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Design And Control of Fuel Cell Based Permanent Magnet Synchronous Motor Drive For Electrical Vehicle:- A Review

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Abstract— The emission and fuel consumption favorable operation of the Hybrid Electric Vehicles have resulted in tremendous popularity increases of these vehicles during the last two decays. The lack of insight in the finite nature and in the environmental impact of the fossil fuels, as well as the fast development of the internal combustion engine during the first world war and the low fuel prices, pushed the electric vehicles aside. Now however, when the environmental impact of the traffic caused pollution is becoming visible and the fossil fuel reserve of this planet fades rapidly, new possibilities to be developed alternative power train concept arises. This development may even be considered as necessary if the freedom of using fast and flexible personal and goods transport are not to be abandoned meanwhile the planets environment is preserved for the future generations. In this proposed work hydrogen is used as fuel and pollutants are not released into the atmosphere hence it can continuously generate electric power as long as hydrogen and oxygen are available. Also, in this work Permanent magnet synchronous motor drive is used in place of dc motor, which makes the system of compact size, more efficient, larger torque to weight ratio, high power density, high torque capability and maintenance free. Due to this permanent magnet synchronous motors are widely used in high performance applications. 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 and SOFC etc.

I. INTRODUCTION

The emission and fuel consumption favorable operation of the Hybrid Electric Vehicles (HEVs) have resulted in tremendous popularity increase of these vehicles during the last two decays [1]. The electric vehicle is however not a new concept and the manufacturing of such vehicles started as early as before 1900. Ferdinand Porsche's first hybrid vehicle produced in 1899 was for instance propelled by four wheel-mounted electric motors with a series driveline solution [1].

The lack of insight in the finite nature and in the environmental impact of the fossil fuels, as well as the fast development of the internal combustion engine (ICE) during the First World War and the low fuel prices, pushed the electric vehicles aside [2]. Since then, the ICE vehicles have dominated the roads and have now probably done that far longer than any of those driving them today can remember. The infrastructure, performance demands, manufacturing process and many other aspects have been influenced and formed by this dominance. Now however, when the environmental impact of the traffic caused pollution is becoming visible and the fossil fuel reserve of this planet fades rapidly, new possibilities to developed alternative power train concepts arise.

This development may even be considered as necessary if the freedom of using fast and flexible personal and goods transports are not to be abandoned meanwhile the planets environment is preserved for the future generations.

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.

A. 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. This reduction in battery dependence is desirable since the battery, at present, can be regarded as the Achilles heel in all hybrids [3] due to e.g. low life time and high cost. The fuel cell technology however introduces other challenging aspects. One issue is the absence of fuel distribution infrastructure, making it hard to commercialize the fuel cell vehicle. To deal with this problem there are several demonstration projects of hydrogen highways around the world and ongoing research on storage possibilities. In a sense this issue is partially addressed in this thesis, where the fuel consumption and storage capacity is investigated.

Naturally it has to be kept in mind that for this emission favorable concept to become reality, the hydrogen needs to be produced and distributed in equally emission favorable way. In the ideal case also the manufacturing process, service and the recycling process all need to be emission favorable. Even if these issues are of great importance and strongly related to the environmental benefits of the FCV and other types HEVs, they are not considered in this text and left for other inspired investigators and future studies.

B. 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.

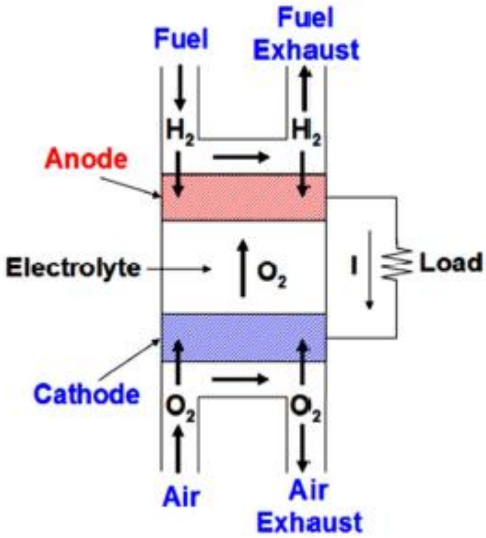

Figure 1: Basic configuration of Fuel Cell with operation

Figure 1.1 shows a block diagram of basic fuel cell operation. As illustrated in this figure, the fuel such as natural gas, coal, methanol, etc. is fed to the fuel electrode (anode) and oxidant (oxygen) is supplied to the air electrode (cathode). The oxygen fed to the cathode allows electrons from the external electrical circuit to produce oxygen ions.

The ionized oxygen goes to the anode through the solid electrolyte and combines with hydrogen to form water. Even though chemical reactions at anode and cathode may be a little different according to the types of fuel cells, the overall reaction can be described as follows:

Overall Reaction: $2H_{2(gas)} + O_{2(gas)} = 2H_2O + energy$

Since hydrogen and oxygen gases are electrochemically converted into water and energy as shown in the above overall reaction, fuel cells have many advantages over heat engines: high efficiency and actually quiet operation and, if hydrogen is the fuel, no pollutants are released into the atmosphere. As a result, fuel cells can continuously generate electric power as long as hydrogen and oxygen are available.

Among several types of the fuel cells categorized by the electrolyte used, four types are promising for distributed generation systems: Phosphoric Acid fuel cell (PAFC), Solid Oxide fuel cell (SOFC), Molten Carbonate fuel cell (MCFC), Proton-Exchange Membrane fuel cell (PEMFC).

C. 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. The Advancements in magnetic materials, semiconductor power devices and control theories have made the PMSM drives play a vitally important role in motion control applications.

The rotor of PMSM is connected to the load that cause low pulsation torque quality. Overlapping control during phase transition may also trim down the torque pulsation. For this PMSM required the power inverter to operate at higher switching frequency. So that it attains overlap control and noise reduction but result is high switching losses and lessening in the overall drive efficiency.

II. LITERATURE REVIEW

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 micro grid 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 micro grid 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 micro grid 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 micro grid 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 micro grid.

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III. PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE

Introduction :- Permanent magnet (PM) synchronous motors are progressively replacing dc motors in high-performance applications like robotics, aerospace actuators and industrial applications. The PMSM is more efficient and has a larger torque inertia ratio and power density when compared to the IM for the same output capacity. The PMSM is smaller in size and lower in weight that makes it preferable for certain high performance applications. The PMSM is a synchronous AC motor, normally with a three phase stator winding similar to induction motors. The rotor however, is different. Permanent magnet provides a constant flux to magnetize the motor. The lack of an electrical magnetization system gives the advantage of a more energy efficient motor. Depending of the armature winding distribution the PMSM can be divided into two types, Brush-Less DC (BLDC) or Permanent Magnet AC (PMAC) motors. The PMAC motor has armature winding that spans close to 1800 electrical degrees, which gives the motor a sinusoidal back emf. This is the motor type that this thesis will focus on. The BLDC has armature windings that spans over a smaller angle, which gives the motor a trapezoidal shaped back emf. The PMSM is normally controlled with a frequency converter that supplies the motor with the correct frequency and voltage/current values.

A. Design of Rotor

There are many possible design choices for the rotor, some of them can be seen in figure 3.1. Magnets can be mounted on the surface, in the surface and under the surface, all with different advantages/disadvantages.

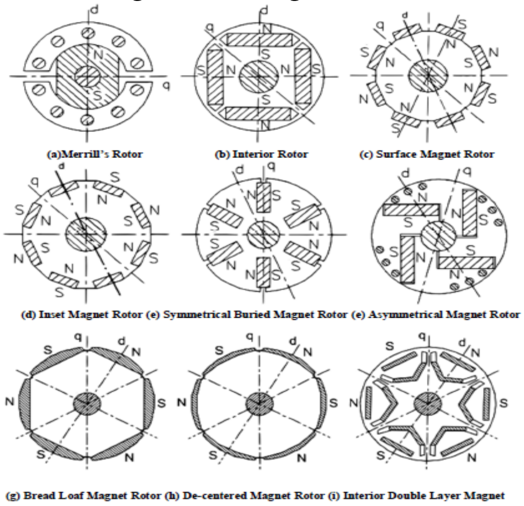

Figure 3.1: Configuration of different type of rotor

Surface mounted magnets will not withstand high rotational speed due to high centrifugal forces which crack or separate the magnets from the rotor. Subsurface- or buried- magnets need to be insulated from each other with slots or non magnetic material to avoid a magnetic short circuit, but the magnets are protected and held into place at high speeds. Figure 3.1a, 3.1b, 3.1e, 3.1f & 3.1i show rotors with buried magnets. Figure 3.1a and 3.1f show rotors with damper windings, the winding provides a possibility for asynchronous starting and dampens oscillations. Figure 3.1g and 3.1h show rotors with rounded magnets, which gives a more sinusoidal field distribution with fewer harmonic.

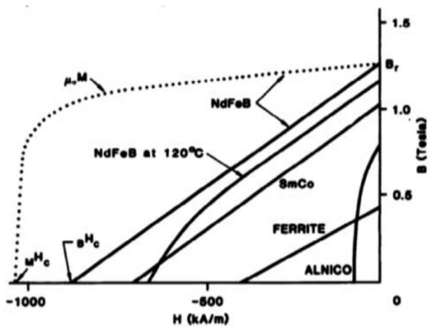

Figure 3.2: Flux Density versus Magnetizing Field of PMSM materials

B. Classification of Permanent Magnet Motor

A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications. In the following section the classification of the motor is discussed.

C. d-q modeling of PMSM

Detailed modeling of PM motor drive system is required for proper simulation of the system. The d-q model has been developed on rotor reference frame as shown in figure 3.3. At any time t, the rotating rotor d-axis makes and angle θr with the fixed stator phase axis and rotating stator mmf makes an angle α with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor.

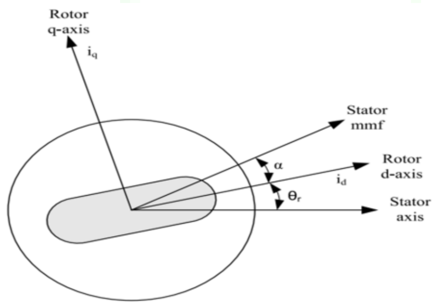

Figure 3.3: d-q modeling of Permanent Magnet Motor

D. Control of PMSM

Control of PM motors is performed using field oriented control for the operation of synchronous motor as a dc motor. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor as shown in figure 3.5.

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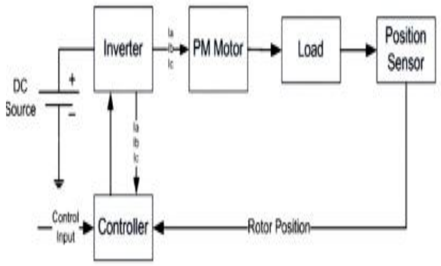

Figure 3.5: Block Diagram of Speed Control of PMSM

Field oriented control was invented in the beginning of 1970s and it demonstrates that an induction motor or synchronous motor could be controlled like a separately excited. dc motor by the orientation of the stator mmf or current vector in relation to the rotor flux to achieve a desired objective. In order for the motor to behave like DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of permanent magnet motor. This needs a resolver or an absolute optical encoder. Knowing the position, the three phase currents can be calculated. Its calculation using the current matrix depends on the control desired. Some control options are constant torque and flux weakening. These options are based in the physical limitation of the motor and the inverter. The limit is established by the rated speed of the motor, at which speed the constant torque operation finishes and the flux weakening starts as shown in figure 3.6.

IV. CONTROL METHOD FOR PMSM

A. Introduction

Synchronous motors have to be driven by a Variable Frequency Drive (VFD) to be able to run at different speeds. Control methods for electric motors can be divided into two main categories depending of what quantities they control. The control algorithm Scalar Control controls only magnitudes, whereas the algorithm Vector Control controls both magnitude and angles. These two main methods can be further divided into a number of different methods depending of their functionality, an overview over different control methods can be seen in figure 4.1.

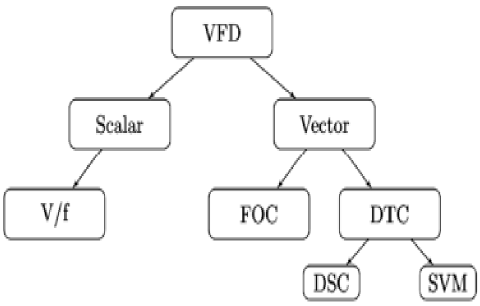

Figure 4.1: Control Strategy of AC Motor speed Control

4.2 Scalar Control

The simplest method to control a PMSM is scalar control, where the relationship between voltage or current and frequency are kept constant through the motors speed range. The frequency is set according to the wanted synchronous speed and the magnitude of the voltage/current is adjusted to keep the ratio between then constant. No control over angles is utilized, hence the name scalar control. The method uses an open-loop control approach without any feedback of motor parameters or its position.

This makes the method easy to implement and with low demands on computation power of the control hardware, but its simplicity also comes with some disadvantages. One of them are instability of the drive system after exceeding a certain applied frequency, to overcome this the rotor has to be constructed with damper windings to assure synchronization of the rotor to the electrical frequency. This will limit the number of design choices for the rotor, e.g. the magnets has to be located on the inside of the damper bars. Most PMSM are therefore constructed without damper windings, and they are not suitable for traditional scalar control. Another drawback with the lack of feedback is the systems low dynamic performance, which limits the use of this control method to e.g. fan- and pump-drives. For applications that demands high dynamic performance, vector control is recommended. One way to improve the performance without the use of position feedback is to use the variations in the inverters DC link voltage to determine the correct modulation.

B. Vector Control

With control of both magnitude and the angle of the flux it is possible to achieve higher dynamic performance of the drive system than scalar control can offer. Two different types of strategies exist for vector control, Field Oriented Control and Direct Torque Control.

C. Speed Control Strategy for PMSM

Many applications, such as robotics and factory automation, require precise control of speed and position. Speed Control Systems allow one to easily set and adjust the speed of a motor. The control system consists of a speed feedback system, a motor, an inverter, a controller and a speed setting device. A properly designed feedback controller makes the system insensible to disturbance and changes of the parameters C1 ,C2and C3 will be LOW and all others will be HIGH.

V. CONCLUSION AND FUTURE SCOPE

Due to limitation of the fossil fuel the trend of automobile industries now moves 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.

Future Scope

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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