DESIGN OF FUZZY CONTROLLER
OF IPMSM FOR ELECTRIC VEHICLE APPLICATION

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ABSTRACT

Electric Vehicles (EVs) run on electricity only. They are propelled by an electric motor powered by rechargeable battery packs. EVs do face significant battery-related challenges. The idea is to focus on increasing efficiencies in motor control strategy. This paper presents the fuzzy logic based speed control of an interior permanent synchronous motor (IPMSM) drive on electric vehicle application. The fundamentals of fuzzy logic algorithms related to motor control applications are illustrated. A new fuzzy speed controller for the IPMSM drive is designed. The efficiency of the proposed fuzzy logic controller (FLC) based IPMSM drive is verified by simulation on IPMSM simulation model and electric vehicle model. The fuzzy logic controller is found to be robust for application in the IPMSM drive.

ABSTRAK

Kenderaan elektrik bergerak dengan hanya menggunakan tenaga elektrik. Kebiasaannya pengangkutan ini digerakkan dengan motor elektrik yang dikuasakan oleh bateri boleh cas. Walaubagaimanapun, kenderaan jenis ini menghadapi cabaran berkaitan dengan bateri. Idea untuk menghadapi cabaran tersebut adalah dengan fokus kepada meningkatkan keupayaan strategi pengawalan motor. Matlamat projek ini adalah untuk membentangkan kawalan kelajuan “Interior Permanent Synchronous Motor (IPMSM)” pada kenderaan elektrik menggunakan kawalan “fuzzy logic”. Projek ini juga akan mengilustrasi asas algoritma “fuzzy logic” yang berkaitan dengan aplikasi kawalan motor; satu sistem kawalan kelajuan motor IPMSM yang baru diperkenalkan. Kecekapan system kawalan berasaskan “fuzzy logic” dibuktikan melalui simulasi pada model IPMSM dan juga model kenderaan elektrik. Sistem kawalan “fuzzy logic’ ini didapati tahan lasak untuk aplikasi pada motor IPMSM.

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LIST OF SYMBOLS AND ABBREVIATIONS

v_d, v_q - d- and q- axis stator voltages

i_d, i_q - d- and q- axis stator currents

R - Stator per phase resistance

L_d, L_q - d- and q- axis stator inductances

J_m - Moment of inertia of the motor and load

B_m - Friction coefficient of the motor

P - Number of poles of the motor

ω_r - Rotor speed in angular frequency

p - Differential operator (=d/dt)

ψ_f - Rotor magnetic flux linking the stator

PMSM - Permanent Magnet Synchronous Motor

IPMSM - Interior Permanent Magnet Synchronous Motor

SPMSM - Surface Permanent Magnet Synchronous Motor

FLC - Fuzzy Logic Controller

FCV - Fuel Cell Vehicle

EV - Electric Vehicle

FIS - Fuzzy Inference System

NB - Negative Big

NS - Negative Small

Z - Zero

PS - Positive Small

PB - Positive Big

CHAPTER 1

INTRODUCTION

1.1 Overview

There is a fast growing interest in electric vehicles (EVs). It is a transport that only uses electricity for its propulsion. Electric vehicles are the cleanest, most efficient, and most cost-effective form of transportation around the world. Supplies of liquid fuels like petrol and diesel are slowly running out, making them more expensive to use. While electric vehicles run on electricity only, they are much cheaper to run.

However, energy storage is the weak point of the EVs that delays their progress. For this reason, a need arises to build more efficient control, light weight, and compact electric propulsion systems, so as to maximize driving range per charge. Due to its high torque-current ratio, large power-weight ratio, high efficiency, high power factor, low noise and robustness, the permanent magnet synchronous motor (PMSM) is the preferred motor topology in today's automotive applications [1], [2]. PMSM with interior or buried magnet in rotor known as IPMSM has higher power density compared with surface mounted magnet (SPMSM) according to industrial standard so far [3].

The challenge comes to researchers on how to control this motor efficiently due to its robustness and non-linearity characteristic. Initially fixed gain PI controllers were employed by researchers as speed controller of IPMSM drive system because of their simplicity [4], [5], [6]. However it's very hard to determine suitable PI controller parameters in controlling complex non-linear, incompletely modeled or uncertain systems since the speed and the torque of the motor always change depends on terrain and traffic condition traveled by electric vehicle. Besides, this PI controller will exhibit poor transient response thus it's not suitable for this application due to complexity of this system. Despite of this limitation, PI controller has an advantage over steady state response with simplest structure [7], [8].

Intelligent controllers offer many advantages as their design do not need the exact mathematical model of the system and theoretically they are capable of handling any non-linearity of arbitrary complexity [9]. Besides they exhibit excellent dynamic response. Among the various intelligent controllers, fuzzy logic controller (FLC) is the simplest and better in terms of response time, insensitivity to parameter and load variations [9], [10].

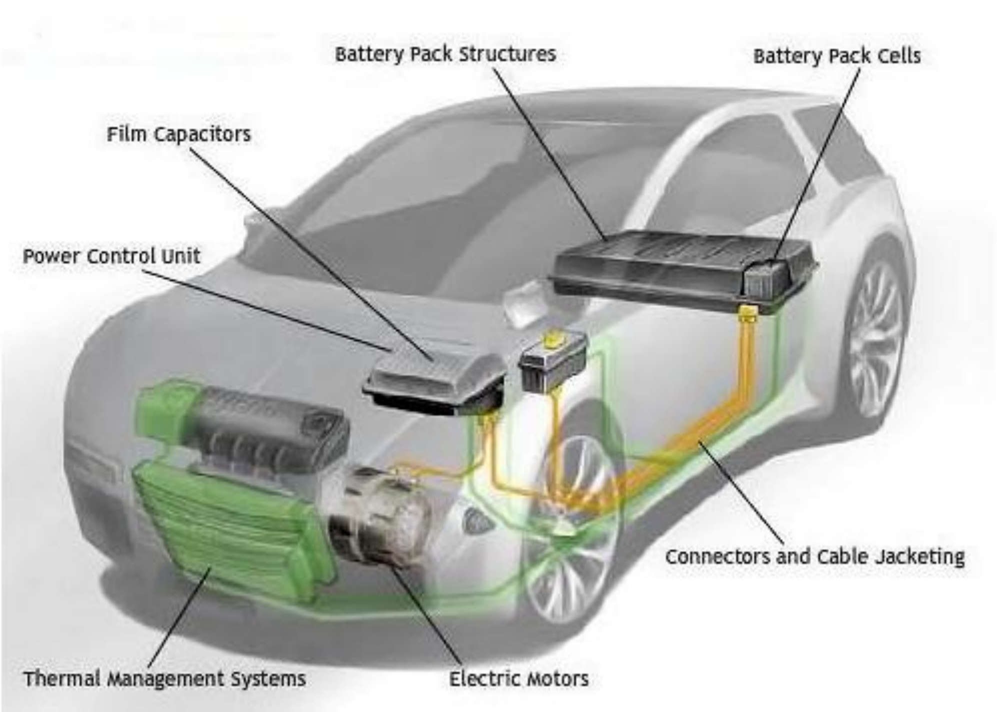


Figure 1.1: System architecture in the electric vehicle. [11]

1.2 Problem Statement

All electric vehicles (EVs) run on electricity only. They are propelled by an electric motor powered by rechargeable battery packs. EVs have several advantages over vehicles with internal combustion engines (ICEs):

- Energy efficient. Electric vehicles convert about 59–62% of the electrical energy from the grid to power at the wheels—conventional gasoline vehicles only convert about 17–21% of the energy stored in gasoline to power at the wheels. [18]
- Environmentally friendly. EVs emit no tailpipe pollutants, although the power plant producing the electricity may emit them. Electricity from nuclear, hydro, solar, or wind-powered plants causes no air pollutants.
- Performance benefits. Electric motors provide quiet, smooth operation and stronger acceleration and require less maintenance than ICEs.
- Reduce energy dependence. Electricity is a domestic energy source.

EVs do, however, face significant battery-related challenges:

- Driving range. Most EVs can only go about 100–200 miles before recharging—gasoline vehicles can go over 300 miles before refueling.
- Recharge time. Fully recharging the battery pack can take 4 to 8 hours. Even a "quick charge" to 80% capacity can take 30 min. [19]
- Battery cost: The large battery packs are expensive and may need to be replaced one or more times.
- Bulk & weight: Battery packs are heavy and take up considerable vehicle space.

However, there are several different ways to deal with these challengers. There are researchers working on improved battery technologies to increase driving range and decrease recharging time, weight, and cost. Some will focus on improving the performance of traction motor used and some will focus on increasing efficiencies in motor control strategy.

Usually, high-performance drives used as traction drives require low to high-speed operation, fast and accurate speed response, quick recovery of speed from any disturbances, and insensitivity of speed response to parameter variations. So far, most of the reported works have utilized proportional-integral (PI) controller as the speed controller. The disadvantages of PI controllers are well known, as its design depends on the exact motor parameters and the performance is sensitive to system disturbances [12].

Thus, one of the main objectives of this project is to replace the conventional PI controller by an intelligent controller, which is capable of handling highly nonlinear IPM motor drive system for high-performance applications like in electric vehicles. In the present work, an intelligent but computationally simple fuzzy logic controller (FLC) is developed. The main advantages of FLC over the conventional controllers are that the design of FLC does not depend on machine parameters. It also can handle nonlinear functions of arbitrary complexity and its performance is more robust as compared to the conventional controllers [12], [13].

1.3 Aim & Objectives

The development of control strategy based on fuzzy controller of permanent magnet synchronous motor with internal magnet (IPMSM) for electric vehicle application is the aims of this research. To achieve this aim, the objectives of this research are formulated as follows:

- To develop a controller based on artificial intelligence.
- To apply newly developed controller on IPMSM model.
- To apply newly developed controller on Electric Vehicle (EV) model.
- To apply conventional controller for comparison purpose.
- To compare the performance of both controller.

1.4 Scope of Project

The scopes of work for this project are outline as below:

- The controller will be based on artificial intelligence technique which is Fuzzy Controller with 5 membership functions implemented as a rule.
- The new develop controller will be implemented on IPMSM model and Electric Vehicle model for evaluation purposes.
- The performance of controller will be evaluated based on power consumption and motor efficiency.

1.5 Thesis Outline

This thesis has been divided into 5 chapters. Chapter 2 deals with literature review on fuzzy logic controller and IPMSM motor for electric vehicle purposes. This chapter will explain generally on research work done by other researchers related to this project. The findings and outcomes will give an idea on the type of problem need to be tackled and improvement that can be done on this project.

Chapter 3 presents on research methodology for this project. It explains in details on the electric vehicle model and the fuzzy logic controller developed for this project. Fuzzy logic and fuzzy control feature a relative simplification of a control methodology description. This allows the application of a natural ‘human’ language to describe the problems and their fuzzy solutions. This chapter will give an insight about designing Fuzzy Controller of IPMSM for electric vehicle application using Matlab/Simulink.

Chapter 4 discusses about the simulation results. The performance of the Fuzzy Logic Controller is evaluated by simulation study using Matlab/Simulink. For the comparison purposes, the simulation results of conventional P-I Controller is also presented.

Chapter 5 summarizes the works undertaken. Recommendations for future work on this project are presented at the end of the chapter.

1.6 Project Planning

Planning is one of the most important project and time management techniques. Planning means preparing a sequence of action steps to achieve some specific goal. Figure 2 below shows a Gantt chart for this project.

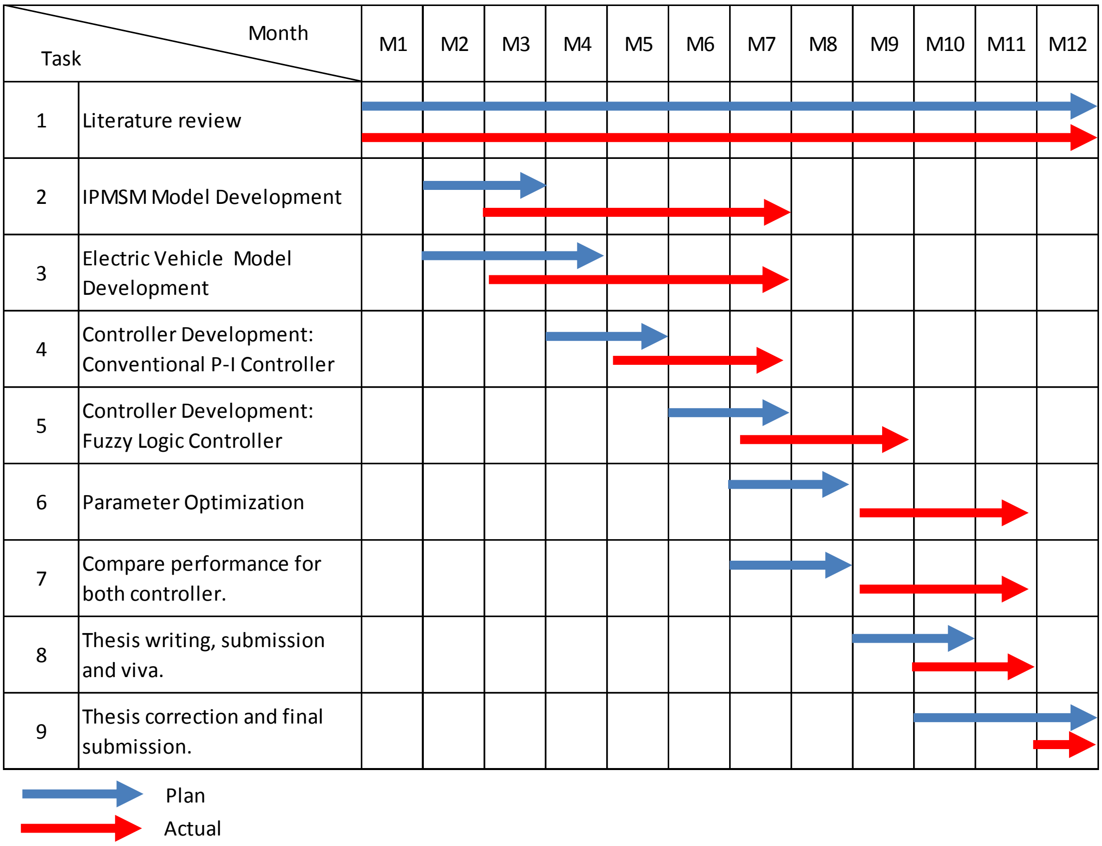


Figure 1.2: Gantt chart of the project.

CHAPTER 2

A BRIEF REVIEW ON FUZZY CONTROLLER OF IPMSM

2.1 Chapter Overview

This chapter explains on the work done by other researchers related to Fuzzy Logic Controller of IPMSM. This section will provide insights on the advantages or problems faced by other researchers. Thus it gives justification of why this project is conducted.

2.2 Permanent Magnet Synchronous Motor (PMSM)

Permanent magnet synchronous motors (PMSM) have emerged as a very strong contender to replace induction motors used in electronically controlled variable speed applications in recent years. In most cases, PMSMs can provide superior performance in terms of increased efficiency and reduced noise. [2, 3].

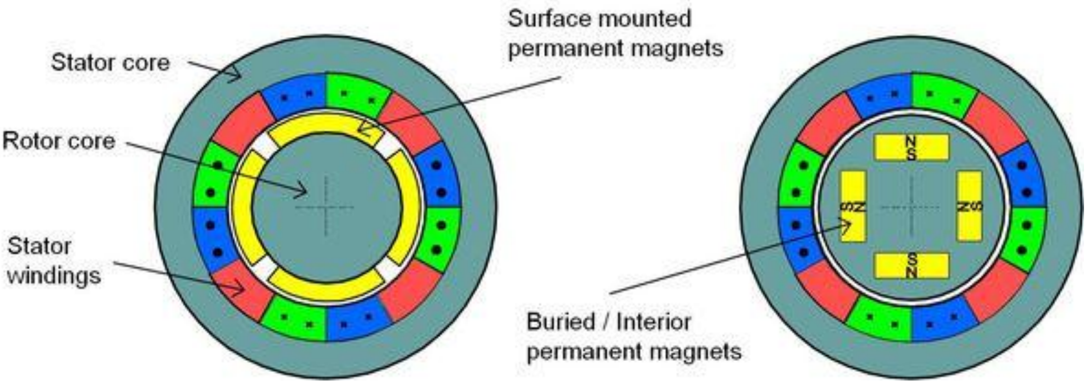


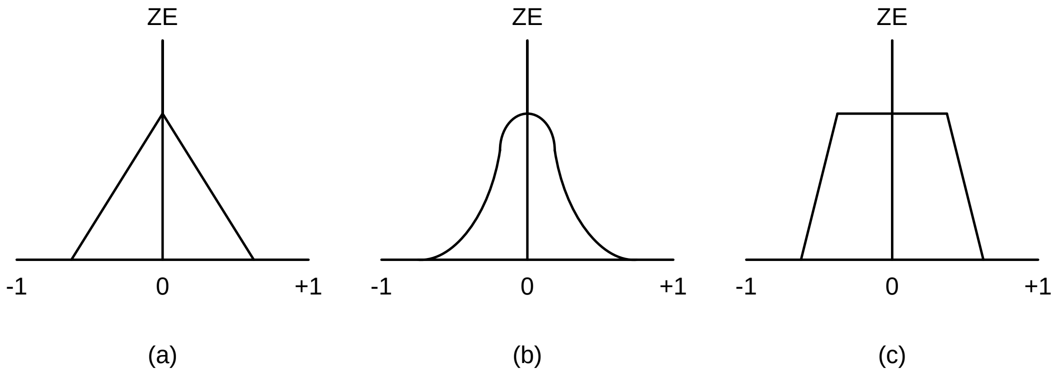
Figure 2.1: Cross section of permanent magnet synchronous motors with surface mounted magnets (SPMSM - left) and interior magnets (IPMSM - right) [3].

At the core of a PMSM are the permanent magnets (PMs), which are placed in the rotor to provide the magnetizing flux. One immediate advantage is that in a typical design, there are virtually no rotor losses. In PM motors, the magnets can be placed in two different ways on the rotor as shown in Figure 2.1. Depending on the placement, they are called either Surface Permanent Magnet Synchronous Motor (SPMSM) or Interior Permanent Magnet Synchronous Motor (IPMSM). SPMSM, having a surface mounted permanent magnet rotor, are generally used for low speed applications because of the limitation that the magnets may fly apart during high-speed operations. On the other hand, IPMSM, having interior mounted permanent magnet rotor, is a good candidate for high-speed operation [20].

2.3 Fundamentals of Fuzzy Logic Control

Fuzzy logic idea is similar to the human being’s feeling and inference process. Unlike classical control strategy, which is a point-to-point control, fuzzy logic control is a range-to-point or range-to-range control. The output of a fuzzy controller is derived from fuzzifications of both inputs and outputs using the associated membership functions. A crisp input will be converted to the different members of the associated membership functions based on its value. From this point of view, the output of a fuzzy logic controller is based on its memberships of the different membership functions, which can be considered as a range of inputs.

The fuzzy logic controller is based on the fuzzy set and fuzzy logic theory introduced by Zadeh [21]. The fuzzy set A on the universe X is defined by a membership function, % from X to the real interval [0,1], which associates a number m(x)~[0,l] to each element x of universe X. Q (x) represent the grade of membership function of x to A i.e., a subjective value for the degree of A-ness of x. %(x)=0.5 means x has A-ness of about 50%. In fuzzy set theory, the boundaries of the fuzzy sets can be vague and ambiguous, just to make it useful for approximate systems. The fuzzy sets are represented graphically by means of their membership functions.



(a) (b) (c)

Figure 2.2: Membership functions of zero (ZE) :(a) triangular,
(b) Gaussian function and (c) trapezoidal.

There are numerous choices for the membership functions. The choice of membership functions depends on the designer's preference and/or experience. Figure 2.2 shows some possible choices of membership functions for a fuzzy set associated with the linguistic value ZE (zero) in the universe X=[-1, 1]. From the Figure 2.2 it is shown that the number 0 fully belongs to the fuzzy sets while the number -1 and +1 not belongs to the fuzzy sets. The complete process of formulating the mapping from a given input to an output using fuzzy logic is the fuzzy inference. Fuzzy inference is mainly based on three parts which are fuzzification, rule evaluation and defuzzification. Figure 2.3 shows a basic structure of fuzzy logic controller.

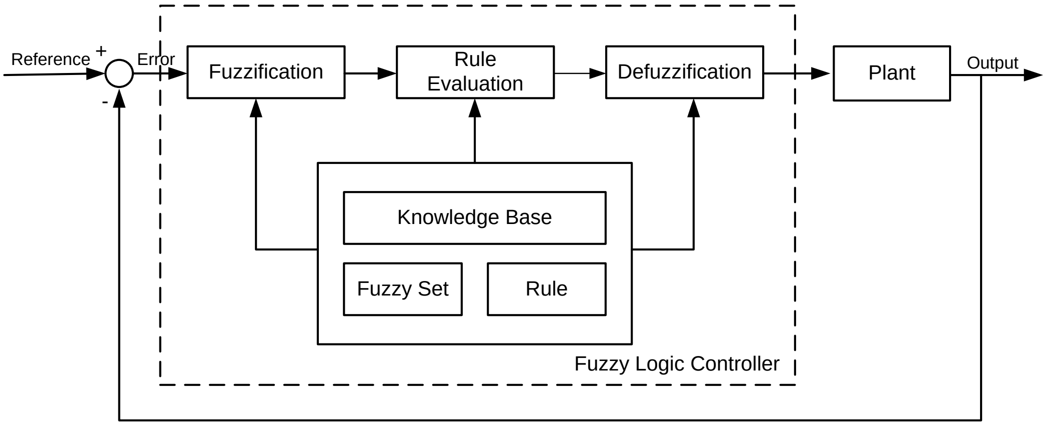


Figure 2.3: Basic structure of fuzzy logic controller

2.3.1 Fuzzification

The process of converting a numerical 'variable (real number) into a linguistic variable (fuzzy number) is fuzzification. In FLC, the input is always a crisp numerical value limited to the universe of the input variable and the output is fuzzy degree of membership in the qualifying linguistic set (always between 0 and 1).

2.3.2 Rule Evaluation

Fuzzy control rule can be considered as the knowledge of an expert in any related field of application. The fuzzy rule is represented by a sequence of the form IF-THEN, leading to algorithms describing what action or output should be taken in terms of the currently observed information, which includes both input and feedback if a closed-loop control system is applied. The law to design or build a set of fuzzy rules is based on a human being’s knowledge or experience, which is dependent on each different actual application. A fuzzy IF-THEN rule associates a condition described using linguistic variables and fuzzy sets to an output or a conclusion. The IF part is mainly used to capture knowledge by using the elastic conditions, and the THEN part can be utilized to give the conclusion or output in linguistic variable form. This IF-THEN rule is widely used by the fuzzy inference system to compute the degree to which the input data matches the condition of a rule.

2.3.3 Defuzzification

The defuzzification process is meant to convert the fuzzy output back to the crisp or classical output to the control objective. Remember, the fuzzy conclusion or output is still a linguistic variable, and this linguistic variable needs to be converted to the crisp variable via the defuzzification process. Three defuzzification techniques are commonly used, which are: Mean of Maximum method, Center of Gravity method and the Height method.

2.4 Related Work by Other Researchers

Casey Butt and M. A. Rahman presents in [14] a simplified fuzzy logic based speed controller of an interior permanent synchronous motor (IPMSM) drive for maximum torque per ampere (MTPA) of stator current with inherent nonlinearities of the motor. Contrary to the conventional control of IPMSM with d-axis current equal to zero, a non-linear expression of d-axis current has been derived and subsequently incorporated in the control algorithm for maximum torque operation.

M J Hossain presents in [15] a simplified fuzzy logic based speed controller for an IPMSM drive with complete vector control scheme incorporating the fuzzy logic controller (FLC). It is found that if the number of rules increases, better performance is obtained, but the computational burden will also be increased, which is a major limitation for real-time implementation. Considering this limitations only four rules have been used in this work.

M. Nasir Uddin and Ronald S. Rebeiro presents in [16] an online loss minimization algorithm (LMA) for a fuzzy logic controller (FLC) based interior permanent magnet synchronous motor (IPMSM) drive to yield high efficiency and high dynamic performance over wide speed range. The loss minimization algorithm is developed based on the motor model. In order to minimize the controllable electrical losses of the motor and thereby maximize the operating efficiency the d-axis armature current is controlled optimally according to the operating speed and load conditions. For vector control purpose, a fuzzy logic controller (FLC) is used as a speed controller which enables the utilization of the reluctance torque to achieve high dynamic performance as well as to operate the motor over a wide speed range.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Chapter Overview

This chapter covers the overall process on how the research was carried out and provide insights in designing Fuzzy Controller of IPMSM for electric vehicle application using MATLAB/Simulink simulation. The research work was executed in the following three developmental stages as showed in Figure 3.1.

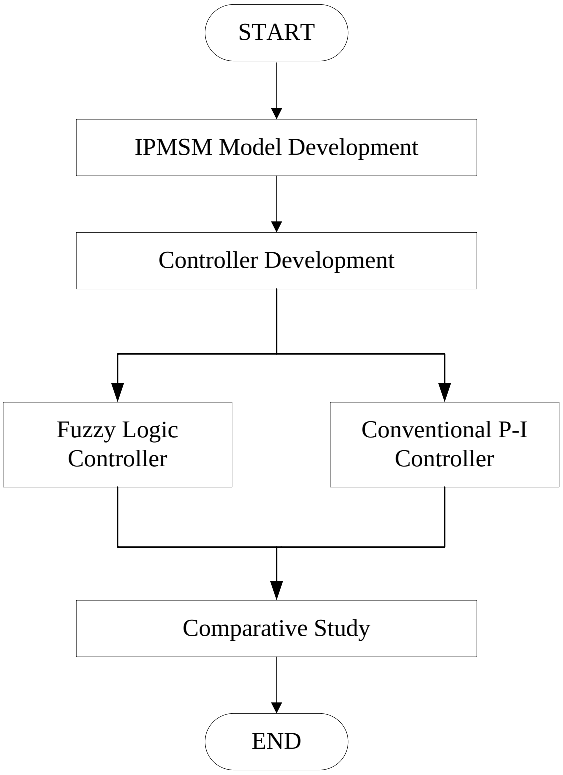


Figure 3.1: Research developmental stage.

3.2 Electric Vehicle Model Development

The main part in this project is to develop fuzzy controller of IPMSM for electric vehicle application whereby the fuzzy controller developed will be applied on existing electric vehicle model. During this stage, several existing models of electric vehicle and IPMSM motor has been researched and studied before they were applied on this project for simulation purposes.

3.2.1 Mathematical Model of IPMSM

An IPMSM can be represented mathematically by the following equations in the d q axis synchronously rotating rotor reference frame for assumed sinusoidal stator excitation as,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -P\omega_r L_q \\ P\omega_r L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ P\omega_r \psi_f \end{bmatrix} \tag{3.1}$$

$$T_e = T_L + J_m p\omega_r + B_m \omega_r \tag{3.2}$$

$$T_e = \frac{3P}{2}\left(\psi_f i_q + \left(L_d - L_q\right) i_d i_q\right) \tag{3.3}$$

Where, $v_d, v_q =$ d- and q- axis stator voltages;

$i_d, i_q =$ d- and q- axis stator currents;

$R =$ Stator per phase resistance;

$L_d, L_q =$ d- and q- axis stator inductances;

$J_m =$ moment of inertia of the motor and load;

$B_m =$ friction coefficient of the motor;

$P =$ number of poles of the motor;

$\omega_r =$ rotor speed in angular frequency;

$p =$ differential operator (=d/dt);

$\psi_f =$ rotor magnetic flux linking the stator;

As seen from the motor model of equations (3.1) to (3.3), the speed of the IPMSM can be controlled by regulating d–q axes components of stator current. In this work, the d-axis current component, which is also known as magnetizing current component, is forced to zero in the vector control scheme of the IPMSM drive. Therefore, all the magnet flux linkages are oriented in the d-axis, and the torque equation becomes linear.

3.2.2 IPMSM Simulink Model

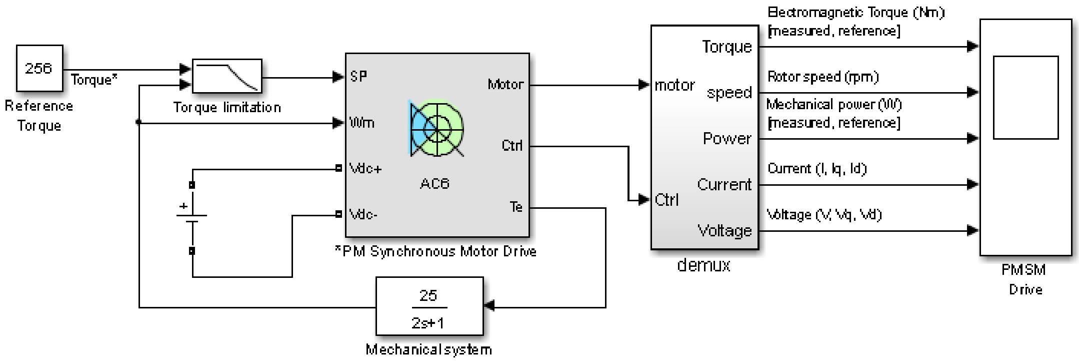


Figure 3.2: AC6 - 100 kW Interior Permanent Magnet Synchronous Motor Drive

This circuit shown in Figure 3.2 uses a modified version of the AC6 block of the SimPowerSystems™ electric drives library. It models a flux weakening vector control for a 100 kW, 12500 rpm, salient pole PMSM powered by a 288 Vdc source. The mechanical system is represented externally. That is why the input of the motor is the speed and the output is the electromagnetic torque.

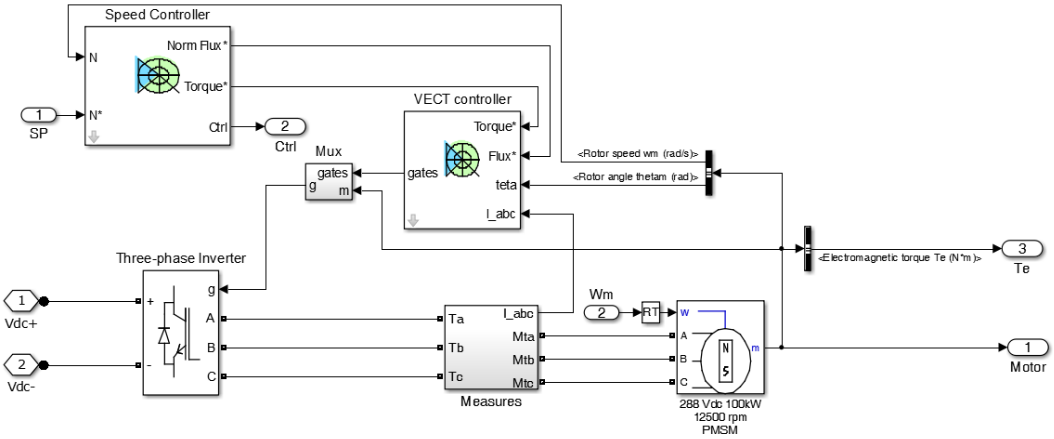


Figure 3.3: PM Synchronous Motor Drive

Figure 3.3 shows the PM Synchronous Motor Drive is composed of four main parts which are electrical motor, Three-phase Inverter, VECT controller and the Speed Controller. The electrical motor is a 288 Vdc, 100 kW PMSM. This motor has 8 pole and the magnets are buried (salient rotor's type).

The Three-phase Inverter is a voltage source inverter, controlled by PWM. This block is built using the Universal Bridge Block. The VECT controller block computes the three reference motor line currents corresponding to the flux and torque references and then generates a corresponding PWM using a three-phase current regulator. When the nominal flux is required, an optimal control is used in order to minimize the line current amplitude for the required torque. When a flux weakening is needed, the amplitude and the phase of the current are changed to extend the torque-speed operating range. And lastly the Speed Controller is used in torque regulation mode. The normalized flux value is computed with the speed of the machine in order to perform a flux weakening control.

The Torque limitation block is used to prevent the limitation due to the torque-speed characteristic of this motor for a 288 Vdc source. When the internal machine's voltage reaches the inverter voltage (because the desired torque is too high for the motor's speed), the inverter turns to saturation mode (the desired current can no longer flow into motor). After this point, there will be a loss of current tracking which will decrease the motor current. This block is used to reduce the reference torque as a function of the motor’s speed and the torque-speed characteristic in order to never operate in inverter saturation mode.

3.2.3 Fuel Cell Vehicle (FCV) Simulink Model

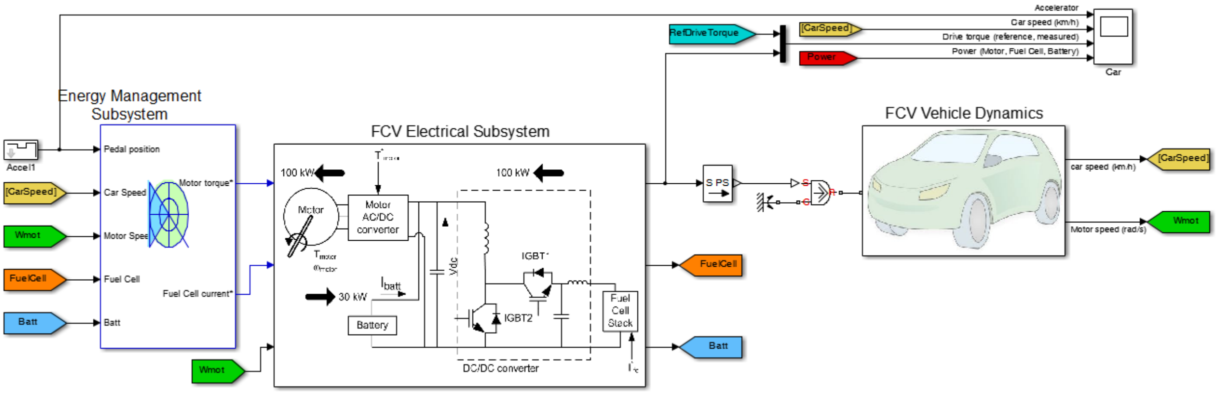


Figure 3.4: Fuel Cell Vehicle (FCV) power train

Figure 3.4 shows a multi-domain simulation of a FCV power train based on SimPowerSystems and SimDriveline. This FCV is propelled by one electric motor powered by a fuel cell and a battery. This was developed by Olivier Tremblay, Souleman Njoya Motapon and Louis-A. Dessaint from Ecole de Technologie Superieure, Montreal.

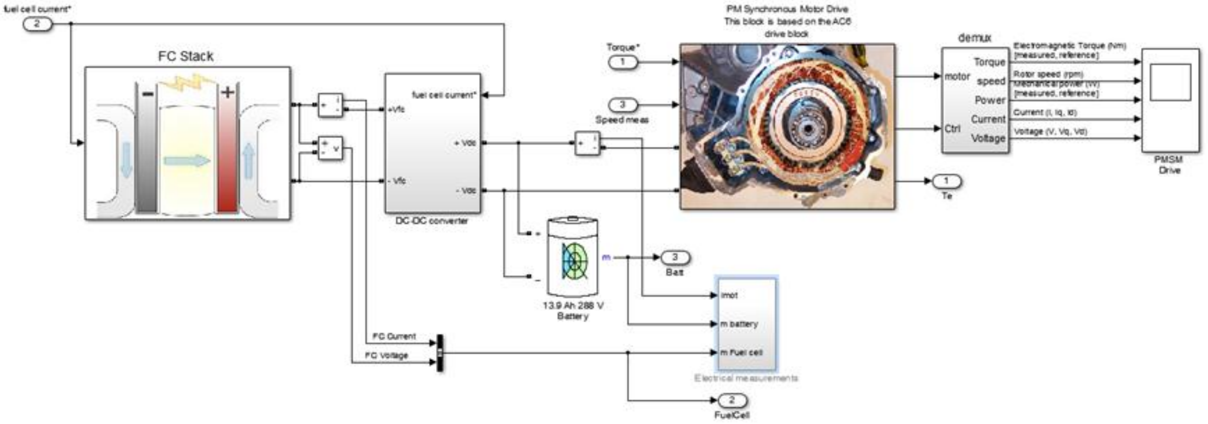


Figure 3.5: FCV Electrical Subsystem

The FCV Electrical Subsystem is composed of four parts as shown in Figure 3.5 which are the electrical motor, the battery, the fuel cell and the DC/DC converter. The electrical motor is a 288 Vdc, 100 kW interior Permanent Magnet Synchronous Machine (PMSM) with the associated drive (based on AC6 blocks of the SimPowerSystems Electric Drives library). This motor has 8 pole and the magnets are buried (salient rotor's type). A flux weakening vector control is used to achieve a maximum motor speed of 12 500 rpm.

The battery is a 13.9 Ah, 288 Vdc, 25 kW Lithium-Ion battery and the fuel cell is a 400 cells, 288 Vdc, 100 kW Proton Exchange Membrane (PEM) fuel cell stack. Lastly the DC/DC converter (buck type) is current-regulated.

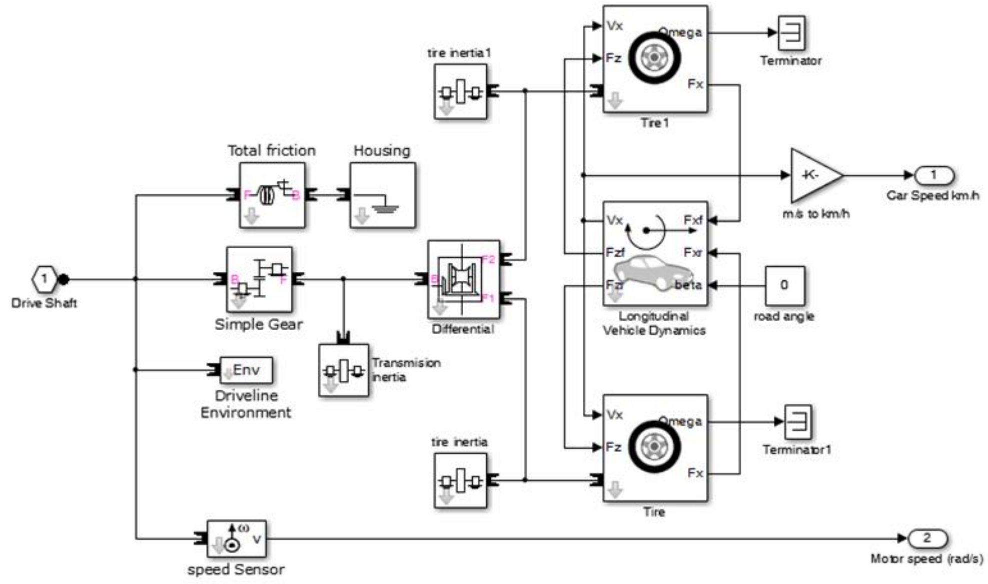


Figure 3.6: FCV Vehicle Dynamics Subsystem.

The FCV Vehicle Dynamics Subsystem models all the mechanical parts of the vehicle as shown in Figure 3.6. The single reduction gear reduces the motor's speed to increase the torque. Then the differential splits the input torque into two equal torques. The tires dynamics represent the force applied to the ground while the vehicle dynamics represent the motion influence on the overall system. Lastly the viscous friction models all the losses of the mechanical system.

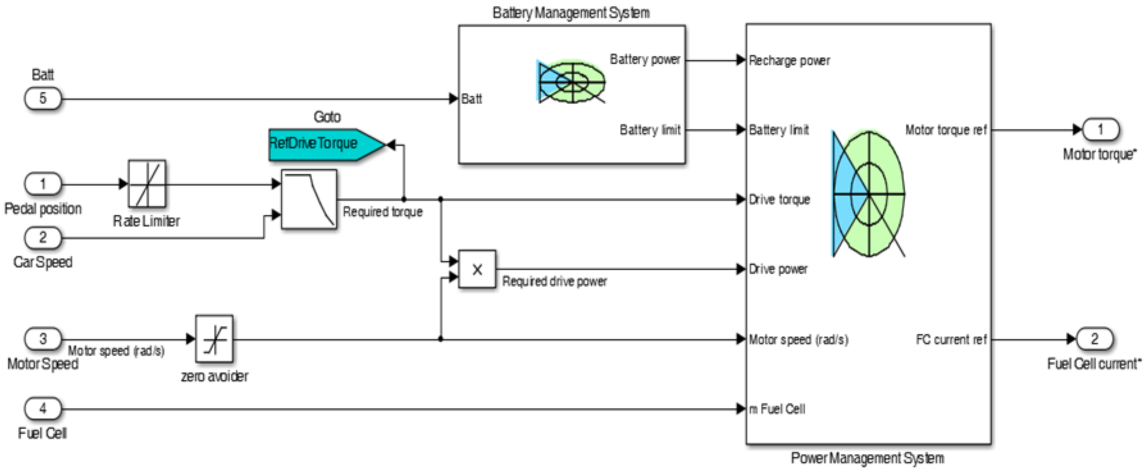


Figure 3.7: Energy Management Subsystem

Figure 3.7 shows the Energy Management Subsystem (EMS). It determines the reference signals for the electric motor drives, the fuel cell system and the DC/DC converter in order to distribute accurately the power from the two electrical sources. These signals are calculated using mainly the position of the accelerator, which is between -100% and 100%, and the measured FCV speed. Note that a negative accelerator position represents a positive brake position.

The Battery management system maintains the State-Of-Charge (SOC) between 40% and 80%. Also, it prevents against voltage collapse by controlling the power required from the battery. The Power management system controls the reference power of the electrical motor by splitting the power demand as a function of the available power of the battery and the fuel cell. This power is controlled by the DC/DC converter current.

3.3 Controller Development

Developing a controller is the most critical part in this project. The process for control development was illustrated in Figure 3.8. The performance of new develop Fuzzy Controller will be apply on IPMSM model first and its performance will be compared with the conventional PI Controller. The comparison will be based on four major characteristics of the closed-loop step response which are:

1) Rise Time: the time it takes for the plant output Y to rise beyond 90% of the desired level for the first time.
2) Overshoot: how much the peak level is higher than the steady state, normalized against the steady state.
3) Settling Time: the time it takes for the system to converge to its steady state.
4) Steady-state Error: the difference between the steady-state output and the desired output.

If the performance of Fuzzy Controller is worse than conventional PI Controller then parameter optimization will be done to get better results. And if better results cannot be achieve after several times using parameter optimization method then a new Fuzzy Controller will be developed.

When better results are achieved by simulation on IPMSM Model, this Fuzzy Controller will be applied on Fuel Cell Vehicle (FCV) Model for simulation and comparison purposed with conventional PI Controller. The comparison will be based on power consumption by motor, the lower power consumption, the better control performance.

Once again if the results produced by Fuzzy Controller is not good compared to conventional PI Controller then parameter optimization process will be executed in order to achieve good results.

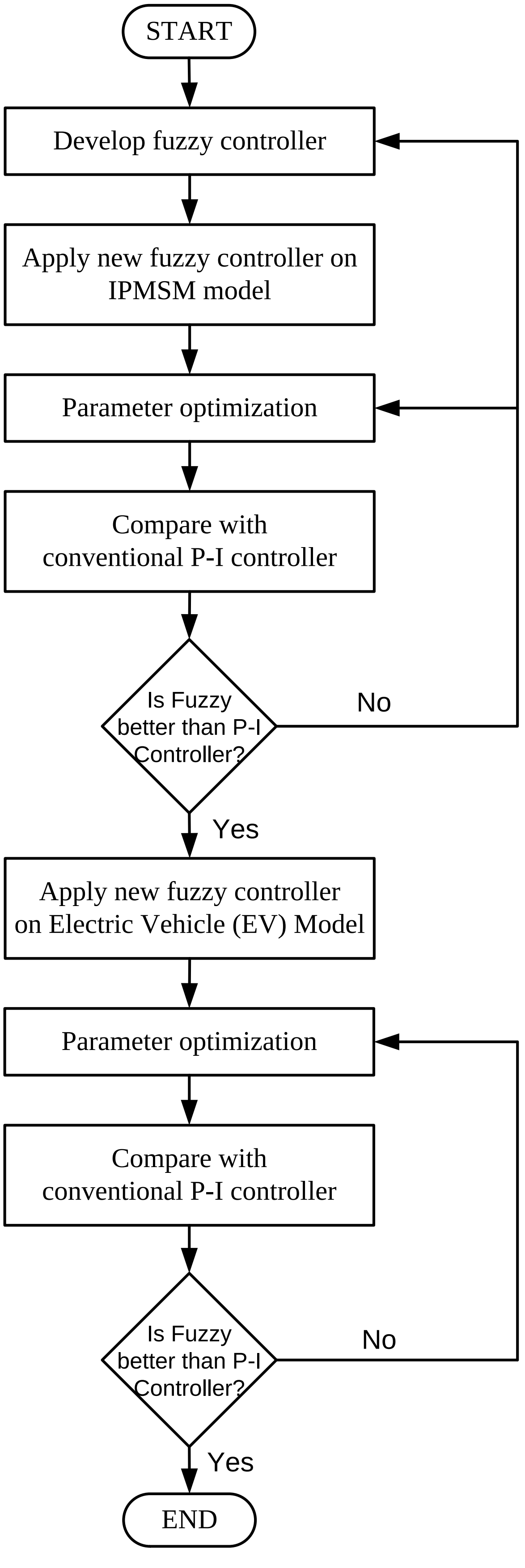


Figure 3.8: Control Development Process.

3.3.1 Conventional P-I Controller

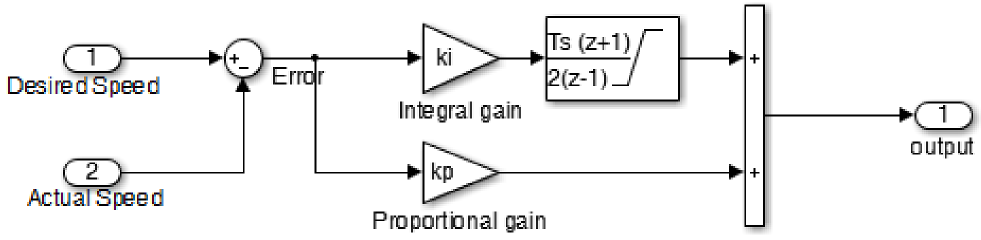


Figure 3.9: Existing P-I Controller architecture.

P-I controller is simple two-term controller. The letter P and I stand for P-Proportional, I- Integral. Figure 3.9 above shows an existing conventional P-I Controller used in IPMSM Model and FCV Model. The results from this existing P-I Controller will be compared with the results from Fuzzy Controller. The Proportional Gain, K_P was set at 1 while for Integral Gain, K_I was set at 100.

3.3.2 Design of Fuzzy Controller

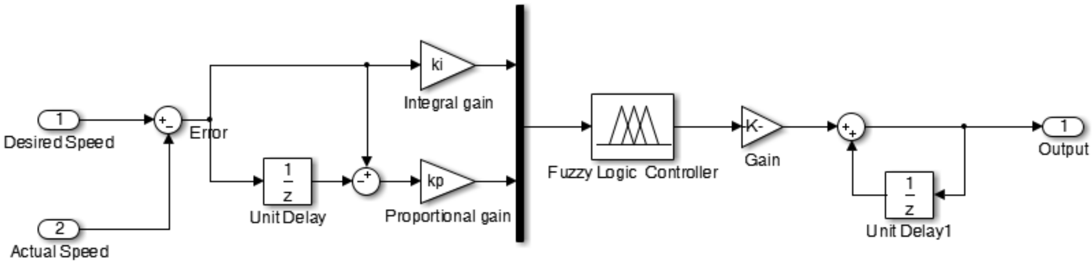


Figure 3.10: Structure of new develop Fuzzy Controller

Figure 3.10 above shows the Fuzzy Controller that has been developed in this project. Fuzzy controller used in this paper is based on two input FLC structure with coupled rules. The fuzzy control rule is in the form of: IF e=Ei and de=dEj THAN

REFERENCES

[1] F. Gieras and M. Wang, Permanent Magnet Motor Technology, New York, NY: Marcel Dekker Inc., 2002.

[2] A. Consoli, G. Scarcella, G. Scelba, and A. Testa, "Steady-State and Transient Operation of IPMSMs under Maximum-Torque-per-Ampere Control," IEEE Trans. Ind. Appl., vol. 46, No. 1, pp. 121-129, JanJFeb. 2010.

[3] University of Paderborn. (2011). Control of Permanent Magnet Synchronous Motors for Automotive Applications. Retrieved June 7, 2013, from http://wwwlea.uni-paderborn.de/en/research/pmsm-control.html

[4] B.K. Bose, "A High Performance Inverter Fed Drive System of an Interior Permanent Magnet Synchronous Machine." IEEE Trans. On Industry Applications, vol. 1A-24, no. 6, 1988, pp 987-997.

[5] S.R. Macminn, T.M. Jahns, "Control Techniques for Improved High Speed Performance of Interior PM Synchronous Motor Drives," IEEE Transactions on Industry Applications, Vol. 27, No. 5, Sept.-Oct. 1991, pp. 997 - 1004.

[6] T. M. Jahns, G. B. Kliman and T. W. Neumann, "Interior Permanent Magnet Synchronous Motors for Adjustable Speed Drives," IEEE Transactions on Industry Applications, Vol. 1A-22, No. 4, July-Aug.1986, pp. 738-747.

[7] F. J. Lin and Y. S. Lin, "A Robust PM Synchronous Motor Drive with Adaptive Uncertainty Observer," IEEE Transactions on Energy Conversion, 1999, vol. 14, no. 4, pp 989-995.

[8] Y. Sozer and D. A. Torrey, "Adaptive Flux Weakening Control of Permanent Magnet Synchronous Motors," IEEElIAS Annual Meeting Conference Record, 1998, pp. 475-482.

[9] M. N. Uddin, M. A. Abido and M. A. Rahman, "Real-Time Performance Evaluation of a Genetic Algorithm Based Fuzzy Logic Controller for IPM Motor Drives," IEEE Transactions on Industry Applications, Vol. 41, No. I, Jan. /Feb. 2005, pp. 246-252.

[10] M. N. Uddin, and M. A. Rahman, "High Speed Control of IPMSM Drives Using Improved Fuzzy Logic Algorithms," IEEE Trans. Ind. Appl., vol. 54, No. 1, pp. 190-199, Feb. 2007.

[11] "Materials Are Critical to Reduce Dependence on Fossil Fuels." Plastics and Packaging. N.p., n.d. Web. 20 June 2013. http://www.plastech.biz/news/Materials-are-critical-to-reduce-dependence-on-fossil-fuels%2Cn4569.

[12] N. Urasaki, T. Senjyu, K. Uezato, "Neural Network Based High Efficiency Drive for Interior Permanent Magnet Synchronous Motors Compensating EMF Constant Variation," Power Conversion Conference, Osaka, Japan, April 2002, Vol. 3, pp. 1273 - 1278 .

[13] Faa-Jeng Lin,Chih-Hong Lin, and Po-Hung Shen, "Self-Constructing Fuzzy Neural Network Speed Controller for Permanent-Magnet synchronous Motor Drive," IEEE Transactions on Fuzzy Systems, Vol. 9, No. 5, Oct. 2001, pp. 751 - 759.

[14] Butt, C.B., M.A. Hoque, and M.A. Rahman, Simplified fuzzy-logic-based MTPA speed control of IPMSM drive. Industry Applications, IEEE Transactions on, 2004. 40(6): p. 1529-1535.

[15] M J Hossain, M A. Hoque, M M. Ali M A. Rahman, “Design and Implementation of A Simplified Fuzzy Logic Based Ipmsm Drive” 4th International Conference on Electrical and Computer Engineering ICECE 2006.

[16] Uddin, M. and R.S. Rebeiro, Online efficiency optimization of a fuzzy-logic-controller-based IPMSM drive. Industry Applications, IEEE Transactions on, 2011. 47(2): p. 1043-1050.

[17] "Documentation Center." AC6. N.p., n.d. Web. 20 June 2013. < http://www.mathworks.com/help/physmod/sps/examples_v2/ac6-100-kw-interior-permanent-magnet-synchronous-motor-drive.html >

[18] Miller, M., Holmes, A., Conlon, B., and Savagian, P., "The GM “Voltec” 4ET50 Multi-Mode Electric Transaxle," SAE Int. J. Engines 4(1):1102-1114, 2011, doi: 10.4271/2011-01-0887.

[19] Chae, H. J.; Kim, W.Y.; Yun, S. Y.; Jeong, Y.S.; Lee, J. -Y; Moon, H. T., "3.3kW on board charger for electric vehicle," Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on , vol., no., pp.2717,2719, May 30 2011-June 3 2011 doi: 10.1109/ICPE.2011.5944762

[20] Y. Li and D. Gerling, "The Comparison of Control Strategies for the Interior PMSM Drive used in the Electric Vehicle," The 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition, Shenzhen, China, Nov. 5-9, 2010

[21] Zadeh, Lotfi A. "Outline of a new approach to the analysis of complex systems and decision processes." Systems, Man and Cybernetics, IEEE Transactions on 1 (1973): 28-44.