International Journal of Scientific Research Engineering & Technology (IJSRET)
Volume 1 Issue 5 pp 101-106 August 2012 www.ijsret.org ISSN 2278 - 0882

Design, Development & Simulation of Fuzzy Logic Controller to Control the Speed of Permanent Magnet Synchronous Motor Drive System

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ABSTRACT
The paper presents the detailed modelling by fuzzy logic controller (FLC) for permanent magnet synchronous motor derive system in Simulink, the simulation includes all realistic components of the system, which enables the calculation of current and voltages in different parts of the invertors and motor under transients and steady state condition. The fuzzy logic controller is used for speed control of this type of motor. The dynamic response of (PMSM) with the proposed controller is studied under different load disturbances. The effectiveness of the proposed fuzzy logic controller is compared with that of the conventional PI & PID controllers. The proposed controller is used in order to overcome the nonlinearity problem of PMSM and also to achieve faster settling response.

I. INTRODUCTION
Industry automation is mainly developed around motion control systems in which controlled electric motors play a crucial role as heart of the system. Therefore, the high performance motor control systems contribute, to a great extent, to the desirable performance of automated manufacturing sector by enhancing the production rate and the quality of products. In fact the performance of modern automated systems, defined in terms of swiftness, accuracy, smoothness and efficiency, mainly depends to the motor control strategies. The advancement of control theories, power electronics and microelectronics in connection with new motor designs and materials has contributed largely to the field of electric motor control for high performance systems.

Traditionally commutator motors, also known as direct current (dc) motors were preferred for variable speed drives while induction motors were used for constant speed applications. Advances in solid state devices helped in development of suitable controllers possessing provision of vector control. Such controllers made it possible to incorporate in the induction motor almost all the characteristics of a dc motor. In vector control scheme, torque and flux are decoupled from each other like in dc motors. Newly developed permanent magnet synchronous motors (PMSM) with high energy permanent magnet materials particularly provide fast dynamics, efficient operation and very good compatibility with the applications but only if they are controlled properly. However, the ac motor control including control of PMS motors is a challenging task due to very fast motor dynamics and highly non-linear models of the machines. Therefore, a major part of motor control development consists of deriving mathematical models in suitable forms. The dynamic models of the motors can be presented in different reference frames to lay down a basis for the motor control design. The mathematical formulations and the equivalent circuit models can be provided to help in better controller design for PMSM drives. There are two competing control strategies for ac motors viz vector control (VC) and direct torque control (DTC) for PMSM.

Vector control scheme with several benefits is the most applied control strategy. The decoupling of torque control and flux linkage control are the basis of vector control technique. The motor phasor diagrams can provide better understanding of different control schemes used for PMSM drives. It is the most straightforward approach for motor modeling and control. It also reduces the analytical burden. The momentum of this popularity will considerably increase in the near future due to the recent availability of the high-energy low-cost Neodymium-Iron-Boron (NdFeB) Permanent magnet.

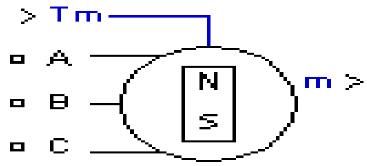
II. ADVANTAGES ASSOCIATED WITH BRUSHLESS MOTORS

1. The absence of the field winding eliminates losses on the rotor and makes these motors highly efficient.
2. The absence of the external rotor excitation renders slip rings on the rotor and brushes obsolete, and thus reduces the maintenance cost
3. The low inertia of the rotor improves the dynamic response of the motor
4. Use of permanent magnet materials results in higher power to weight ratio as compared to other motors of the same size.
5. Rotor construction is simpler due to absence of commutator.
6. These motors operate at improved power factor.
7. These motors have high torque to inertia ratio.

These motors basically fall into two main categories: Permanent Magnet Synchronous Motor (PMSM) also known as Sinefed motor, which is designed to be supplied by sinusoidal current waveforms. This type is again of two types: 1) surface mounted and interior buried. Surface mounted are again of two types:
1. Projecting type, in which magnet projects from the surface of the rotor and
2. Inset type, in which magnets are inserted into the rotor, provides a smooth rotor surface. In interior type magnets PM motors magnets are embedded in the interior of the rotor.

III. PERMANENT MAGNET SYNCHRONOUS MACHINE DESCRIPTION

The Permanent Magnet Synchronous Machine block operates in either generator or motor mode. The mode of operation is dictated by the sign of the mechanical torque (positive for motor mode, negative for generator mode). The electrical and mechanical parts of the machine are each represented by a second-order state-space model. The model assumes that the flux established by the permanent magnets in the stator is sinusoidal, which implies that the electromotive forces are sinusoidal. The block implements the following equations expressed in the rotor reference frame (qd frame)



Permanent Magnet Synchronous Machine1

Electrical System

$$\frac{d}{dt} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_r i_q$$

$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q + \frac{L_d}{L_q} p\omega_r i_q - \frac{\lambda p \omega_r}{L_q}$$

$$T_e = 1.5 p[\lambda i_q + (L_d - L_q) i_d i_q$$

Where (all quantities in the rotor reference frame are referred to the stator)

Lq, Ld	=	q and d axis inductances
R	=	Resistance of the stator windings
iq, id	=	q and d axis currents
vq, vd	=	q and d axis voltages
ωr	=	Angular velocity of the rotor
p	=	Number of pole pairs
Te	=	Electromagnetic torque

Mechanical System

$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - F\omega_r - T_m)$$

$$\frac{d\theta}{dt} = \omega_r$$

Where

J	=	Combined inertia of rotor and load
F	=	Combined viscous friction of rotor and load
θ_r	=	Rotor angular position
T_m	=	Shaft mechanical torque

The Permanent Magnet Synchronous Machine block assumes a linear magnetic circuit with no saturation of the stator and rotor iron. This assumption can be made because of the large air gap usually found in permanent magnet synchronous machines.

IV. PERMANENT MAGNET RADIAL FIELD MOTORS

In PM motors, the magnets can be placed in two different ways on the rotor because of that PMSM can be categorized based on mounting of permanent magnets

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fig.2 a shows one possible rotor structure with two pole pairs. The magnets are mounted on the surface of the rotor (SPMSM).

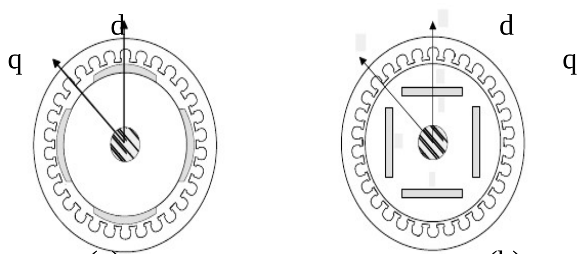

Fig.2 (a) PMSM with surface mounted magnets,
(b) PMSM with interior mounted magnets, two pole pairs

In the case of IPMSM there are flux paths in d axis direction where the reluctance is high due to low permeability of the permanent magnet material fig.2 b. thus the inductance is clearly larger in the q axis direction. The buried magnet placement enables a small air gap. Thus the inductances are large as compared to a SPMSM.

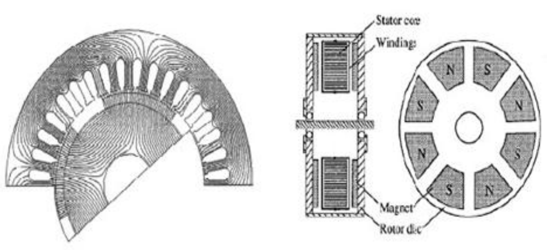

Fig.3 (a) Radial flux structure and (b) axial flux structure

V. FUZZY LOGIC CONTROLLER

Fig.4 shows the basic configuration of a Fuzzy Logic Controller (FLC). A FLC consists of the following components:

- Fuzzification Interface
- Knowledge Base (KB)
- Decision Making Logic
- Defuzzification Interface

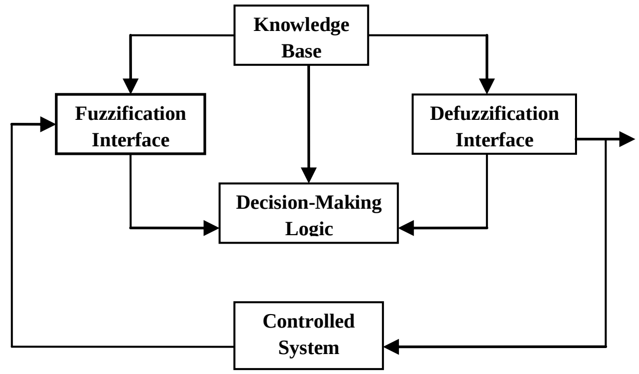

Fig.4 Basic Configuration of FLC

A fuzzy controller is a special fuzzy system that can be used as a controller component in a closed-loop system. The integration of a fuzzy system into a closed loop is shown. Special emphasis is put onto the transfer behaviour of fuzzy controllers, which is analyzed using different configurations of standard membership functions. An example for the design of a fuzzy controller for a loading crane is given. Finally, the module series is closed by a general discussion about the contribution of fuzzy control.

VI. PERMANENT MAGNET MOTOR CONTROL

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.

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 Fig.5.

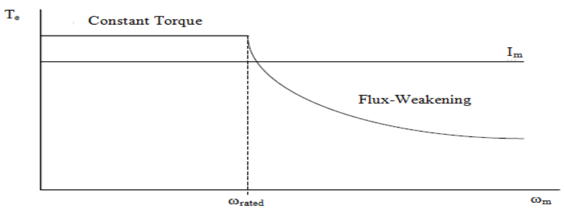

Fig.5 Steady State Torque versus Speed

VII. MODELING OF THE PMSM DRIVE SYSTEM

1. PI Controller Modeling

In the PI speed controller the motor speed is compared with the reference speed and the speed error is the nth sampling interval as

$\omega_{e[n]} = \omega_{r*[n]} - \omega_{r[n]}$

The output of the speed controller gives the reference torque. Hence the output of the speed controller at the nth sampling interval is

$T_{[n]} = T_{[n-1]} + Kp(\omega_{e[n]} - \omega_{e[n-1]}) + Ki.\ \omega_{e[n]}$

For constant air gap flux operation reference quadrature axis current is given as

$i_{q*} = T_{[n]}/K_t$

The limiter is used to limit the maximum value of output of speed controller. The maximum motor rated current and device current of the converter dictate the limit.

Where,

$\omega_{e[n]}$ is speed error at nth instant
$\omega_{r*[n]}$ is the reference speed at nth instant
$\omega_{r[n]}$ is the actual motor speed at nth instant
$\omega_{e[n-1]}$ is the speed error at (n-1)th instant
$T_{[n]}$ is the reference torque at nth instant
$T_{[n-1]}$ is the reference torque at (n-1)th instant
K_p is proportional gain of the speed controller
K_i is integral gain of the speed controller
is reference quadrature axis current
K_t is torque constant

2. PID Controller Modeling

In the PID speed controller the motor speed is compared with the reference speed and the speed error is the nth sampling interval as

$\omega_{e[n]} = \omega_{r*[n]} - \omega_{r[n]}$

The output of the speed controller gives the reference torque. Hence the output of the speed controller at the nth sampling interval is

$T_{[n]} = T_{[n-1]} + K_p(\omega_{e[n]} - \omega_{e[n-1]}) + K_i.\ \omega_{e[n]} + K_D(\omega_{e(n)} - 2\omega_{e(n-1)} + \omega_{e(n-2)})$

The limiter is used to limit the maximum value of output of speed controller. The maximum motor rated current and device current of the converter dictate the limit.

Where,

$\omega_{e[n]}$ is speed error at nth instant
$\omega_{r*[n]}$ is the reference speed at nth instant
$\omega_{r[n]}$ is the actual motor speed at nth instant
$\omega_{e[n-1]}$ is the speed error at (n-1)th instant
$T_{[n]}$ is the reference torque at nth instant
$T_{[n-1]}$ is the reference torque at (n-1)th instant
K_p is proportional gain of the speed controller
K_i is integral gain of the speed controller
K_D is derivative gain of the speed controller
i_{q*} is reference quadrature axis current

VIII. SPEED CONTROL OF PMSM MOTOR

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.

The purpose of a motor speed controller is to take a signal representing the demanded speed, and to drive a motor at that speed. Closed Loop speed control systems have fast response, but become expensive due to the need of feedback components such as speed sensors.

IX. IMPLEMENTATION OF THE SPEED CONTROL LOOP

For a PM motor drive system with a full speed range, the system will consist of a motor, an inverter, a controller (constant torque and flux weakening operation, generation of reference currents and PI controller) as shown in Fig.6

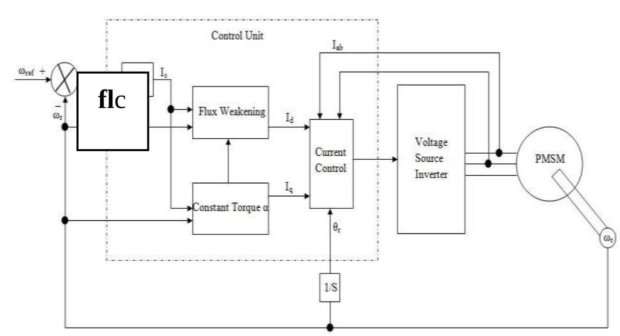

Fig. 6 Block Diagram of FLC Controlled PMSM

X. SIMULATION OF PMSM DRIVE SYSTEM

Simulink has the advantages of being capable of complex dynamic system simulations, graphical environment with visual real time programming and broad selection of tool boxes. The simulation environment of Simulink has a high flexibility and expandability which allows the possibility of development of a set of functions for a detailed analysis of the electrical drive. Its graphical interface allows selection of functional blocks, their placement on a worksheet, selection of their functional parameters interactively, and description of signal flow by connecting their data lines using a mouse device. System blocks are constructed of lower level blocks grouped into a single maskable block. Simulink simulates analogue systems and discrete digital systems.

The performance of the PMSM drive under different speed and current controllers is examined through simulation studies using the SIMULINK toolbox of the MATLAB software package. In this thesis, simulation of PMSM drive has been done with the following speed and current controllers:

1. PI speed controller with PWM current controller
2. PID speed controller with PWM current controller
3. Fuzzy Logic controller with PWM current controller

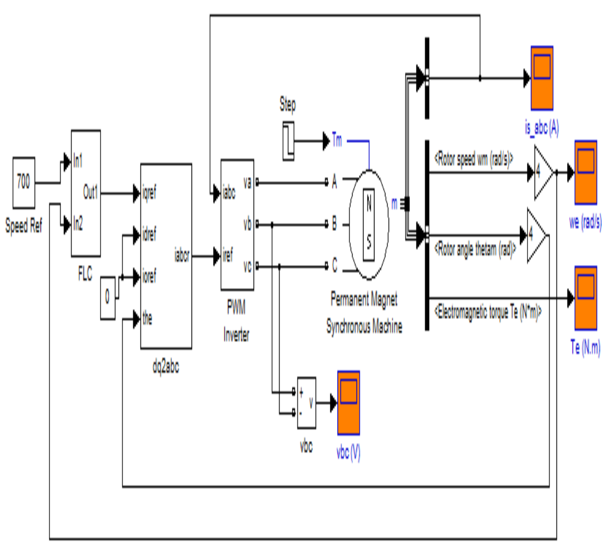

Fig.7 Simulink Block Diagram of PMSM with fuzzy logic controller

XI. SIMULATION RESULT OF FLC CONTROLLER

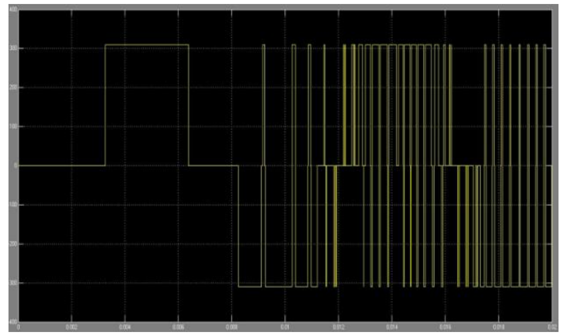

Fig 8. Vabc

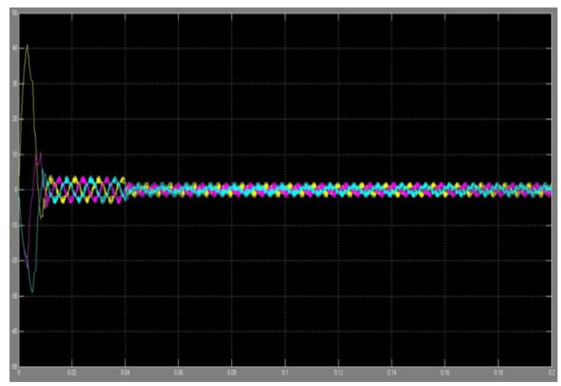

Fig 9 Is_abc Stator Current

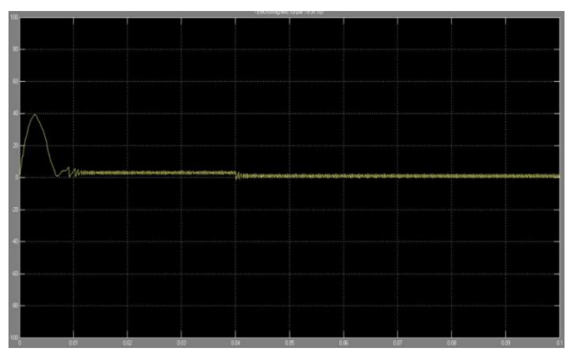

Fig 10 Torque Nm

XII. RESULTS AND DISCUSSIONS FOR FUZZY LOGIC

The FLC has exhibited high performance in tracking the speed reference. The stator current, flux and torque response of PMSM with fuzzy controller is faster than PI and PID controllers during start up and during a step change in torque. At the same time, dynamic behavior of PMSM with fuzzy logic controller is more stable than PI and PID controllers.

A performance comparison between the fuzzy logic controller and conventional PI and PID controllers has been carried out by several simulations confirming the superiority of the Fuzzy Logic Controller.

XIII. CONCLUSION AND FUTURE SCOPE

The overall idea of this work is to compare the performance of different speed and current controllers for PMSM drive. For this purpose, the motor drive system simulation model was developed and verified through the SIMULINK toolbox of the MATLAB software package. For current controller, PWM is examined and for speed controller, performance of PI, PID and Fuzzy Controllers are compared.

The simulated results confirmed the viability of the model used in this work and it has been shown that the model is suitable for transient as well as steady state condition. These results also confirmed that the transient torque and current never exceed the maximum permissible value. Among all the speed controllers discussed, Fuzzy Logic Controller makes the system robust as there is no speed overshoot and also minimum pulsation in torque and current The implementation of additional control techniques like unity power factor control, constant mutual air gap flux linkages control, optimum torque per ampere control and sensorless control can be taken up for detailed simulation and performance calculation of PMSM drive systems. Detailed modelling and simulation of other types of synchronous motor drives can also be taken up for transient and steady state analysis.

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