Protection of DC Motor under Transient Condition for Electric Vehicle using SENSEFET based Current Limit Controller

A Dissertation submitted in fulfillment of the requirements for the Degree
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Submitted by

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "Protection of DC motor under transient condition for Electric Vehicle using SENSEFET based current limit controller", 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 institute of engineering and technology, Patiala is as authentic record of my own work carried under the supervision of Dr. Smarajit Ghosh & Mr. Shailesh Kumar. 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 degree to any other university or institute except as reported in text and references.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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I dedicated my work to my nanaji,Mr. Jagdish P. Shukla who has been a constant pillar of knowledge and learning for the whole family. His spirit towards gaining knowledge at this stage is my source of inspiration.

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NOMENCLATURE

Main symbols and notations used in this work study are listed below

V	Voltage
E_b	Back emf
I_a	Armature current
R_{a}	Armature resistance
$\emptyset_f$	Flux per pole
ω_m	Speed of DC motor
τ	Load torque
R_{sense}	Sensing resistor
V_{sense}	Voltage drop across R_{sense}
$R_{ds(on)}$	On state drain to source resistance of MOSFET
I_p	Primary current
m	Mutual inductance
B	Magnetic flux density
R_f	Feedback resistance
t_S	Temperature of sense MOSFET
t_M	Temperature of main MOSFET
K_S	Temperture coefficient of sense MOSFET
K_M	Temperature cofficient of main MOSFET

LIST OF ABBREVIATIONS

ICE	Internal Combustion Engine
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
PHEV	Plug in Electric Vehicle
EM	Electric Machine
DC	Direct Current
AC	Alternating Current
PM	Permanent Magnet
IM	Induction Machine
SRM	Switched Reluctance Machine
VVVF	Variable Voltage Variable Frequency
EMI	Electro-Magnetic Interference
BLDC	Brushless DC
CT	Current Transformer
CR	Current Ratio

ABSTRACT

In Todays world, with the increase in fuel consumption leads to carbon emission which further cause global warming. The most feasible solution of this problem is the hybrid electric vehicle, electric vehicle and plug in hybrid vehicle. Performance of the electric vehicle depends upon the efficient operation of the motor utilized in it. In the proposed work, design of a current limit controller using SENSEFET technique for the protection of DC motor used in vehicle during transient condition such as breaking, starting, sudden load change and speed reversal has been done. The sensing of the voltage in the proposed controller has been done through the sensing resistor. The power losses in the current sensing techniques are minimized through the selection of the optimal value of sensing resistor. The switching of the motor for controlling the winding current during the transient condition was done through microcontroller programming. To improve the overall efficiency of the circuit, Cooling unit is incorporated in the circuit. The simulation of proposed controller has been done through Proteus software and its hardware implementation is also achieved to check its feasibility in the practical scenario. Current controller has been utilized for Permanent magnet DC motor working under the transient condition and the waveforms at different operating points of the controller are recorded at different instant of time.

CHAPTER-1

INTRODUCTION

1.1 OVERVIEW

Due to excessive usage of fuels and over-exploitation of resources like petrol, diesel cause carbon emission, which further leads to global warming. Nowadays, each and every vehicle depends upon the combustion of hydrocarbon fuels for the energy, which is further used for propulsion. Combustion is a reaction between air and fuel that generates heat as well as combustion products. Further, the generated heat was converted into mechanical energy by the mechanical system and the combustion product was further extracted into the surroundings. Except carbon dioxide and the water, some of the combustion products are also extracted into the environment, which contains some amount of nitrogen oxides (NO_x), carbon monoxides (CO) and unburned hydrocarbons (HC), all of which are toxic to human health leads to a development of Various types of vehicles shown in Figure 1.1 such as Battery operated vehicles, hybrid-electric vehicles and plug-in hybrid electric vehicles [1,2].

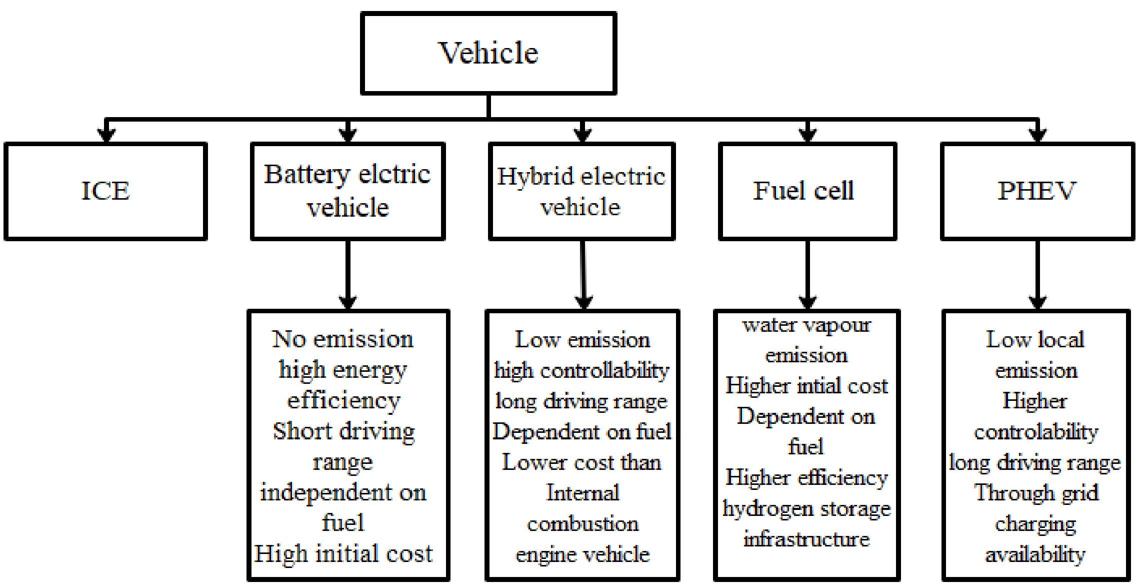


Figure 1.1: Different types of vehicle

Electric vehicles (EVs) utilize an electric engine for traction, as well as chemical batteries for energy sources and in some of the cases, fuel cells and ultra-capacitors are also used. The electric vehicle having several advantages in comparison to conventional internal combustion engine vehicles (ICE), such as there will be no emission, completely independent on petroleum, higher efficiency and quite well operation. However, some of the factors such as quite high initial cost as well as short driving range and longer charging time are also consider as the various limitations of these vehicles [3,4].

Commercially developed Battery Electric Vehicles bring revolution in the small automotive markets, due to higher initial cost still there is a production of battery electric vehicles by some of the manufactures for short distance range. The hybrid electric vehicles are considered as a turning point to overcome the various limitations as in the case of battery electric vehicles and internal combustion engine vehicles. Battery electric vehicles (BEVs) are considered as one of the feasible solution for avoiding carbon emission in urban areas. They have also some of the limitations such as recharging duration is quite long, driving range is quite short, higher cost as well as mass increment to detriment of transported load. Due to the previous technology, literature is considered for the identification of most innovative technology that will be beneficial for thermal management, sometimes for battery cell as well as battery pack development where as hybrid vehicle becomes one of the best alternative technology that combines battery electric vehicle and internal combustion engine vehicle [5].

The combination of energy storage system as well as electric machine (EM) with the conventional propulsion system leads to a development of HEVs. When hybrid electric vehicles are utilized within the electric mode, there is no emission that leads to improve fuel economy in comparison with other vehicles such as ICE vehicles. Hybrid electric vehicles also have higher driving range in comparison to Battery electric vehicles but the battery of plug in electric vehicles can be recharged by connecting to the grid, which makes their driving range quite long in comparison to the other vehicles. Hybrid Electric Vehicles also help to overcome various obstacles related to the pollution as well as energy crises. Moreover, plug in electric vehicles are considered as the most innovative solution in comparison to the internal combustion engine in the global market. Presently, there are three configurations of Hybrid Electric Vehicles such as series, parallel and series-parallel configuration [8,9].

The selection of motor is mostly based on the three factors such as weight, efficiency and cost. But in some of the cases, the various parameters such as reliability as well as technological innovation are the primary one and efficiency is the secondary one [16]. Amongst the previously reviewed motor propulsion framework, there were basically two characteristics, which was highly affected by the vehicle dynamics and the system outlook such as energy efficiency as well as speed range capability. Therefore, the active choice of speed drive for the hybrid electric vehicle focuses on these two basic characteristics. Still, the issues related to the extended speed range affect the vehicle acceleration performance, which comes under design criteria usually determined by user demand. The type of Electric motors used in various electric vehicles such as hybrid electric vehicle as well as plug in hybrid electric vehicle are basically AC and DC type. But DC motors are well-known for electric propulsion because their speed control is quite simple in comparison to others as well as their torque-speed characteristics highly match the traction requirements. They had some of the major issues like they had heavier construction in comparison to other, lower efficiency, lower reliability, constant maintenance requirement is also one of the major issues because of the commutator where as in case of AC motors such as Cage IMs, which are highly appreciated due to electric propulsion of HEVs, having various advantage such as higher reliability, lower cost, lower maintenance problem as well as their capacity to operate in such abnormal environment that leads to its usage in the industrial applications as well as traction drive atmosphere. Permanent magnet motors as well as Brushless DC motors are used in Electric vehicles based application due to various advantages such as they had very low fuel consumption, zero emission as well as higher power to volume ratio [8,16].

Under transient conditions such as starting, sudden change in motor speed, breaking and speed reversal, current may exceed the rated value. If the DC motor starts with a full voltage, it will carry very high current, which is 20 times more than the rated current that much current causes the severe heating in the windings of the motor. This further leads to the permanent damage of the motor. So, to protect the motor from unwanted increase in load current, Current controlling is required. The current sensing can be done for various purposes such as control, monitoring, power-management and protection in automotive applications. Some of the examples such as motor drive control, also used for over-current protection as well as for converter control application and for the batteries state of charge measurement [17].

The various current sensing techniques that are commonly used such as current sensing can be accomplished by using the calculated value of resistor within the current sensing circuit but the major problem related to this technique is high power losses. Except this, several other lossless current sensing techniques were developed, including sensing conduction voltage across the power MOSFET as well as utilization of current transformer and the use of RC filters for detection of inductor current. Hall effect current sensing technique is more accurate than current transformer technique as well as Rogowski coil technique. It is also accurate, but quite expensive in comparison to MOSFET based current sensing technique [18,19]. MOSFET based current sensing technique was one of the widely used technique for current sensing having various advantages in comparison to other techniques in terms of cost, accuracy and measure but due to its temperature dependency its overall efficiency reduces [19,20].

In case of SENSEFET based current sensing technique, this technique gives a highly productive path for the measurement of load current flowing through the main MOSFET. Due to its simplicity, this technique splits motor current through the main MOSFET as well as sense MOSFET on the basis of the current ratio. Further, signal level resistors are to be used for sampling. Since, this technique results, lower cost as well as efficient performance in comparison to the other techniques [20,21].

In the proposed work, a current limit controller using SENSEFET technique for the protection of DC motor for any electric vehicle during transient condition has been designed. The sensing of the voltage in the proposed controller was done through the sensing resistor. The power losses in the current sensing techniques were minimized through the selection of optimal value of sensing resistor. The switching of the motor for controlling the winding current during the transient condition was done through the microcontroller programming. The overall efficiency of the system is increased by incorporating a temperature sensor that controls a cooling unit. The prototype of current limit controller for any type of electric vehicle is presented in this thesis work.

1.2 LITERATURE SURVEY

Chan [1] provided a thorough information about the current status of electric and hybrid vehicles around the world and with accentuation on the building philosophy and key innovations. The significance of the integration of innovations of the car, electric engine drive, gadgets, energy storage as well as the significance of the involvement of various governmental as well as non-governmental societies such a government agency, colleges, power industries etc were addressed. The commercialization of EV is one of the major challenges nowadays discussed here.

Emadi *et al.* [3] discussed about the current trends as well as future trends within the automotive industry and the interaction of power electronics components in automotive application as well as the requirement of electric motor drives in a vehicle application for their improvement. The future vehicle such as fuel cell vehicle facing several problems related to the weight of the vehicle, problems related to the initial cost of the vehicle and the volume too. There were also some of the issues related to the rotating machines that can affect the efficiency of the complete framework as reviewed here. But nowadays, the cost of motor drives was quite less in comparison to previous years that can affect the efficiency Still, some of the progress required in the field of power electronics components to improve the overall efficiency by reducing the cost of motor drives.

Rajashekara and Kaushik [4] discussed about the recent status and the necessity of various electrical components that were utilized for the working of electric vehicles such as battery, different types of motor that were suitable for the effective working of complete system and the power electronic framework. It also reviewed about the various long term patterns that was highly essential like the various types of power-trains as well as the charging conditions of the battery. The progression of drive framework innovation for various battery based vehicle were centered at 5 important factors such as problem related to the high cost of vehicle, problems related to the driving range of vehicle, the cost of the substitution of battery pack within the vehicle framework, the life of the battery pack utilized for the effective performance of the electric vehicle and at last the issues related to the speed of the vehicle and recharging problems. The cost was the major factor that needed to be reduced to improve their production in the global market. Due to which automotive industries work for the advancement of batteries used in the vehicle for improving the effectiveness of the system. Most of the electric vehicles work converted to the plug in electric vehicle for the overall system efficiency was explained briefly within this paper.

Chan *et al.* [5] presented a novel approach for the energy management in the electric vehicle, hybrid vehicle and plug in electric hybrid vehicles and also provided a review of their structure such as series hybrid, parallel hybrid and series parallel hybrid. It also discussed about the various levels of functionality such as micro hybrid, mild hybrid, full hybrid and plug in hybrid.

The various types of modeling approaches whether new or old are also reviewed. There were various types model such as steady state and quasi dynamic model, structural and functional models, forward and backward models were presented here.

Wirasingha *et al.* [6] presented the categorization of different control strategies implemented for hybrid and plug-in hybrid vehicles as general control strategy, Rule-based method, optimization based and global control strategy. Simulation results showed that rule based control is simpler among all and not able to provide optimum solution where as global optimization method improved the performance as well as minimized the carbon emission from the vehicle, so it is clear that global control strategy must be optimized in real time and considered as the ideal solution.

Loukakou *et al.* [7] presented the design and analysis of ultra-capacitor which was used as a energy storage system in PHEV to store energy during de-acceleration and used that energy to accelerate. This PHEV operated in two modes: electric and hybrid mode where as electric mode to avoid carbon emission in town and hybrid mode in outside the town to make its working economically feasible, separate converter was used to control the energy of ultra- capacitor. The experimental results showed that approach was quite effective in reducing the cost of the vehicle.

Rind and Jamshed [8] provided a survey of the structure and designing parameters of electric vehicles and hybrid electric vehicles, as well as traction motors for the electric propulsion framework. The important components of the hybrid vehicle and distinctive power-train arrangements in terms of applications and their limitations were also discussed as well as high execution traction motor control methods were also examined here.

Ehsani *et al.* [11] provided a survey of HEVs over the range of drive-train setup, electric engine drives and energy storages. Various configurations like series, parallel and series-parallel were the foremost commonly utilized structures that were examined. For the points of interest and drawbacks, a series hybrid configuration was generally utilized in overwhelming vehicles, military vehicles and buses. With respect to the electric engine drives, a long steady control region could essentially diminish the control rating of the electric system which diminished the entire weight of the framework. The combination of batteries and ultra-capacitor for the hybrid energy capacity system became a most trusted way to meet the several challenges such as power demand as well as energy demand with its quite compact and less weight architecture.

Emadi *et al.* [13] reviewed about the battery based vehicles, hybrid vehicles and the fuel cell based vehicles operational characteristics and the various types of topologies incorporated within the vehicle framework. It also discussed about the innovative electric propulsion system for various vehicles. The utilization of fuel cell based vehicles for the light duty cars as well as sometimes for the heavy duty cars. At last, that paper highlighted the several challenges faced by the development of these innovative vehicle technologies. A survey of various vehicle designs showed that vehicle topology fell towards the lower power framework due to which it was a serious challenge for the battery to design according to the motor drives so that under any circumstances the performance of the complete system was unaffected.

Rahman *et al.* [14] discussed about the modeling of plug in electric vehicle and it was also introduced the several control strategies that were important for the few and at last the management of energy within the vehicle framework for the efficient operation of the whole system. The EMS was accountable to decide the operating mode of the vehicle. The management of energy was verified by the simulation results in terms of current, voltage and output power provided the output to minimize the fuel emission and to achieve the target performance.

Khaligh *et al.* [15] discussed about the different energy storage topologies for various battery based as well as internal combustion engine based vehicles and their comparison because advanced ESS's basically focused about the energy requirements of HEV and PHEV. Due to its several advantages like the cost was very low in comparison to other vehicles, efficient technology for fast charging was available as well as guarantee for efficient operation of the hybrid electric vehicle, which proved superior in comparison to others in world.

Hashemnia and Belazad [16] discussed about the various types of motor that could be used in the electric vehicles on the basis of cost, innovative technology and pollution free. DC motor, induction motor, switched reluctance motor, permanent magnet synchronous motor and brushless

DC motor. These motor had been done through the Advisor software at different driving cycles to compare them at various platforms such as fuel consumption and air pollution. The simulation results showed that induction motor is more accurate technology but brushless and permanent magnet motors were of light weight, pollution free and cost effective with respect to competing alternatives.

Patel *et al.* [17] discussed about the various current estimation techniques that could also be used in several applications such as DC-DC convertors, speed motor drives, which were further used in hybrid electric vehicle. Various current sensing techniques were analyzed on the basis of cost, simplicity and maturity of innovation and further compared to provide a best sensing technique for the effective measurement in that particular application.

Xiuohua *et al.* [18] discussed about the various advantages as well as disadvantages of the Rogowski coil transducer in comparison to conventional CTs**.** This transducer involved absence of core immersion effect, problem related to hysteresis was completely eliminated, the measurement through this transducer was highly accurate in comparison to others as well as the measurement could be achieved over the wide range. Due to those advantages it could easily be withstand several short circuit current and utilized over the wide frequency run, having extremely great linearity. This particular sensor could be advantageous for the estimation of income generated by the current flowing through the complete system as well as for the protection of power system by connecting this transducer with several other components such as transformers, connection with the line breakers as well as into the line, etc. along with a modern advanced relay. In the case of the electric meter, this particular sensor could be the feasible choice for the future scenario.

Lavric and Fiser [20] presented an approach to improve the accuracy of R_{ds} current sensing technique by minimization of current ratio (CR) and temperature dependence through theoretical as well as experimental analysis. The results proved this technique as a cost effective and having higher efficiency.

Nanda *et al.* [21] provided a relative information about the characteristics of various motors used in electric vehicles and comparative study of these motors on the basis of reliability, cost, power density had been discussed. In terms of reliability, Induction motors and switched reluctance motors were far way better than others, but in terms of controllability and maintenance DC motors were on the top of the list as lots of research was done over the years on this particular motor.

Zeraoulia *et al.* [22] reviewed about a various electric propulsion framework that were more suitable for their utilization within the different types of hybrid vehicle technology. It also discussed about a comprehensive review of the modern technology and provided a comparative study of the four different propulsion frameworks on the basis of performance, to be specific the DC motor as well as the use of an induction motor (IM). The construtional features of permanent magnet synchronous motor, and switched reluctance motor.was also discussed .The best result obtained on the basis of literature discussed about different motor and Cage Induction motor was more superior than the others to achieve future goals related to hybrid electric vehicle.

Santiago *et al.* [23] discussed about the various motor topologies that could be utilized in the battery based vehicles. It also had reviewed about the drive-train for all the battery based vehicles produced by the automotive industry. The various drawbacks and the advantages related to the electric propulsion system were also reviewed in that paper. It showed that innovative technology was still in a slow run while considering the production of cars based on battery related applications Due to which MOSFET of the car manufacturers were only considering induction motors or they could also use permanent magnet motors for the production at the global level. IMs were still the transcendent innovation indeed with less than 75% of efficiency The cost of the crude material decide, whether the permanent magnet motor would be considered or not. In case of Hybrid vehicle, it considered the combination of two power source that could improve its overall efficiency in comparison to electric vehicle.

Benbouzid *et al.* [24] discussed about the highly efficient induction machine fault tolerance control mechanism for the various battery based vehicles as well as battery plus internal combustion engine based vehicle. The proposed frameworks easily reorganized itself within any condition of sensor loss or any problem related to sensor recovery, to provide efficient control signal for the effective operation of the remaining sensors. The simulation of the proposed methodologies was done over the 4 kW induction motor and the output speed as well as output torque response was considered to check the effectiveness of the proposed work technique. At last, the simulation results discussed about the effectiveness of the technique at worldwide on the basis of speed as well as the output torque response in terms of various modern and efficient control strategies.

Finch *et al*. [25] discussed about the various AC machines that were utilized for the various controlled drive applications. It also discussed about the sorts as well as the properties of various AC machines that could further affect the control strategies considered for the electrical drives. The several control techniques were applied across the AC drives to improve the response as well as the range were briefed here, but at the starting voltage control was accomplished by the commutator for the DC drives.

Wang *et al.* [26] discussed about the various characteristics considered for the designing of induction motor. That was further utilized for the hybrid electric vehicle. It also reviewed the various identical circuits related to the several conditions such as starting, harmonics and the operating conditions. The analysis was done over the relationship between the iron core and the copper loss vs frequency curve, further comparative study of the analysis was achieved. In the middle of the paper, a brief discussion was done over the influencing of induction motor by the system harmonics. Design standards for the induction motor were also presented, considering the various conditions such as the starting condition, harmonic condition and last but not the least operating condition.

Zhang [27] presented a novel approach of sensor less EV IM drive incorporated with a backhanded vector controller and a fixed-boundary-layer sliding mode (FSM) observer. As the requirement of current transducer increases, it directly affected the cost of the motor system. It might also be possible in some conditions that the value of speed and the value of flux could be measured easily without knowing the value of load torque. The speed and flux might be estimated indeed without known load torque. By the utilization of indirect vector control with the help of feed forward compensation, the fast processing within the controller was achieved. In the meantime, the transitory execution was improved. The experimental results proved that the efficiency of the design of the proposed controller for the DC motor load in different conditions and also, the effectiveness of the applied technique over the battery based vehicle was verified.

Zhu and Howe [28] presented the relative merit of various machines like switched reluctance machine as well as permanent magnet machine utilized in the various vehicle applications of battery based vehicles and the battery plus internal combustion engine based vehicle. But the complete attention was on permanent magnet machine. Several merits and the operational characteristics of the machine was given as high power density. The effectiveness was quite high over the wide operating range. Those machines were highly capable of reaching extreme speed value. All merits were also discussed here. Several strategies were reviewed which was providing a improved Permanent magnet excitation torque and all these strategies involved in the improvement of reluctance torque were also discussed here.

Krishnamurthy *et al.* [30] provided three important technologies, which were developed over the last few years resulted in the exceptional increment in the performance of SRM for improvement of efficiency and removal of position sensors from the SRDs. The sensor less strategy had been formulated with an auto-calibrating modeling approach, which did not require any additional equipment or memory. It was trusted that the proposed technology would definitely provide attention towards the switched reluctance innovation for car applications.

Kawa *et al.* [31] provided a novel profiling strategy, to diminish acoustic noise and vibration. The proposed strategy had been incorporated into an high-efficiency SRM with 18/12 stator and rotor shafts. Proficiency comparison of the FEM investigation was also displayed. Further, the test confirmation was presented in the future work.

Chau *et al.* [32] discussed about the various topologies that were considered in drive operations and the control techniques of the permanent magnet brushless DC machine to use it in the various vehicle applications. The research was done in the field of permanent magnet DC machine framework for battery based vehicles to produce three types of PM brushless DC machine framework such as the permanent magnet brushless ISG machine framework for the various types of hybrid electric vehicle as mild one and the micro one where as the second type of permanent magnet EVT framework for the all types of hybrid electric vehicle was discussed.

Shen *et al.* [33] discussed about the various applications and examples related to the high speed electrical machines and also categorized the machine framework. The important aspects related to the design and control such as rotor stress analysis, thermal analysis and over temperature were discussed. The high speed machine had also undergone some challenges such as heat dissipation, power losses and power range that restricted their use in high-speed applications. Therefore, the important aspect needed to be considered is the uniform distribution of losses so that the temperature related issue could be avoided.

Naseri *et al.* [34] presented a novel approach of a modern Regenerative Braking Framework (RBF) for the various types of battery based vehicles as well as battery plus internal combustion engine based vehicle and the internal operation were performed by the highly effective brushless DC (BLDC) motor by the utilization of batteries and super-capacitors within a HESS. Those techniques had various advantages such as highly effective regenerative breaking, problem related to battery security was also eliminated and it also helped to improve the vehicle acceleration. Thus, utilizing appropriate switching algorithm, the DC-link voltage was boosted and the energy is exchanged to the super-capacitor or the battery through the inverter.

Patel and Ferdowsi [35] presented a different types of current detection strategies for the efficient working of the vehicle as well as introduction of different control techniques to improve the over-all efficiency of the vehicle based on the accuracy, bandwidth and losslessness. Advantages and disadvantages of these techniques were also analyzed in that paper as well as electromagnet based current sensing techniques were also discussed.

Forghani *et al.* [36] discussed about the techniques used for improving of accuracy of filters utilized in the current sensing through the adjustments done on the bandwidth as well as some of the adjustments were also done over the gain with the help feedback control loop. During the starting condition as well as the reset condition, the filter automatically came in contact with the inductor so that the measurement could be done easily by sensing the voltage across the inductor.

The proposed design was further simulated and the simulation results had been verified to conclude that the proposed technique had high power efficiency and the problem related to the sensitivity to the switching noise was completely eliminated.

Pooya *et al.* [37] presented the analysis and comparison of the different techniques for lossless current sensing, which was quite applicable on HEV and PHEV. They also discussed the traditional ways of current sensing and their advantages and disadvantages of various techniques. Simulation results showed that SENSEFET method is the only approach independent of external component values.

Zieger *et al.* [38] proposed an intensive review of various sensing techniques. It basically classifies the various sensors on the basis of physics based principle, such as Ohm's law of resistance as well as Faraday's law of induction, attractive field sensors and utilization of Faraday's principle in this technique in order to point out their qualities and weaknesses. In addition, it also discussed about the several current sensing hardware such as open loop current sensor with reference to magnetic field sensor as well as closed loop sensor with specific reference to magnetic sensor and also the utilization of both the sensors in the particular combination to satisfy various requesting execution requirements. There were several current sensors such as Hall Effect and the magneto resistance effect based sensor and at last optical fiber procedures gave appealing options for current sensing, in spite of the fact that generally had at a higher cost than conventional strategies.

Chen *et al.* [39] presented an optimization technique for the various applications related to the plug in electric vehicles such as battery charging as well as for the power management purpose to improve the overall efficiency of the vehicle. The three cases with high, medium and low network CO_2 levels were considered for a small-size PHEV. The results showed that the dependency of PHEV on power usage was improved whenever the CO_2 was diminished and its energization was increased within the region of minimum carbon emission.

Niu and Lorenz [40] presented a novel approach for the measurement of junction temperature in correlation with MOSFET gate drive whenever this technique was applied on the lower power side of the power converters. In order to examine the MOSFET junction temperature, a push pull gate drive was connected with the current divider circuit as well as the output of gate drive was further utilized for the measurement of MOSFET junction temperature. The model of gate drive utilized in that technique, described the various components used in the respective circuit and the results provided the impact of the device temperature gradient over the exactness of the junction temperature measurement in that paper.

Zieglar *et al.* [42] upgraded the previously discussed work on that particular circuit so that it was feasible to estimate currents declined to zero. The circuit complexity was not an impediment since in digital controlled control supply, the DSP gave the specified assistant functionalities and overcame the circuit complexity of the past transformer based current sense arrangements. where it required as many components and was incapable to measure little streams. If auxiliary winding was utilized to bias the main current, it became easy to measure current decreases to zero with high accuracy.

Crescentini *et al.* [43] discussed about the broadband current sensors utilized for the various control applications, which was completely dependent on hall effect based sensor used for current detection purpose. In comparison to previously discussed technique, the proposed design was quite stable as well as cheap for its implementation within the system without knowing about the control circuit. A model of the proposed design was worked at an 8MHz spinning frequency. To verify the effectiveness of the proposed design, that particular work was tested on two different cases related to the battery based vehicles. Specifically, for the estimation of inductor current within the power converter, in which waveform recreation and issues related to the average current sensing were critical.

Liu *et al.* [44] showed a novel approach by the utilization of silicon based MOSFET within the power module. There were a several advantages related to the utilization of silicon based MOSFETs such as they directly reduced the overall cost of the system as well as the variations in the temperature was eliminated. Whenever the two MOSFETs were not fully matched. Then, it had affected the overall accuracy of the system that was also examined as well as the selection of sensing resistor value was also analyzed on the basis of minimum CR ratio error. Test results verified the effectiveness of particular MOSFET as there was also improvement within bandwidth performance due to very less CR ratio error even less than 1.8% in comparison with the calculated values.

Niwa *et al.* [45] discussed about a dead time controlling of the gate drive within the silicon carbide MOSFET module and the utilization of SENSEFET technique. There was no need of any outside component as gate driver itself was sufficient to interrelate with the control. This controller abbreviated the diode conduction time inside 0.1 μs. The diode of the Silicon carbide based MOSFET module utilized as a freewheeling diode within the circuit having high forward voltage and the efficiency of the converter improved to 1%. The power losses were also eliminated. The effectiveness of the battery based vehicle increases whenever the utilization of silicon carbide MOSFET with the gate driver was achieved as explained.

Aiello *et al.* [46] presented a novel approach of current sensing by a new current sensor, which sensed the current that, was further subjected to radio frequency interference. There was no need of amplifier to limit the performance of the SENSEFET that technique provided a faster response compared to previous current sensing techniques. It also discussed about the comparative study of various sensing techniques of modern time as well as the past time through the simulation. The simulation results verified the effectiveness of recent current sensing technique in comparison to previous techniques.

Xiao *et al.* [47] considered a designing of power MOSFET due to simple controlling feature as well an over-protection scheme. It consisted of low drain to source resistance and high current ratio. Some of the factors that affect the normal working of power MOSFET were also evaluated. It was realized that sensed ratio change like 2.7% when V_{gs} was 5V to 10V and 2.9% at temperature of -50℃ to 150℃. This particular circuit was only applicable for low-frequency motor application and the experimental results were further evaluated to verify the feasibility of that current sensing technique.

Shulin *et al.* [48] discussed about various current sensing methods that could be used in the DC-DC convertors by the measurement of voltage within the circuit as all these sensing techniques were lossless. By adjusting the value of resistor on both ends of trans-conductance amplifier, the accuracy of the scheme was improved. The proposed design was simulated and the simulation results verified the accuracy and economic feasibility of that current sensing technique.

Biglarbegian and Parkhideh [49] discussed about the control technique that had been further implemented in the boost converter during boundary conduction mode. That approach was basically recognizing the cursor to differentiate further between converter operation mode and the boundary conduction mode, i.e. CCM/BCM. The estimation of sensing current was done within the SENSEFET based module and it was quite accurate for its utilization in the high power devices. The effectiveness of the implemented scheme was also discussed.

Bryant and Kazimierczuk [50] discussed about the impact of sensing resistor that could be utilized within the PWM convertor during various control mode such as current control mode in a particular MOSFET aspect proportion. The current flowing through a MOSFET was highly affected by the resistance at particular gate voltage. The value of source resistance was so much important that if there was a 0.1% increase in source resistance, the value of leakage current reduced by 386%. The value of source resistance was so high to achieve a desired load current and it was necessary to had a higher gate voltage in a similar manner as source resistance. The test results were displayed confirming the legitimacy of the theoretical results.

1.3 RESEARCH GAP

The previously proposed current sensing techniques was not accurate due to higher power losses and also quite expensive due to presence of high cost components. The implementation of current limit controller using SENSEFET technique for the protection of DC motor in the electric vehicle, hybrid electric vehicle and Plug in electric vehicle was not accomplished by the previously designed protection techniques.

1.4 OBJECTIVE OF STUDY

- To limit armature winding current during transient condition faced by the DC motor load.
- Designing of current limit controller using current sensing technique in Proteus software.
- Designing of respective controller in hardware.
- Analysis of the results to verify the accuracy of the current sensing technique.

1.5 ORGANIZATION OF THESIS

The thesis work divided into six chapters according to the content are as follow:

Chapter 1: This chapter discusses about the complete work in a summarized way and also provide a introduction about the need of electric vehicles, importance of current sensing techniques for the vehicle application and different types of motors that can be utilized for the vehicle application.

Chapter 2: This chapter discusses about the various types of motors that can used in the electric vehicle, hybrid electric vehicle and the plug in electric vehicle and also about the impact of their characteristics over the normal working of the vehicle.

Chapter 3: This chapter discusses about the various types of current sensing techniques that are commonly used for various applications.

Chapter 4: This chapter discusses about the design of the current limit controller for the protection of motor under transient conditions in plug in electric vehicle.

Chapter 5: This chapter discusses about the simulation results and the hardware results of the proposed controller on PM DC motor load.

Chapter 6: This chapter discuss about the conclusion and the future scope related to the proposed work.

References

CHAPTER-2

COMPARATIVE STUDY OF DC MOTOR USED IN HYBRID VEHICLE

Choice of traction motors for hybrid propulsion systems could be an exceptionally critical move that completely needed uncommon consideration. In recent times, several industrial bodies searching for the foremost suitable electric propulsion framework that is highly required for Electric vehicles as well as hybrid electric vehicle. There are several parameters needed to consider in the mind but the important out of them are like the cost, system performance as well as its reliability. The method for the consideration of suitable electric-propulsion frameworks was, in any case, troublesome and ought to be done at the system level. According to a practical point of view, the selection of the most optimal electric propulsion framework must be done on the several basis but the primary ones are the common drawbacks of any vehicle, the requirement of best energy source to provide max power at efficient level and the customer demand [8,16,21]. Subsequently, selecting the foremost suitable electric-propulsion framework for the Hybrid Electric Vehicle consider as a biggest challenging task.

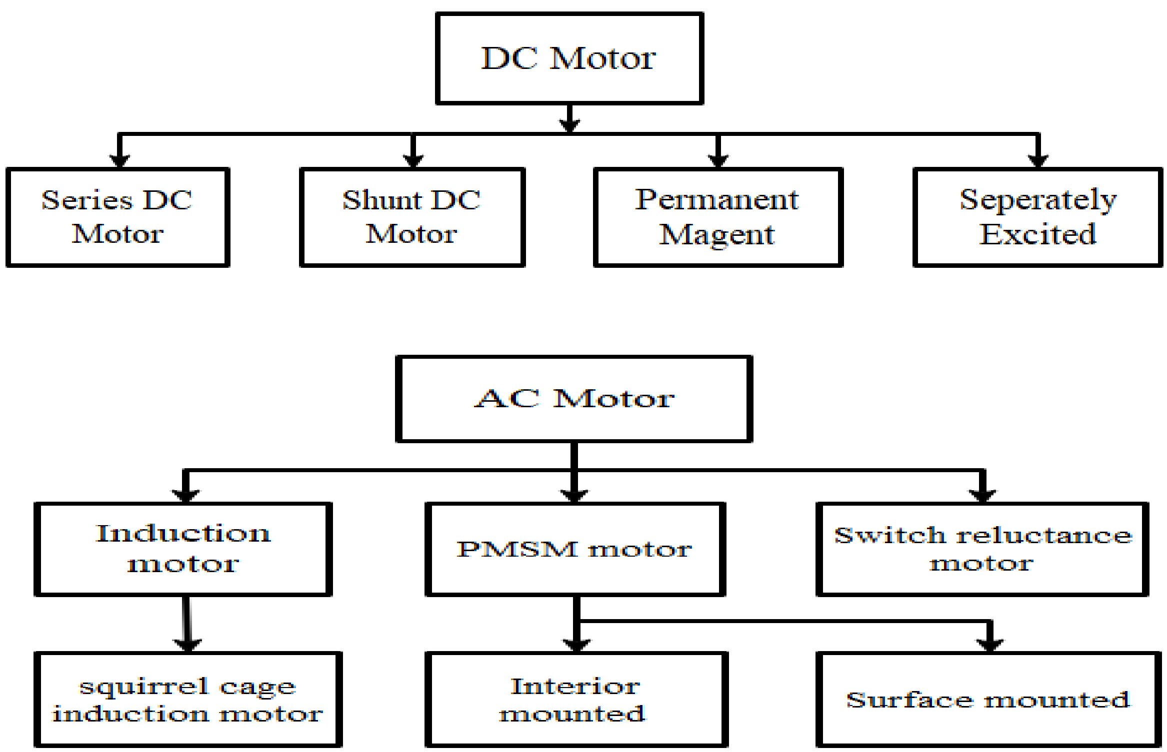


Figure 2.1: Different types of DC and AC motor

While Considering the industrial view , the various motors that are satisfying the hybrid electric vehicle and electric vehicle requirement such as DC motor, the switched reluctance motor (SRM), the permanent magnet (PM) synchronous motor as well as the induction motor (IM) shown in Figure 2.1. Besides, a survey related to the structural and the functional background of electric-propulsion frameworks, it was monitored that examinations on the Induction motors and the Permanent magnet motor was overwhelming, while those related to the DC engines was diminishing and the rest on switching reluctance motors was getting much interest. There was a brief discussion about various motors used in various battery as well as internal combustion engine based vehicles [16,21].

2.1 DC MACHINE

DC machine utilization was broadly acknowledged for their utilization in the Electric Vehicles. On the basis of several methods with respect to the field excitation, these were further divided into self excited DC motors as well as independently excited DC motors. Now, if the source for the field excitation is considered, these were subdivided into wound field DC motor as well as Permanent magnet DC motor. If we consider the common interconnection between the various windings like field winding as well as the armature windings or also the Permanent magnet excitation, all of them were comprised of independently energized DC types such as permanent magnet types as well as series type and at last shunt type. Both the field windings and the armature windings of the independently excited DC machines having separate voltage control with respect to each other. If speed decreases, the torque will increases. In case of shunt DC machine, the field windings as well as the armature windings both were associated with a common source. Both the armature current as well as the field current was equal to the case of series DC machine due to which they had a reverse torque speed characteristics. Uncontrollable field voltage can be seen in the case of permanent magnet motor as the torque speed characteristics of this motor is quite comparable with the shunt DC machine. In case of permanent magnet machines, losses are quite negligible and has higher efficiency in comparison to other [22,23].

Due to continuous utilization of commutators for a long time, it leads to a torque ripple as well as affect the normal speed of motor. These issues are same for all the DC machines. In addition to previously discussed drawbacks, commutator and the brushes are also suffering from regular maintenance issues. A basic speed control mechanism, innovative maturity, relatively low cost of fabricating as compared to other motors, and better speed control are the most reasons to legitimize the substantial use of DC motors within the electric vehicles.

2.1.1 Steady state equation of DC motor

The voltage steady state equations which are mainly used for DC motor is given by Equation (2.1).

$$V = E_b + I_a R_a \quad (2.1)$$

Where,

V is the terminal DC supply to the motor (V)

E_b is the back Emf of the motor (V)

I_a is the armature current of motor (A)

R_a is the armature resistance of motor (**Ω**)

The direction of torque in motors depends on the direction of the armature current. The back emf depends upon speed of motor as well as flux generated in the motor which is given by Equation (2.2).

$$E_b = K_b \emptyset_f \omega_m \quad (2.2)$$

Where,

K_b is a constant depending on geometry and winding of motor

$\emptyset_f$ is the flux per pole due to field winding

ω_m is the speed of DC motor in rpm

For the permanent magnet, Equation (2.2) become,

$$E_b = K_b \omega_m \quad (2.3)$$

Then, the load torque developed in motor due to combination of field flux and armature current conductor interaction is represented by Equation (2.4).

$$\tau = K_1 \emptyset_f I_a \tag{2.4}$$

where,

τ is the load torque of the motor

K_1 is a constant depends upon the geometry of motor

$\emptyset_f$ is the field flux of the winding of the motor

For the motor of wound field, speed of the motor can be controlled by field flux of the motor but as bellow

$$\tau = K_t I_a \tag{2.5}$$

Where,

Kt is depends on the geometry parameters of shunt motor

For separately excited DC motor,

The resultant torque will be produced due to interaction between the flux produced by the field winding with the current continuously flowing through the armature winding and both the windings get supply from the two completely different sources.

Mathematical relations between speed of motor and torque is given by Equation (2.6).

$$V = E_b + I_a R_a + L_A \frac{d_{i_a}}{dt} \tag{2.6}$$

From the Equation (2.1), Equation (2.2), Equation (2.3), Equation (2.7) can be obtained.

$$V = \frac{\tau}{K_1 \theta_f} R_a + K_1 \tag{2.7}$$

Equation (2.8) present the speed of motor.

$$\omega_m = \frac{V}{K_1 \emptyset_f} - \frac{\tau}{(K_1 \emptyset_f)^2} \tag{2.8}$$

Therefore, for the speed control of DC motor, basically three different parameters are used such as terminal voltage (V), field flux ($\emptyset_f$) and armature resistance (R_a). The value of resistance chosen in such a way that the losses across it will be minimum under working condition as similar occur in the case of variable voltage source when the voltage induce by the source across motor is quite well so that the losses within control gear will be minimum. Whenever the speed proportion will be quite large, this particular method will be used.

The speed control was achieved by the several techniques such as flux control as well as field control but in a regular manner field or in a continuous manner field weakening was considered. This particular technique was responsible for the operation at higher speed in comparison to normal speed. Further, machine comes in a saturation state so that, if the field current is increased it was not able to change the speed. Therefore, large field mmf must be generated to cause little variations in the speed. As it has been discussed earlier that field weakening cause operation at higher speed and it leads to torque decrement, which is generated by the machine for the armature current. If this condition occurs within the system, the armature current becomes constant and the power delivered to the motor becomes constant. Therefore, the motor comes in a constant power mode with field weakening. Commonly the stress over the commutator insulation must be less under the normal condition. Sometimes, it increases whenever the increased voltage applied across the motor during constant flux mode. Therefore, the operation at a speed above the nominal one can be performed by the field weakening and the operation under nominal speed, can be performed by the utilization of voltage control. The utilization of series resistance is quite high as in the case of shunt as well as compound motor. To weaken the field in similar way, diverters are utilized within series motor. The use of diverters are achieved in a parallel configuration across the series winding to decrease the value of field current without interrupting the value of armature current.

2.2 Induction machine

In todays world, induction machines are the foremost developed innovation out of different commutator less machines. Basically, there are two sorts of induction machines, the wound-rotor induction machine as well as the cage-rotor induction machine. The wound rotor induction machines are less considered for any application in comparison to cage rotor induction machine due to several issues such as problem related to high cost. It also needs regular maintenance. That is why due to several advantages, these machines are commonly known as induction machine. Except several advantages in comparison to brushless DC machine as they provide maintenance free operations, induction machine also have some advantages related to low cost as well as These machine are also at better side in terms of toughness. But if we compare both the machines in terms of control mechanism, induction machines were on the lower side due to complex control. The induction machines having two types of control such as variable voltage variable frequency control and also the field oriented control, out of which FOC considered as an additional control. The vector control in case of induction machine is just a speed control, which has been introduced for the electric drives [23,24]. The Variable Voltage Variable Frequency control mechanism is based on the principle of constant V/H criteria. This particular control mechanism utilizes the rated voltage for the value of frequency below rated value. Whenever there is a very low frequency, only voltage boosting is considered. The main working of this technique is to compensate the error value between the applied voltage as well as induced voltage produced by the voltage drop across the stator resistance. The variable voltage variable frequency control would not be considered for the high performance operation within electric vehicles due to several drawbacks such as variable air gap flux as well as slow reaction. Still, due to several advantages such as reliability, strength, problem related to low maintenance as well as the capacity of the machine to work in a unfriendly environment make squiral cage induction motor as the foremost candidate for the electric vehicles [25,26,27]. The induction motors in comparison to other AC alternatives had the most innovative technology to encounter any small problem. IM drawbacks incorporate high losses, poor power factor and low efficiency. In addition, its weight and volume were more prominent than PM-motor at same power ratings. In inverter fed IM, the high starting torque as well as low starting current shown in the Figure 2.2

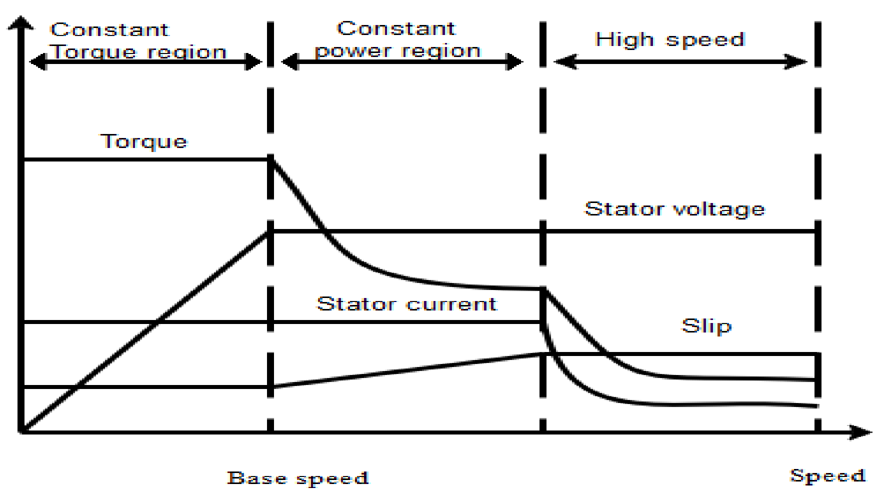


Figure 2.2: induction motor characteristic curve

can easily be achieved by the proper selection of effective supply voltage as well as frequency whereas highly efficient operation can be obtained by least slip control. In IM, the dependency of the rotor copper losses over the motor slip is considered, which is specifically corresponding to the rotor frequency and rotor voltage.

Induction motors with the higher efficiency need to work within the 3% slip value that gives less rotor core losses than stator. The effectiveness of IM is maximum when iron loss and copper loss both are similar [27,28].

To improve the IM drive effectiveness, some control methods given to HEV applications have been proposed. Multi-phase pole-changing Induction Motor drives used for various applications such as footing application that had been proposed in for expanded steady control operation without over-sizing the motor. Another approach uses the dual inverters to improve the consistent power region operation. However, IM dominance is challenged by PMSM due to high power density, high efficiency and few rotor losses. Regardless, utilization of PMSMs are limited for high-performance applications due to their high cost and restricted ratings. Extensive reviews on machine setups and drives for electric vehicles are displayed in [16,29].

2.3 SWITCHED RELUCTANCE INDUCTION MOTOR

SR machines had been considered for having impressive potential for various vehicles such as electric vehicle as well as hybrid vehicle. This particular motor has a major advantages of basic construction, problem related to low fabricating cost as well as exceptional torque-speed characteristic. The guidelines related to the operation of SR motor is completely depended upon the principle of low reluctance rule. Switched reluctance motor speed can be maximized by the proper variations within the constant power region as well as it needs some changes in the constant torque region as shown in Figure 2.2 because it was also partially depends upon the rotor pole design. Although, the efficiency of this machine is quite less in comparison to the permanent magnet machine but still, some of its features like wide speed as well as the torque range is quite high in comparison to other motors. All these advantages led the foundation of its production by the several car manufactures. There are few basic key characteristics of SRM such as basic robust rotor structure without utilizing the magnets or the windings. These benefits help for its utilization within high speed applications and the best part of its characteristics that is its insensitive nature towards high temperature surrounding, problem related to cost is completely eliminated. At last, constant power region is due to its insensitivity towards temperature variation offsets [8,23]. Supply voltage decrease is additionally helpful in order to diminish the acoustic noise at light stack condition. SRMs can have essentially lower noise level when it is operated under voltage control instead of current control. Since current controller arbitrary switching may result in wide-band harmonic spectra, this increases the induced mechanical resonances.

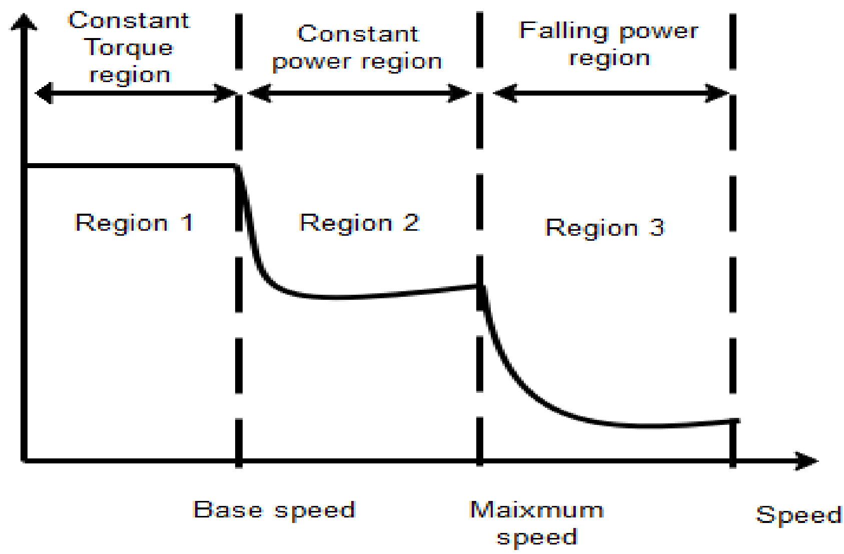


Figure 2.3: Switched reluctance motor characteristic curve

These motors usually require uncommon converter topology. Electromagnetic interference (EMI) noise generation is a few other impediments of such motors. The motor high-speed operation may cause high mechanical losses because of optimal design drag and viscosity losses. However, these mechanical losses can be decreased by optimally planned rotor shape.

2.4 PERMANENT MAGNET

Now a days, permanent magnet machine are considered for having extreme potential for electric vehicles and the hybrid vehicles. The machine having several advantages such as the high energy magnets are utilized for the generation of magnetic field, for the particular output, its weight as well as its volume ratio can easily be decreased. It can also be used at higher power density but the problem related to losses is completely negligible. Hence, its efficiency becomes so high. Due to motor operation, continuous heat is generated within the motor structure, which can easily be extracted within the environment. Its electromechanical time constant is quite low that helps in the rotor acceleration according to the demand. These machines are also suffered from the several disadvantages such as high fabric cost and the uncontrollable nature of permanent magnet motor flux. On the basis of the waveform, that continuously provided at the motor terminal cause division of permanent magnet brushless motor into two types such as AC as well as DC machines. However, the sinusoidal waveform is provided to the permanent magnet AC machines and the rectangular AC waveform is used to fed Brushless DC machine. The brushless AC machines are also called as synchronous machine. Whenever there is interaction between the rectangular current and the magnetic field, it leads to a generation of high resultant torque. This further leads to a creation of sinusoidal current as well as generation of sinusoidal field as the power density of Brushless DC machines is quite high in comparison to the brushless AC machine. The torque produced by the brushless AC machine is quite smooth as compared to the Brushless DC machine [32,33].

However, Brushless DC motors is subjected to various types of system failures during the normal working of the motor due to which fault tolerance drive framework had some task under this condition such as the fault was detected in a continuous manner as well as identification of the type of fault was also done to remove the fault as soon as to achieve stability within the complete system. Several research had been continuously done for the detection of fault occur in the field of Brushless DC motor. Detecting dynamics eccentricity in BLDC motors under varying speed operation through explanatory wavelet transform has been displayed. A few analysts have used a neural network and fuzzy framework for fault diagnosis of BLDC motors. To create BLDC motor fault tolerance inalienably through the design, highlights was discussed in [16,34].

For the excitation point of view in the permanent magnet motor, high productivity as well as the effective compactness was achieved [29, 54]. Need of cooling is required in some portion as the only heating part within the whole machine is the stator one. This machine has several advantages such as problem related to the maintenance was completely eliminated, extraordinary lifespan and the absence of brushes leads to a higher reliability and mechanical commutator as well as low noise emissions as requirement of mechanical brushes or slip rings. The efficiency as well as the speed range can be increased by the proper controlling of the converter conduction angle above its base speed. If the controlling is done in a proper way, the speed range is definitely improved up to 4 times above the base speed. So, due to closeness of both the high power density magnets present in the permanent magnet motor leads to a high power density of permanent magnet motor. In addition, permanent magnet motor has higher efficiency in comparison with other motors due to absence of motor losses [3,32].

In the proposed work study, selection of motor is completely based upon various parameters such as cost, construction, weight and maturity of technology etc. Permanent magnet motor can be used in the proposed work even AC motors are highly used in several industrial related applications as well as for the drive applications. But the permanent magnet motors as well as brushless DC motors has been regularly utilized within the Electric vehicles based application due to various advantages such as they have very low fuel consumption, zero emission as well as higher power to volume ratio.

CHAPTER-3

VARIOUS CURRENT SENSING TECHNIQUES

Current estimation is additionally utilized for different purposes such as control, security, monitoring and power management purposes and also for few other applications like mode hopping, over-current protection, current sharing etc. A few current detecting methods have been proposed within the literature, which is distinctive in precision, cost, operating range, having linear behavior, magnitude of current, required electrical segregation, complexity, sensitive for the switching noise as well as AC response [35]. Various current sensing techniques like current sensing using resistor, current sensing control MOSFET, average current sensing, MOSFET drain-source resistor and observer strategy are also reviewed that are utilized for DC-DC switching converters. In case of high power applications, such as Rogowski Coil, fiber optic current detecting sense, current transformer, DC current detecting and Hall Effect current sensing are broadly utilized [36,37].

3.1 VARIOUS CURRENT SENSING TECHNIQUES USED IN DC-DC CONVERTER

3.1.1 Resistor based current sensing technique

This technique is basically a conventional way to measure sensing current by inserting a suitable resistor in the sensing circuit as shown in the Figure 3.1 [35].

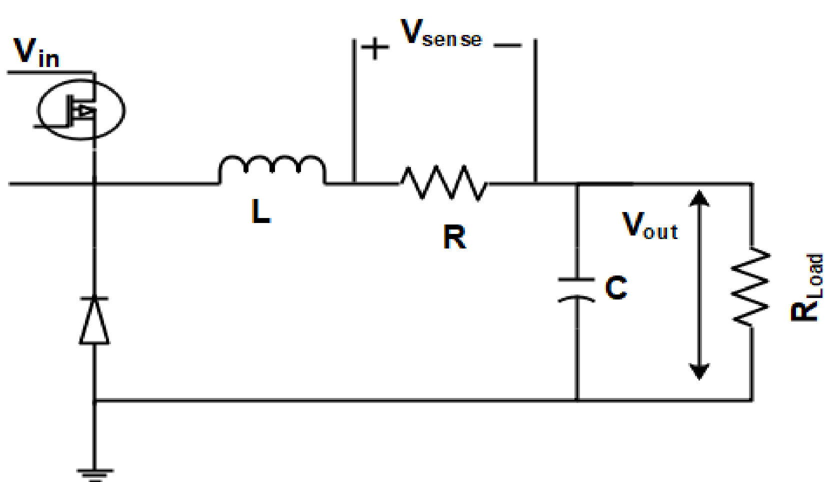


Figure 3.1: Current sensing technique using resistor

This technique is quite simple and precision. This method was also used for various purposes like power factor correction as well as also for the over current protection. There are various criteria for the choice of sensing resistor such as on the basis of voltage drop across the resistor, sensing accuracy, productivity and the power loss across the resistor as well as cost factor. The major drawback of this current sensing technique is the power dissipation across the sensing resistor during on condition. Hence, this strategy is quite wasteful for DC-DC converters. To improve the overall bandwidth of the sensing circuit, the implementation of noise filter is quite essential. For the DC-DC converter with the high productivity requirement such as 75%, this current sensing technique can not be applicable.

$$I_m = \frac{V_{sense}}{R_{sense}} \tag{3.1}$$

In Equation (3.1)

I_m is the current flowing through the sensing resistor

V_{sense} is the value voltage drop across the sensing resistor

R_{sense} is the value of sensing resistor

If resistor R_{sense} is put on the load side, it will only provide a information related to the load current. Input current estimation is required to realize variable voltage switching in respective controller [38].

3.1.2 Current sensing using the internal resistance of the inductor winding

This technique can eliminate the utilization of the sensing resistor and also help to remove the power losses by the use of inductor for the respective current sensing technique as shown in Figure 3.2. However, this particular technique is highly suitable for the low voltage converters. where R_l is consider as the internal resistance or it can also be a direct current resistance of the windings [17].

The voltage across the inductor winding is expressed by Equation (3.2).

$$V_l = (R_l + sL)I_l \tag{3.2}$$

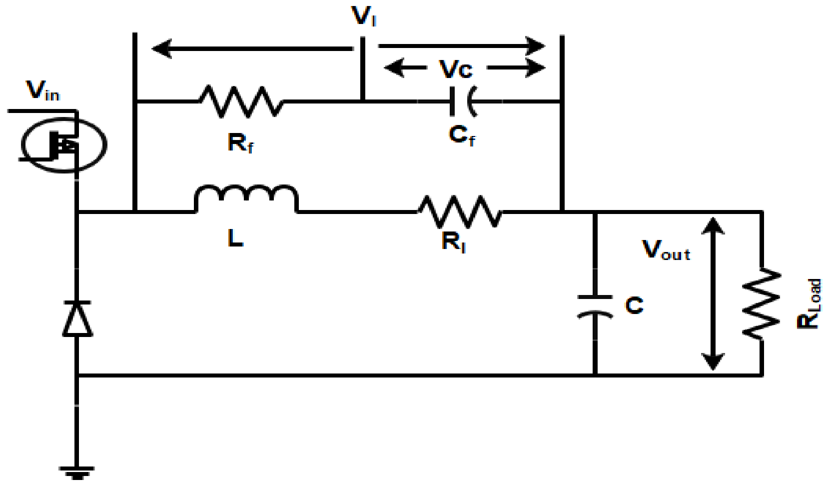


Figure 3.2 current sensing using inductor current

Where L is the value of inductor and R_l is the internal resistance of inductor winding

Now, voltage across capacitor is expressed by

$$V_c = \frac{V_l}{1 + sR_f C_f} = \frac{(R_l + sL)I_l}{1 + sR_f C_f}$$

$$= R_l(\frac{1 + s(\frac{l}{R_l})}{1 + sR_f C_f})I_l$$

$$= R_l\left(\frac{1 + s\tau}{I + s\tau_1}\right)I_l \qquad (3.3)$$

In Equation (3.3)

$$\tau = \frac{l}{R_l} \ \& \ \tau_1 = R_f C_f$$

And $$\tau = \tau_1 \ \& \ V_c = R_l I_l$$

So, $$V_c \propto I_l$$

To utilize this procedure, the values of L and R_l must be known. Hense, R and C are selected accordingly. This strategy is not suitable for integrated circuits since of the tolerance of the components is required. It is, in any case, an appropriate design for a discrete, custom arrangement where the sort and value of the inductor are known [38,39].

3.1.3 MOSFET based current sensing technique

The main advantage of MOSFET based current sensing technique was the elimination of sensing resistor that cause unwanted power loss in the whole system shown in Figure 3.3. Actually, the existence of sensing resistor was completely replaced by the drain to source resistance of the MOSFET. The working of MOSFET is quite simple as it behaves like resistor during on condition Therefore, it is quite easy to measure the voltage across the drain to source terminal of the MOSFET for the estimation of inductor current flowing through it [20].

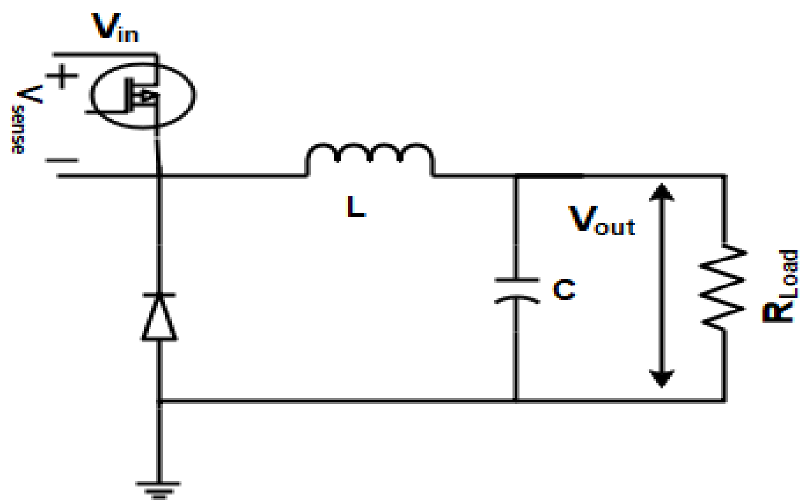


Figure 3.3 MOSFET based current sensing technique

The value of R_{ds} resistance for the MOSFET based current sensing technique is given by Equation (3.4).

$$R_{ds} = \frac{L}{\omega\mu C_{ox}(V_m - V_t)} \quad (3.4)$$

In Equation (3.4), μ is the electron mobility, C_{ox} is the oxide capacitance, and V_t is the threshold voltage. The value of on state drain-source resistance is given within the MOSFET data sheet.

The accuracy of this strategy depends on the sensing resistance because datasheet only give us a most typical as well as ordinary value of sensing resistor, not a minimum one [37].

MOSFET based R_{ds} current sensing could be an exceptionally low-cost strategy for current sensing. There is a various applications in which this method can be used such as low-voltage application. Since, the value of current flowing through the MOSFET depends upon the R_{ds} of the MOSFET, and the value of R_{ds} depends upon the temperature behavior as well as gate drive voltage of the separate device. If there will be a variation in the gate drive it leads to a poor current measurement precision within a multiphase converter. There are also some limitations like sometime switching frequency become quite high and the value of input voltage also become high, which makes this technique little bit complicated in comparison to others [37,40].

3.1.4 Current sensing using current transformer

The voltage transformer is quite equal in terms to a current transformer as shown in Figure 3.4 in terms of construction but the major difference comes in the input side as current transformer having current as its input.

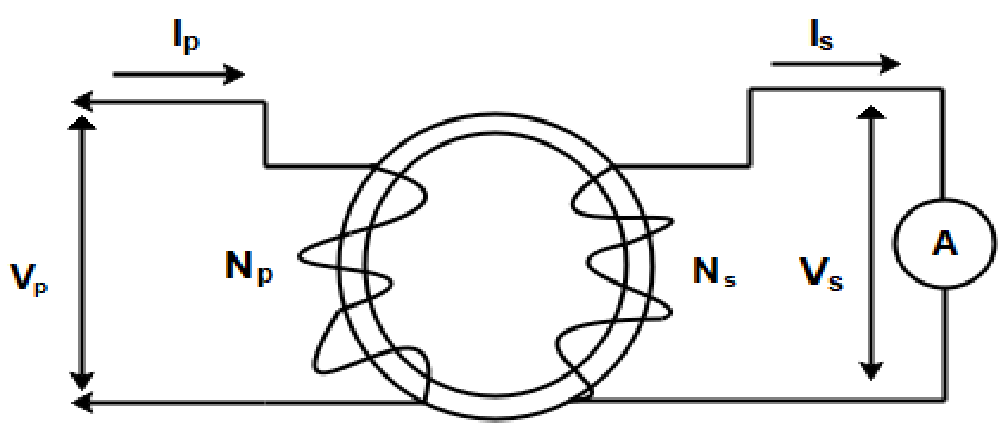


Figure 3.4: Current sensing using CT's

There are various types of current transformer present in the literature such as DC current transformer, fly-back current transformer, AC current transformer and at last unidirectional current transformer out of which commonly used transformers is AC current transformers and unidirectional current transformers. For the high current applications, DC current transformers are used in a frequent manner where as fly back current transformers are used whenever the value of current pulse is quite less [41].

According to Ampere's law, the current flowing through a particular conductor will definitely produce magnetic field. It will provide the accurate information related to the current flowing through it. The electromagnetic based sensor also works on the similar principle and in addition, it also provide isolation between the power as well as the control stages. It also has some advantages such as bandwidth is quite high, very low power dissipation that leads to a improvement within a signal to noise atmosphere in a control framework as well as the respective sensor based on electromagnet permit higher flag position [17].

CTs are highly utilized for control as well as constraint applications. There are various advantages of CTs, but the major one is the signal to noise ratio, which is quite high. To protect the sensing resistor from high voltage signals as well as to eliminate the power losses from the circuit, galvanic segregation is highly essential. To reduce the auxiliary side current, it is required to increase the turn ratio. They don't need any type of additional circuitry for the normal working of the complete circuit. ACCT gets saturated in the event that input is direct current. However, a few strategies were needed to be utilized for the sensing of switch current in the power converter utilizing CTs [42].

3.1.5 Rogowski coil current sensing technique

This technique for current measurement is basic, reasonable as well as precise approach. The constructional approach of rogowski coil is quite similar to the CTs structure where as in comparison to CTs except iron core, as these coils were completely based on the ironless bobbins with lots of turns. The measured current is quite linear for this particular technique because it will never immersed to iron core [18].

In Figure 3.5, the rogowski coil was surrounding a conductor through which current was continuously flowing. So, for placing the current carrying conductor within the coil without even opening it leads to a production of magnetic field. This further induces voltage (E) within the auxiliary coil. Voltage (E) is corresponding to the time derivative of current flowing through the conductor, which is given by Equation (3.5).

$$E = M\frac{dI_p}{dt} \tag{3.5}$$

Where, I_p is a primary current and M is the mutual inductance of the circuit, which is given by Equation (3.6).

$$m = \frac{\mu_\circ n_S A}{l} \tag{3.6}$$

Where, $\mu_\circ$ is the permeability, A is the cross sectional area of the coil, n_S is the total number turns in auxiliary winding, and l is the mean path length of the coil. Rogowski current sensor is only used to measure AC or pulse DC because derivative of DC is zero. This particular technique can also be utilized whenever the value of approximate current is not available before its implementation.

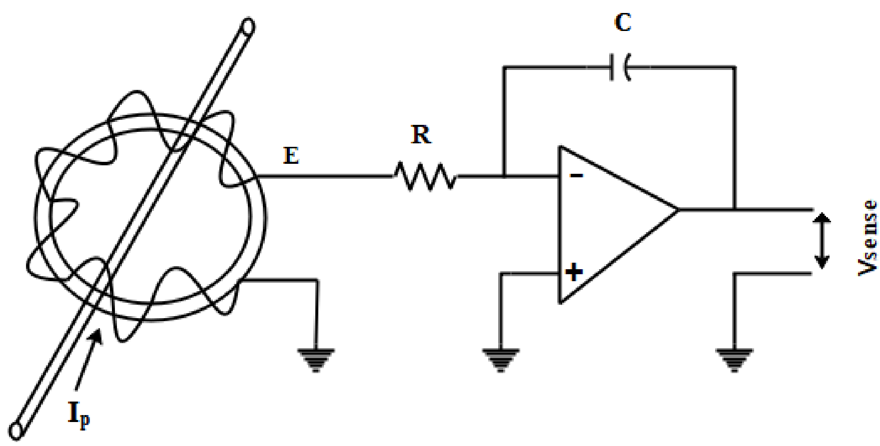


Figure 3.5: Rogowski coil current sensing technique

This technique was also utilized for the measurement of current pulses at higher energy side as well as for the measurement of higher switching frequency because upper bandwidth can easily be extended up to MHz. Due to quite high bandwidth, it can easily be used for the estimation of switching transients in semiconductors. Other points of interest such as it has wide dynamic extend as well as quite simple and accurate calibration, its output become linear, due to quick reaction towards the transient current makes it highly perfect technique for the current pulse estimation as well as for ensuring framework [18]. So, current sensing is the major contributor in the success of various applications. There are several techniques for current sensing as we discussed earlier. All these techniques have several advantages as well as disadvantages, but the selection of particular technique for any application depends upon the requirements of that particular application.

3.1.6 Current measurement using hall effect current sensor

These sensors was widely used for various current measurements such as AC current, complex and DC current as well as it also provides isolation. This technique is utilized in such a manner that the rest of the circuit won't get interrupted. This sensor was quite small in size and also provide a signal that is completely noise independent and also consume small amount of power during operation. Its principle depends upon the Lorentz force, that whenever a charging particle travel through a magnetic field, it acts on that charging particle shown in Figure 3.6. According to Hall-effect principle, voltage developed across the sides of any conducting material if a current is travelling through it and a magnetic field is applied across the material [38].

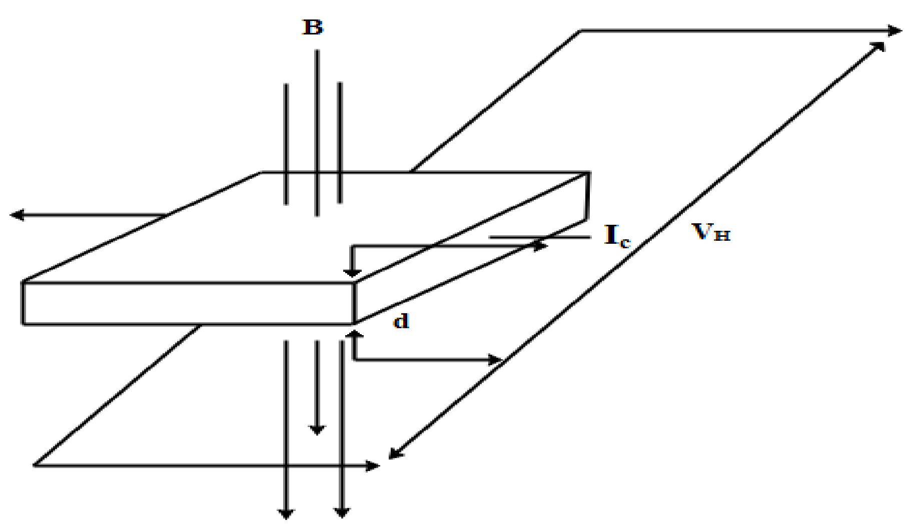


Figure 3.6: Current sensing Using Hall effect sensor

Here, 'I_c' is the main current flowing through the sensor, 'B' is magnetic flux density, 'K' is the constant of conducting fabric, 'd' is the thickness of a sheet, and 'V_{OH}' is the offset of the hall effect sensor within the absence of the outside field So, the output voltage of Hall-effect sensor 'V_H' is given by Equation (3.7).

$$V_H = \frac{K}{d} B I_c + V_{OH} \tag{3.7}$$

Where, the product of $\left(\frac{K}{d}\right) * I_c$ is the sensitivity. The output voltage as well as the sensitivity of the respective sensor is completely depends upon the temperature. Other disadvantages of this sensor, it had quite low sensitivity in comparison to others, the requirement of concentrator was quite high, problem-related to mechanical positioning as well as highly sensitive to the mechanical stress and restricted linearity run, variations in the surrounding temperature and its maximum frequency range was bounded [43].

3.3 COMPARISON BETWEEN DIFFERENT CURRENT SENSING TECHNIQUE [17,35,38]

Table 3.1 shows a comparison between different current sensing techniques.

Table 3.1: Comparison between different current sensing techniques

SENSING TECHNIQUE	ADVANTAGES	DRAWBACKS
Using an external added resistor	Simple in nature, quite accurate, low cost	High Power loss across the sense resistor
Using internal resistance of the inductor	Accurate as well as lossless	Can't be useful for high power applications
Using the internal resistance of a MOSFET	Lossless, no additionally sensing component is required, low cost	This technique is not accurate for using on high voltage as well as high switching frequency, affected by temperature variations, discontinuous and noisy
Using current sensing power MOSFET	Lossless, quite practical, accurate with respect to temperature variations, no additional sensing component required as well as low cost	The need of some typical MOSFET, introduce switching transients and noise at high frequency, accuracy depends upon the matching of power as well as sense MOSFET,

		switching noise, restricted applications, irregular and noisy
Using ACCT	Lossless, good Signal to Noise Ratio, good common mode rejection	it can measure only ac current, core restrictions, restricted frequency range, not appropriate for multiple-inductor converters
Using ACCT with sample and-hold	Accurate, very low power loss, measure ac current having dc components also	The necessity of high transmission capacity sample-and-hold ICs and two transformers, core limitations
Using UCT	Lossless, accurately measures ac current having dc current Component	Can't be considered for higher switching frequencies, core Limitations
Using DCCT	Direct Current CTs can also work with primary current in either direction	Restricted bandwidth (<100 kHz), Critical yield distortion, requirement of exact transformers, core limitations
Using Rogowski Coil	Accurate, low weight, no DC current saturation, low sensitivity to parameter variations, AC and pulsed DC current measurements	Outside circuit is required to analyze yield, open structure leads to estimation error, an error is introduced by processing electronics
Using open loop Hall effect Current sensor	Low auxiliary power consumption, small size, low cost, AC, DC as well as complex current measurements	Low sensitivity, temperature dependent yield, linearity errors, core limitations
Using closed loop Hall effect Current sensor	Quite Accurate, AC, DC, as well as complex Current	A compensation circuit is needed, high secondary

	measurements, quick response time, wide bandwidth, low temperature Drift	Current utilization, costly, bulky for low streams, core limitations

3.4 APPLICATION BASED ON DIFFERENT CURRENT SENSING TECHNIQUE [17,47,48]

These current sensing techniques used in various applications whether it is used for sensing purpose or for switching purposes. These applications are further divided into

- Low power application
- High power application

➢ Low power applications

1. Battery Charger applications- There are various current sensing techniques that can be used for this application like MOSFET based current sensing, SENSEFET technique, CT's but the best suited technique for this particular application is Hall affect sensor technique.
2. Voltage Regulators- There are various current sensing techniques that can be used for this application like SENSFET Technique, Series resistor technique but the best suited technique for this particular application is Filter based current sensing technique.
3. Power Factor Correction- There are various current sensing techniques that can be used for this application like MOSFET Based current sensing technique, SENSEFET technique but the best suited technique for this particular application is Filter based current sensing technique.
4. Telecom Communication- There are various current sensing techniques that can be used for this application like CT's, Filter based current sensing but the best suited technique for this particular application is FOCs.
5. Uninterruptible Power Supply-There are various current sensing techniques that can be used for this application like Series Resistor, MOSFET based current sensing, Filter based current sensing but the best suited technique for this particular application is Hall- effect sensor technique.

6. Control of Power semi-Conductors--There are various current sensing techniques that can be used for this application like Rogowski coil, SENSEFET based current sensing but the best suited technique for this particular application is saturable inductor sensor.

- High Power application

1. Traction drive systems- There are various current sensing techniques that can be used for this application such as Rogowski coil but the best suited technique for this particular application is Hall effect sensor.
2. Crusher and grinder motor- There are various current sensing techniques that can be used for this application such as Rogowski coil but the best suited technique for this particular application is Hall effect sensor.
3. Convertors for Servo motor- There are various current sensing techniques that can be used for this application such as CT's, SENSEFET technique sensor but the best suited technique for this particular application is Hall effect sensor.
4. Current Measurement for power analysis-There are various current sensing techniques that can be used for this application such as Hall effect sensor but the best suited technique for this particular application is Rogowski coil.
5. Electric vehicles- There are various current sensing techniques that can be used for this application such as Hall effect sensor, MOSFET based current sensing but the best suited technique for this particular application is MR sensor.
6. High Voltage distribution- There are various current sensing techniques that can be used for this application such as Hall effect sensor but the best suited technique for this particular application is CT's.
7. Static Converters for DC Drives- There are various current sensing techniques that can be used for this application such as Hall effect sensor but the best suited technique for this particular application is MR sensor.

CHAPTER-4

CURRENT SENSING USING SENSEFET TECHNIQUE

This technique gives a highly productive path for the measurement of load current flowing through the main MOSFET in the SENSEFET based current sensing circuit shown in the Figure 4.1. Due to its simplicity, this technique splits motor current through the main MOSFET as well as sense MOSFET on the basis of current ratio. Further, a low signal level resistor is to be used for sampling. This technique results lower cost as well as efficient performance in comparison to the other techniques [44,45].

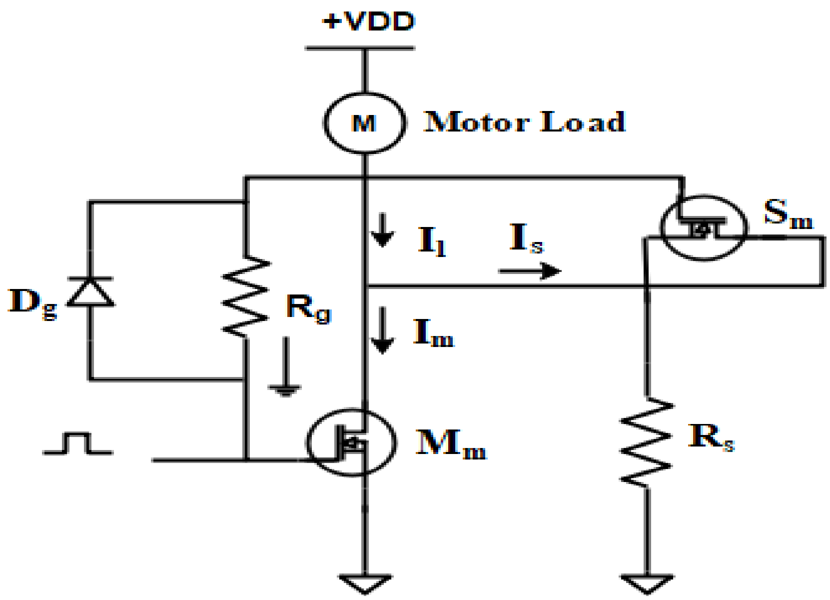


Figure 4.1: Current sensing circuit

Due to its several advantages this technique is used in the proposed work for the switching of permanent magnet motor in any type of electric vehicle. Basically, the base of this technique depends upon the coordinated device principle, which is generally utilized within the integrated circuits. Such as integrated circuit transistors, the on-state drain to source resistance ($R_{ds(on)}$) of various units present in the power MOSFET needs to be well matched but if some of the units out of many others were connected with the different pins. There will be a ratio between a on-state resistance of sense units as well as of source units. At that point, if the device is turned on, there will be flow of load current. Finally, splits into the source side as source current and sense side as sense current but inversely [20,46].

The relative estimate of the two devices such as main MOSFET and sense MOSFET determine the amount of current split between them. The proportion of current flowing through the main MOSFET and the sense MOSFET is indicated as the "Current sense Ratio". This particular proportion has only been true for the situation when source and the sense terminals are at the same potential. If current ratio is in the order of 2000:1, that's only been possible when the ratio of on state drain to source resistance of sense and power section is in the order of 1:2000. Main current roughly equals to the current flowing through the load due to which current ratio also become the proportion of current flowing through the load to the current flowing through the sense branch [47,48].

When a signal level resistor is placed in series with a sense component, a particular amount of load current is sampled across the sense resistor without an insertion loss. Due to which, the technique of sensing current in terms of voltage across the sensing resistor with two parallel MOSFETs is known as "lossless current sensing". Sometimes, the sense voltage generated was not enough to cause conduction within the circuit. So, it was highly essential to use R_{sense} of larger values that can be fulfilled by the accomplishment of virtual grounding circuit [49].

4.2.1 Virtual grounding circuit

According to this technique, the voltage sensed across the sensing resistor R_{Sense} is quite low approximately in millivolts but in some of the applications, we need a voltage on a higher side. This can be accomplished using a dual Op-Amp configuration shown in the Figure 4.2. This particular configuration is used for the conversion of sensed current into the negative output voltage. Further, that negative output voltage is inverted with the help of dual Op-Amp configuration to produce a positive output voltage. The negative output voltage was generated by the utilization of quite simple as well as cheap 555 charge pump [20].

The sensed voltage can be calculated by Equation (4.1), where R_F = Feedback resistance and I_S = Current through the sensing MOSFET,

$$V_{SENSE} = -I_S R_F \tag{4.1}$$

Whenever the SENSEFET technique was used with this particular circuit, the problems related to the accuracy as well as efficiency started to rise. As the error related to the Op-Amp configuration also included with the sense resistor error as well as sense branch error, then all these error needed to be reduced within the ±5% over the temperature range. Hence, in this configuration, temperature stability, as well as Unit to Unit variations was considered first during design implementation.

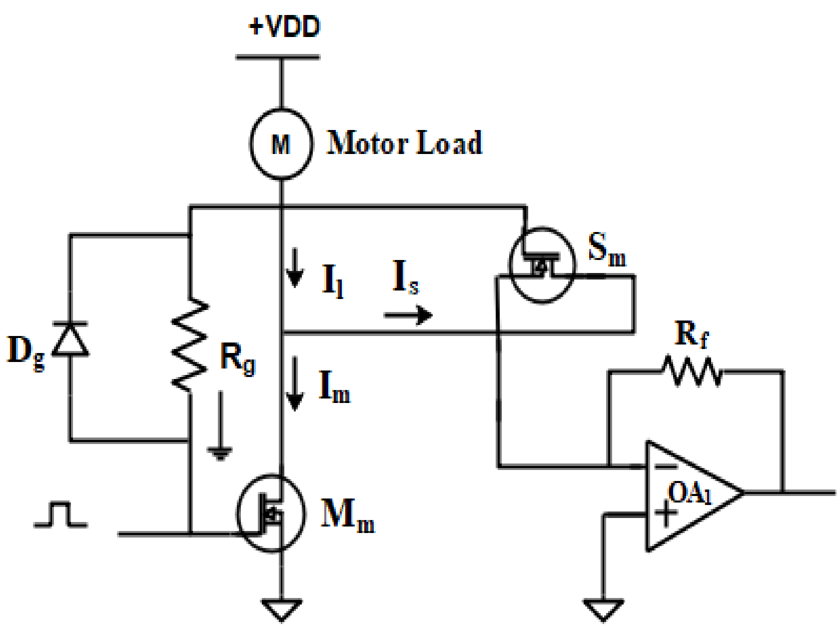


Figure 4.2: Virtual grounding circuit

4.2.2 Theoretical analysis of proposed sensing technique

On the basis of SENSEFET technique, the relationship between the main current and sense current is given by Equation (4.2).

$$V_S = I_S * R_S = I_M * R_S * \frac{R_{ds(on)M}}{R_S + R_{ds(on)M} + R_{ds(on)S}} \tag{4.2}$$

The value of $R_{ds(on)}$ at particular temperature is exponential in nature and is expressed by Equation (4.3).

$$R_{ds(on)}(T) = R_{ds(on)}^{rt} e^{\frac{(t-rt)}{K}} \tag{4.3}$$

R_{ds} is the drain-source on-resistance of the MOSFET at room temperature and the value of K is expressed as temperature coefficient. K is $R_{ds(on)}$ temperature coefficient which is distinctive for main as well as sense devices. As the thermal coupling between both the MOSFETs are not perfect due to which the temperature of sense MOSFET can be considered as directly slacking behind the main MOSFET and the value of t_S & t_M are calculated from the equation (4.4) [44,20] where,

t_S = Temperature of sensing MOSFET
t_M= Temperature of main MOSFET

$$t_S = t_M - (t - 25℃)K_{\Delta T} \tag{4.4}$$

$K_{\Delta T}$ is actually the value of thermal coupling between the two devices, when they will placed on the same platform

CR= $\frac{I_M}{I_S} = \frac{R_S + R_{ds(on)S}}{R_{ds(on)M}}$

$$= \frac{R_S(T)}{R^{rt}_{ds(on)M}} e^{-\frac{t-rt}{K_M}} + \frac{R^{rt}_{ds(on)S}}{R^{rt}_{ds(on)M}} e^{\frac{(K_M - K_S)(t-rt)}{K_M K_S}}$$

$$= \frac{R_S(T)}{R^{rt}_{ds(on)M}} e^{-\frac{t-rt}{K_M}} + \frac{R^{rt}_{ds(on)S}}{R^{rt}_{ds(on)M}} e^{\frac{(K_M(1-K_{\Delta T}) - K_S)(t-rt)}{(K_M K_S)}} \tag{4.5}$$

However, the temperature reliance of the R_{sense} is much lesser than CR's reliance on temperature, CR subsequently characterizes sensing performance as well as it will be the beginning point of a plan. The temperature resilience of CR can be characterized as the relative contrast between the most extreme and least values of the CR at room temperature around 25℃ to 130℃. As the conditions discussed earlier, $K_{\Delta t}$ is considered as a planning variable within the power module. When $K_S = K_M$, the ideal value of the thermal coupling coefficient become zero. Further, the value of sensing resistor ought to be as little as conceivable; in the event that $K_S > K_M$, temperature resilience will be more regrettable. But in the event that $K_S < K_M$ reliance of both the MOSFETs can compensate the value of current ratio, which become completely independent on the temperature variations by the selection of optimal value of sensing resistor.

4.2.3 Selection of R_{SENSE}

The backbone of SENSEFET technique is the optimal value of sensing resistor that can be calculated by the combination of experimental as well as theoretical analysis. current ratio will be different for different values of R_{sense} . So, the optimal value of R_{sense} will be chosen on the basis of error value obtained by the difference in Current ratio obtained through experimental results as well as theoretical results. Also the value of sensing resistor must be chosen in such a manner that the voltage drop across the resistor is in milli volts. So that, the losses across it will be minimum and the efficiency of the system will be maximum.

a. Current ratio Vs Temperature graph at different values of R_{sense} obtained through the experimental

Under working condition, the flow of current through the Main MOSFET as well as Sense MOSFET was continuous in nature. Due to which temperature across both the MOSFETs start rising but maximum current is flowing through the Main MOSFET as shown in Figure 4.3.

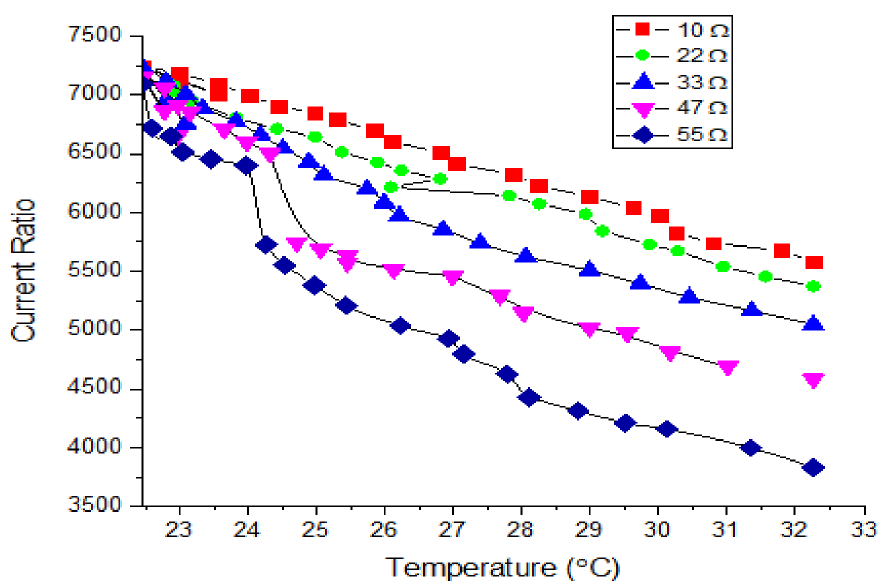


Figure 4.3 Temperature Vs Current Ratio Curve by Experimental Analysis

This reflect sudden rise in the temperature value is seen across the Main MOSFET in comparison to Sense MOSFET. As the temperature increases across the main MOSFET, the value of $R_{ds(on)}$ is also increased and it directly affects the flow of current through the Motor Load that leads to a unwanted variations in the current ratio. Variable current ratio reduces the effectiveness of the protection circuit that was directly decreasing the overall efficiency of the system

To maintain system efficiency by eliminating the temperature dependency of current ratio can be achieved by the selection of optimal value of sensing resistor. The experimental setup has been considered for the selection of sensing resistor by the utilization of several resistors in the current protection circuit to calculate various values of Current ratio within a particular temperature range.

b. Current ratio Vs Temperature graph at different values of R_{sense} using theoretical model

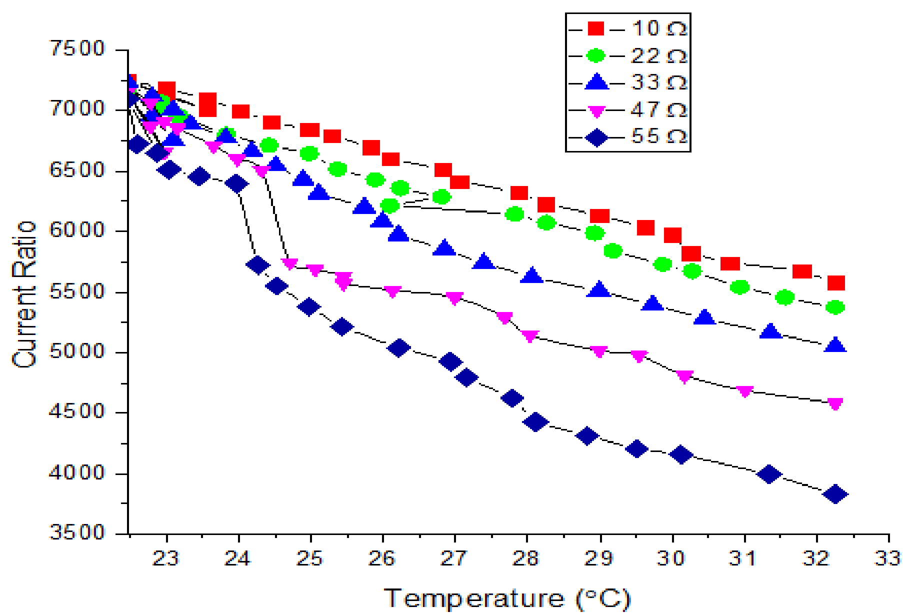


Figure 4.4: Temp Vs Current Ratio Curve by Theoretical Model

As discussed in the previous case, the selection of optimal value of sensing resistor was done by the experimental values. Here, theoretical modeling has been utilized for the effective selection of R_{sense} by considering the different values of sensing resistors in the motor circuit. The value of current ratio at different sensing resistor has been calculated by the theoretical formulas with the help of temperature coefficient as well the various temperature values has been shown in the Figure 4.4 in a similar manner as discussed in the previous case. Further, the current ratio error has been calculated, it is basically a difference between the current ratio calculated through the experimental setup as well as theoretical analysis.

c. CR error Vs R_{sense} graph at different value of R_{sense}

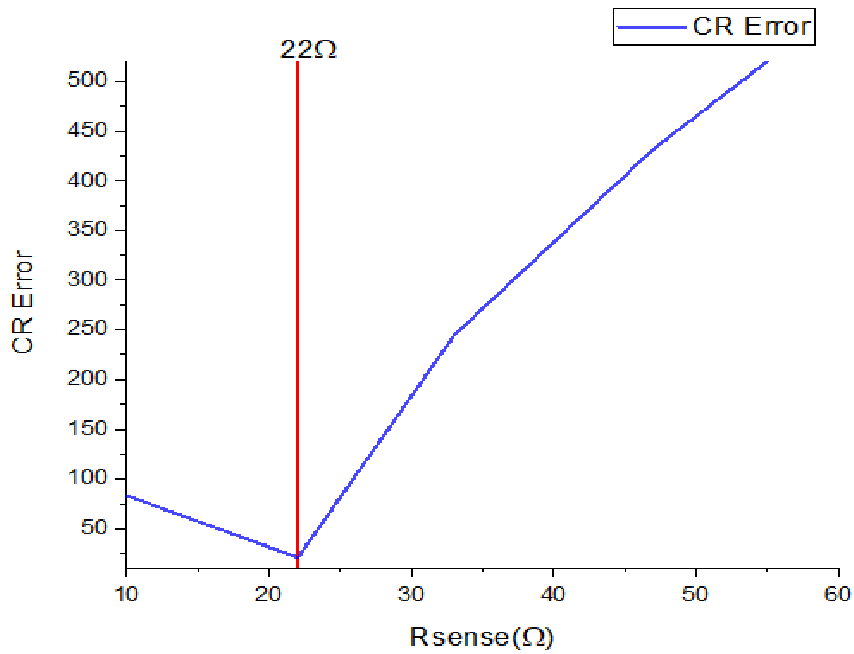


Figure 4.5: CR Error Vs R_{sense}

According to the graph as shown in the Figure 4.5, CR error was calculated at different values of Sensing resistor. At the starting, the CR error was continuously decreasing where as the value of R_{sense} was continuously increasing. At the particular value of R_{sense} about 22 **Ω**, the CR error considered to be minimum and after that an inverse pattern of the previously generated values have been followed. The variations in the value of Current Ratio is minimum at the value of R_{sense} equals to 22 **Ω** i.e. it was considered as the optimal value of sensing resistor for the effective analysis of the current protection circuit and also to improve the efficiency and the performance of the motor circuit.

CHAPTER-5

DESIGNING OF CURRENT LIMIT CONTROLLER

The block diagram of the proposed controller scheme

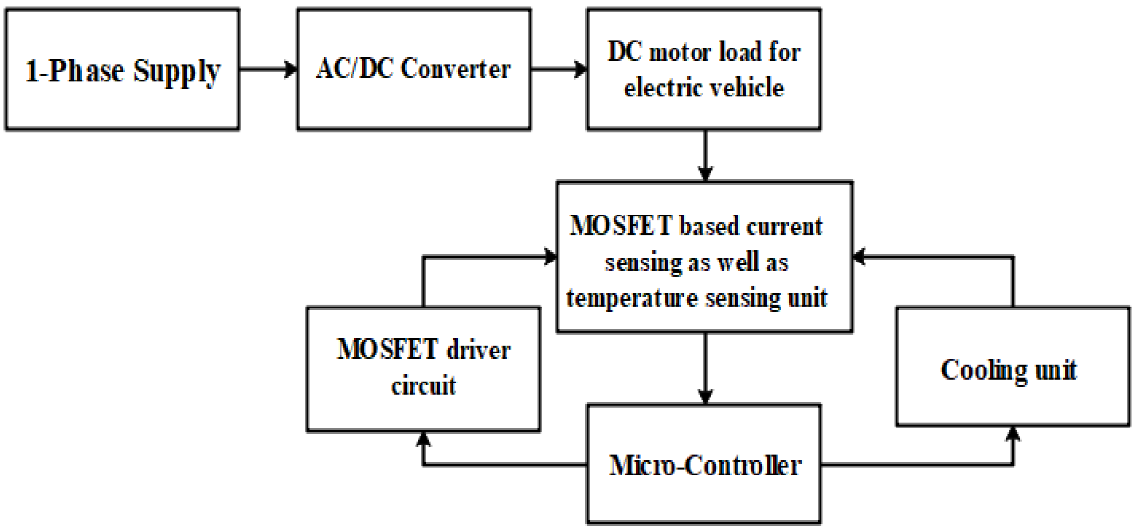


Figure 5.1: Block diagram of proposed Current controller circuit

In the proposed work study, the designing of current controller has been achieved as shown in Figure 5.1. The current controller circuit consist of various small electronic circuitry such as AC/DC Converter circuit, MOSFET driver circuit, current sensing circuit and at last cooling circuit. Initially, a Single phase AC supply is obtained from an autotransformer, which is further given to the input terminal of AC/DC converter to produce a DC output voltage similar to the battery output. The current sensing unit continuously measured a current flowing through the motor load, which is sensed in terms of voltage across the sensing resistor. The sensed voltage is further read by the Arduino board at its input analog pin, which is further compared with the preset voltage value. Under the normal condition, the current starts to flow through the main MOSFET at a rated value so that, the sensed voltage appears across the resistor also within its preset limit. Therefore, Arduino provides a digital pulse of 5V to the input of gate driver circuit as the input voltage is sufficient to cause conduction. The gate driver circuit provides a triggering pulse to cause conduction at the gate terminal of main MOSFET, which further leads to the flow of current through the main circuit. But under the transient condition, the current starts to exceed its preset value in the circuit that causes similar increase in the sensed voltage across the sensing resistor. Further, the sensed voltage is compared with the preset value. If it exceeds its preset value, the output of the Arduino becomes zero and it is insufficient to cause the conduction of gate driver circuit due to which the output triggered signal is not enough to cause conduction at the gate terminal of both the MOSFETs. This further leads to the zero current flow through the whole circuit as MOSFETs comes in open state.

Arduino is not only a backbone of main circuit but it also helps to increase the efficiency of current protection circuit by controlling a DC fan of 12V present across the MOSFETs for maintaining their temperature within its desired limit. During the normal operation of the current protection circuit, the temperature across both the MOSFETs starts rising to some higher values due to regular current flow across both the MOSFETs but the temperature rise is quite high across main MOSFET in comparison to sense MOSFETs. Since, higher temperature across both the MOSFETs causes unwanted change in the operating characteristics of R_{ds} of both the MOSFETs that partially affect the sensing accuracy. If the temperature across both MOSFETs is less than the preset value sensed by the LM35 temperature sensor the output of Arduino becomes zero that causes zero current flow through the transistor base, which is not sufficient to turn on the fan. So, the Fan turns off where as if temperature across both the MOSFETs is greater than the preset value, the Arduino output turn on the fan to maintain system efficiency.

5.1 AC TO DC CONVERTER UNIT

To produce a desired output, four individual diodes were connected in a particular manner to form a single phase rectifier and their arrangement of connection in a circle called bridge configuration shown in the Figure 5.2. The main benefit of this particular configuration was the absence of center tapped transformer in the complete circuit due to which the cost as well as the size of the whole circuit reduced. In this circuit, load was situated on the secondary side where as the winding was placed on the primary side of diode network. It consists of four individual diodes starting from d1 to d4 were assembled in such a manner that only two of the diodes were conducted during each half cycle. Now, in case of a positive half cycle, d1 and d2 starts conducting whereas the rest two diodes d3 and d4 were reverse biased whereas in case of the negative half cycle, d3 and d4 starts conducting but diodes d1 and d2 are switched off as they presently reverse biased and the load current streaming through the load is in the same direction as discussed in the previous case.

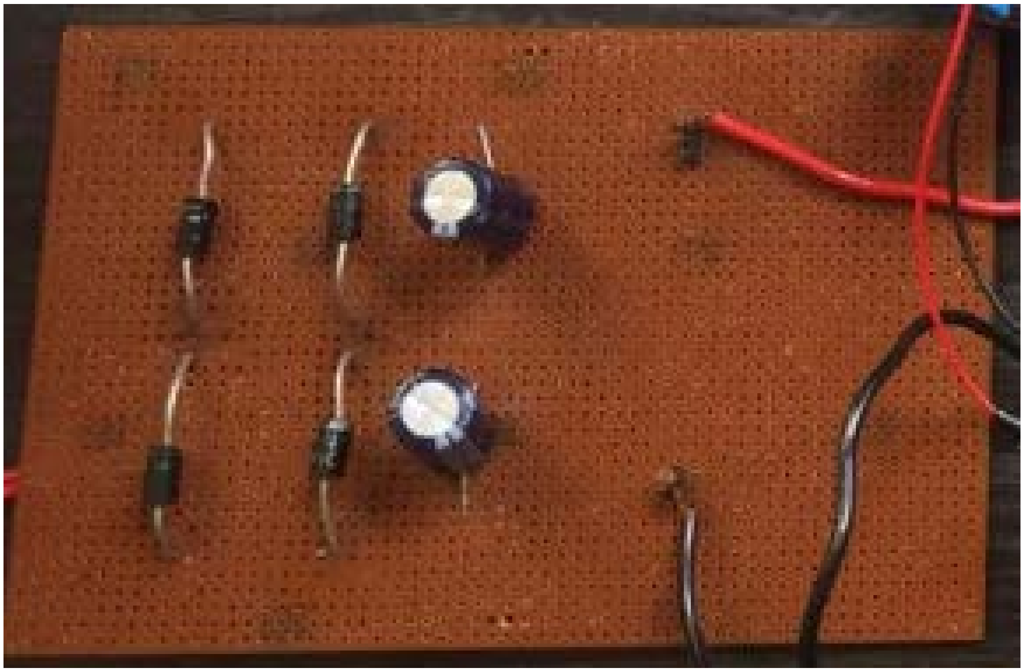


Figure 5.2: AC to DC Converter Unit

As the current streaming through the load is unidirectional. So, the voltage appearing across the stack is also unidirectional. Subsequently, the average DC voltage appearing across the load will be 0.637 Vmax [51].

For improving the overall efficiency of the circuit, it is highly necessary to improve the average DC output voltage of the single phase rectifier. This condition has been achieved by reducing the continuous AC variations within the DC output voltage by the utilization of Smoothing capacitor in the rectifier circuit. The connection of smoothing capacitor has been placed across the load in a parallel manner so that the output average DC voltage becomes quite high in comparison to previous state without smoothing capacitor. The main working of smoothing capacitor is to convert a rippled output voltage in a smooth output voltage.

5.2 CURRENT SENSING UNIT

The current sensing unit shown in the Figure 5.3 is the most important unit of this protection circuit because by sensing the voltage across the sensing resistor incorporated in this unit helps to limit the unwanted rise in the load current. There are various components present in the circuit such as MOSFET, resistor, opto-coupler, diodes etc. The major working of current sensing unit depends upon the switching performance and the matching of both the MOSFETs as main MOSFET and sense MOSFET. The current sensing technique incorporated in this circuit gives a highly effective path of measuring load current in power conditioning circuits. Due to its simplicity, these devices basically split load current into power and sensing components, in such a way that the current ratio becomes quite high. It is basically a ratio of current flowing through the main MOSFET and the sense MOSFET. Another important consideration of this circuit is the selection of the value of sensing resistor across which, voltage will be sensed continuously to protect the motor under transient condition.

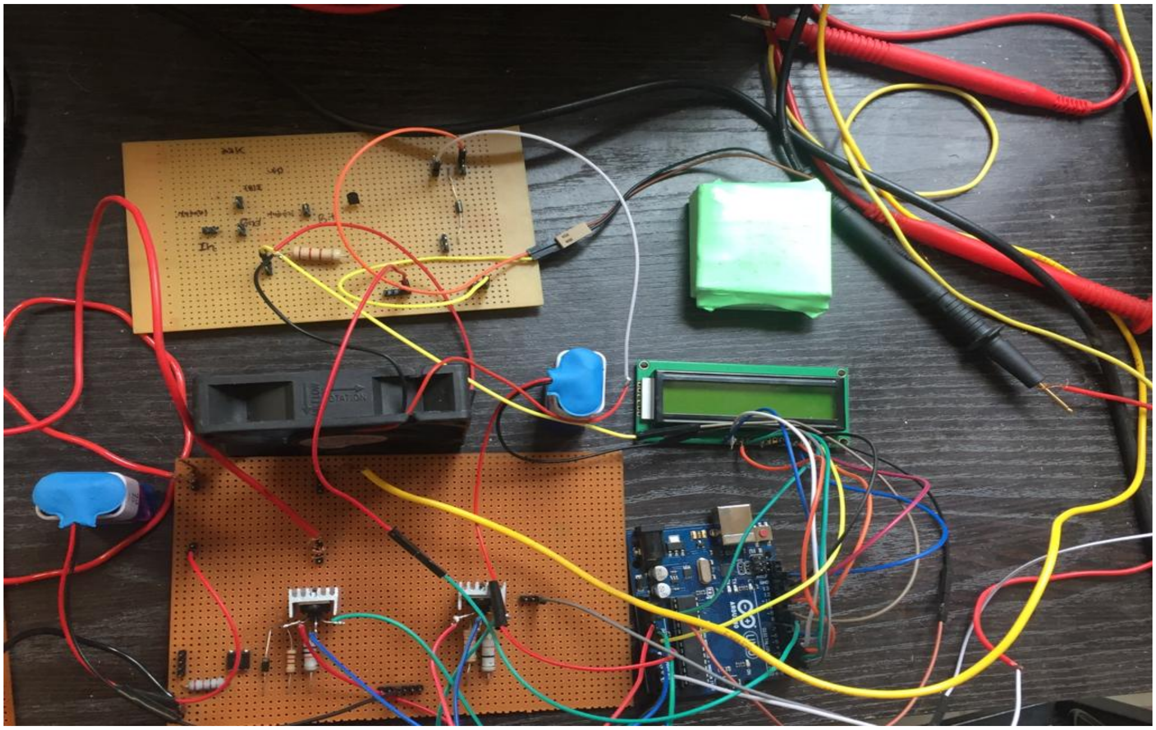


Figure 5.3: Current protection Unit

Now, the selection of sensing resistor depends upon several direct or indirect factors such as the value of resistance so that the losses across the sensing resistor during on condition becomes minimum. The value of resistance has to satisfy the current ratio, so that the chances of

MOSFET mismatching becomes less and at last, the value of resistance must be independent of the temperature dependency of both the MOSFETs. So, that the sensing results become efficient and it will increase the overall efficiency of the current protection framework.

5.3 CONTROLLER UNIT

Quick and speedy torque responses are the foremost critical and primary characteristic of high dynamic performance traction drive. DC motor gives amazingly high control over the speeding up and de-acceleration of the vehicle. It has most extreme torque at low speed and torque consistently decay as speed increases. Due to there, torque-speed characteristics DC motors are so congruous with diverse mechanical loads that increase its employment in an electric vehicle.

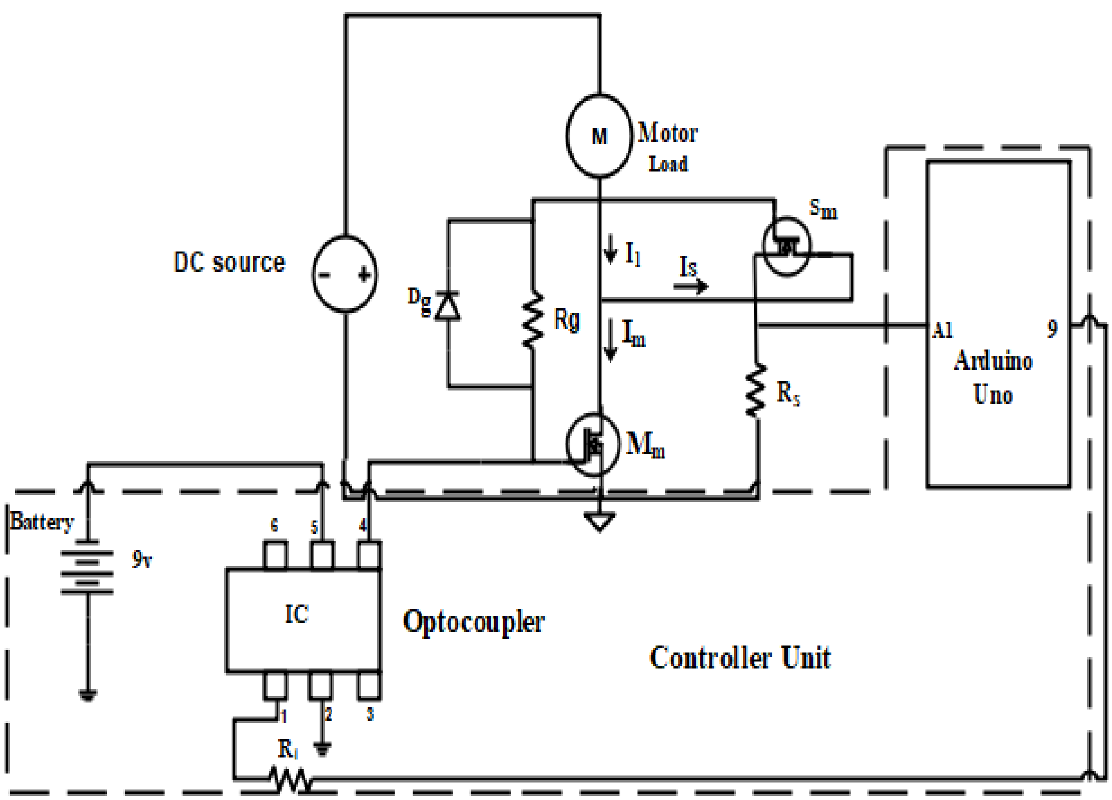


Figure 5.4: Controller Unit of current protection circuit

Under the transient condition, the current abruptly increment over its preset constrain that causes extreme spark over the winding of DC motor and at last, overheating damage the motor permanently. So, some control mechanism is required to stop the streaming of current through the motor that will be actualized by employing a microcontroller that gives flag on the premise of past states of the system shown in the Figure 5.4. There will be an outline of a few devices that control during normal operations as well as abnormal operation.

5.3.1 Arduino Uno

Arduino is basically a open-source hardware stage depends upon the easy-to-work equipment and computer program shown in the Figure 5.5. Arduino sheets were quite smart that they can easily able to study inputs like the light on a sensor and it will provide us a opportunity to do according to the requirement of the user by just providing a command signal at the analog input of Arduino Uno and the working of Arduino Uno partially depends upon the programming done within the Arduino brain for doing a specific task through the specific pins. Over a long period of time, Arduino had been utilized in several applications related to the automotive industry as well as the artificial intelligence. But the best part of Arduino Uno was that anyone can use this controller due to simple user interface weather it will be a student, teacher and researcher etc. They can easily share their information on the same platform which can help everyone to learn new things and explore their creativity on global level [51].

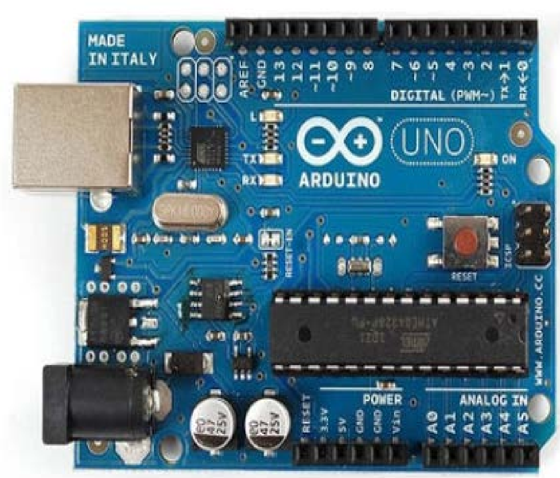


Figure 5.5: Arduino Uno

Arduino moreover simplify the working with microcontrollers as well as it offers some advantages over other frameworks such as the cost of Arduino based board is so less in comparison to the other micro controller which can motivate people to try new things without losing their pockets, the programs that was made on the Arduino board are quite flexible with different softwares such as Linux, windows as well as the Mac OSX but in the case of other microcontrollers most of them were only comfortable with the windows, the programs made on the Arduino board was so simple that a armature can easily learn from them where as it was also that advance so that expert can work on its chip too. The Arduino programming is so interesting to learn as it is quite similar as the C programming that help instructors to teach this level of programming in a simple way. At the end, it is better for all as expertise can change the module design to create new to new circuits for different applications where as a learner can implement its design on the breadboard for better understanding [52].

Table 5.1 gives the specification of Arduino Uno.

Table 5.1 Specification of Arduino Uno

Micro-Controller Unit	ATmega328
Clock speed	16MHz
Operating voltage	5V
Maximum Supply Voltage	20V
Supply Voltage	7-12V
Analog pins	6
Digital pins	14
DC current per input/output pin	40 mA
DC current in 3.3V pin	50 mA
EEPROM	1 kB
SRAM	2 kB
Flash memory	32 kB out of which 0.5 kB used by boot loader

In the proposed work, the programmable Arduino has been used. The principle working of Arduino is completely based upon the sensing of voltage across the sensing resistor, the analog pin at the input of Arduino reads the sensed voltage and provides a digital output, whenever the sensed voltage is less than the preset value. The preset voltage value is set according to the rated current flowing through the motor load. Further, the sensed voltage will again compared with the preset value and if the sensed voltage is greater than the preset value, the Arduino output becomes zero and it will shut down the complete working of whole circuit to protect the motor from unwanted rise in load current.

5.3.2 Optocoupler

The common outlook of an opto-coupler, moreover known as Opto-isolator shown in the Figure 5.6, comprises of a LED that is used to emit infra-red light. It also consists of a semiconductor photo-sensitive gadget that is utilized to identify the radiated infra-red light. Both the LED as well as photo-sensitive gadget are encased in a lightly-tight body. Whenever the current streaming by the LED is hindered, the infra-red transmitted light gets cut-off leads to the termination of conduction by the photo transistor.

Figure 5.6: 4N35 optocoupler

They can also be utilized for their own purposes or for the switching purposes over the higher range electronics circuits such as triacs as well as transistors for providing the specified electrical segregation between lesser voltage flags. There are various applications where opto-couplers can easily be used such as for switching purposes in the microcontroller chip on input and output terminals, AC as well as DC power control, also used for establishing communication with the PCs, signal segregation and also to regulate the power supply within its limits etc. The transmission of the signal can easily be done in any of the forms such as analogue and the digital. [53].

The electrical flag being transmitted can be either an analogue signal or a digital (pulses) signal. The use of 4N35 opto-coupler in this particular circuit is to provide gate pulse at the gate terminal of both the MOSFETs to trigger them for conduction or in other words it works like a part of controller that control the working of current protection circuit according to the command signal send at the input terminal of opto-coupler as well as it also provide isolation in the circuit that is highly essential for the effective working of any circuit in long term scenario. The pin diagram of the Opto-coupler is shown in the Figure 5.7.

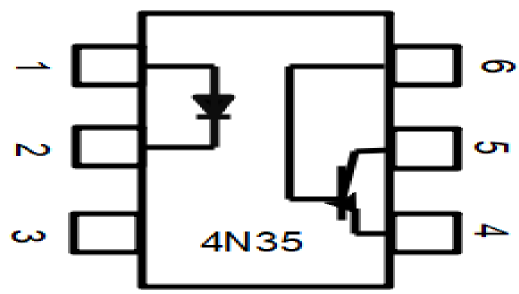


Figure 5.7: Pin diagram of 4N35

5.3.3 Flow chart of Control Mechanism

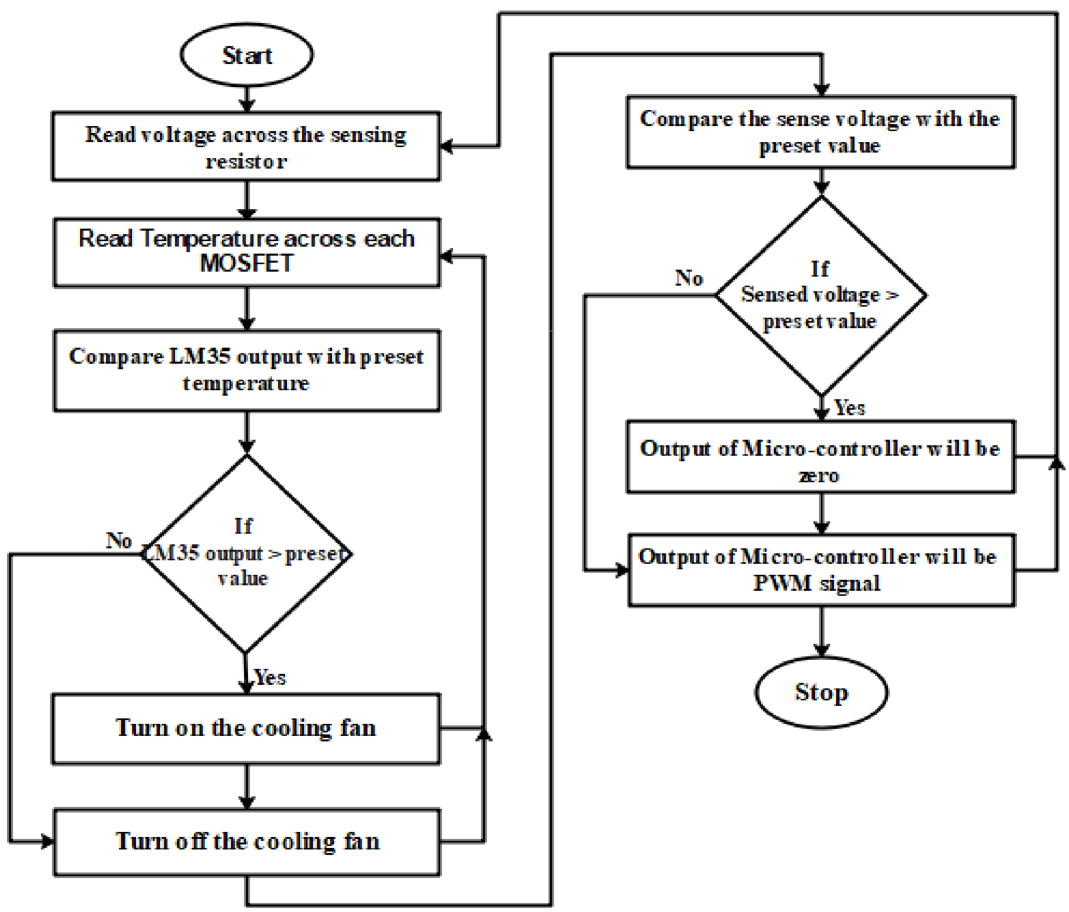


Figure 5.8 Flow chart of control mechanism

There are various components that are also used to control the working of Permanent magnet motor such as Ardino and opto-coupler. Arduino Uno is basically a open source equipment with innovative platform, quite easy to work equipment as well as program. The activities performed by the microcontroller depends upon the coding done by the programmer on the board. The main advantage of opto-coupler is that it provides complete fault protection within the circuit by isolating input and output unit permitting moderately little-computerized signals to control much expansive DC voltages, current and power.The flow chart of the proposed control mechanism is shown in the Figure 5.8. Initially, the voltage across the sensing resistor was sensed and then it was further compared with the preset value that was completely based on the main current value. If the sensed voltage is greater than the reference value, the output of the micro-controller becomes zero, which further deactivates the gate signal provided by the optocoupler to the gate terminal of main MOSFET. The temperature across both the MOSFETs is to be sensed regularly to limit the unwanted temperature rise across the MOSFET, if the temperature across the MOSFET rise above the preset limit a signal is transferred from the microcontroller to turn fan on until the temperature across the MOSFET decay beyond the reference value. This in turn increases the overall efficiency of the system.

5.4 COOLING UNIT

Even under normal loading condition, current is continuously flowing throughout the circuit for a short as well as long time due to regular current flow across the MOSFETs. The temperature of that particular MOSFET starts rising, which ultimately affects the on state drain source resistance of the MOSFET (R_{dson}). This further cause random variation in the voltage drop across the sensing resistor, Due to these unwanted variations, the efficiency of the protection circuit decreases. However, to improve the efficiency of the current protection circuit. Cooling unit is incorporated in the circuit to provide efficient cooling across both the MOSFETs to maintaine their temperature at desired value. Cooling unit consist of various components such as LM35 temperature sensor, BC547 transistor, 12V battery as well as 12V DC fan and Arduino Uno . During the ON condition of current protection circuit, the LM35 temperature sensor sense the temperature across both the MOSFETs in terms of voltage, which is further read at the input analog pin of Arduino Uno. The output of Arduino depends upon the sensed temperature value and the programming done within the Arduino board is based upon the preset temperature value,which is further compared to the sensed temperature value to produce the desired Arduino output. Initially, the sensed temperature value is compared with the reference value set by the program to get the desired output.

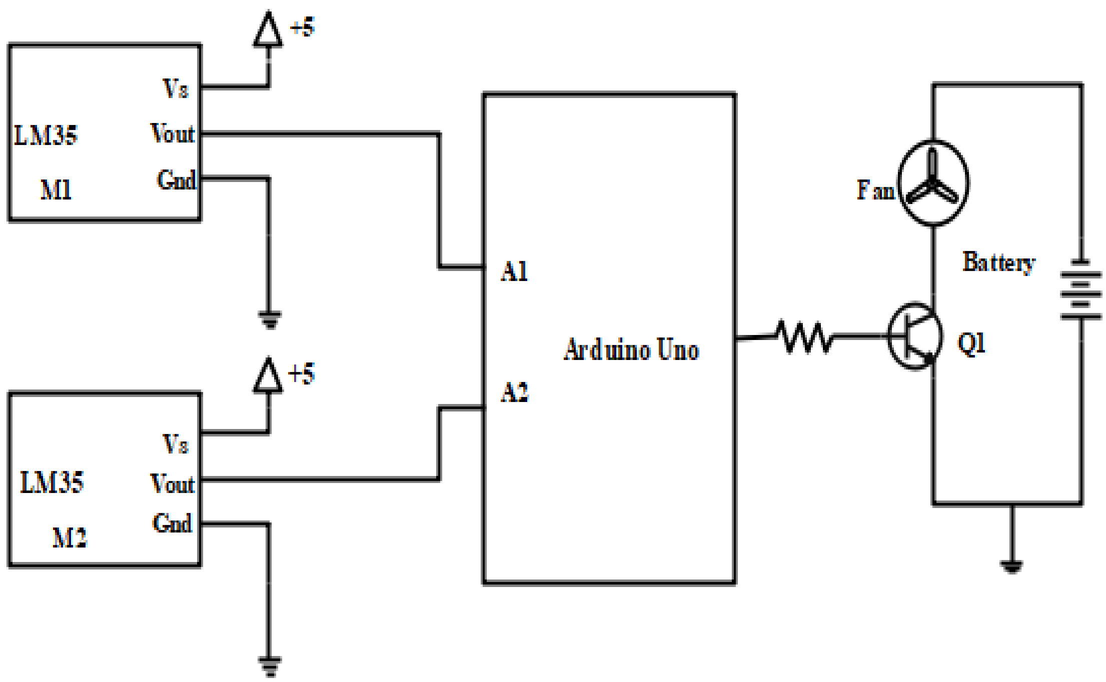


Figure 5.9: Cooling Unit for the MOSFET

The sensed temperature across main MOSFET is sent at the analog input pin A1 where as the sensed temperature across the sense MOSFET is sent at the analog input pin A2 as shown in Figure 5.9. Further, the sensed value is compared with the preset value. If the sensed temperature is greater than the preset value, the current starts to flow through the Arduino output to the transistor input to cause conduction of current through the emitter collector junction so, that transistor become short and the battery voltage completely appears across the DC fan placed across the output terminal. The fan starts rotating until the sensed temperature becomes less than the preset value. Whenever the sensed temperature becomes less than the preset value, the current through the Arduino output become zero due to which no current will flow through the emitter collector junction of transistor. This makes it to open circuited and the fan stops rotating as the voltage across the fan become zero. So that, the wastage of energy during normal operation become very less, which in term increases the overall efficiency of the protection circuit.

5.4.1 Various components used in cooling Unit

5.4.1.2 LM35

The LM35 is a set of many electronic circuits that is brought together to form a single chip for the effective measurement of temperature in terms of electrical parameter and it is proportional to the temperature (in °C) is shown in Figure 5.10. The main advantage of LM35 includes its use for the effective measurement of temperature in comparison to thermister and the circuitry involved in the LM35 circuit was completely fixed to eliminate the chances of oxidation in the circuit. The output voltage generated due to LM35 is highly accurate in comparison to the thermocouple and the need of amplification of the output voltage for the better performance is diminished. It basically senses in terms of voltage that was proportional to the temperature in Celsius. The calculations done by the sensor was in terms of .01V/°C [54].

Figure 5.10: LM35 Temperature sensor

LM35 gives a recent temperature in terms of voltage value to the micro-controller board. As the value of temperature increases across the MOSFET in a continuous manner, it will also affect the value of load current flow through that particular MOSFET, to eliminate the unwanted variations in the load current. A cooling circuit is implemented with the help of Arduino Uno and LM35.Whenever temperature increases above the preset value, it turns on the cooling fan to maintain the temperature within the desired values [51] and to control the working of cooling unit, a program is created in terms of C code in the microcontroller. The Arduino continuously measure the temperature across both the MOSFETs. During normal condition, the fan is continuously on until the temperature gets down from the preset value but whenever the temperature become less than the preset value Arduino turn off the fan through the transistor used in the cooling circuit.

5.4.1.3 BC547 Transistor

This is an NPN bipolar junction transistor (BJT). A transistor is ordinarily utilized for intensification of current. The higher current at the emitter and collector can be affected by the little sum of current at the base. BC547 can be utilized commonly for speakers and switches. Compared to all the other transistors BC547 has moreover three terminals, e.g. collector terminal, base terminal and emitter terminal. The sum of current streaming from base to the emitter controls the sum of the current streaming through the collector. BC547 is commonly utilized for intensification and switching purposes. It has a maximum current gain of about 800 [55].

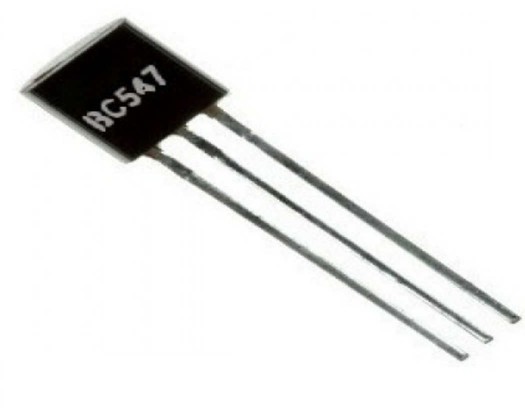


Figure 5.11: BC547 transistor

BC547 is one-sided in a way like it is partially on for all the connected inputs, for the intensification reason. The input flag has amplified on the base and Further, transferred to the emitter. The use of BC547 is to control the operation of cooling fan by connecting a fan to a 12V DC battery like a switch. Whenever the temperature is above the preset value, a command signal sends by the Arduino to the base terminal of BC547 transistor to work like a on switch. Therefore, a fan starts rotating due to battery voltage and the cooling across both the MOSFETs starts to maintain the temperature below preset value for improving the overall efficiency of the system.

5.5 TEMPERATURE SENSING ACROSS BOTH THE MOSFETS FOR THE EFFECTIVE ANALYSIS OF THE SENSEFET TECHNIQUE

Due to regular flow of current through the main MOSFET and sense MOSFET, temperature across the MOSFET increases which in term also increase the value of on state drain source resistance so, the voltage drop across the MOSFETs vary simultaneously, which can also affect the sensing voltage that can be sensed using microcontroller across the sensing resistor and affect the overall efficiency of the system. It is necessary to optimize the value of R_S so that the variation in the sensed voltage will be minimized in comparison with the sensed voltage at room temperature.

This can be accomplished using LM35 temperature sensor used to measure the temperature across each of the MOSFET in real time. The measurement through LM35 is much accurate than thermistor. The output voltage generated through LM35 is proportional to Celsius scale and it sense over the range of $0℃\ to\ 100℃$.

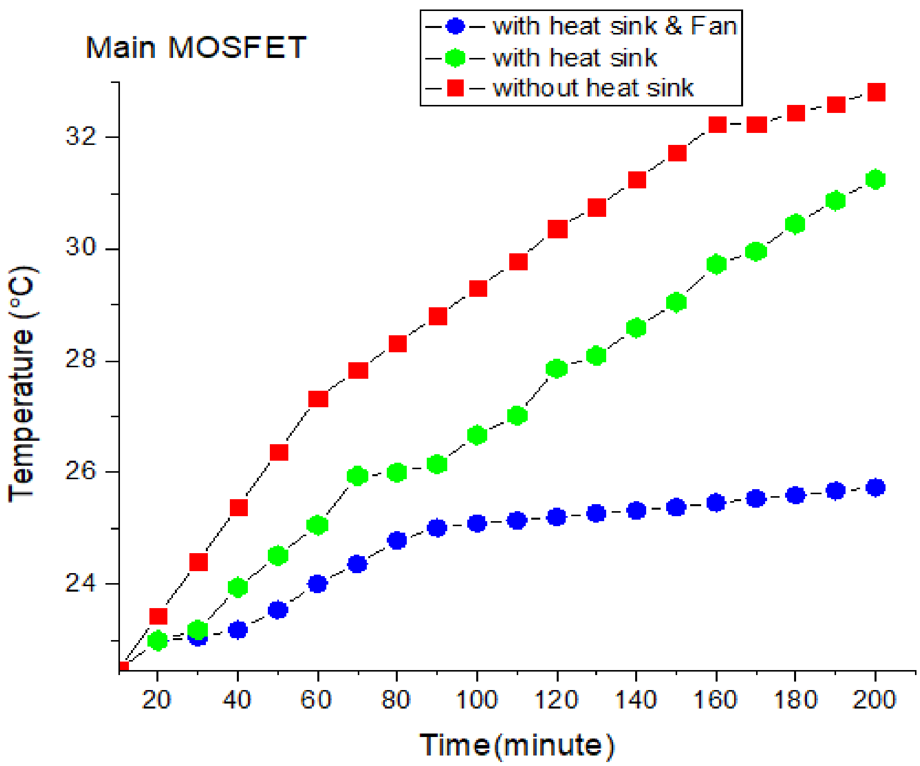


Figure 5.12: Time vs. Temperature graph for Main MOSFET

This is basically a temperature vs time graph originated on the basis of experimental results. It is well known that, the unwanted temperature rise across the main MOSFET and sense MOSFET cause unwanted variations in the voltage drop across the sensing resistor. The over all efficiency of the system completely depends upon the voltage drop across sensing resistor so that, any variation in the voltage drop will decrease the overall efficiency so, to maintain the system efficiency. It is hardly needed to stop the continuous variations in the voltage drop across the sensing resistor and this can only be possible if the temperature variations will be eliminated from the protection circuit. This is the main reason that a hardware implementation of the circuit will be analyzed in terms of MOSFET temperature dependency in three different cases as shown in the Figure 5.12 for main MOSFET. Initially, when motor is running under steady state still by varying the time interval of continuous running, the temperature across the MOSFET also varies. When using heat sink with the MOSFET, the temperature rise across the same MOSFET is very less under normal running of motor for similar time interval as in the previous case of MOSFET without using heat sink. Now, consider a third case of MOSFET with heat sink and Fan, the temperature rise across main MOSFET and sense MOSFET is negligible as shown in the Figure5.13 during the free running of motor for similar time interval as discussed in previous cases. The efficiency of the respective circuit is very high in the third case and further, decreases as going from second case to first case.

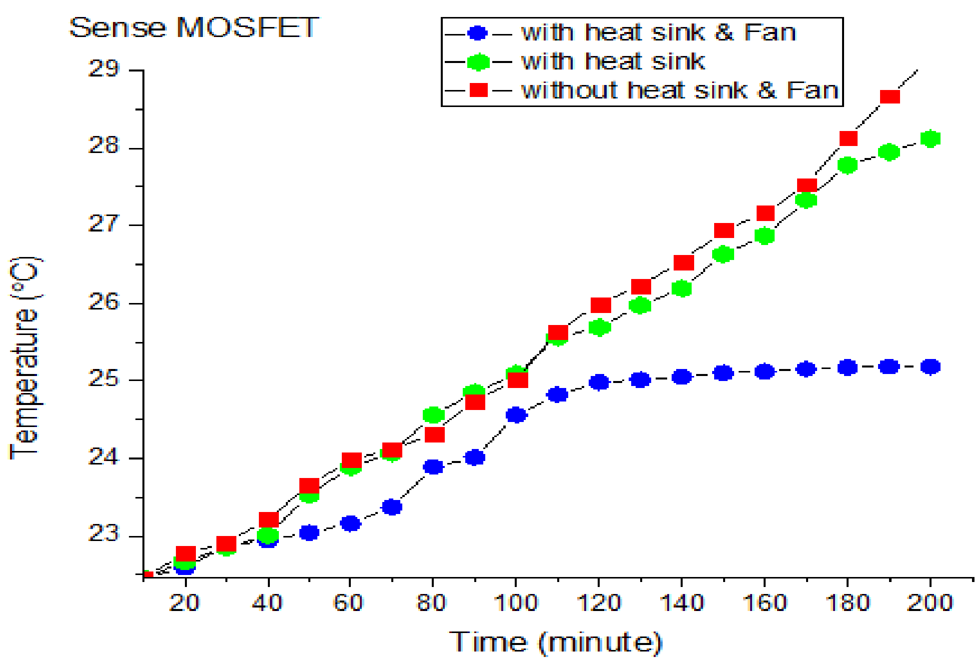


Figure 5.13: Time vs. Temperature curve for sense MOSFET

According to both the graphs, additional component for measuring temperature across each MOSFET is required to limit the unwanted rise in temperature across both the MOSFETS during normal as well as abnormal condition with the help of cooling unit include 12V DC fan, battery and transistor. If the temperature across main MOSFET does not increase rapidly, it will also limit the rise so, that the deviation in the sensed voltage will be minimum and the sensing technique accuracy will be improved.

CHAPTER-6

RESULTS AND DISCUSSION OF PROPOSED CONTROLLER

Based on the above methodology, the designing of current limit controller for the protection of DC motor has been done for the any type of electric vehicle. The simulation of the respective controller was achieved through the Proteus software and the simulation results were further verified by the hardware implementation of the proposed technique. To improve the overall efficiency of the system, cooling unit has been accomplished. Figure 6.1 shows the simulation diagram of current limit controller in the Proteus software.

6.1 Simulation Circuit

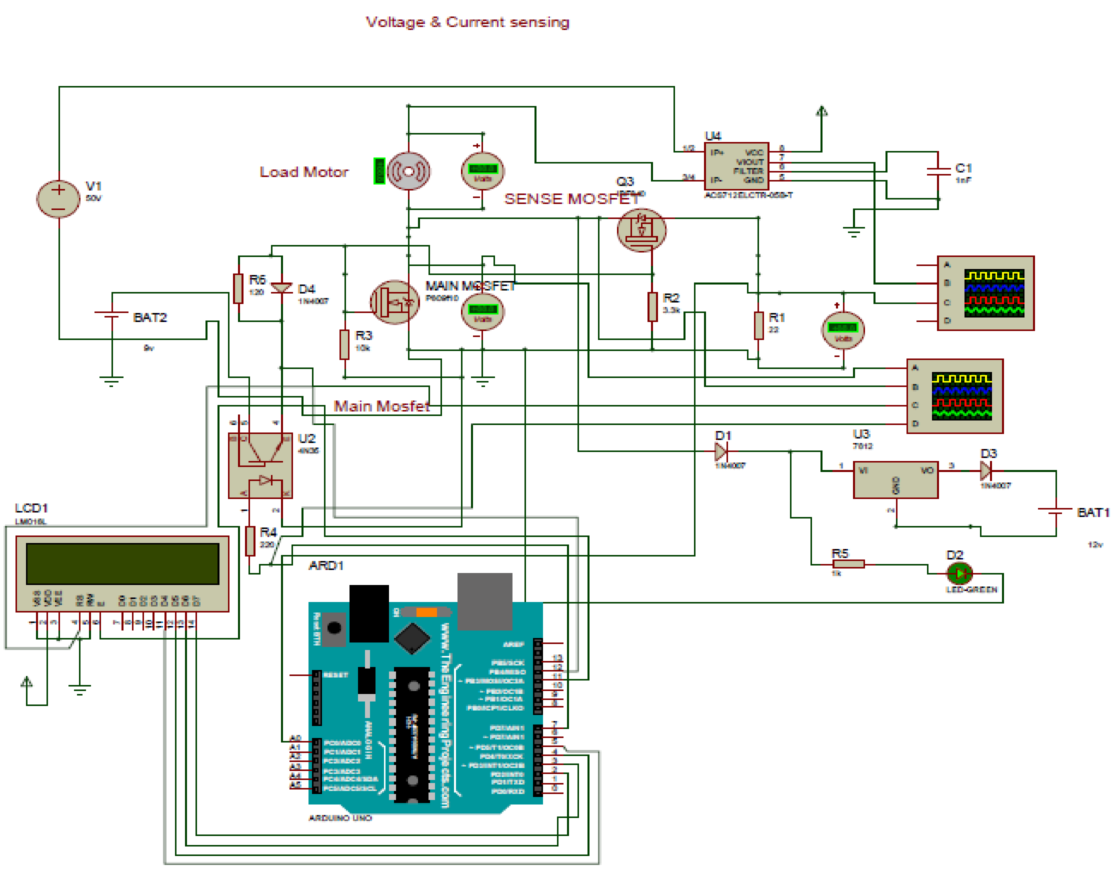


Figure 6.1: Simulation Diagram of Current limit controller

The simulation of the respective controller has been done using a SENSEFET technique. The motor load is placed in series with the main MOSFET so that, the current flowing through the main MOSFET is equal to the load current. Further, sense MOSFET is placed in parallel to the Main MOSFET but in series to the sensing resistor. The voltage drop across the sensing resistor is in milli volts, which further transfer to the Arduino that works as a micro controller. After that, Arduino reads the analog signal on its analog pin and provides output on its digital pin according to the programming done for the switching of motor during abnormal condition. The digital output trigger the optocoupler to provide pulse voltage at the gate terminal input of both the MOSFETs. However, during on condition voltage across the both the MOSFET become zero and during abnormal Condition, the source voltage appears across both the MOSFET.

6.2 Simulation Results

6.2.1 Using Motor load

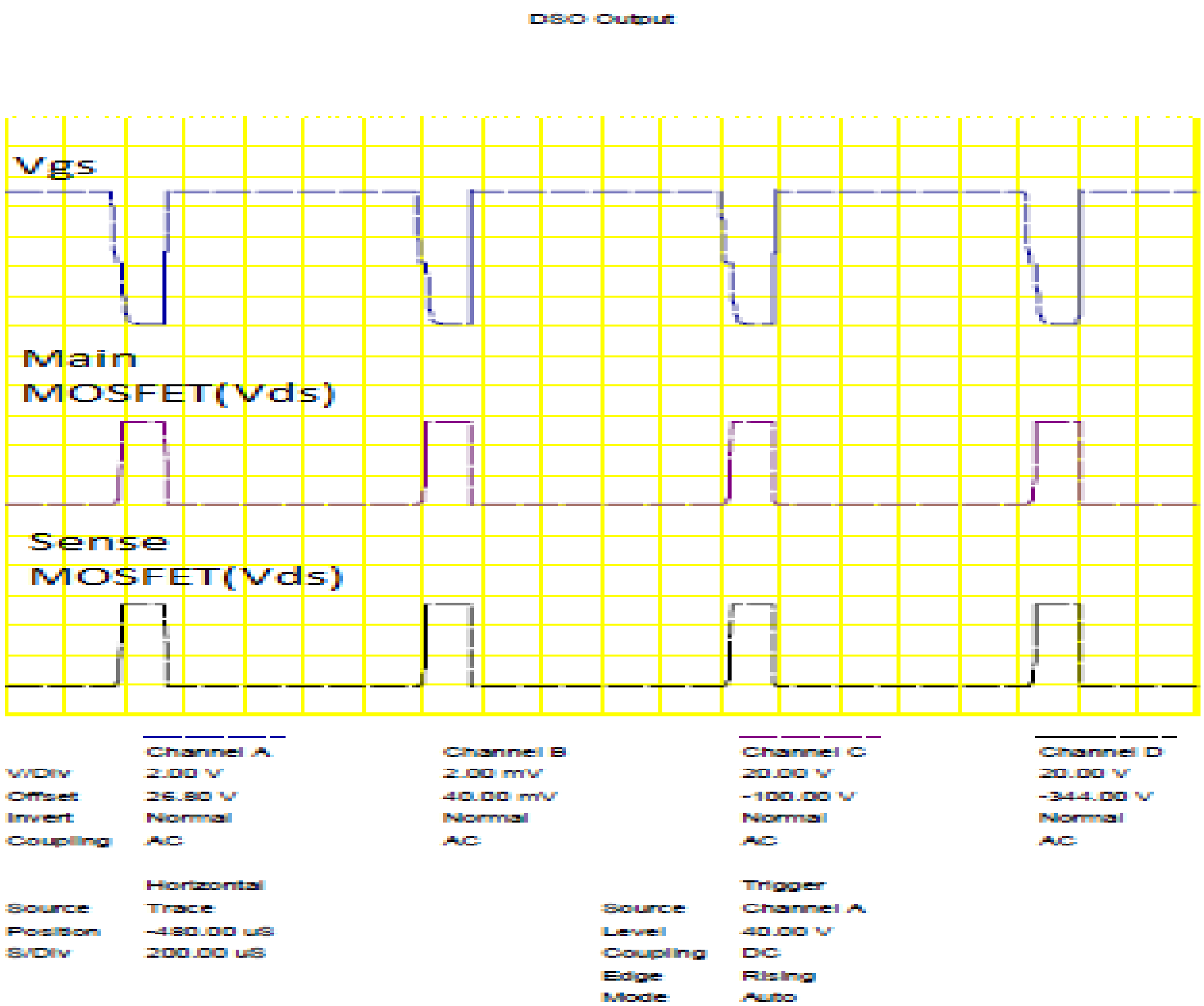


Figure 6.2: Various waveforms at Motor Load

During the normal operation of the proposed controller, the gate terminal of main MOSFET is continuously triggered by the PWM pulse provided by the opto-coupler for the continuous conduction of MOSFET as shown in the Figure 6.2 where Vgs as gate voltage and V_{ds} as the voltage across the main MOSFET as well as sense MOSFET is shown respectively. However, during the conduction period of gate pulse the voltage across both the MOSFETs is zero but at the particular instant whenever the output gate voltage become zero, the voltage across both the MOSFETs become equal to source voltage. During the switching interval, whenever the load current starts to increase suddenly due to heavy Loading it can also increase the voltage drop

6.2.1.1 Switching waveform at Motor Load

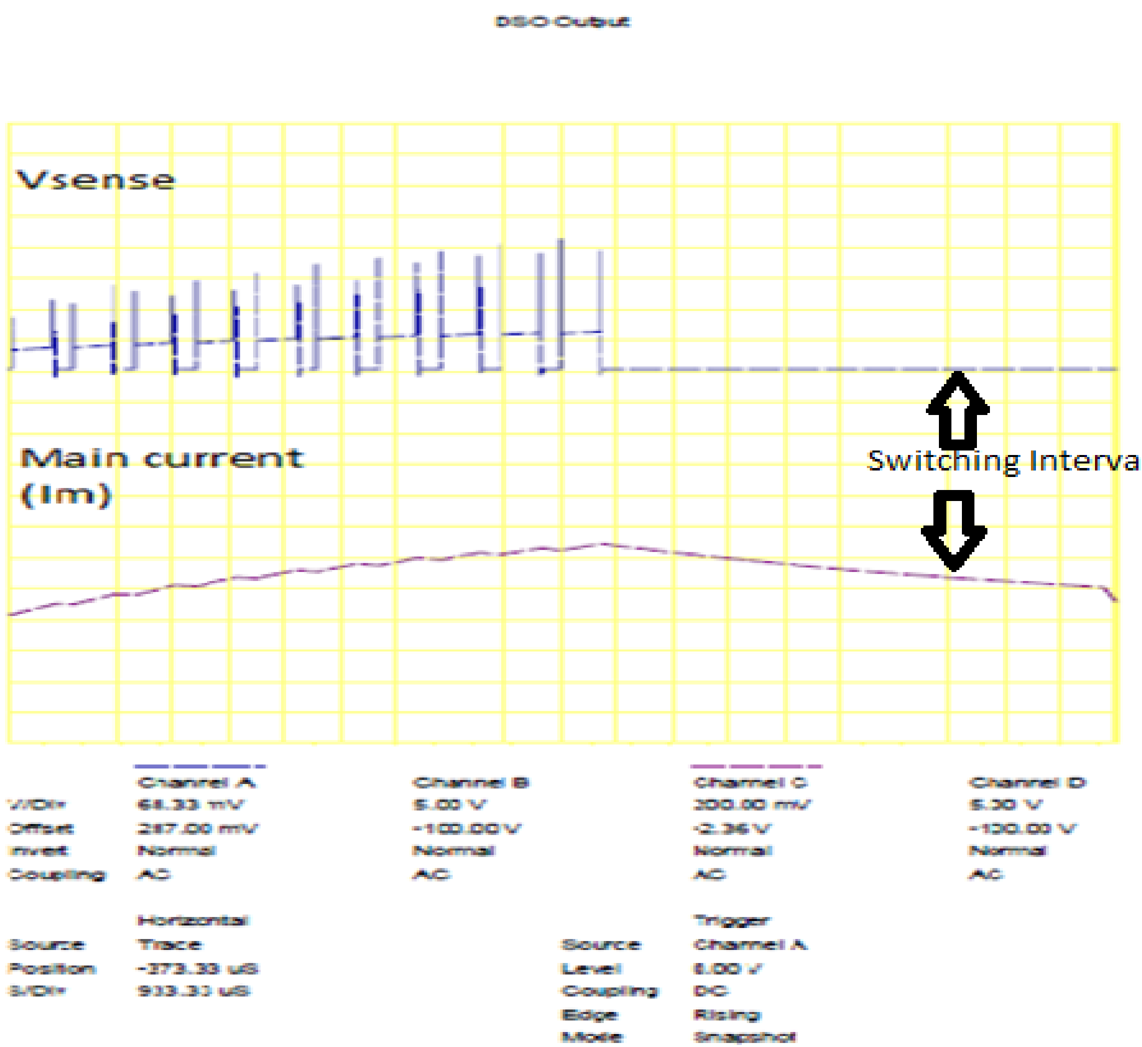


Figure 6.3: Switching waveform at Motor Load

across the sensing resistor up to its preset value. At the instant when load current exceeded its preset value, the digital output of micro controller become zero, which completely depends upon the preset value set in the micro-controller programming done by the programmer according to the rated value of load current due to which the triggering pulse output of opto-coupler also become zero. Therefore, triggering of gate terminal of Main MOSFET as well as sense MOSFET is stopped and the complete source voltage appears across the main MOSFET and the sense MOSFET due to which the current through the motor load become zero and the motor stops working as shown in the Figure 6.3.

6.2.2 Using Lamp Load

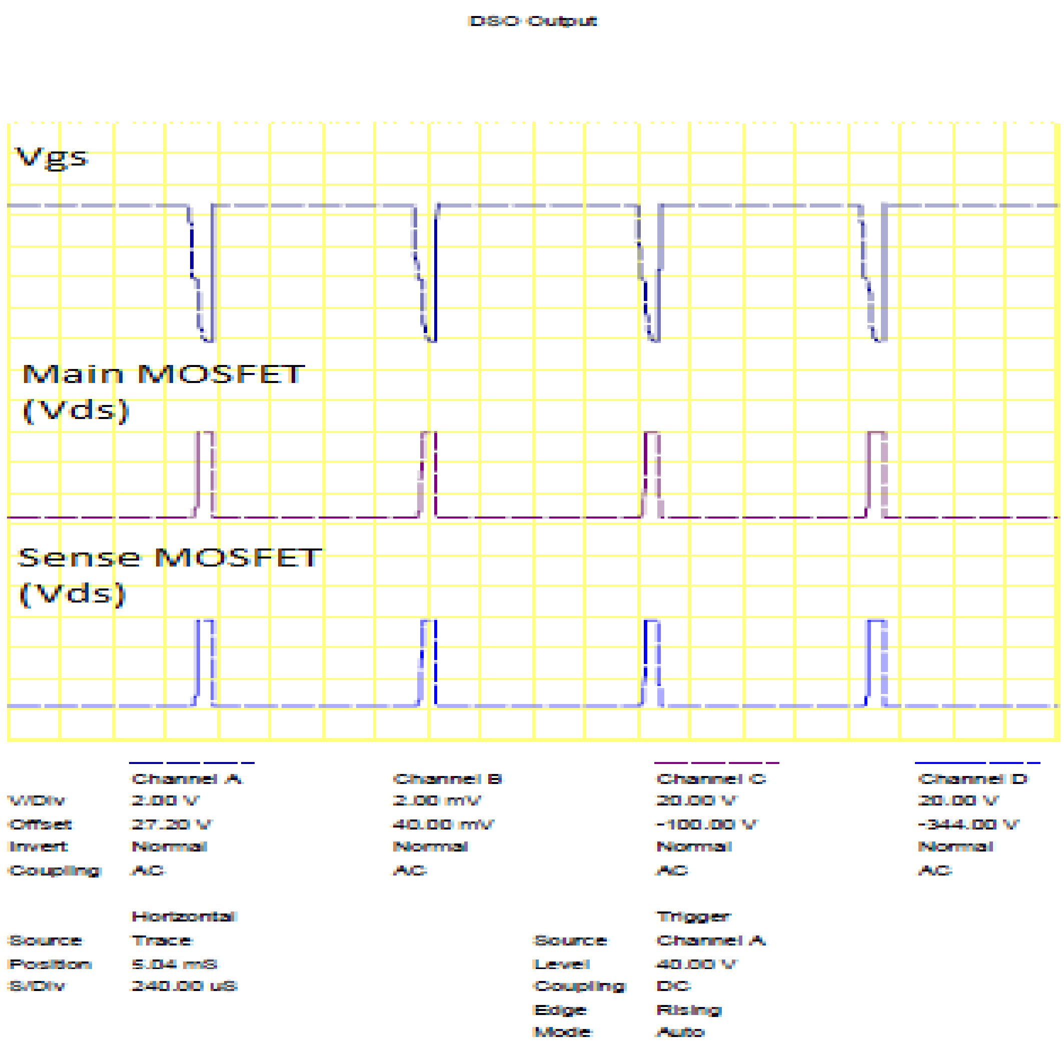


Figure 6.4: Various waveform related to Lamp Load

In a similar way as we discussed earlier, this time current sensing technique was used for the protection of lamp load from transients by switching the MOSFETs from on condition to off condition. This can easily be done by applying a similar current sensing technique in the protection circuit. Whenever the voltage across the sensing resistor becomes less than the reference value set according to the rated value of load current. Arduino Uno provide a digital output at the input terminal of MOSFET driver such as 4N35 opto-coupler, it can also provide isolation in the main circuit.

If the output at the input terminal of opto-coupler is more than the threshold value, the opto-coupler generate triggering pulse as shown in the Figure 6.4 to trigger the gate terminal of Main MOSFET and Sense MOSFET. During the on period of gate pulse, both the MOSFETs get short and the voltage across them become zero due to which current start to flow through the motor load.

6.2.2.1 Switching waveform at Lamp Load

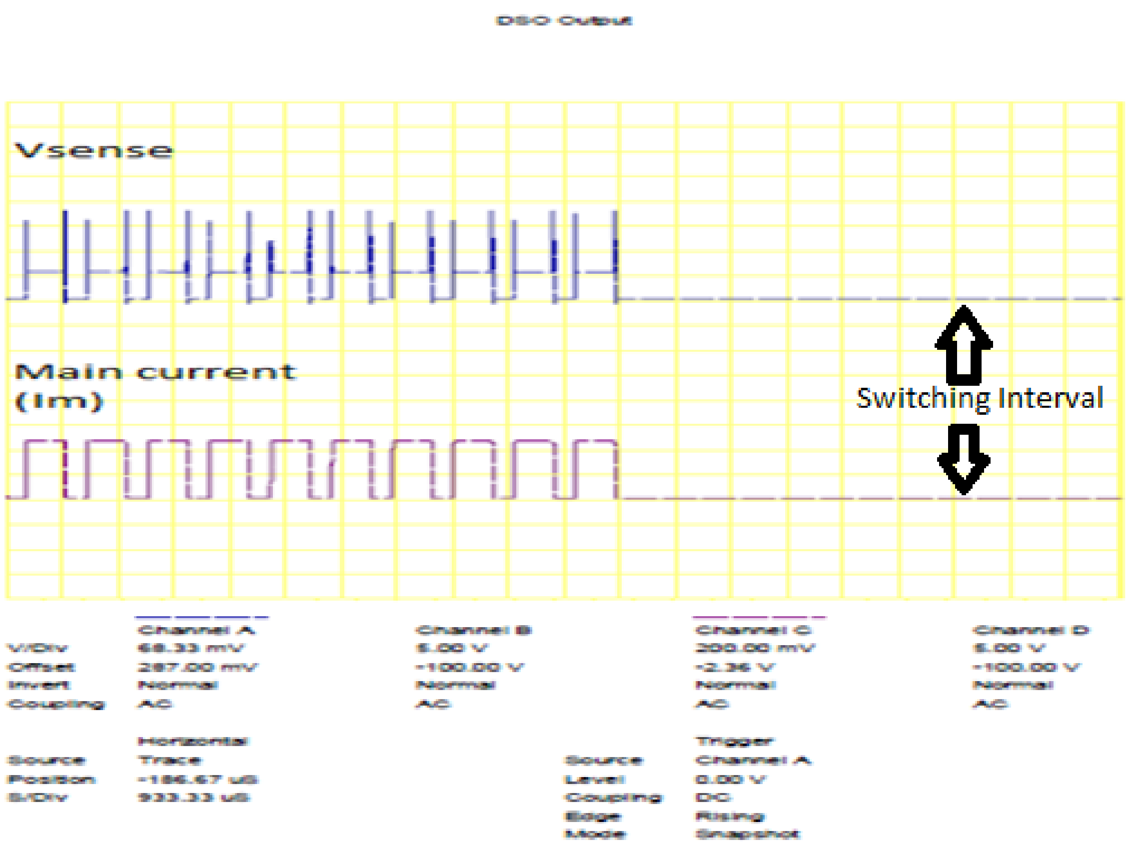
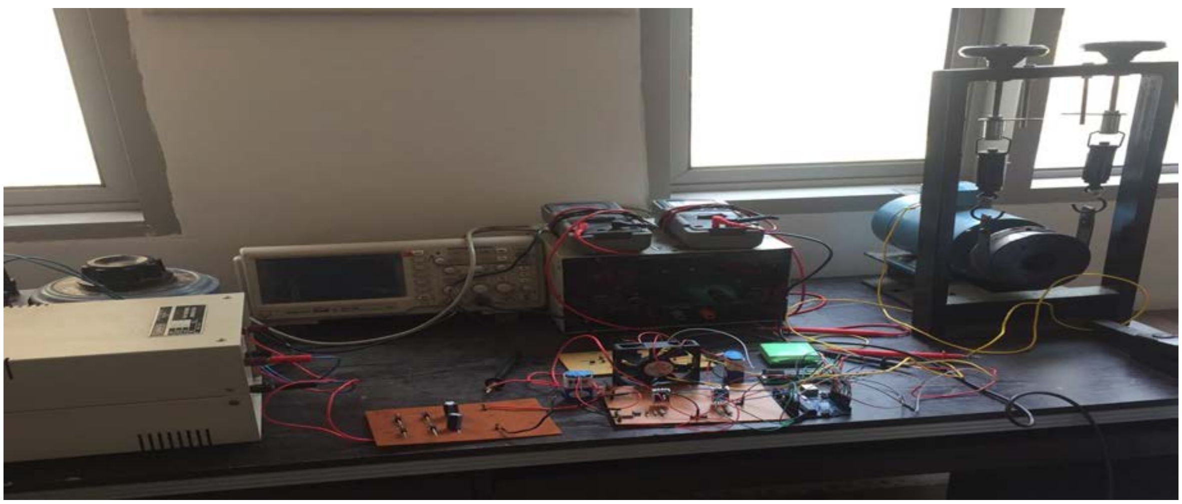


Figure 6.5 Switching waveform at Lamp Load

During abnormal condition, whenever the current starts to exceed its preset value as shown in the Figure 6.5. The Voltage across the sensing resistor also increases in the same proportion. If the value of sensed voltage becomes greater than the reference voltage set according to the rated value of load current, the digital output provided by Arduino Uno becomes zero. This is obviously insufficient to start conduction of opto-coupler due to which the trigger voltage at the input gate terminal of main MOSFET is not able to cause conduction of both the MOSFETs. This further leads to the implementation of source voltage across the both the MOSFET as shown in the Figure 6.5 and due to which load current become zero in the main circuit.

6.3 Hardware Implementation



(a)

(b)

Figure 6.6 (a) shows the hardware setup of current limit controller at motor load
Figure 6.6 (b) shows the hardware setup of current limit controller at lamp load

6.4 Experimental Results

The hardware implementation of current limit controller circuit verifies the feasibility of current sensing technique in the practical environment. As the triggering pulse provide by the opto-coupler is shown in the Figure 6.7 is PWM in nature. During the positive half cycle of the gate pulse, the gate voltage applied at the gate terminal of both the MOSFETs was sufficient enough to cause conduction of current through the Main MOSFET as well as Sense MOSFET and the motor starts rotating because MOSFETs become short circuited and complete supply voltage appears across the motor load.

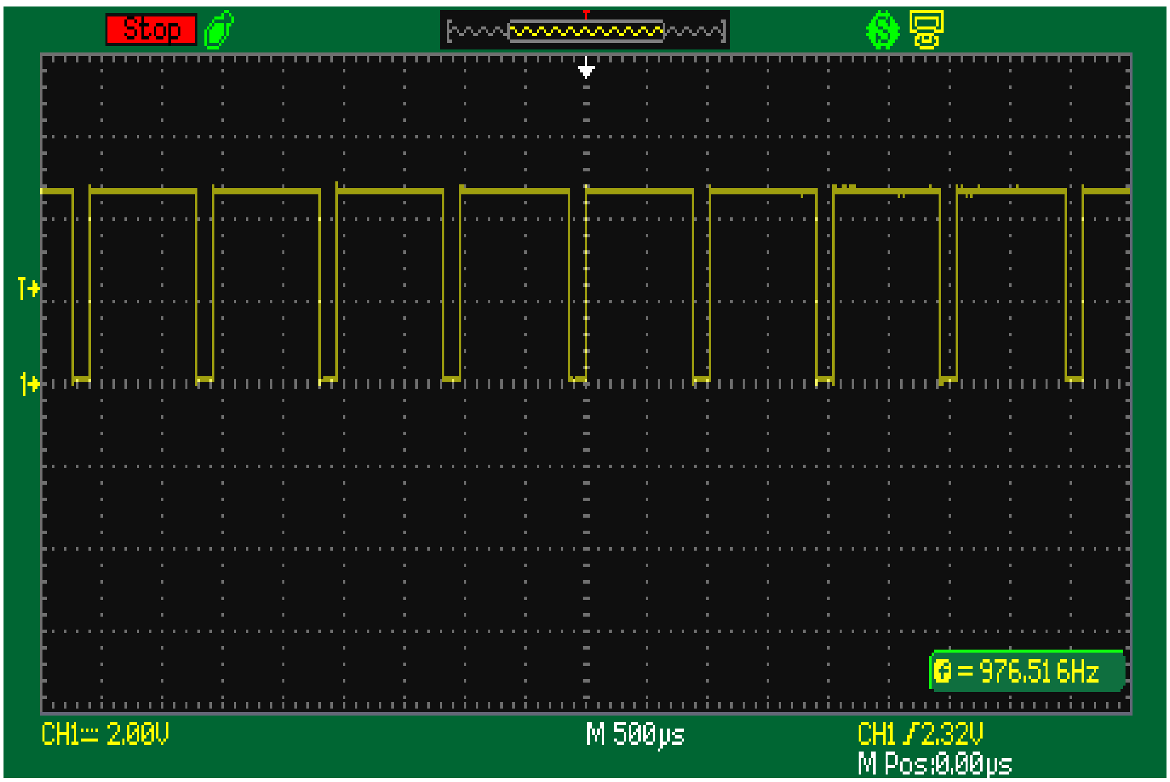


Figure 6.7: Gate to Source voltage (Vgs)

However, the voltage across both the MOSFETs will vary according to the gate pulse, which further leads to the switching of both the MOSFETs under transient condition for the protection of DC motor load. Whenever the gate pulse become positive in nature, the voltage across both the MOSFETs becomes zero and the current starts to flow through the motor load. Whenever the gate pulse becomes zero, both the MOSFETs will get open circuited and the complete source voltage will appear across both the MOSFETs. The voltage across both the MOSFETs in the

Figure 6.8 was approximately equal to the source voltage, To display on the DSO screen properly, the voltage can be reduced by the multiplying factor of voltage probe in terms of 10X (giving a 10:1 attenuation ratio),.it means a probe attenuates the voltage signal level by the factor of 10.

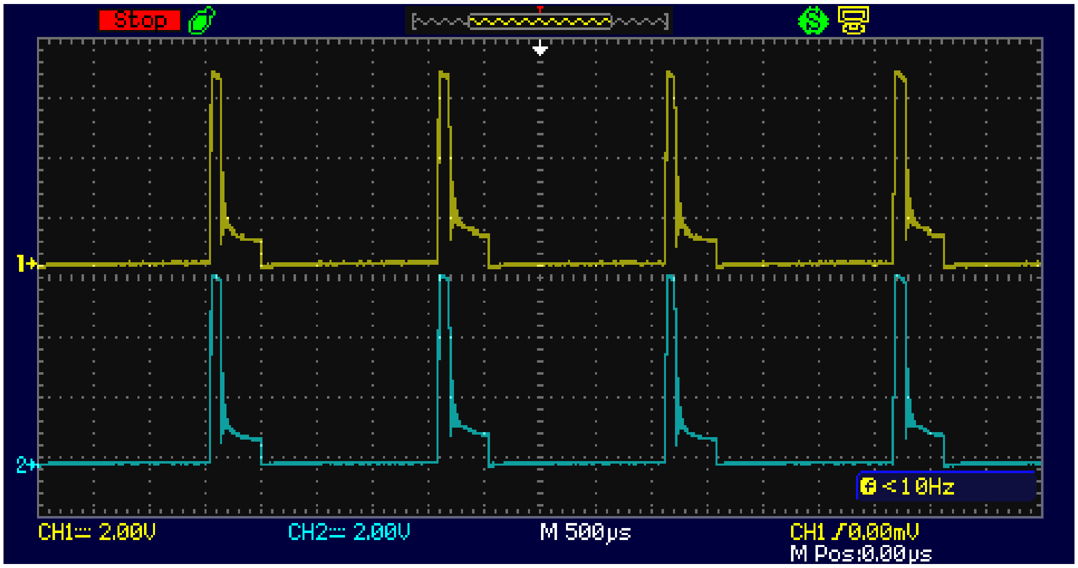


Figure 6.8: Drain to source voltage of Main MOSFET & Sense MOSFET

Here, the gate voltage and the drain to source voltage of main MOSFET is obtained by using a Digital oscilloscope during hardware implementation as shown in Figure 6.9. Whenever the gate voltage become positive about 8V, the output of optocoupler trigger the main MOSFET and the sense MOSFET due to which voltage across both of the MOSFETs become zero.

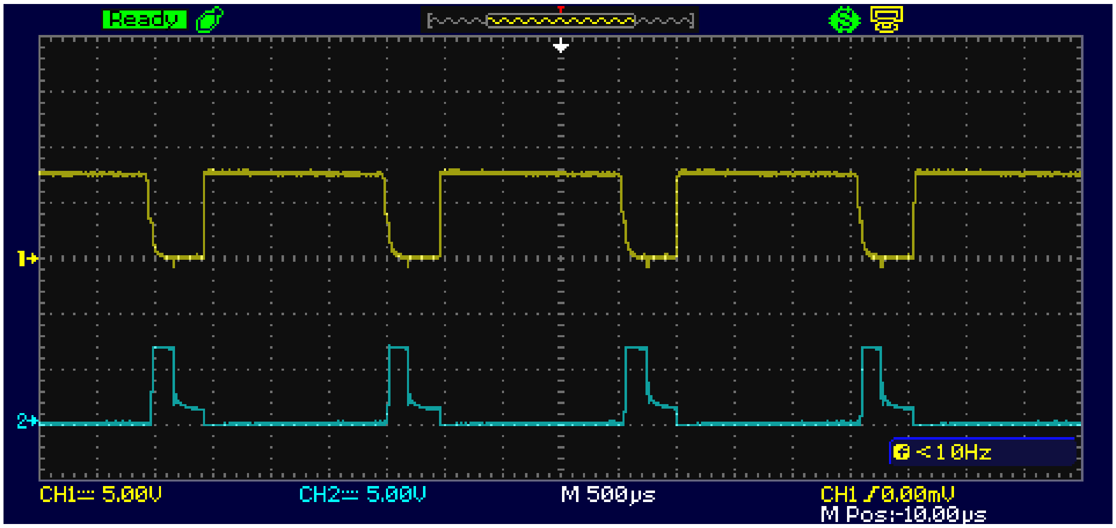


Figure 6.9: Gate Voltage (V_{gs}) & Main MOSFET (V_{ds})

Whenever the gate pulse becomes zero, the output of opto-coupler was not able to trigger both the MOSFETs and the MOSFETs become open circuited, which causes supply voltage to appear across the main MOSFET.

During normal condition, the motor starts to run at a constant speed. The current flowing through the motor has been shown in the Figure 6.10. The measurement of load current was done by the utilization of current probe. The current probe was placed across the current conducting wire and the value of current was measured in terms of 10 mV/Amp. During the positive half cycle of current pulse, the MOSFETs start conducting and the current flowing through the motor is continuous in nature whereas in case of negative half cycle, the MOSFETs stop conducting and the current flowing through the motor load becomes zero in nature. The off period of current pulse is very small due to which the motor continuously runs at a constant speed without any change in the rated speed.

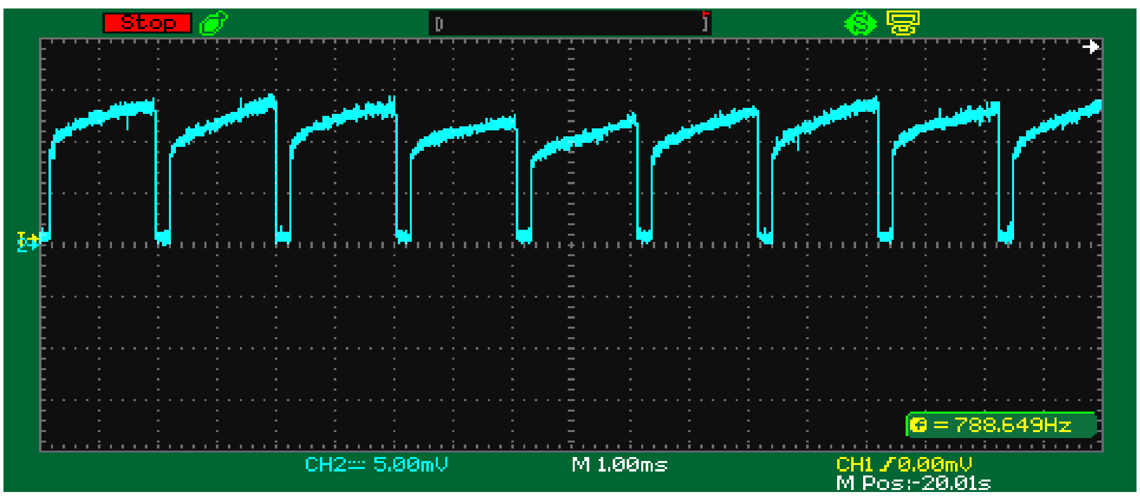


Figure 6.10: Main Current (I_m)

a) Under the Normal Condition, the current flowing through the motor load wouldn't exceed the rated value of load current is represented by the blue color waveform shown in the Figure 6.11 in a similar manner, the voltage across the sensing resistor become less than the preset value is represented by the yellow color waveform also shown in the Figure.6.12 . In this case, the value of sensed voltage become less than the preset voltage value which is stored in the Arduino programming for its utilization in the switching of motor if needed. Due to this condition, Arduino Uno provides a positive 5 V output that has been fed at the input terminal of opto-coupler, which is sufficient to produce a triggering pulse for the conduction of current controller circuit. The major advantage of this circuit is the sensing of voltage across the sensing resistor in terms of mili-volts as shown in the Figure 6.11 which leads to the minimization of losses across the sensing resistor and it will further improve the overall efficiency of the system in long term scenario and the measurement of current was achieved through the utilization of current probe in terms of 10mV/ Amp. with the help of Digital oscilloscope.

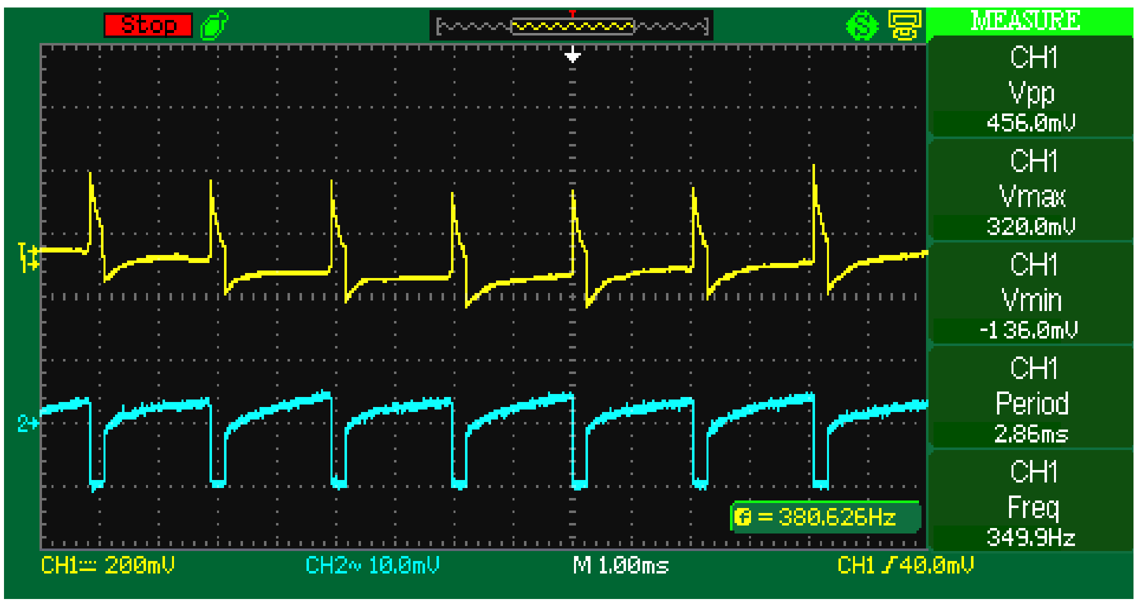


Fig 6.11: Wave form of Sensing Voltage (V_{sense}) and Main Current (I_m)

b) Under the transient condition, the current flowing through the motor load exceed its rated value is represented by the blue color waveform shown in the Figure 6.12 in a similar manner the voltage across the sensing resistor exceed its preset value is represented by the yellow color waveform also shown as shown in the Figure 6.12. In this case, the value of sensed voltage has been greater than the preset voltage value stored in the Arduino programming for the switching of motor under transient condition. Due to which, the output of Arduino becomes zero which has been further fed at the input terminal of opto-coupler. The output of opto-coupler in this condition becomes quit less to cause conduction at the input terminal of both the MOSFETs due to which both the MOSFETs become open circuited. As shown in the Figure 6.12. the middle region of the voltage as well as current waveform represent the switching condition, where the voltage across the R_{sense} become zero and the current flowing through the motor load also become zero due to open circuit condition which has been implemented in the current controller circuit during the transient condition.

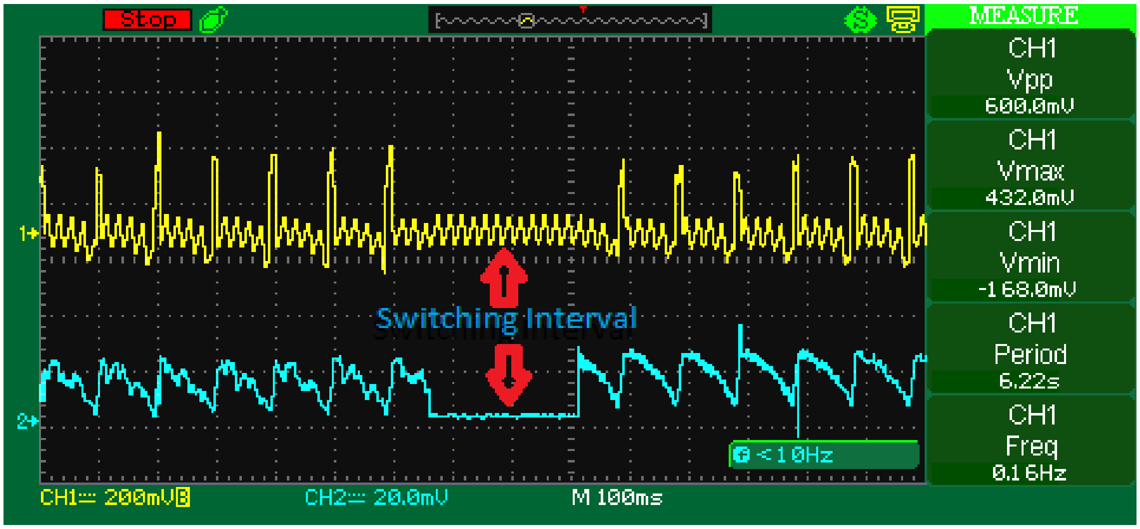


Figure 6.12: Wave form of Sensing Voltage (V_{sense}) and Main Current (I_m)

CHAPTER-7

CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

In this work, a current limit controller for the protection of DC motor during transient condition when current exceed its rated value using SENSEFET technique has been proposed. This technique is basically linked with the voltage sensing across the external resistor which makes this technique much effective because the power losses across the sensing resistor was negligible. The value of sensing resistor has been optimized through the experimental as well as modeling results. The switching of motor during the transient condition was done by the utilization of micro-controller programming and the voltage across the sensing resistor is used as the reference value. Thus, in this work a design of a current limit controller using Proteus software and its validation through the hardware experimental setup has been done. The benefit of such a system is the increase in overall efficiency and its real time practical implementation analyzing its feasibility and reliability. Also, to enhance the overall system performance by maintaining the internal temperature of the MOSFET, an external cooling unit has been incorporated in the system.

7.2 Future Scope

Implementation of Proposed Technique for the real time operation of any electric vehicle. This technique can directly be used for its operation by the replacement of main MOSFET and sense MOSEFT according to its utilization in various application. Due to the evolution of technology in hybrid vehicles in the global market where the power electronics and machine involves leads to a great scope of current controller in any electric vehicle.

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