Design and Control of Fuel Cell Based Permanent Magnet Synchronous Motor Drive for Electrical Vehicle

Dilip Verma[1], Vijay Anand Bharti[2]

[1]*M.Tech*, [2]*Assistant Professor*

Department of EE, Mittal Institute of Technology, Bhopal, India

Abstract— ***Permanent-magnet synchronous motors (PMSM) are capable of providing high torque-to-current ratios, high power-to-weight ratios, high efficiency and robustness. Owing to these advantages, PMSM are widely used in modern variable speed AC drives, especially in electric vehicle (EV) and hybrid EV applications. In this study, a novel PMSM drive system with a bidirectional Z-source inverter (ZSI) is proposed and tested. By introducing ZSI to the drive system, the DC-link voltage is controllable so that PMSM can operate at high speed without field weakening. The operating principle and modulation method of ZSI are described in this study. After presenting the constraints of the motor maximum line current amplitude and maximum available voltage, a modified vector controlled scheme of PMSM drive is developed by considering voltage boosting. Finally, the feasibility and effectiveness of the proposed system are verified by several simulation and experiment results. Simulations have been done in MATLAB/SIMULINK environment to explore the system response. The response obtained for stator current, electromagnetic torque, rotor speed of PMSM and bus voltage of the fuel cell.***

Keywords— ***PMSM, FOC, DTC, PEMFC, HEVs, MCFC, SOFC, etc.***

I. INTRODUCTION

A substantial amount of research and development time, as well as financial means is now invested by the manufacturers and political organs in order to meet the demands from a constantly more aware public. Even if large advance has already been made, there are still many aspects to be considered and problems to be solved regarding the HEVs before they can be fully commercialized. Two such aspects are the cost and performance of these vehicles. Because even if the environmental concern has been brought to attention, the customers must be able to afford the product and the product needs to fulfill its purpose. Another aspect is the origin of a substitution fuel and its distribution. Various research and development activities have resulted in a variety of different hybrid solutions, from the electric motor assisted bicycles to more advanced plug in hybrid cars and the fuel cell vehicles (FCV).

1.2 FUEL CELL BASED VEHICLE

When there are at least two forms of energy stored on board a vehicle that can be used for propulsion and if the energy in at least one of the cases is electric, such a vehicle qualifies to be called a HEV. Since this is the case for the FCV, where the propulsion energy can be taken from the hydrogen supplied to the fuel cell or from the electric energy stored in the battery, these vehicles can be regarded as HEVs.

The drive line of the HEV is usually one of three basic types. One type is the series drive line imposing that only one energy form is used to power the propulsion. The other two types are the parallel and complex drive line solutions [2]. The parallel drive line impose that two energy forms can be used at the same time and the complex driveline impose that both the series and parallel drivelines are implemented and that a choice is made which solution to use in a certain situation. All these drive line solutions have their pros and cons when compared to one another. However, since the energy used to power the propulsion motor of the FCV is electric, the series drive line solution is only one studied in the following work.

Since the FCV is propelled by electric energy, this types of vehicle posses the same potential of emission favorable transportation as the battery sourced electric vehicle (EV). The fuel cell however, gives the benefit of extended travelled distance for the same or even smaller battery size.

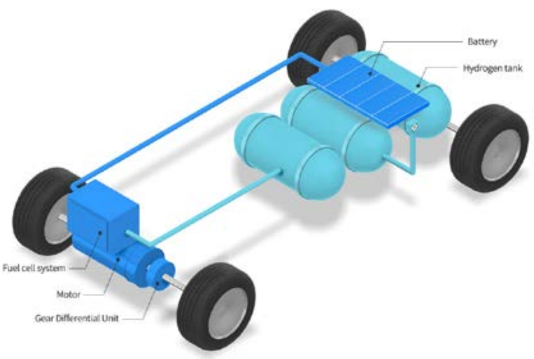

Figure 1.1 Fuel Cell Electric Vehicle

1.3 FUEL CELL

A fuel cell converts chemical energy to electrical energy with the help of an electrochemical reaction. Out of the many clean source of energy, fuel cell is considered as one of the most efficient and reliable as it don't consists any moving parts and have water and heat as the only byproducts. A fuel cell can be classified according to the type of electrolyte used. Out of different types of fuel cell, proton exchange membrane fuel cell (PEMFC) is widely used because of its low operating temperature, low noise, high efficiency and low pollution. In present day 1 kW to 2 MW power ranges of fuel cell are used in various applications. A fuel cell is defined as an electrical cell, which unlike other storage devices can be continuously fed with a fuel in order that the electrical power can be maintained. The fuel cells convert hydrogen or hydrogen-containing fuels, directly into electrical energy, heat, and water through the electrochemical reaction of hydrogen and oxygen.

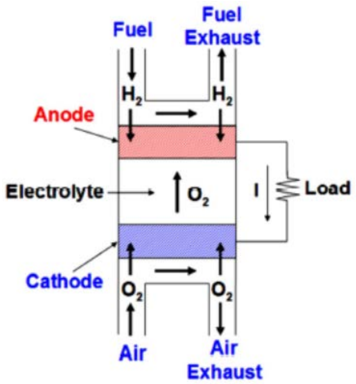

Figure 1.2: Basic configuration of Fuel Cell with operation

1.3 PMSM DRIVES

In recent years, the permanent-magnet synchronous motor (PMSM) has emerged as an alternative to induction motor due to the increasing energy saving demand. PMSM are widely used in high-performance applications such as industrial robots and machine tools because of its compact size, high-power density, high air-gap flux density, high torque/inertia ratio, high torque capability, high efficiency and free maintenance.

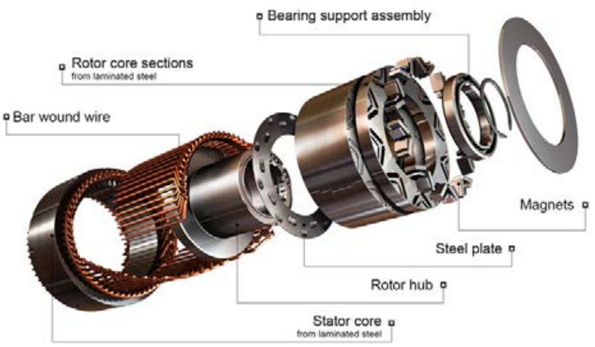

Figure 1.3: Permanent-Magnet Synchronous Motor

II. LITERATURE REVIEW

2.1 INTRODUCTION

A fuel cell is an electrochemical device that produces electric power in the form of direct current by converting chemical energy present in the fuel (hydrogen). William Grove of United Kingdom and Friedrich Schoenbein of Switzerland were among the first who pioneered the work in the field of Fuel Cell in 1830s. General electrical of the united states was the first to develop the Proton exchange membrane fuel cell(PEMFC) for the use of National Aeronautics and Space Administration (NASA) in 1960s for their first manned space vehicle Gemini. Several companies are developing PEMFC technology for space power applications. Ballard power system was one of the first power companies that pioneered in the field of fuel cells for military application. Ballard started making power system for military application that would run longer and virtually silent as compared to other sources of power. Preferably hydrogen is used as a fuel and oxygen is used as an oxidant for Fuel Cells. Although air can be used instead of oxygen but there is decrease in the Fuel Cell efficiency for this kind of arrangement [2].

The concept of microgrid system as found in several literatures is presented here. Since a large population on earth does not have access to electricity and most of this population lives in rural and remote areas, the distribution generation technology is one of the most effective ways to eradicate the power deficiency in these areas [4]. The DERs consist of a variety of generation technologies such as fuel cells, solar, micro-turbines and wind etc. and the main advantage is that there is reduction in the transmission distance and hence the cost of installation and maintenance of transmission infrastructure is very much reduced [5]. A microgrid is a power system consisting mainly of distributed energy resources, interconnected loads and capable of operating in grid connected as well as islanded mode including critical and noncritical load selectivity [6]. As mentioned in [7] the centralized model of generation, transmission and distribution has become outdated and less efficient due to high transmission and distribution loss. The existing high voltage transmission of power is controllable and reliable but it has the problem of complexity in interconnected grid system which requires control system for reliable operation. The conventional generating power systems which comprise of large generating units are less flexible to the ever increasing load demand. Any problem in one grid can have cascading effect on other grids. This has given way to more efficient, environment friendly microgrids. The developments in the field of microgrids include increase penetration levels of distributed energy resources (DER), improved generation efficiency through use of CCHP (combined cooling heat and power. Again as mentioned in [7], for the effective operation of microgrid the different typed of distributed energy resources that are connected with each other must be provided with various electronic interfaces. These electronic interfaces makes microgrid more flexible in case of fault as well as load variations. This increases the reliability and flexibility of the microgrid. Microgrid either operates in grid connected mode or in islanded mode. In grid connected mode voltage and frequency parameters of microgrid are controlled by main grid but controlling operation in islanded mode is quite complicated due to less storage capacity and lack of inertia because of increasing penetration of DER units. Also there is natural uncertainty in various DER technologies like wind, photovoltaic etc. [8, 9].

It was observed in [10], while operating in grid connected mode any fault arising in utility grid will result in large fault current in microgrid. This can be overcome using traditional over current relay. However the use of multiple DER inherently producing D.C electric power and then converting it into A.C electric power using semiconductor devices introduces complications in the protection scheme of microgrid as fault current in case of grid independent mode may not rise to a value to use traditional over current protection techniques. As traditional protection equipments are based on the principle of current sensing, the lower values of fault current in case of inverter interfaced distributed generation makes traditional over current protection schemes non effective.

Also it was mentioned in [11] that the presence of multiple distribution generators in case of microgrid makes power and fault current non unidirectional. The conventional protection schemes are made for unidirectional power flow. So this is a hindrance to selection of conventional protection schemes for microgrid.

2.2 FUEL CELL TYPES

There are many types of Fuel cell line PEMFC, MCFC, AFC, SOFC. But only PEMFC can be operated at normal air temperature. PEMFC is lightweight so it can be easily transported, used for distribution power generation. There are a number of fuel cells that can be chosen according to the power rating. 1kW FC has the output voltage range of about 25-50 V and 30 kW and above Fuel cells have output voltage of about 200-400V [12]. As stated in [13], a fuel cell system has five basic sub systems these include fuel processor, water management, air management, thermal management and power conditioning sub system.

2.3. COMPARISON OF DIFFERENT TYPES OF FUEL CELLS

As explained in [17] PAFC technology is commercially available as well as technologically more advanced in comparison with other type of fuel cells. MCFC still needs some improvement to overcome technical and economical barriers before they could be commercialized at par with other type of fuel cells. SOFC is very useful particularly in stationary fuel cell. They are very much commercialized. If economic issues are resolved then SOFC can be very successful in distributed generation applications. PEMFC have become very popular in the recent years due to technological breakthroughs in the field of cell power density as well as reduction in the cost. These are the only type of fuel cells which are being tested for the vehicular applications.

2.4. FUEL CELL APPLICATIONS

The increasing demand for clean sources of energy due to fast depleting fossil fuels has put use of unconventional sources of energy more in demand. Among the unconventional sources of energy, Fuel Cell is becoming more popular because of virtually silent operation, environment friendly and higher efficiency [24]. Also the hydrogen is used as fuel in the fuel cells which is abundant in the earth and less prone to depletion as compared to other hydrocarbon fuels used for electricity production like diesel, coal, natural gas etc.

III. PROBLEM FORMULATION

A hybrid electric vehicle (HEV) augments an electric vehicle (EV) with a second source of power referred to as the alternative power unit (APU). Pure electric vehicles currently do not have adequate range when powered by batteries alone, and since recharging requires several hours, the vehicles are viewed as impractical for driving extended distances. If air conditioning or heating is used, the vehicle’s range is further reduced. Accordingly, the hybrid concept, where the alternative power unit is used as a second source of energy, is gaining acceptance and is overcoming some of the problems of pure electric vehicles.

IV. PROPOSED METHODOLOGY

In recent years, many countries across the world have been exploring and developing green vehicles since the petrol crisis and environmental problems throughout the world are becoming more and more severe. Consequently, electric vehicles, a vehicle of zero pollution, become a wise choice in these countries.

However, due to the cost of high-efficient batteries and the limited number of charging stations, Battery Electric Vehicles (BEVs) have not been widely applied into automotive market in many developing countries. Thus a more suitable vehicle, the Plug-in Hybrid Electric Vehicle (PHEV) is a better option in comparison with the BEV.

A PHEV is a hybrid vehicle which adopts rechargeable batteries that can be recharged by plugging it into external electrical outlets. A PHEV has an electric motor and an internal combustion engine (ICE). PHEVs are expected to consume less petroleum, lessen carbon dioxide emissions, counteract global warming, and be conducive to nations' energy independence, see [1].

The electric drive system is one of the key components of a PHEV. The electric drive system can largely affect the performance of the vehicle. For the current development of the motor, the crucial parts of the technical upgrade are to improve its reliability and life expectancy.

Due to the restrictions of space and environment, the PMSM drive system applied in PHEVs has some advantages compared to the conventional electric drive system, such as higher efficiency in steady-state and operates constantly at synchronous speed. PMSMs also have the advantages of high power density, high power factor and are easy to maintain. Therefore, PMSMs have become one of the significant development directions of electric motor in automotive applications.

V. SIMULATION RESULTS

A prototype model of proposed system is developed in the MATALB/SIMULINK environment. Here in the proposed work fuel cell is taken as the MATLAB tool box. The whole system is simulated in the MATLAB Simpower system tool box. Figure 5.1 shows the Simulink model of proposed fuel cell based PMSM drive.

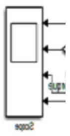

Figure 5.1: SIMULINK model of Proposed Fuel Cell Based PMSM Drive

A closed loop control scheme is used for controlling of the Permanent magnet synchronous motor drive. The basically here use vector control strategy for controlling of the PMSM motor. Figure 5.2 shows the Simulink model of the control scheme of the PMSM.

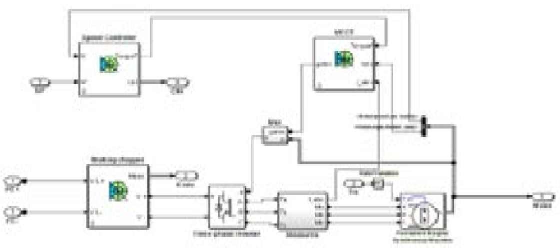

Figure 5.2: SIMULINK model of PMSM control Strategy

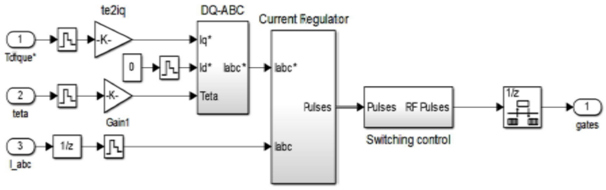

Figure 5.3: SIMULINK model of DC/DC Converter Block of Braking Chopper

Figure 5.3 shows the Fuel Cell configuration for power supply to the proposed PMSM drive.

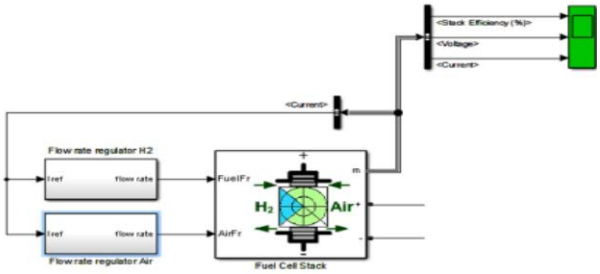

Figure 5.4 SIMULINK model of Fuel Cell for Power Supply

5.2 Result & Discussion

In this section here discuss the result generated by the proposed system. Table 5.1 shows the parameter used in the simulation of proposed system. The whole system is simulated in MATLAB/SIMULNIK environment. For running the simulation here ode23tb solver is used for the time Ts=2µS.

Table 5.1: System Parameter used in Simulation

Fuel Cell Parameter	
Voltage at 0A, and 1 A	400V, 380V
Nominal Operating Voltage	400
Nominal Operating Current	258
Number of Cell	400
Stack Efficiency	57%
H_2 Composition	99.95%
O_2 Composition	21%
Fuel Cell response Time	2 sec
Peak O_2 Utilization	80%
Voltage Overshoot at O_2 utilization	10V
Fuel Pressure	3 bar
Air Pressure	3 bar
PMSM Parameter	
Motor Rating	400 V, 50Hz, 3 Phase 4 pole
Stator Phase Resistance R_s	0.2 Ω
Inductance	L_d=8.5 mH, L_q= 8.5mH
Flux Linkage	0.175 wB

5.2.1 Performance of the Fuel Cell System

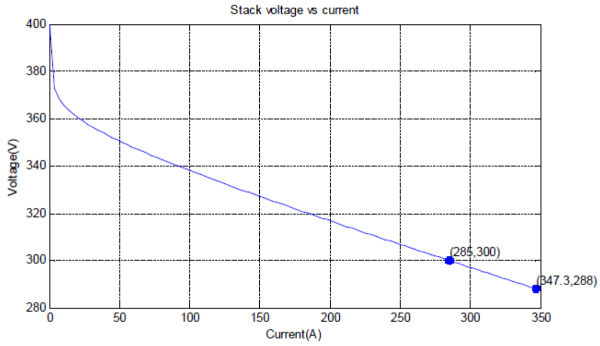

Figure 5.7: Stack Voltage versus current plot of proposed fuel cell configuration

Figure 5.7 shows the performance of the fuel cell in the form of stack voltage versus current output of the system. Here the operating voltage is shown in the figure with the current at the cell operating voltage.

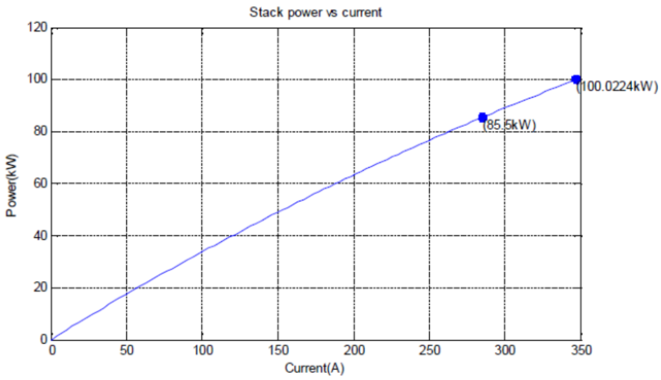

Figure 5.8: Stack Power versus Current plot of proposed fuel cell configuration

Figure 6.8 shows the performance of the fuel cell in the form of stack power versus current output of the system. Here the operating power is shown in the figure with the current at the cell operating current.

Figure 5.9 shows the stack efficiency of the fuel cell of the proposed system.

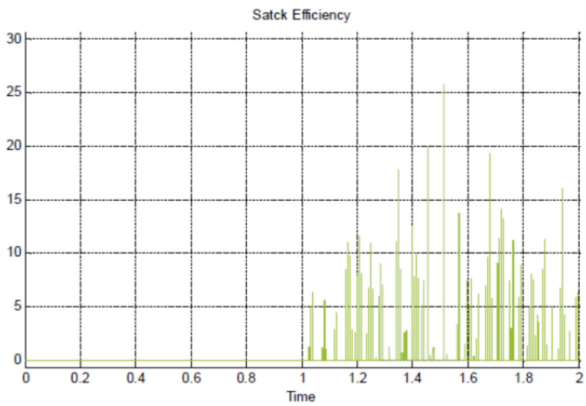

Figure 5.9: Fuel Cell Stack Efficiency of the proposed System

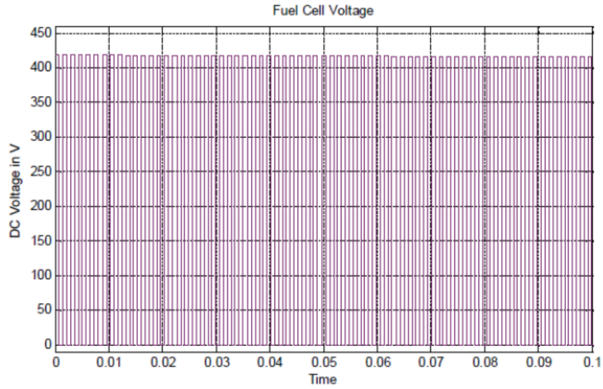

Figure 5.10: Fuel Cell output Voltage of the proposed system

Figure 5.10 shows the output voltage of the fuel cell system. Here it is shown that the output voltage of the system is in pulsating nature. Figure 5.11 shows the current output voltage of the fuel cell system. The output of the fuel cell is in pulsating in nature.

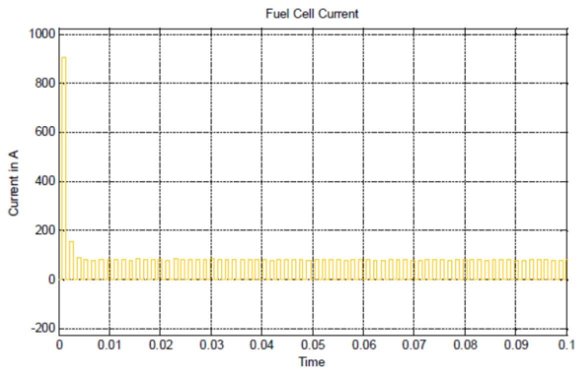

Figure 6.11: Fuel Cell Output Current of the Proposed System

5.2.2 Performance of the PMSM

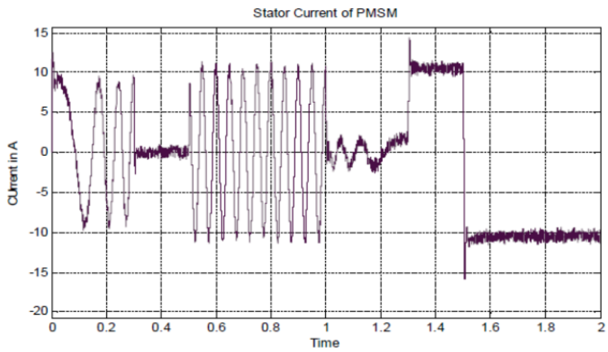

Figure 5.12: Stator Current of the PMSM

As shown in the following figure 5.12, stator current is 10A. After 0.3 sec it becomes to 0 at that time the rotor speed is at maximum. At t= 0.5 sec, stator current again build up due to smooth run of the motor.

ISSN: 2395-2946

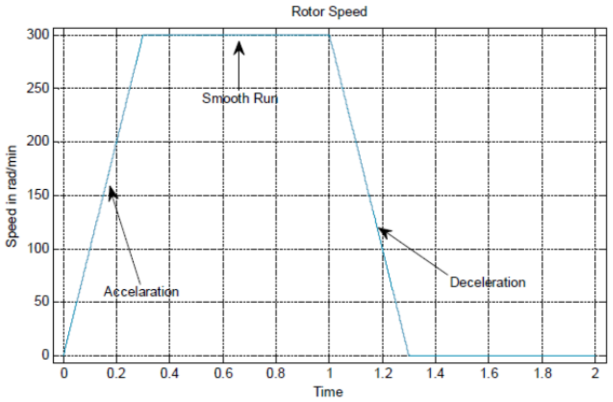

Figure 5.13: Rotor Speed in rpm of the PMSM drive

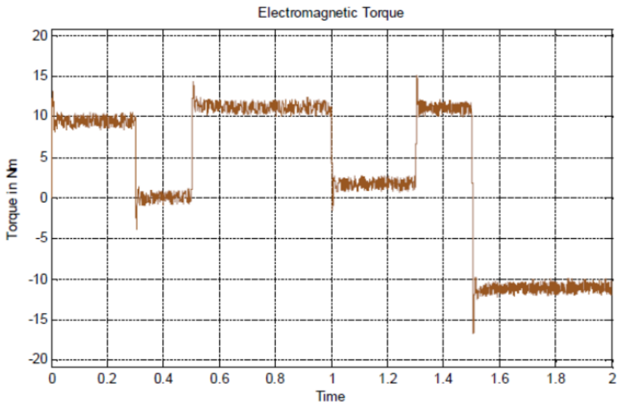

Figure 5.14: Electromagnetic Torque of PMSM Drive

Figure 5.13 shows the rotor speed in rpm and figure 5.14 shows the developed electromagnetic torque of the system. The speed precisely follows the acceleration ramp at the initial. At t = 0.5 s, the nominal load torque is applied to the motor. At t = 1 s, the speed set point is changed to 0 rpm. The speed decreases to 0 rpm. At t = 1.5 s., the mechanical load passes from 11 N.m to −11 N.m.

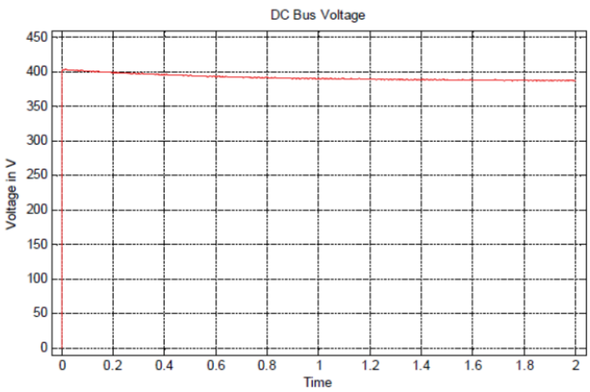

Figure 5.15: DC Bus voltage of the proposed system

Figure 5.15 shows the DC bus voltage which is generated by the breaking chopper of the PMSM drive.

The first block is *d-q to abc* block performs the conversion of two phase current component to rotor reference frame into three phase variable. The current regulator is used for controlling current ripple present in the rotor. It also adjusted by the use of hysteresis band to produce the pulses for the converter. The angle conversion block is used for computing the electrical rotor angle from the mechanical rotor angle. And the last switching control block is used for limiting the inverter commutation frequency to the maximum value specified for the proposed PMSM drive. Figure 5.3 shows the braking Chopper Simulink block. This block is used for DC to DC conversion of the proposed work. It is a dynamic braking chopper because it uses

VI. CONCLUSION & FUTURE WORK

6.1 CONCLUSION

Due to limitation of the fossil fuel the trend of automobile industries now move toward the electrical vehicle. The vehicle uses DC motor which has more restriction in the field of transportation. So now the researcher's works in the field of the implementation of the AC motor. AC motor has more advantage with respect to DC motor. The industry grows with the application of the AC motor. The main problem is the power supply. Fuel cell is a new type of power generation source which utilize a small area and mostly suitable for the electrical vehicle.

In this thesis proposed fuel cell based permanent magnet synchronous motor drive. For making the project here firstly reviewed the fuel cell technology. The concept of the fuel cell utilized in the drive is also discussed. The main aim objective of this proposed work is associated with the controlling of the drive based on PMSM. So for this the thesis also discusses the basic concept of permanent magnet synchronous drive system in brief. The control strategy is based on the field oriented control of the PMSM. Also here in this work discussed the fuel cell technology with their control strategy. The whole work is simulated in MATLAB software in SIMULINK environment to check the performance test based on the variable load torque of the system. On the basis of the simulation of the proposed work in different condition the result is found satisfactory in nature.

6.2 FUTURE WORK

The whole work is based on the application of fuel cell as a power source for PMSM drive system. There are some suggestions which can be used in the future for proposed work. Also some idea is here for improvement of the electrical drive application of the proposed work. The future scope of the proposed work is:

- Here in this thesis the field oriented control strategy is used for speed control of the PM Synchronous motor, in future direct torque control method is implemented for better control of the motor.

- The pulse width modulation technique here is used is SPWM. In future SVPWM technique can be used for more efficient PWM Technique.
- In future the optimization techniques like FUZZY, ACO, PSO etc is also implemented in the proposed system.
- Here in this proposed work harmonic related issues is not discussed so in future it is also useful for improving the dynamic behavior of the drive.

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