
The control technique discussed above is simulated in LTspice for the circuit without

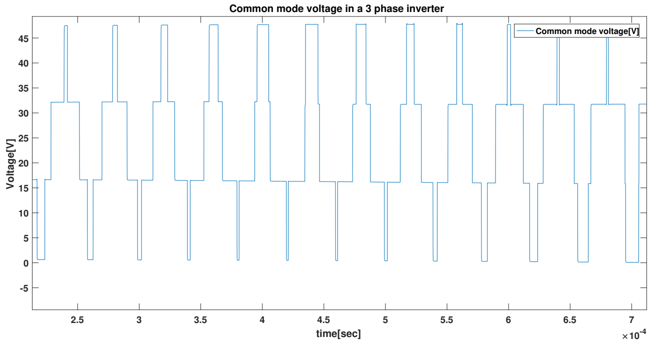
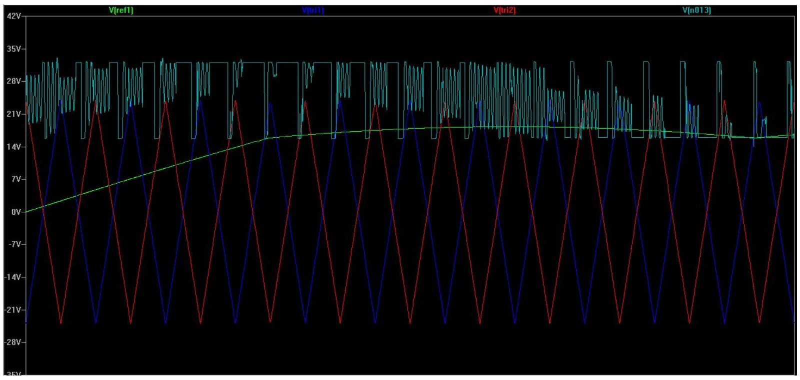
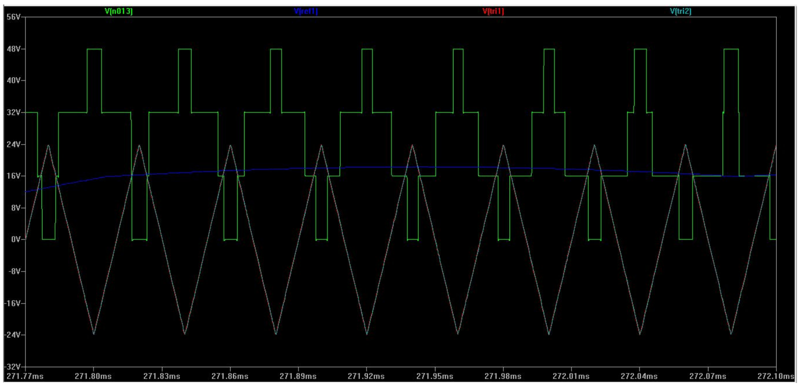


Figure 3.2: Waveform of common mode voltage



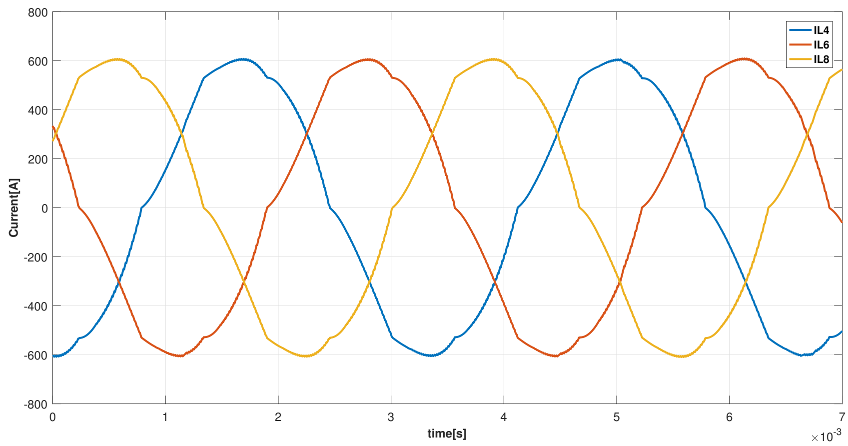
(a) Point of intersection of sin wave lower than intersection of triangular wave



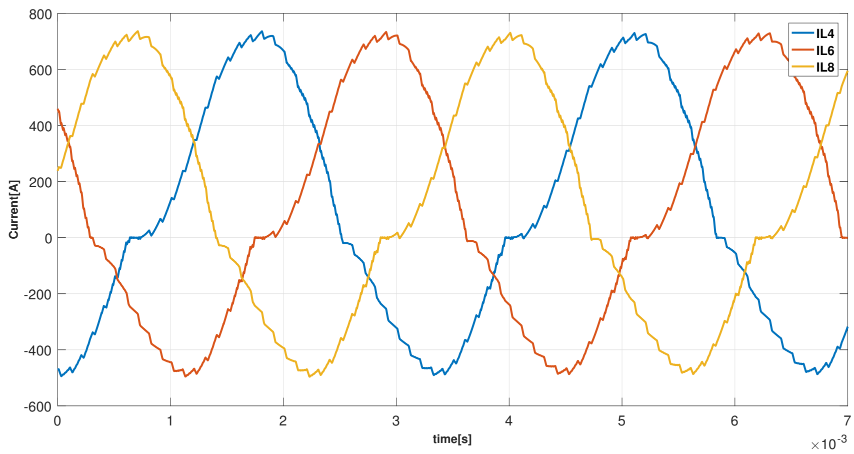
(b) Point of intersection of sin wave higher than intersection of triangular wave

Figure 3.3: Control of common mode voltage using STM pwm technique

having integrated 12V charging and by using integrated 12V charging. The circuit used to simulate the above circuit can be seen in Figure 3.5, To get the result, MOSFET Q7 is kept turned off so that, the 12V battery is isolated from the motor. The resulting waveform of phase currents refer figure3.4a shows that its not perfectly sinusoidal and some disturbances can be observed. Figure3.4b shows phase currents waveforms when 12V charging is integrated with motor, the waveforms shows that, there are lot of disturbances in pahse currents which can affect the normal operation of motor. One of the objective of this thesis is to develop a topology which will have no effect on required operation of motor and hence, it is decided not to implement this control metheod to control the common mode voltage.



(a) Without integrated 12V charging



(b) With 12V charging

Figure 3.4: Phase currents in electric motor

3.3 New Integrated charger topology circuit description:

After deciding the control strategy to control the common mode voltage which is used to charge the 12V battery in regeneration mode, The results are discussed in chapter 4 of this thesis. After that, the same circuit is utilized to check the operation of circuit during motoring mode, now in this mode, the 3 phase inverter is used as an inverter and the electric machine (EM) is used as a motor. The strategy used in this mode is adapted from 'Dual voltage inverter topology'[5]. Please check chapter 4 for the results. As discussed in previous section that, in order to keep the number of components minimum in the topology, it is important to use same circuit for all three modes of operation and hence, same circuit is used to check the feasibility of topology in idle model. In this mode, the 3 phase inverter is used as a interleaved buck converter to charge the 12V battery. Refer chapter 4 for the results. The Figure 3.5 shows electrical schematic of the new integrated charger topology

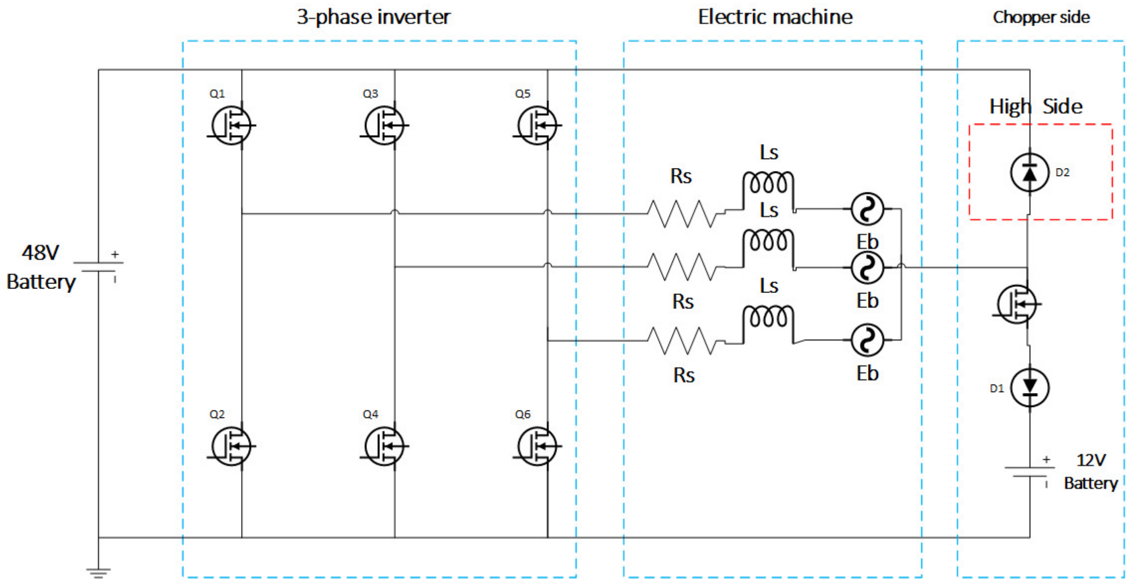


Figure 3.5: Electrical schematic for New Integrated Charger topology

to charge the 12V battery in all three modes of motor operation for mild hybrid vehicle application. It consists of 48V battery to supply ISG, an inverter shown by 6 MOSFET switches making 3 phase connection for the ISG which convert dc voltage output of the battery into required ac input for ISG. The circuit described until now is a conventional 3-phase electric drive circuit. As seen, the circuit on right most side of the ISG is the circuit for charging 12V battery integrated with 48V 3-phase electric drive. The 12V battery is connected between the star point of the ISG and the common system ground. The MOSFET Q_7 and diode D_1 connected in series with 12V battery are used to control the input voltage at the 12V battery and to avoid any supply from 12V battery respectively, in different modes of operation. The following table shows, the different parameters that are used to simulate the circuit in LTspice.

Sr no	Component Type	Rating
1	Application type	Mild Hybrid Vehicle
2	Traction voltage [V]	48
3	ISG type	EESM, 3-phase
4	Peak power of ISG [kW]	20
5	Nominal power of ISG [kW]	5
6	Stator Inductance of ISG [μH]	17.3293
7	Stator Resistance of ISG [mΩ]	1.9
8	Switching frequency of inverter [kHz]	21
9	Fundamental frequency of ISG [Hz]	600
10	Auxiliary Voltage [V]	12V
11	Peak charging power of 12V battery [kW]	3
12	Internal resistance of auxiliary battery [mΩ]	3.5

Table 3.1: Table showing all the parameters used to simulate the Integrated charger topology in LTspice

The next chapter will discuss all the results obtained by simulating above topology in different modes of electric machine operation.

4

Results

4.1 Regeneration Mode

In this chapter, the simulation results are obtained by simulating the Electrical machine in regeneration mode. Initially, the working of simulation models will be described in detail based on two types of topology, then simulation results will be shown based on different types of loading conditions for the DC/DC chopper and at different speeds. Then, the conclusion will be made depending on the obtained results. The two types of topologies are considered for this mode and the description of both these topologies are given below,
Case 1: MOSFET is used in high side of the chopper acting as freewheeling component for the switch (MOSFET Topology).
Case 2: Diode is used in high side of the chopper acting as freewheeling component for the switch (Diode Topology).

4.1.1 Switch Topology

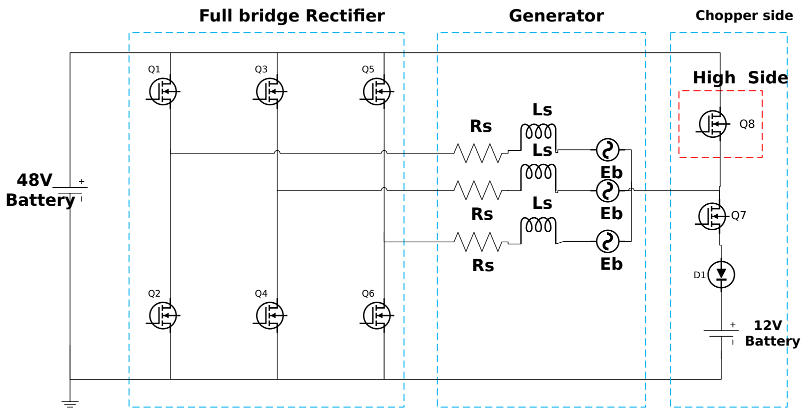


Figure 4.1: Schematic of Regeneration mode using Switch topology

The main reason to use MOSFET in this case is that, MOSFETs are the best match for low voltage high frequency applications because; they have small losses which increases the efficiency of the system. The Figure 4.1 shows electrical schematic for charging 12V battery in the regeneration mode, Regeneration mode is simulated by using the switches in conventional 3 phase inverter as diode rectifier and using back emf (E_b) in equivalent simplified circuit of motor as a source (generator). The topology is used to charge both 48V battery and 12V battery and the strategy to achieve this depends on the value of voltage amplitude in the generator 4.1. Thus, the regeneration mode is divided into three levels; low speed generation, moderate speed generation and high-speed generation. The three levels of regeneration mode are explained in following sections. This strategy is based on[4]

4.1.1.1 Low speed generation:

In this level, the generator speed is considered very less generating back emf of very low amplitude in the range of 18V-24V sufficient enough to charge the 12V Battery. The back emf is directly proportional to the generator speed by the equation,

$$E_b = k_b\omega \tag{4.1}$$

Where, E_b= Amplitude of emf generated in the generator [V]
K_b= Flux constant
ω = Generator speed [rpm]
The figure 4.2 shows simulation circuit used to simulate low speed generation mode

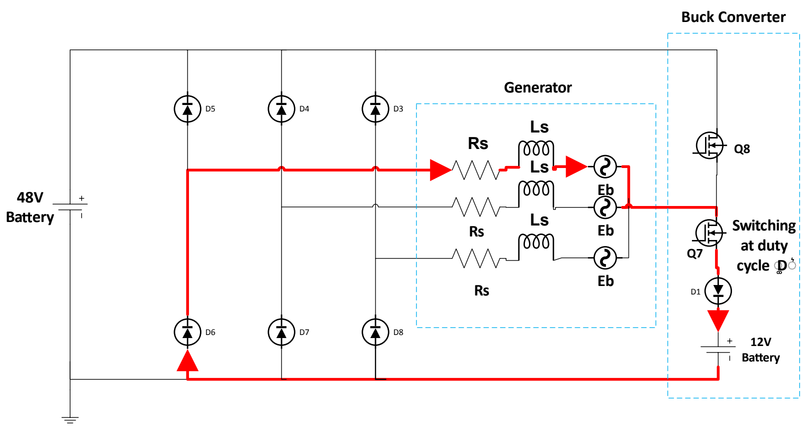
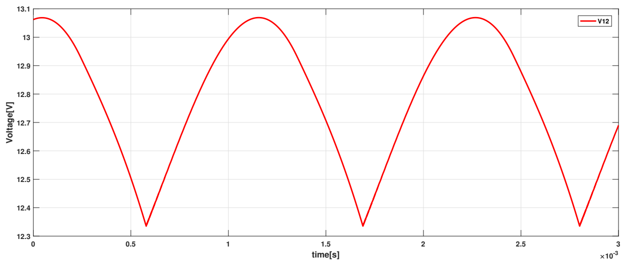
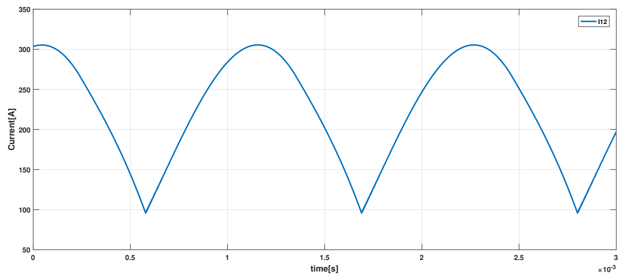


Figure 4.2: Simulation schematic for low speed level regeneration mode

to charge the 12V battery. The amplitude of emf E_b in the generator is kept at 24V so that the generator has enough energy to charge the 12V battery at 3kW power; Constant current strategy is used to charge the 12V battery. The important point here to note is that the MOSFET switch Q_7 in the half bridge chopper is kept always ON i.e. duty cycle D=1 since, the amplitude of voltage in the generator is optimal to charge the 12V battery at peak power of 3kW without the need to chop any voltage thereby, the system works as a simple diode rectifier, rectifying the ac voltage of the generator into dc voltage and charging the 12V battery. As, the Q_7 is always ON, the 12V battery can be charged continuously at this voltage range amplitude. Also, the switch Q_8 is not used and hence can be kept open which makes the circuit without any switching elements and thus, there is small ripple in the circuit. The voltage ripple is 5.5% The Figure 4.3a & Figure 4.3b waveform for charging voltage and current in 12V battery and it shows smooth rectified waveform due to the absence of switching elements in the circuit. The 48V battery is not supplying or charging i.e. it is idle because, at such a low speed there is not enough voltage in the generator to charge the 48V battery and hence, there is no flow of



(a) Charging voltage [V].



(b) Charging current[A]

Figure 4.3: Waveforms showing charging of 12V battery 3kW power

power between generator and 48V battery i.e. the power generated in the generator is entirely flowing to charge the 12V battery. The switches in the lower part of the 3-phase inverter are used to complete the current loop in the circuit.

4.1.1.2 Moderate speed operation:

In this level, the amplitude of emf is kept in the range of 25V-33V and now the 12V battery is charged but, for this voltage range, the charging power is exceeding the peak power limit of 3kW for 12V battery for simple diode rectification as in previous level. Thus, active rectification is required to keep the power limited to 3kW and this is obtained by stepping down the rectified voltage amplitude of the generator so as to have constant current of 250A for 3kW charging power for 12V battery and hence, switch Q_7 is used to chop the excess voltage or as a buck converter. In a buck converter, the output voltage is less than the input voltage and its value is dependent on the duty cycle of the switch. The relationship between input and output voltage of buck converter in continuous conduction mode (The average current in an inductor is greater than zero) can be given by [10],

$$V_0 = D \times V_{in} \tag{4.2}$$

Where, V_{in}= Input voltage of buck converter
V_0= Output voltage of buck converter
D=Duty cycle of MOSFET switch

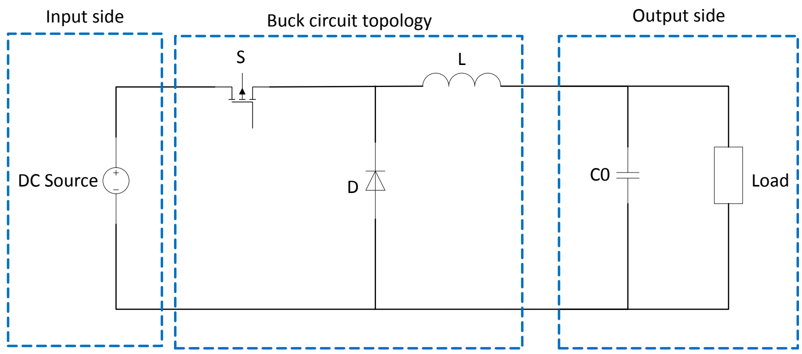


Figure 4.4: Electrical schematic of a simple buck converter circuit

The duty cycle of switch is the ratio of the duration of time the switch is on and the total period of switching and is given by,

$$D = \frac{T_{on}}{T_s} \tag{4.3}$$

Where, t_{on}= turn on time of the switch[sec]
T_s=Total switching period=t_{on}+t_{off}[sec]
The input to the converter is a constant dc source which is stepped down at the output load by adjusting the duty cycle of the MOSFET switch 'S' by using equations 4.2 & 4.3. The working of the converter can be divided into two parts; when the switch 'S' is turned ON, the inductor 'L' is charged to voltage input and there is power transfer between the input source and the output load. When the switch is turned off, the input source is completely isolated from the circuit and hence, the inductor acts as a source for the output and the circuit is completed through the freewheeling diode 'D' which also prevent the voltage spike across switch by conducting the current in the remaining cycle. The output capacitance 'C_0' is assumed to be very large so that, the value of output voltage can be considered as constant. To keep the converter in continuous conduction mode, the circuit should follow the voltage-second law given by [10],

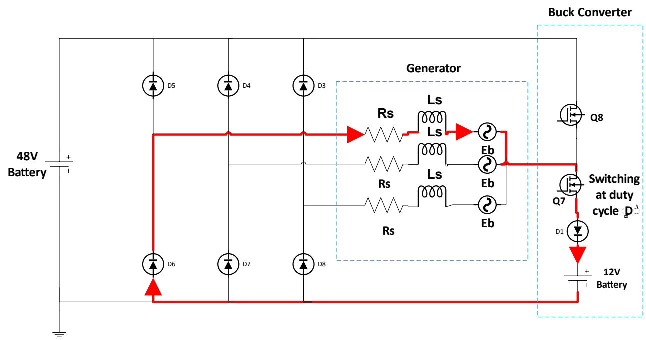
$$V_{in} \times t_{on} = V_0 \times t_{off} \tag{4.4}$$

Selection of components for optimal buck converter design:
To increase the reliability and efficiency of buck converter, it is crucial to select proper ratings of the components used in buck circuit. Failing to do so can result in undesirable heating of these components at normal working conditions and since, the converter is also considered as the generator of ripples in the system, it is extremely important to select the proper values of inductance and capacitor to keep the ripple in acceptable limit [10] The switch used in the converter can be a MOSFET or IGBT depending on the voltage rating and operating frequency of the circuit. The thumb rule is that MOSFET are generally used for low voltage rating (<200V) and higher frequency range (>20 kHz). The voltage rating of the selected switch should be twice that of input voltage to have reliable operation. The continuous current rating in the MOSFET is equal to the Ion (current conducted by the MOSFET during the

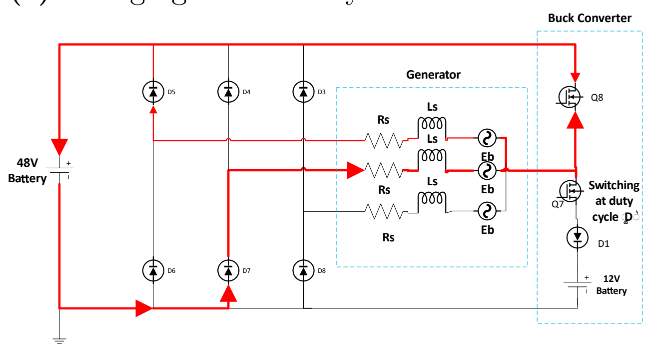
ON time). Also, the MOSFET should withstand the short circuit current in the circuit and its value is given by [10],

$$I_{sc} = \frac{V_{ON}}{L} \tag{4.5}$$

Where, I_{sc} = Short circuit current [A]
V_{ON} = Voltage across switch during its condution period [V]
L= Inductance [H]
The value of the source inductance also greatly influence the circuit efficiency and reliability, since, value of the inductance limits the current in the circuit. It is important to select the optimal value of inductance for the given application, because, too large value of inductance limits the shaping of the current, while, too small value injects large ripples in the circuit and may also saturate the core of the inductor under normal conditions which can cause additional losses in it. For A buck converter, the average value in an inductor is equal to the load current [10]. It is also necessary to choose appropriate value for output capacitance as, the higher value will increase the overall size and cost of the system while, small capacitor value will not be sufficient to dampen the ripples in the circuit.
New topology for moderate speed generation:
The Figure 4.5a & Figure 4.5b shows simulated schematic for moderate speed level



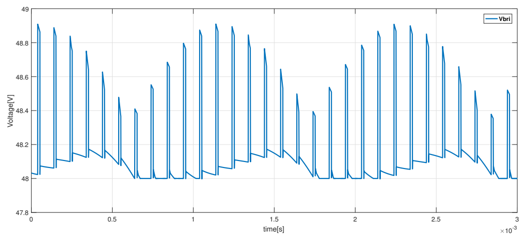
(a) Charging 12V battery.



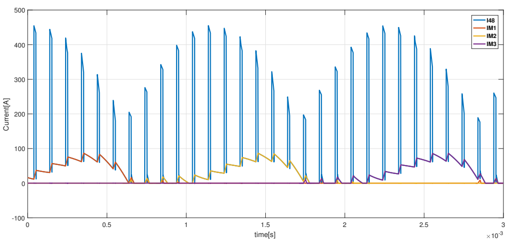
(b) Charging 48V battery

Figure 4.5: Simulation schematic for moderate speed level in regeneration mode

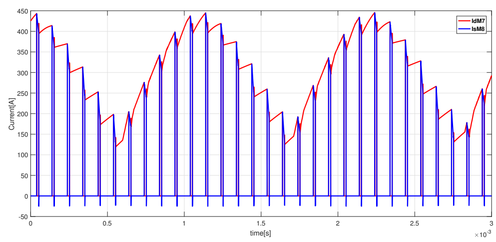
in regeneration mode and also the flow of power in the circuit, the emf amplitude of the generator is set to 33V according to the 4.1 the objective is to charge the 12V battery with the power of 3kW & 1.5kW and analyze the effect of charging on various new topology components. Switch Q_7 is used to step down the rectified voltage amplitude of the generator because; the charging power exceeded the limit of 3kW by using simple diode rectification as in low speed generation section. The duty cycle 'D' of the MOSFET Q_7 is adjusted to have the optimal charging current for 12V battery i.e. it is used as buck convertor to step down the voltage at common mode. During switching cycle, it allows conduction of power when it is ON and it prevents conduction of power when it is turned off. Inductance in 3 phase windings of the generator is used as an inductor (Refer Figure 4.2) for this buck converter and due to the presence of the inductor, energy is stored when the MOSFET is turned off and in this scenario if the MOSFET is turned ON again, it will experience a huge voltage spike due to the accumulated energy in the inductor and MOSFETs are susceptible to breakdown due to excessive voltage across them. Hence, it is required to have an alternate path for dissipation of this energy in the circuit. MOSFET Q_8 provides this alternate path of conduction and so the duty cycle of this MOSFET is set to '1-D' to prevent voltage spike across Q_7 .



(a) Voltage across high side MOSFET



(b) Current in high side mosfets of rectifier



(c) Current in integrated charger circuit

Figure 4.6: Resulting wave forms moderate speed operation for E_b=33V and charging power of 3kW for 12V battery

Figure 4.5a shows direction of flow of current when the 12V battery is charged. The direction of flow of current in the system depends on the conduction of MOSFET

Q_7 & Q_8. At instant, when MOSFET Q_7 is conducting, the current will flow from generator to 12V battery and complete the loop back to the generator through the diodes in lower leg of 3 phase conventional inverter Figure 4.5a. During conduction of MOSFET Q_8 (Refer Figure 4.5b, the current flows from generator to 48V battery through the body diode of MOSFET Q_8 because, the high side of the half bridge is greater than 48V as shown by V_{bri} in Figure 4.6a. Also, current flows from generator to 48V through the body diodes of M1, M2 and M3 in the upper leg of 3 phase conventional inverter shown by currents I_{M1}, I_{M2} and I_{M3} and charging current of 48V battery I_{48} in Figure 4.5b, Figure4.6b & Figure4.6c Hence, it can be said that, 48V battery is charged most of the time during this level. Similarly,

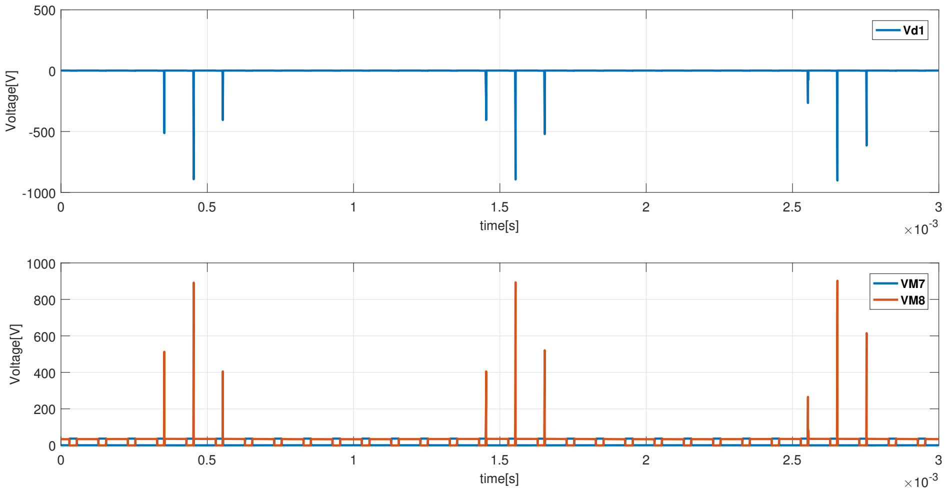
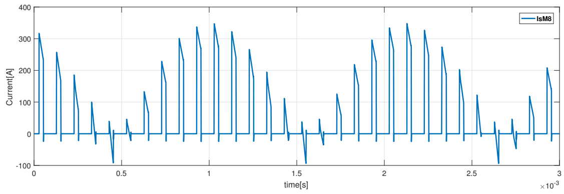
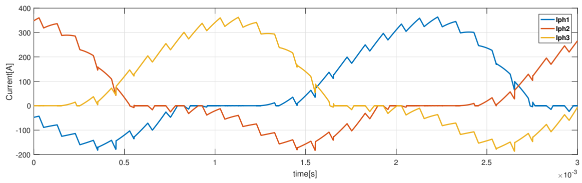


Figure 4.7: Voltage across MOSFET Q_7 switches and diode D_2 in half bridge chopper.

the simulation is performed for charging power of 1.5kW for 12V battery to see the ripple in the system. It is observed that the voltage across switch M_8 and diode d_1 has huge voltage spike as shown by voltages V_{d1} and V_{M8} in Figure 4.7. This happened because, For 1.5kW, the duty cycle of Q_7 is reduced than for 3kW which resulted in increased conduction time for switch Q_8, and that cause a loop between generator MOSFETs in upper leg of 3 phase conventional inverter and the switch Q_8 causing increasing in the amount of current I_{M1}, I_{M2}, I_{M3}, current in upper leg of 3 phase conventional inverter. I_{L1}, I_{L2}, I_{L3}, current in 3 phase windings of generator and I_{M8} current in switch Q_8, as shown in Figure 4.8a and Figure4.8b due to the fact that the loop is almost like a short circuit and hence, this increase in current cause high voltage spike across MOSFET Q_8 and diode d_1. This increase in unwanted flow of current loop also causes higher losses in MOSFETs and in generator windings reducing the efficiency of the system. To avoid this, the switching frequency can be decrease but, that will increase the ripple in the system so, the only way is to add filter across MOSFET which will increase number of components in the system increasing cost and losses and also increase the losses in the system decreasing further the overall efficiency. Hence, it is decided to replace MOSFET Q_8 with a diode, which will be discussed in next section.



(a) Current in high side mosfet of rectifier



(b) Phase current in generator

Figure 4.8: Current in different components for charging power of 1.5 kW for 12V battery

4.1.2 Diode Topology

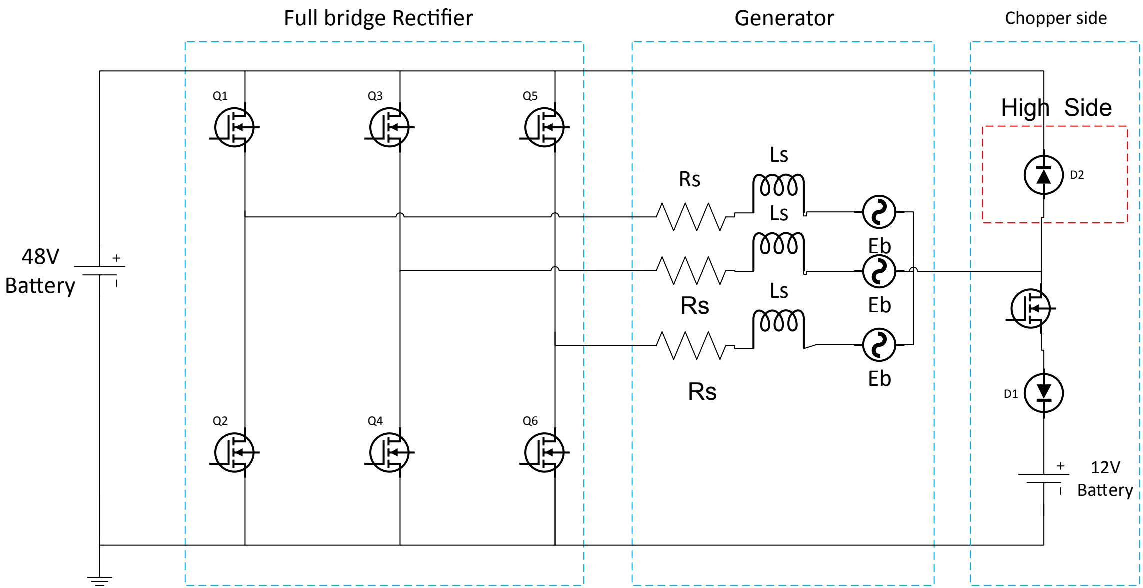


Figure 4.9: Simulation topology for regeneration mode using diode topology

The Figure 4.9 shows electrical schematic for diode topology for regeneration mode. 6 MOSFETS represents the conventional full bridge rectifier. The Generator section is shown by equivalent electrical circuit having 3 phases consisting of Stator

Resistance(R_s), Stator Inductance(L_s) and back EMF(E_b) denoted by an ac source connected as shown in Figure 4.9. The chopper side shows electrical schematic of diode topology to charge the 12V battery in generation mode. The diode is connected in the high side of the chopper as shown in the figure 4.9. The high side component in a converter is the one in which, one terminal is connected to the highest potential in the circuit, in this case the cathode of the diode (D_2) is connected to the positive rail of 48V battery as shown in the circuit in Figure 4.9 and the other terminal is connected to the star point of the motor. The primary principle of this diode is to dissipate the energy in the inductor (L_s) when the switch of the 12V charging is not conducting which will reduce the overvoltage spikes across the switch charging the 12V battery, due to the inductor (L_s). The working of the system can be explained as follows, for simplicity the variation in the speed of the generator and corresponding generation of back emf can be shown by varying the ac source voltage in three phases. The working strategy of the system in regenerative mode is divided in three modes depending on the magnitude of emf.

4.1.2.1 12V Battery charging for low emf magnitude:

In this mode, the charging of only 12V battery is achieved since, the voltage magnitude of emf is not sufficient to charge the 48V battery and the charging circuit for 12V acts as a rectifier.

It is to be noted that the 12V battery is charged with current range of 70A-250A

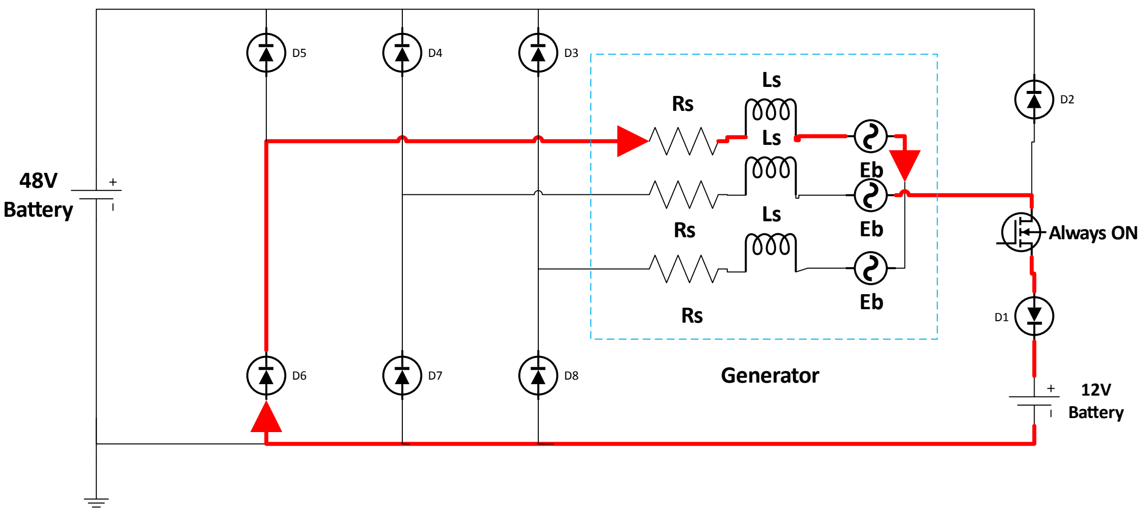


Figure 4.10: Simulation schematic for low back emf i.e. slow machine speed

which is the requirement from VOLVO cars and hence, the corresponding value for the magnitude of emf voltage is 18.5V-25V where, the peak power charging of 3kW is obtained at emf voltage magnitude of 25V and the resulting charging current is 250A assuming that the voltage is 12V which is the nominal voltage of the lead acid battery. The operation of the system in this mode can be seen in the Figure 4.10. At any given instant, charging current is always flowing through the battery (*shown by red arrow trace*) and the circuit for the charging current is completed through any one of the 3 phases. It can be observed that, the lower side MOSFETS of the

conventional rectifier acts as a return path for the current. The major advantage in this mode is that the ripple generated by the converter is almost negligible as there is no switching element in the operation of the circuit.
The resulting waveforms of the simulated circuit in LTspice can be seen in Figure

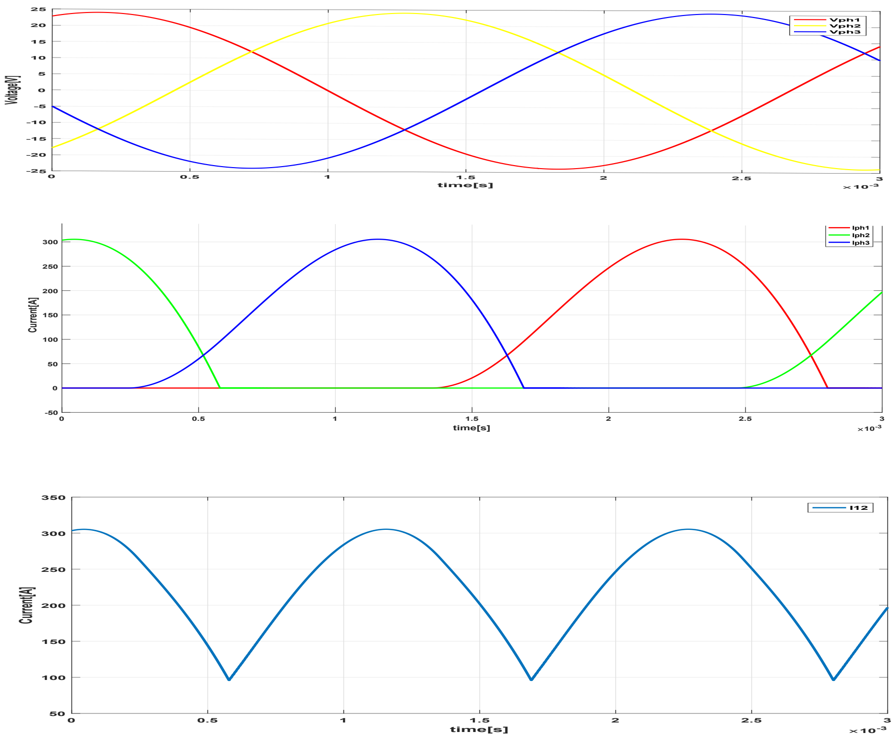


Figure 4.11: Waveforms for low emf mode

4.11. The top figure shows 3-phase voltage magnitude in the generator, the simulation is run for 25V emf. The middle and bottom figure shows the phase current in the windings and charging current in the 12V lead acid battery respectively. The total average charging current is equal to the sum of average current of Inductors in each phase i.e.

$$I_0 = I_{ph1} + I_{ph2} + I_{ph3} \tag{4.6}$$

Where, I_0= Charging current in 12V lead acid battery [A]
I_{ph1}= Average Current in inductor of phase 'a' [A]
I_{ph2}= Average Current in inductor of phase 'b' [A]
I_{ph3}= Average Current in inductor of phase 'c' [A]
Ideally, the average current in inductor of each phase should be equal, since; all the impedance values are equal. In terms of losses, the only loss components in this circuit are the diodes and hence in order to improve the efficiency of the circuit, the schottkey diode can be used in place of D_1 and the MOSFETs in the lower part of conventional rectifier can be chosen such that, the forward voltage drop of internal body diode is less so as to keep the conducting losses of body diode to the minimum or schottkey diodes can be used in parallel with the MOSFETs to reduce the conduction losses in regenerative mode.

4.1.2.2 Charging of 12V & 48V battery in complementary fashion:

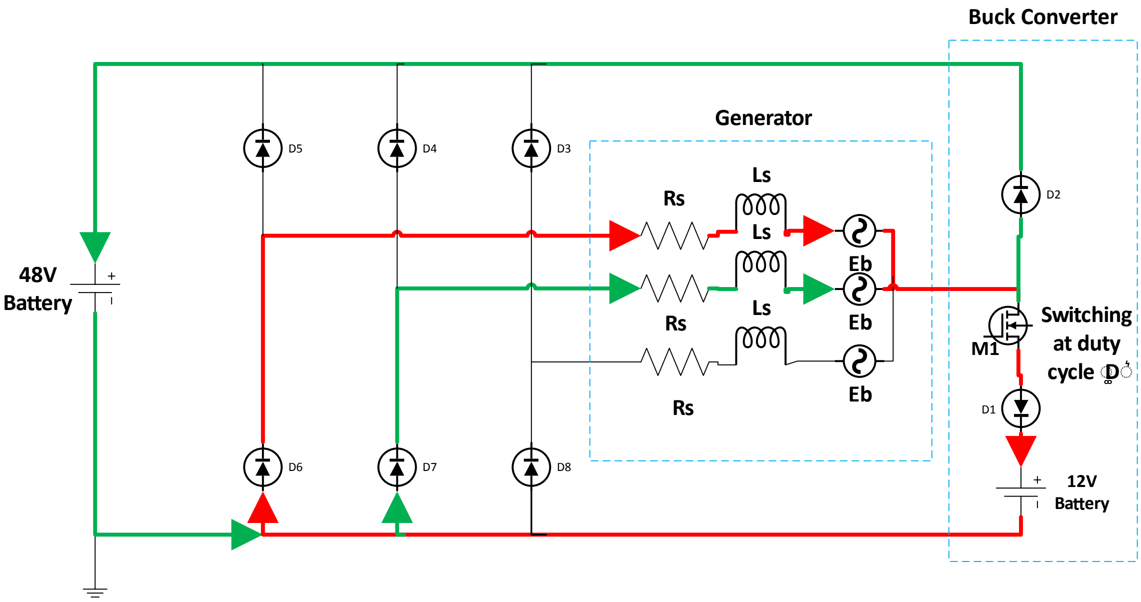
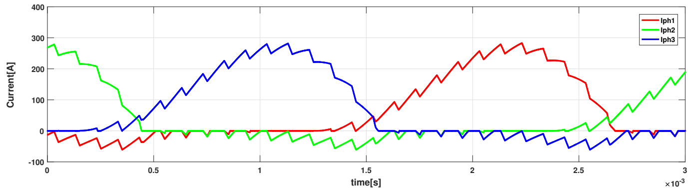
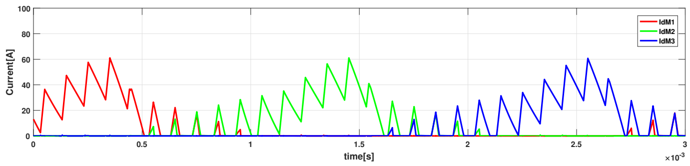


Figure 4.12: Working of simulation model for charging 48V battery & 12V battery in complementary fashion

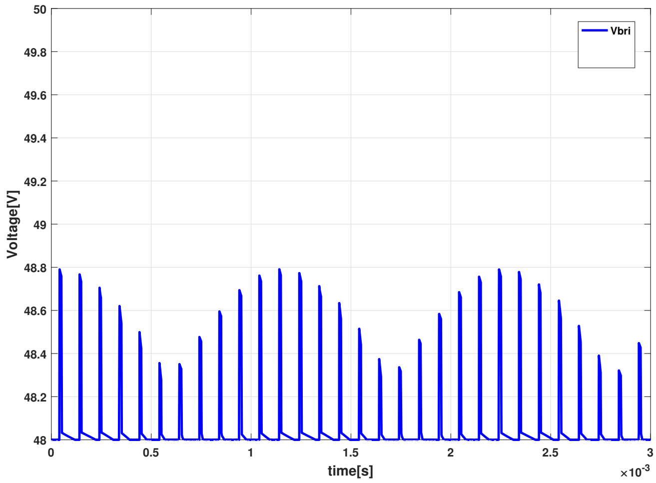
This mode is quite interesting because, it is possible to charge both the batteries in complementary fashion. When the voltage magnitude is above 25V, it is required to step down the common mode voltage to the desired value such that the 12V battery can be charged with constant power of 3kW and this buck operation in this case is achieved by the single MOSFET (Q_7) on the converter side in Figure 4.12 & Figure 4.4 . The required duty cycle is calculated depending upon the value of common mode voltage and equation 4.3. The 48V battery is charged when the MOSFET Q_7 is not conducting and instead diode D_2 starts conducting. In this mode, it is possible to charge the 48V battery by the power of up to 2kW (Refer Figure 4.13c). The flow of power is as shown in Figure 4.12 with red path shows charging of 12V lead acid battery and green path shows charging of 48V battery. Since, the MOSFET Q_7 is switching in this mode to step down the voltage, there is a ripple generation in the system but it is within the tolerable limit of current and output voltage ripple. Comparing the Figure 4.13a & Figure 4.13b with Figure 4.8b & Figure 4.8a suggest that, the diode topology has less leakage of current in the conventional rectifier than the MOSFET topology and hence, there are no voltage spikes observed across any component for 33V generator amplitude and 1.5kW charging for 12V battery. Which resulted no requirement of additional components to reduce voltage spikes in diode topology, Therefore, diode topology is adapted for further circuit topology.



(a) Phase Current



(b) Current through upper leg MOSFET of conventional rectifier



(c) Voltage across high side diode

Figure 4.13: Waveforms for diode topology in moderate speed operation in regeneration mode for charging power of 1.5kW and generator voltage amplitude of 33V

4.1.2.3 Charging of 48V battery at higher emf magnitude:

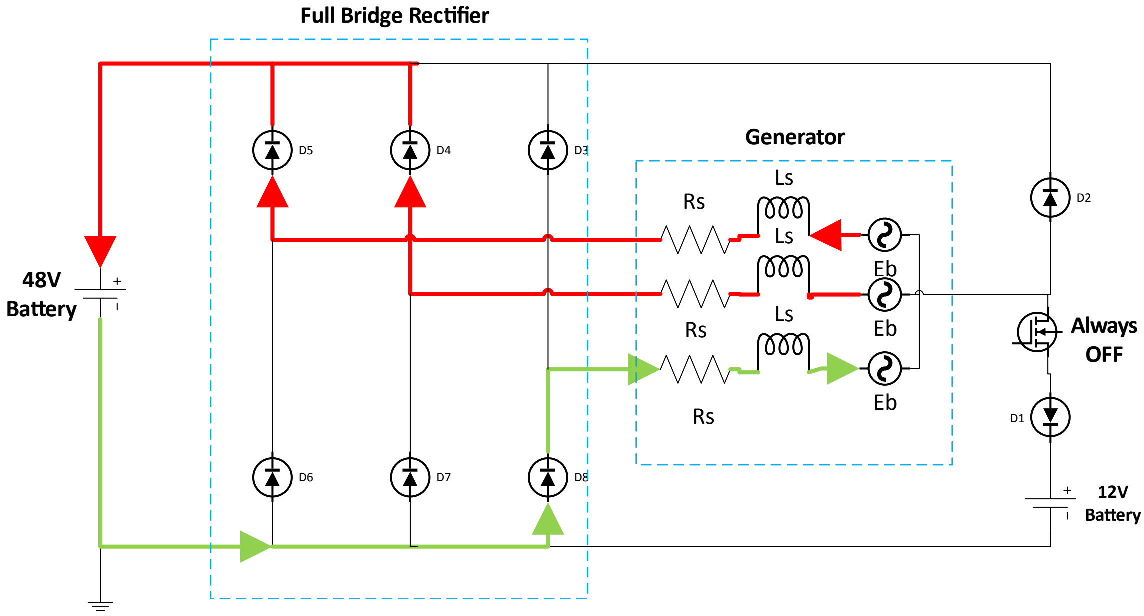
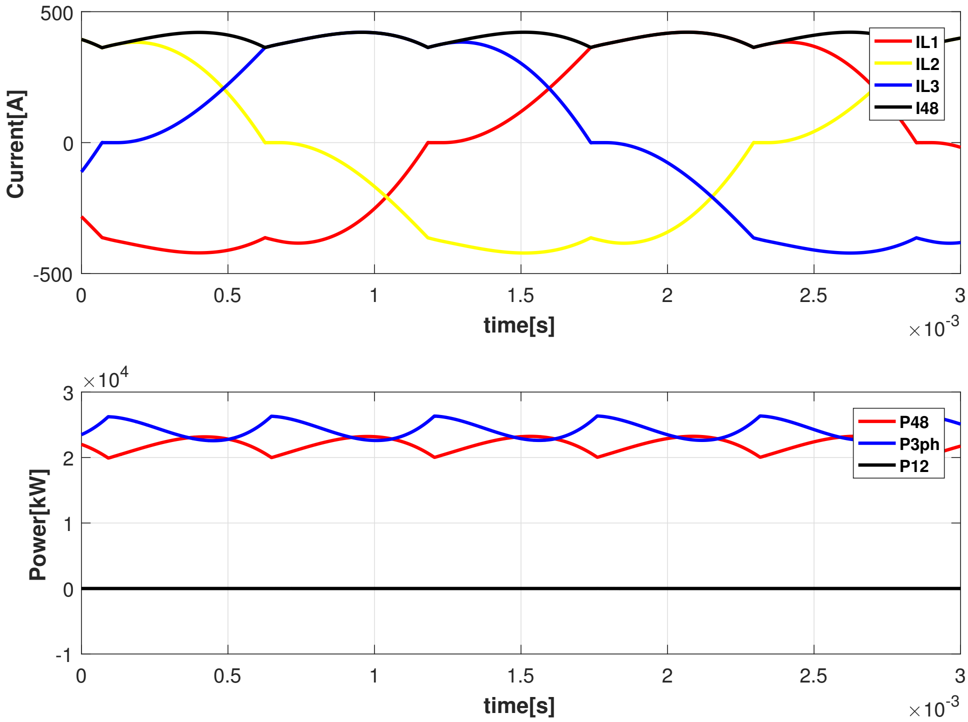


Figure 4.14: Simulation schematic for charging 48V battery

In this mode, the charging of 48V can only be achieved because, if the MOSFET (Q_7) is switched to charge the 12V battery, the voltage across 48V battery goes up to 50V, which can cause current of very high magnitude since, there is no element in the circuit which can limit the current flowing in 48V battery and eventually this will damage the battery and reduce its life. This is the conventional rectification method charging of 48V battery. As shown in figure4.14 , The MOSFETS in the 3-phase inverter acts as a conventional rectifier and hence they are shown by the internal body diode.
The Figure 4.15a shows waveforms obtained from LTspice when charging 48V battery by conventional rectification method. The first figure shows phase current I_{ph1}, I_{ph2} & I_{ph3} in the generator and charging current of 48V battery. The shape of the current waveform is a typical current waveform of a conventional rectification process. The second figure of Figure 4.15a shows power in the system, P_{3ph}[kW] is the total average 3 phase power of the generator, in this case, the input power of the rectifier while, P_{48}[kW] is the input for charging power of 48V battery. The P_{12} [kW], charging power of 12V is zero since; there is no charging of 12V in this case. The third figure is the sinusoidal voltage in each phase of the generator V_{ph1}, V_{ph2} & V_{ph3} respectively. The ripple in the system is almost negligible as there are no switching devices in the operation of the system.



(a) Charging current and power in 48V battery

(b) Phase voltage in electrical machine

Figure 4.15: Waveforms of charging 48V battery by conventional full bridge diode rectification

4.1.2.4 Summary of Regeneration Mode:

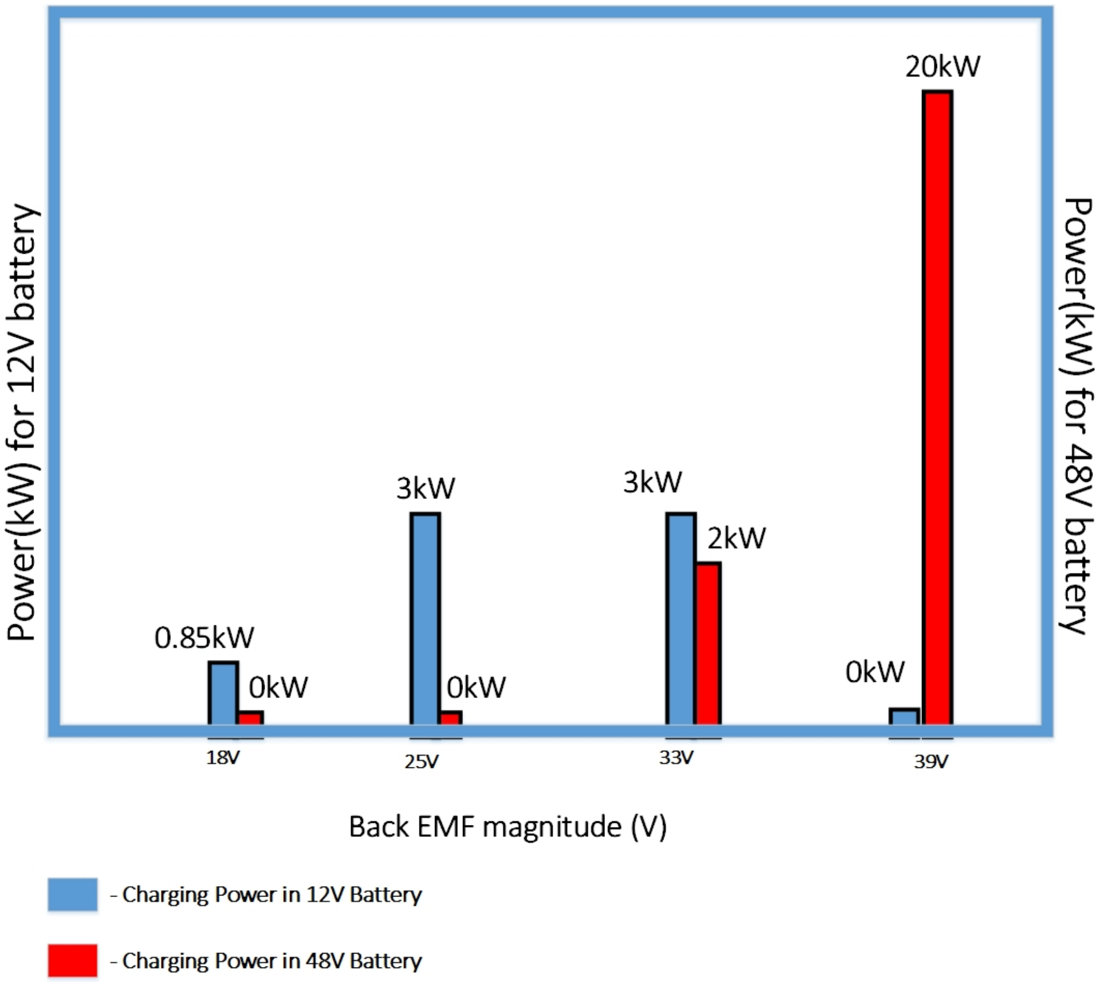


Figure 4.16: Summary of Regeneration mode with diode topology

The Figure 4.16 shows the charging strategies for dual voltage system in regeneration mode. The graph shows charging power for each battery for low emf voltage magnitude and high emf voltage magnitude.

4.2 Motoring Mode

In this mode, the 48V battery is supplying power to the electrical machine for motoring mode during coasting and starting the engine and also for charging the 12V lead acid battery. In motoring mode, the dc voltage of the battery is converted into ac voltage and this ac voltage will be supplied to electrical machine to operate it as a motor. On the other hand, the 12V lead acid battery needs a dc voltage of suitable amplitude and that this voltage should be a controlled dc source to avoid over or under voltage to charge itself and to charge it quickly. Ideally, this is done by a separate dc-dc converter which steps down the 48V of a battery to a suitable voltage value and charge the 12V battery and this unit contains bulky inductors

and capacitors which make the unit costly, bulky and heavy. If we consider motor as source of energy to charge the battery, then it will require a rectifier to convert ac voltage of the motor to dc voltage and a chopper to control the voltage. So, the system may be even bulkier, costlier and heavier.
Common mode voltage of the inverter can be used as a source to charge the 12V battery since, it is a positive voltage due to the fact that, it is the voltage measured between star point of the machine and the ground of the system which makes the potential of this source always above zero amplitude. Hence, only a chopper will be required in this case to get the voltage of required amplitude to charge the battery which can make the system less bulky and cost effective.
The Figure 4.17 shows common mode voltage charging topology in motoring mode.

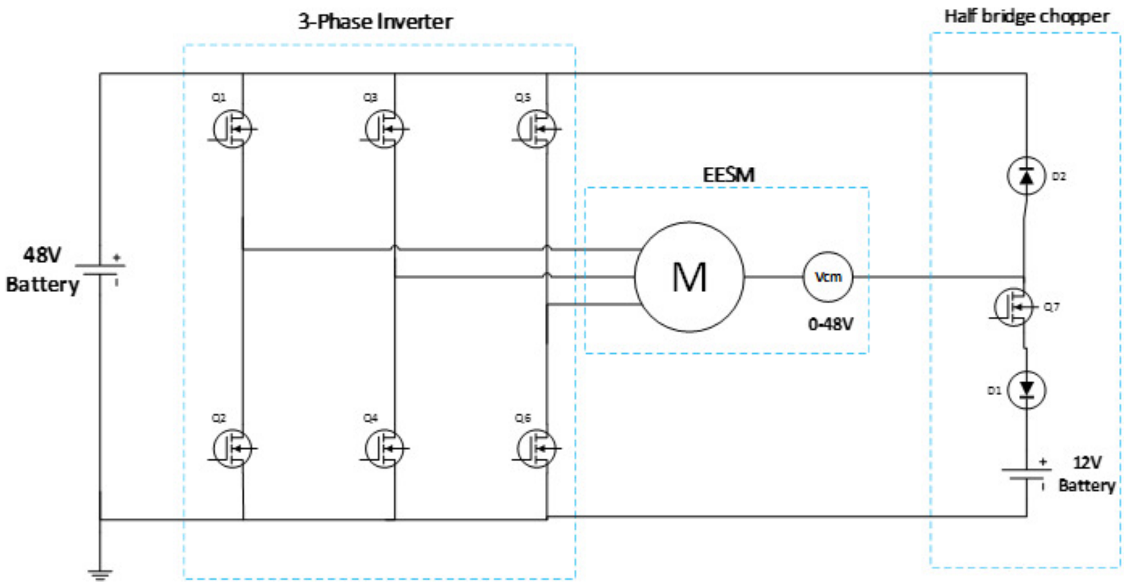
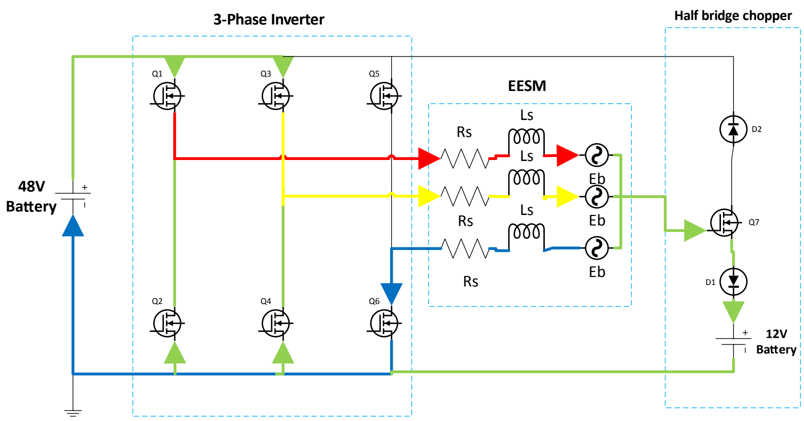


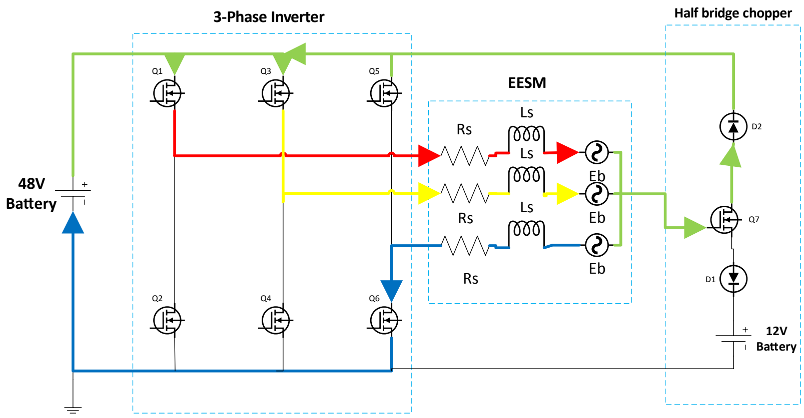
Figure 4.17: Electrical schematic in motoring mode for charging 12V battery

The electrical schematic looks similar to the conventional 3-phase drive supplied by 48V battery pack. Integrated dc-dc topology is simulated by connecting half bridge chopper between star point of the EM and the ground of the system as shown in Figure 4.17. Half bridge chopper consists of only three extra components, a MOSFET switch Q_7 to chop off the common mode voltage to a suitable value to charge the 12V battery which is connected in series with this switch Q_7. Note that, the inductance which is required for the buck operation is provided by the stator winding inductance in electrical machine. Diode D_1 is connected to avoid any supply from 12V battery to the electrical machine as, the 12V battery is used to power low voltage electronics in the vehicle. Diode D_2 connected to the high side of the chopper is used to conduct the energy stored in the inductor when the switch Q_7 is not conducting to avoid voltage spike across Q_7 due to the inductor.

4.2.1 Circuit Operation



(a) Circuit operation when 12V battery is charging during motoring mode

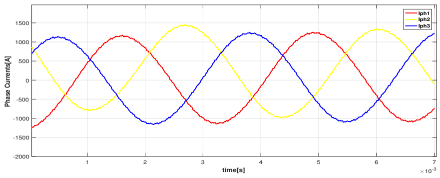


(b) Circuit operation when 12V battery is not charging.

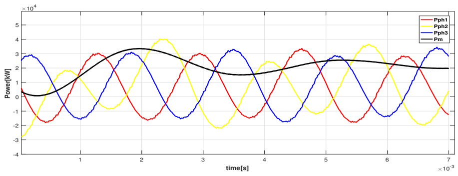
Figure 4.18: Working strategy in Motoring mode

The first half of this circuit in Figure 4.18a works as conventional motor driven by 48V battery through a 3-phase inverter which converts dc power of the battery into ac and supply the motor and on the other hand, by switching the MOSFET Q_7, 12V battery is charged continuously at a constant power by adjusting the duty cycle of the Q_7. The common mode voltage is changing from 0V to 48V and its switching speed is equal to the speed of the switches in conventional 3-phase inverter refer to Figure 3.2, The average voltage at the star point is 24V 3.1 so depending on required charging power for 12V battery duty cycle of Q_7 is adjusted and 12V battery is charged. Although, the average voltage is 24V, there is need for switching MOSFET Q_7 because, the instantanous value of common mode voltage is varying as described in chapter 3. The peak power for charging the 12V battery is 3kW since; the peak load connected to this battery is of 3kW as provided by VCC (Volvo cars). Hence, the charging current at peak is 250A. The Figure 4.18a shows the operation of circuit when the switch Q_7 is conducting i.e. 12V battery is charging at peak power of 3kW and Figure 4.18b shows the operation when switch Q_7 is not conducting. Figure 4.19 & Figure 4.20 shows waveforms of phase currents and total power in electrical machine and also the charging voltage & current for peak charging power of 3kW. The half bridge chopper acts as a buck convert stepping down the common mode voltage and hence for the buck converter, its load current is equal to the current flowing through its inductor. In this case, the load current is the charging current of the 12V battery and this current is flowing through the stator inductor of the electrical machine, since; this inductor is used as an inductance for the buck converter in the topology. That is why, the waveforms of the phase currents and phase powers of electrical not symmetrical about x-axis in the Figure 4.19 and this can be also seen in Figure 4.23 in which, its shows fft (Fast Fourior transform) of phase currents in EM (Electrical machine). There is presence of component at 0 Hz in the phase currents which proves that there is a homopolar component of current present in the stator windings of the EM due to the zero-sequence charging of 12V battery. Figure 4.22 also shows that, there is high voltage and current spikes in the charging power of 12V battery and the spike is higher at 5kW load on EM. It was observed that when the switch Q_7 is not conducting refer Figure 4.18b, the energy stored in the inductor is conducting through the diode d_2 which is a low resistance path which results in increasing the amplitude of current which further increases the energy in inductor for a brief moment and again when the switch Q_7 starts conducting that energy is dissipated on the switch and because of the controlled duty cycle of switch Q_7, there is voltage and current spike observed during the charging of the 12V battery.The presence of homopolar current in the motor causes very high copper losses in the windings which may result in excessive heating of the motor. A very simple solution for this problem would be to connect a capacitor across battery which will absorb these spikes and keep the conditions under safe level.

Figure 4.24a & Figure 4.24b shows that the spikes in charging voltage and current can be significantly reduced by adding a capacitor across battery. 3.2. Current ripple is 30.8% which is just on margin as far as tolerable value of ripple goes for the switching devices for vehicle application and the voltage ripple is 2% which is within acceptable range. [6]

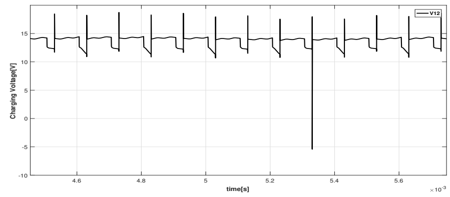


(a) Phase Current

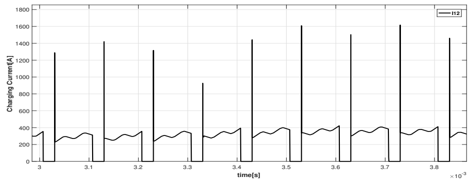


(b) 3-phase Power in Electric motor

Figure 4.19: For 20k power in electric motor

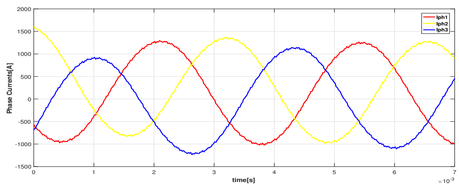


(a) Charging Voltage

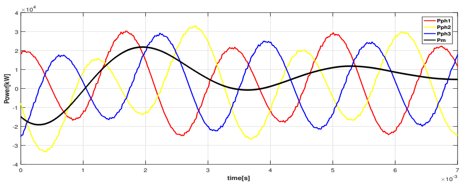


(b) Charging Current

Figure 4.20: For 12V battery 20k electric motor power

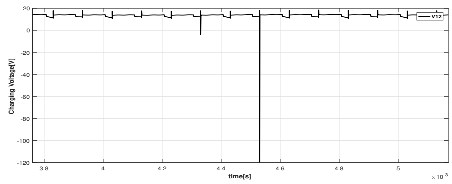


(a) Phase Current

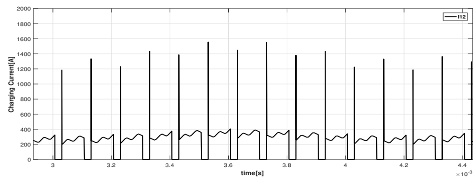


(b) 3-phase power in Electric motor

Figure 4.21: For 5k power in electric motor



(a) Charging Voltage



(b) Charging Current

Figure 4.22: For 12V battery 5k electric motor power

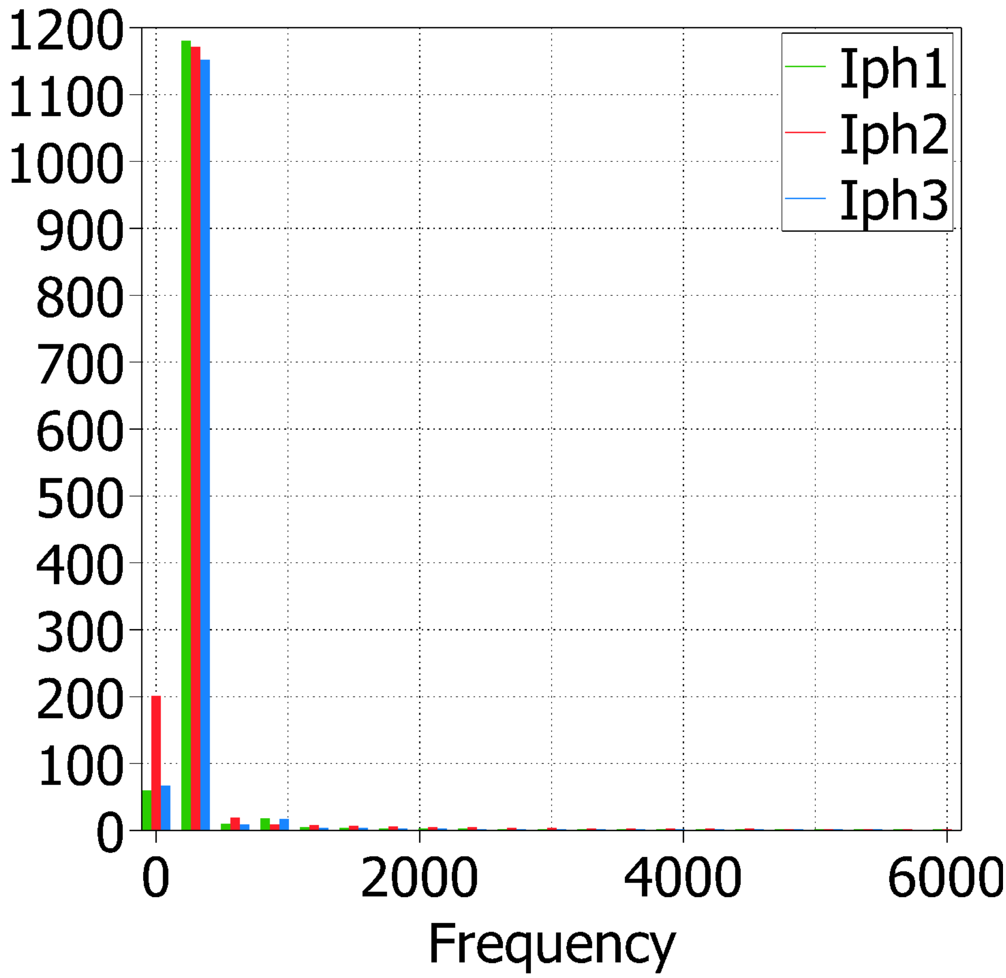
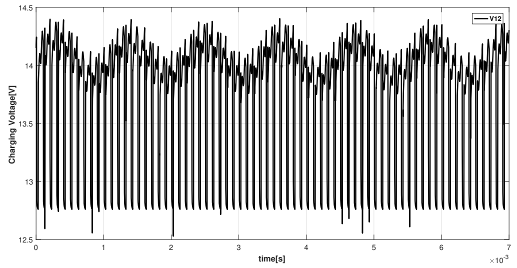
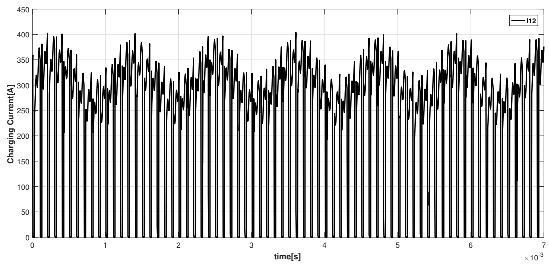


Figure 4.23: Fft of phase currents in EESM 20kW, for charging power of 3kW for 12V battery

Although, As seen above it is possible to charge the 12V battery using the integrated dc-dc converter topology in motoring mode, there are few problems in the operation as discussed above, the presence of homopolar currents in the windings causes additional copper losses in the windings resulting excessive heating which may affect the normal operation of motor. Also, the instantaneous value of current is also quite high because of the lower value of inductance in the system which may put stress on other components and on conducting cables causing additional losses in components and reducing overall efficiency of the system. The efficiency of the integrated converter is found to be 75%. This can also results in requirement of thicker cables increasing further cost and size of the overall system. Therefore, it is not efficient to charge the 12V battery in motoring mode. Also, the duration of motoring mode is limited in the mild hybrid system therefore; it would be convenient to charge the 12V battery with less power or to avoid charging completely to keep the additional stresses in safe region so that it will not affect the normal operation of the system.



(a) Charging Voltage



(b) Charging current

Figure 4.24: For 12V battery with capacitor 5kW electric motor power

4.3 Idle mode operation

This mode represents the standstill condition of the vehicle or the vehicle is running at very low speed. For the simplicity, we will consider the standstill case to have better understanding of the charging strategy.

The main aim in this mode is to charge the 12V battery using 48V battery as a source, as regeneration is not possible in this mode because of zero speeds. Since, back emf is directly proportional to speed 4.1. Hence, back emf is almost negligible and therefore, not sufficient to charge the 12V battery. Also, the solution should be cost effective which is possible by using least number of extra components.

4.3.1 Circuit Operation

The circuit in Figure 4.25 is simulated in LTspice for a charging power of 3kW for 12V battery, the red arrows in the figure indicate direction of current flow in the system and hence, it can be said that the power in the system is flowing from 48V battery to 12V battery. Also notice that, the three high side MOSFETs are switched for the buck converter. The other objective in this case, is to keep the current ripple below 30% [6] therefore, the switching frequency of these switches is kept at 20kHz which is on higher side, since, the only inductive component in the system is the inductance of stator winding of EM which is generally low, in few nH which results in generation of very high ripples that is not accepted in a vehicle.

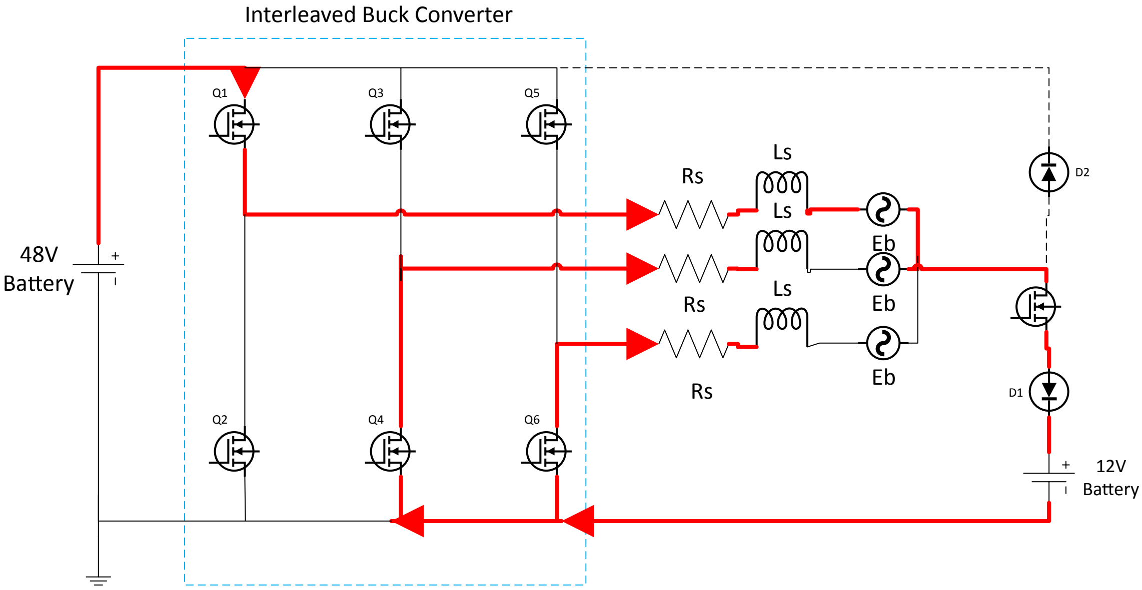
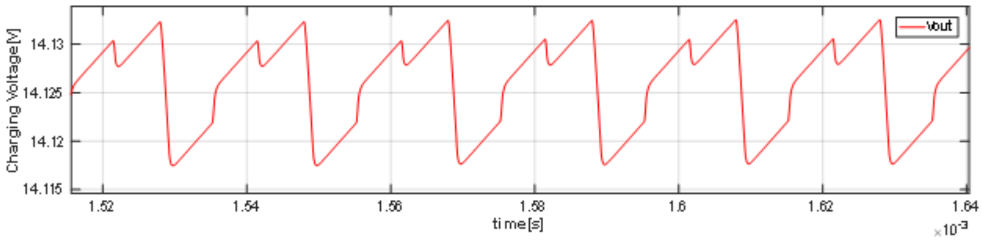


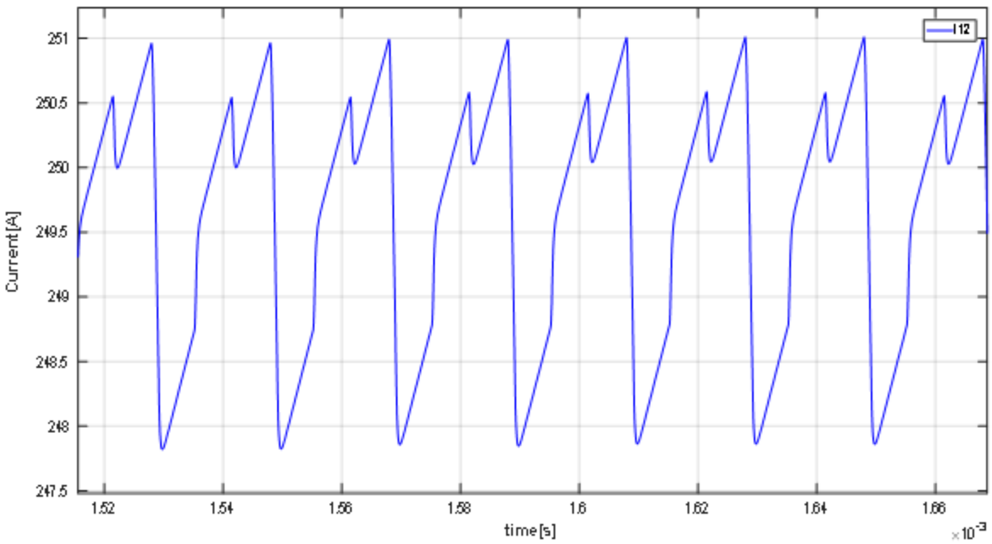
Figure 4.25: Working strategy for New Integrated charger topology in idle mode

4.3.2 Simulation results for idle mode of Electrical machine:

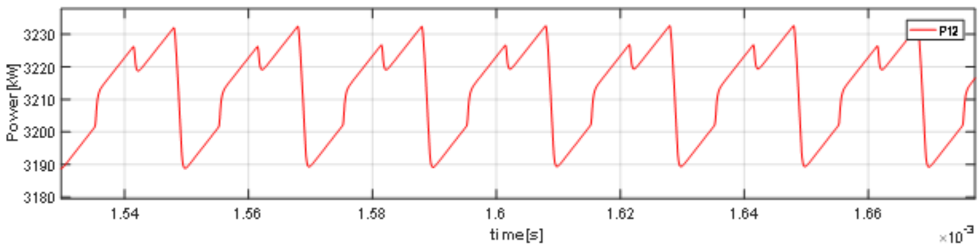
The spikes in the Figure 4.26a, Figure 4.26b & Figure 4.26c are due to the turning on of any two mosfets simultaneously, and hence, precise control of switches is required such that only one Mosfet is turned on in an instant. Also, note that, interleaved style switching of switches is implemented in this mode to reduce the ripple in the charging current and voltage for 12V battery and also the overall efficiency of the system is higher i.e. 85% in this mode for interleaved type buck converter. The Figure 4.27a & Figure 4.28a shows the ripple in the charging current and voltage, for when only one switch is switching, when two switches are switching refer Figure 4.27b & Figure 4.28b and when all three switches are switching, refer Figure 4.27c & Figure 4.28c. The current ripple for single switch switching is 14.45% while for three switches switching is 3.2% also, the voltage ripple for single switch switching and interleaved three switches switching is 0.4% and 0.1% which proves that the ripple in interleaved switching of three switches improves significantly for charging power of 3kW. The efficiency of the interleaved switching is 85% which is higher than the single switch switching because the current is distributed in three inductances and hence the overall losses reduces increasing the efficiency of the system.



(a) Charging Voltage

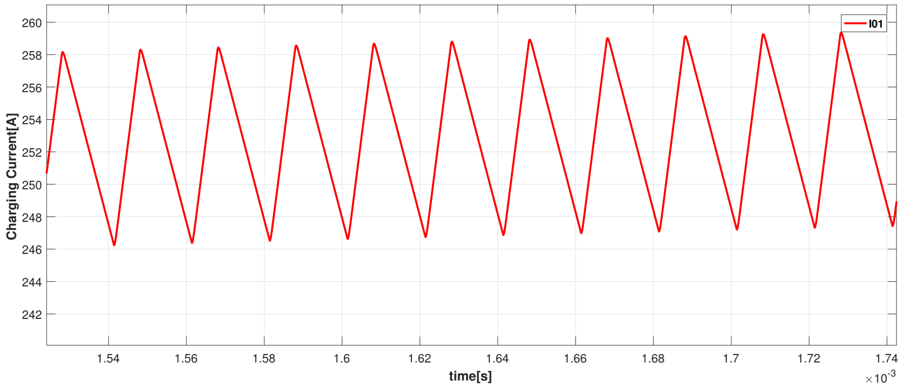


(b) Charging current

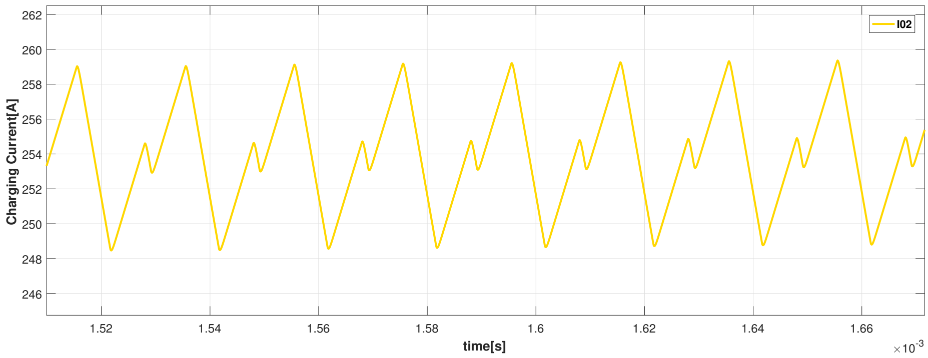


(c) Charging power

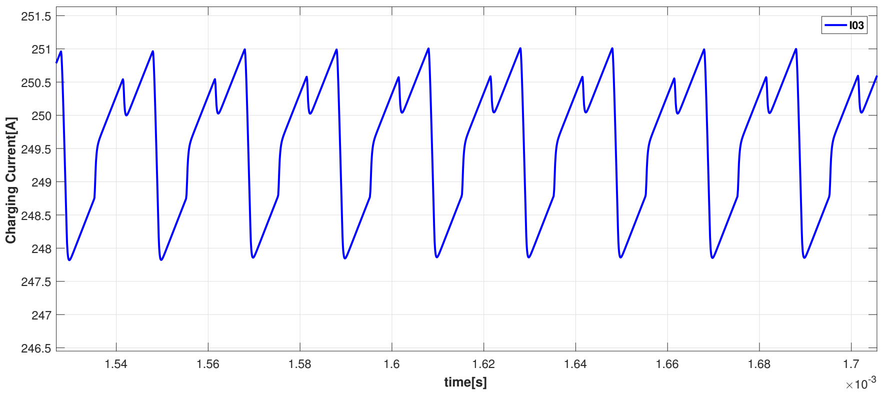
Figure 4.26: For 12V battery in idle mode of machine operation



(a) Single switch conducting

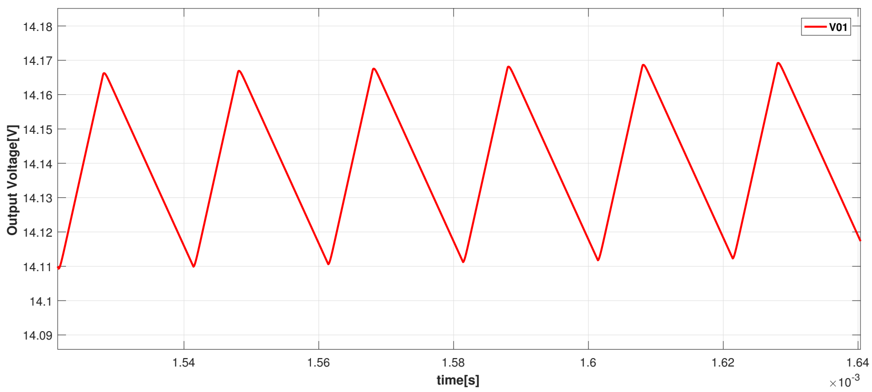


(b) Two switches conducting

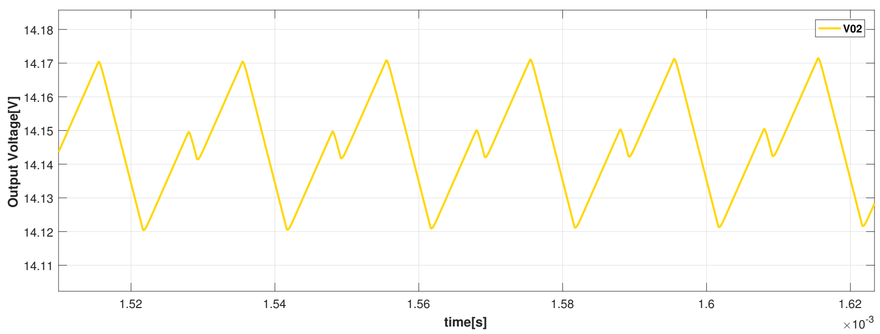


(c) Three switches conducting

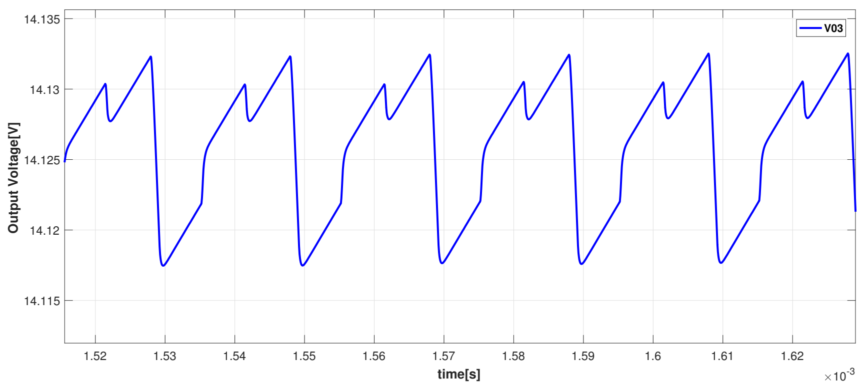
Figure 4.27: Ripple Current comparison for different switching strategies in idle mode



(a) Single switch conducting



(b) Two switches conducting



(c) Three switches conducting

Figure 4.28: Voltage ripple comparison for different switching strategies in idle mode

5

Conclusion

The Thesis showed the feasibility of connecting 12V battery with 48V drivetrain and the topology is developed for charging 12V battery continously in three modes of motor operation.

- In regeneration mode, circuit topology is changed from switch topology to diode topology. Since, it is possible to simulate diode topology for different speed of generator without having any voltage spikes in the circuit. Also, the output voltage ripple of charger was found to be in acceptable tolerance.

- The same circuit is simulated in motoring mode and it was shown that, it is possible to charge the 12V battery in motoring mode. Although, it is also observed that, there is presence of dc component in the stator winding of the motor from the fft plot. This will result in additional losses in the motor. Also, there is posiibility of saturation of inductor of stator winding which can reduce the value of effective inductance thereby, affecting the operation of motor and also increasing ripples in the circuit. Hence, it will require to modify the motor design to increase the value of inductance.

- It is also shown that 12V battery is charged in idle mode by using inverter as interleaved buck converter which resulted in reduction of ripple. The switching strategy of the switch needs to be studied, since, it is possible to introduce vibration in the machine which can cause mechanical degradation of the machine.

In addition, it is concluded that this topology is only possible in case of star connected motor and also it is required to have an additional neutral connection from motor so that 12V battrey can be integrated with its charging strategy. The result of the thesis can be summarized in following table,

Mode of Operation	48V Battery	12V Battery	Efficiency[%]
Idle	Supply	Charging	86.4
Regeneration mode: low speed operation	Idle	Charging	86.4
Regeneration mode: Moderate speed operation	Charging	Charging	85.45
Regeneration mode: High speed operation	Charging	Idle	91
Motoring mode	Supplying	Charging	75.37

Table 5.1: Summary of the thesis

5.1 Future Work

This thesis was mainly focused on developing simulation model to establish a charging strategy for Integrated charger topology of 12V battery with 48V drivetrain for Dual voltage Mild hybrid system. The simulation results were obtained for steady state, generic model of Battery and 3-phase motor. For increasing power demand, generally a 5-phase ISG is considered and hence, it is necessary to check the feasibility of this model for a 5-phase machine. Also, The analysis should be made based on a dynamic model of batteries in which, the effect of change in different voltage of both the batteries on the charging strategy can be studied. It is also important to study the dynamic model of ISG which can make it possible to study the following effect on motor;

- In the motoring mode, the actual torque that is available for motor when integrated charging of 12V is initiated when, there is a limit on maximum power limit on motor.
- The change in stator inductance due to the presence of homo-polar current in the stator winding of ISG when integrated charging is initiated in motoring mode.
- The additional losses and heating of ISG for different load condition, which will give idea on an additional cooling, if required for the ISG due to the integrated charging.

This study will help to predict the total cost and size required to for the proposed integrated strategy which then can be compared with the existing dc/dc solution. Further, The complex controller logic needs to be designed for this strategy which will make an easy transition between various charging strategy for 12V battery to attain continuous charging as explained in this thesis work for different modes of motor operation.

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