IJETST- Volume||01||Issue||03||Pages 393-398||May||ISSN 2348-9480 2014

Open access Journal International journal of Emerging Trends in Science and Technology

Adaptive Fuzzy Logic Based Speed Control of Permanent Magnet Synchronous Motor Using FPGA

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Abstract:
The proposed project reveals the FPGA based Sensor-less speed control of permanent magnet synchronous motor (PMSM) by using adaptive fuzzy logic technique. The FPGA scheme integrates Fuzzy logic control technique and space vector pulse width modulation principle to control the rotor position angle and motor speed. The Back-EMF based Sensor-less algorithm combined with vector control strategy implemented to estimate rotor position and speed. This control algorithm based on estimation of rotor position and speed with respect to Back-EMF without sensor. To achieve a high performance fuzzy logic control Permanent magnet synchronous motors drive is employed. The simulation for speed control of PMSM by using fuzzy logic controller is developed using Xilinix ISE 9.1.

Index Terms — FPGA, Fuzzy Logic Control, Back-EMF, Permanent Magnet Synchronous Motor (PMSM), Space Vector Pulse Width Modulation (SVPWM), Sensor-less control.

I. INTRODUCTION

The variable speed drives are increasingly used in industries. PMSM drives are used in many applications especially in industrial servo applications due to its high performance, high power density, maximum speed capability, low maintenance and high efficiency. The vector control of Permanent Magnet (PM) motors requires motor position and speed. This may be either using mechanical sensors or by using sensor-less technique. The sensor-less control focus on estimating position and speed with the electrical information. It can be achieved by injecting high frequency signal or by using Back-EMF. The Back-EMF based sensor-less method estimates rotor position from stator voltage and current. However high frequency signal injection provides audible noises and energy losses.

First the FLC principle is presented and its application to the speed control is considered. We know the Proportional- Integral (PI) Controller widely used in PMSM due to their simple implementation. But PI control algorithm is sensitive to plant parameter changes and it cannot assure satisfying dynamic behavior than Fuzzy control. The Adaptive Fuzzy Logic technique tunes the controller so that it can adopt into different motor condition. The Adaptive Fuzzy Logic Control first approach the adaption mechanism which observes the position of the rotor and adapts the parameter of the controller to maintain the performance even if the changes occurs. Recently search coils are mounted around the stator teeth of each phase to achieve position estimation [1]. The condition monitoring of Permanent Magnet rotor has been achieved by estimating the winding resistance and rotor flux linkage of the PMSM. But the small amount of direct axis current i_d is required to inject for the estimation which reduces the performance/complexity ratio. [2].

There are many type of adaptive speed control techniques are designed, among them Sliding Mode Control techniques give robust speed control and reduce chattering. The design of torque observer with fuzzy sliding mode control reduces the chattering and control the speed of PMSM. However input and output scaling factor to be fully established [3]. Solution to this problem addressed by AFC to maintain consistence performance. Another literature introduce the trajectory tracking system evaluates PMSM states under unknown load torque and difficult to obtain systematic design [4]. AFC has the advantages of providing robust performance for both linear and nonlinear functions, and it does not require knowledge of the system's mathematical model [1-2]. Besides that, input and output scaling gains are determined and has to be varied to tune FLC for the required performance, which makes its design time consuming task [4]. Different types of adaptive FLC's such as self-tuning and self-organizing controllers have also been developed. However, the input and output SF's to the performance of a fuzzy logic control system is yet to be fully established [6]. To make the FLC self-adapting towards varying operating conditions, papers such as [6] and [10] have proposed into the control algorithm without sensor. Implementation of FPGA based speed control IC requiring more memory and time to execute [7].

Most of the research works on mathematical model vector control presented in current loop and parameter adjustable mechanism in position loop. Some uncertainties not fully established to solve [8]. A solution to this problem is addressed by the adaptive FLC, whose aim is to maintain consistent performance of a system by adjusting the controller parameters adapting to varying conditions. Also it can be reprogrammed using FPGA which helps to change its behavior according to its state [2, 3]. Recently, point-to-point motion trajectory designed with velocity profile to smooth the start and stop condition [9].

In this paper, the adaptive control of fuzzy logic controller for a vector controlled PMSM is investigated using FPGA. However it consumes more memory and large position error during execution. A Fuzzy Adaptive Scheme is proposed in which the Adaptation mechanism is executed by fuzzy logic based on the error and change of error measured between the motor speed and the reference signal. The control performance of the adaptive fuzzy controller is evaluated by simulation for various operating conditions.

II. MODELLING OF PMSM

The model of PMSM has been developed on rotor frame using the following assumptions:

Saturation is neglected.

Eddy current and hysteresis losses are negligible.

Sinusoidal induced EMF.

No field current dynamics.

The stator flux linkage equations are:

$V_{qs} = R_q i_{qs} + p\lambda_{qs} + w_r\lambda_{qs}$ [1]

$V_{qs} = R_d i_{ds} + p\lambda_{qs} + w_r\lambda_{ds}$ [2]

The dq axis flux linkages in rotor reference frame are given by:

$\lambda_{qs} = L_s i_{qs} + L_m i_{qr}$ [3]

$\lambda_{ds} = L_s i_{ds} + L_m i_{dr}$ [4]

The developed torque of motor is given by:

$T_e = 3/2\ (P/2)\ (l_d i_q + l_q i_d)$ [5]

The Mechanical Torque equation is:

$T_e = T_L + B\omega_m + J\ d\omega_m/dt$ [6]

Solving for the rotor mechanical speed

$\omega_m = \int (T_e - T_L - B\omega_m/J)\ dt$ [7]

$\omega_m = \omega_r\ (2/P)$ [8]

The dynamic d q modeling is used for the study of motor during transient and steady state. It is done by converting the three phase voltages and current to d_{qo} variables by using Park transformation. Converting the phase voltages variables V_{abc} to V_{dqo} variables in rotor reference frame the following equations are obtained.

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r\text{-}120) & \cos(\theta_r+120) \\ \sin\theta_r & \sin(\theta_r\text{-}120) & \sin(\theta_r+120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad [9]$$

Convert V_{dqo} to V_{abc}

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} \quad [10]$$

III. FUZZY LOGIC CONTROLLER

The form of knowledge representation suitable for notions cannot be defined precisely and it depends upon their contexts. Fuzzy logic is a set of well defined logic available in membership function to perform some specific electrical task on the electrical problem.

A. Representation of Fuzzy Set

A Fuzzy set is a set of containing elements that have varying degrees of membership in the set in the interval [0,1] This idea is in contrast with classical or crisp sets because members of a crisp set would not be members unless their membership was complete in that set. The definition of a fuzzy set is given by the membership function

$$\mu_{\underset{\sim}{E}} : U \rightarrow [0,1] \quad [11]$$

Elements of the universe of discourse U can belong to the fuzzy set with any value between 0 and 1.

The degree of membership of an element

$$0 \leq \mu_{\underset{\sim}{E}}(u) \leq 1 \quad [12]$$

B. Fuzzy Controller

A fuzzy controller consists of three operations:

(1) Fuzzification,
(2) Inference engine, and
(3) Defuzzification.

A common definition of a fuzzy control system is that it is a system which emulates a human expert. In this situation, the knowledge of the human operator would be put in the form of a set of fuzzy linguistic rules. The human operator observes quantities by observing the inputs, i.e., reading a meter or measuring a chart, and performs a definite action (e.g., pushes a knob, turns on a switch, closes a gate, or replaces a fuse) thus leading to a crisp action. The human operator can be replaced by a combination of a fuzzy rule-based system (FRBS) and a block called defuzzifier. The input sensory (crisp or numerical) data are fed into FRBS where physical quantities are represented or compressed into linguistic variables with appropriate membership functions. These linguistic variables are then used in the antecedents (IF-Part) of a set of fuzzy rules within an inference engine to result in a new set of fuzzy linguistic variables or consequent (THEN-Part). Variables are combined and changed to a crisp (numerical) output.

The rule-base is defined by:

1. If the motor is running too slow, then more voltage.
2. If motor speed is about right, then no change.
3. If motor speed is too fast, then less voltage.

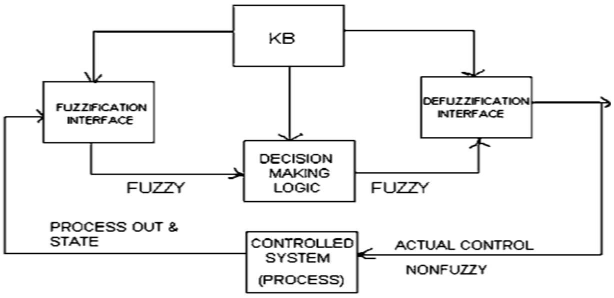
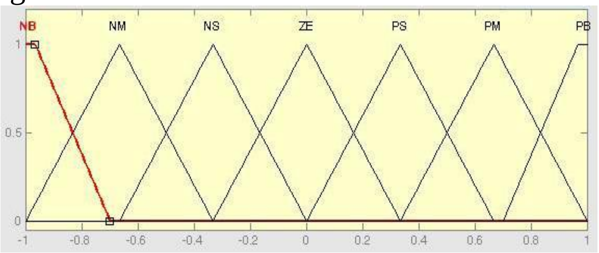
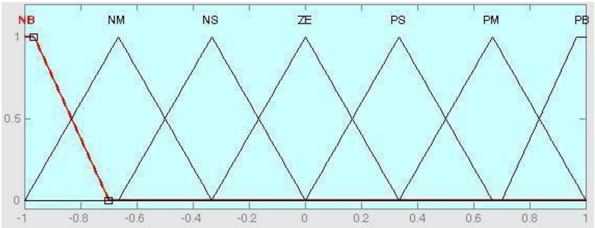


Fig 1. Block Diagram of Fuzzy Controller

In the first stage the crisp variable *e(k)* and *de(k)* are converted in to fuzzy variables. *E(k)* and *dE(k)* using triangular membership functions shown in Fig. 2.



(a) Input MF



(b) Output MF

Fig.2. Membership functions of the FLC

Each universe of discourse is divided into five fuzzy sets: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium) and PB (positive big). Each fuzzy variable is a member of the subsets with a degree of membership varying between [-1, 1]. In the second stage of the FLC, the fuzzy variables *E* and *dE* are processed by an inference engine that executes a set of control rules contained in (7 X 7) rule bases. The control rules are formulated using the knowledge of the PMSM behavior. Each rule shown in Table 1 is expressed in the form

Rule1: *IF x is A AND Y is B THEN Z is C*

The definition of the spread of each partition, or conversely the width and symmetry of the membership functions, is generally a compromise between dynamic and steady state accuracy. Equally spaced partitions and consequently symmetrical triangles are a very reasonable choice.

The universe of discourse is normalized over the interval [-1, 1]. So, we need to multiply the controller input and output variables by adjusting gains in order to accommodate these variables into the normalized intervals [3, 4].Different inference algorithms can be used to produce the fuzzy set values for the output fuzzy variable U_{FUZZY}

Table 1 gives rules of fuzzy logic controller

.

→ CE E ↓	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Table 1. Rule Base for Fuzzy Logic Controller

In this paper, the max-min inference algorithm is used, in which the membership degree is equal to the maximum of the product of E and dE membership degree. The inference engine output variable is converted into a crisp value U_{FUZZY} in the defuzzification stage. In this paper, the centroid defuzzification algorithm is used, in which the crisp value is calculated as the centre of gravity of the membership function.

IV. ADAPTIVE FUZZY LOGIC SPEED CONTROL

For the speed control of PMSM, many controllers are used. In conventional P, PI and PID controllers, very fine tuning is required which cannot cope up with system's parameter variations. Also the performance of such controllers is affected due to variations in physical parameters like temperature, noise, saturation etc. Many control systems use adaptive controllers for PMSM, which can track only linear systems. Therefore, FPGA based fuzzy logic controller (FLC) may be used to achieve more accurate and faster solutions and to handle complicated non-linear characteristics. A simple structure of FPGA based FLC is used in the speed control loop to regulate the motor speed. Fig. 3 shows the block diagram of the proposed control system.

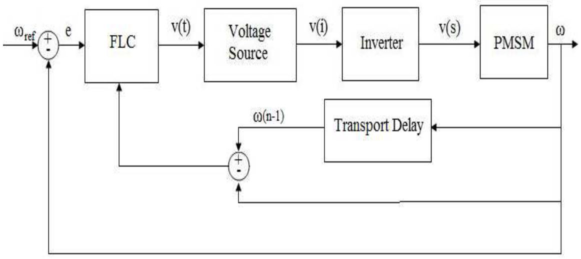


Fig.3. Speed Control using FLC for PMSM

The Adaptive Fuzzy Logic Algorithm has explained in the following steps:

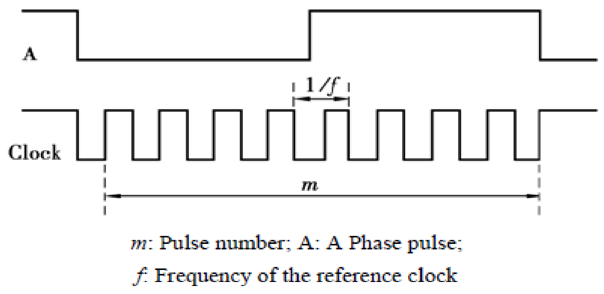
1. Define the linguistic variables and terms (Initialization)
2. Construct the membership functions (Initialization)
3. Construct the rule base (Initialization)
4. Convert crisp input data to fuzzy values using the membership functions (Fuzzification)
5. Evaluate the rules in the rule base (Inference)
6. Combine the results of each rule (Inference)
7. Convert the output data to non-fuzzy values (Defuzzification)

V. FPGA MODULES

The proposed FPGA-based platform for PMSM consists of several function modules, including a speed measurement module (detecting with position), a fuzzy regulator module, a controller module, a space vector pulse width modulation (SVPWM) module, a DC-link voltage compensation module, a scaling module and so on. The function blocks, configured by the FPGA treated as programmable hardware modules, gaining both efficiency and flexibility in system design.

A. Speed measurement module:

In the system, a key problem is to measure the rotor position and speed. This scheme adopts incremental encoder and Hall switch sensors to detect rotor position. When power is on, Hall switch sensors detect a rough initial position that can be used to start the motor softly. Then they can detect an accurate position as soon as the zero pulse of the encoder occurs. Before the quadrature pulses of the encoder arrive at the processor, their frequencies have been quadrupled. The feedback speed measurement is accomplished using the T method, which is suitable for low speed measurement shown in Fig 4.



m: Pulse number; A: A Phase pulse;
f: Frequency of the reference clock

Fig. 4 Time method of low speed measurement

We can express the digitized speed as
$n = 60f/2mP_N\,(r\ min^{-1})$, [18]
where P_N is the equivalent pulse per revolution.

B. Fuzzy regulator module

In the fuzzy logic, the error (e) and error change rate (Δe) of the system output are the two main input variables used in the fuzzy system. The control rule of the fuzzy regulator module is basically composed of many IF-THEN statements shown as follows:

IF e is A_i and Δe is B_j THEN u is u_{ij}, [19]
Where the i and j are indexes of control rules; u is the output of fuzzy controller.

C. Communication module

The system carries the communication between the information system and the PC by RS232 interface and uses MAX232 to act as a corresponding driver. MAX232 is the interface manufactured by the Maxim Company. It uses a single electrical source (+5) to supply power and contains a charger converter. Having two drives and two receivers, only the RS-232 interface can download control program conveniently.

V1. SIMULATION RESULTS

Each module is described by Verilog hardware description language (VHDL) and simulated by Xilinx. To validate the effectiveness of the proposed AFC scheme, simulation and experimental results are presented Assume that the disturbance input $di\ (t) = 30 \cdot \sin(2\pi \cdot 50 \cdot t)$. From the nominal parameters, the dynamic model (1) can be expressed as

$v_{qbf} = -c\beta - (k1.\delta 1 + \varepsilon 1).sgn(\sigma 1)$ [13]
$i_{ds} = -k4.i_{ds} + v_{dbf} + d_2$ [14]
$v_{qbf} = -c\beta - (k1.\delta 1 + \varepsilon 1).sgn(\sigma 1)$ [15]
$v_{dbf} = -(\delta 2 + \varepsilon 2).sgn(\sigma 2)$ [16]
$J.d/dt\ \Omega = T_e - T_l - B\Omega$ [17]

The performance of PMSM speed control using FLC is compared to a conventional PI controller by extensive simulation for various operating conditions. In FLC scheme the output of the FLC is used as the input of the controlled voltage source which converts the input signal into an equivalent voltage in order to regulate the motor speed. The PMSM parameters are given in table 2.

TABLE 2
PMSM DRIVE PARAMETERS

Parameter	value
L_d , d axis inductance	1.4 mH
L_q , q axis inductance	2.8 mH
ϕ_f , Flux induced by magnets	0.12 wb
P. no of poles	4
Rated Speed	1500 rpm
Rated Current	1 A
J ,Inertia	$1.1*10^{-3}$ Kg m^2
f_r , combined viscous friction	$1.4*10^{-3}$ Nm/rad/s
R , resistance	2.875 Ω

All membership functions are iteratively adjusted and the result of the FLC corresponds to the minimum training error.

The below Fig.5 waveforms are the simulation result of speed variation which is implemented in Xilinx ISE 9.1. It gives the information about variation of speed with respective to the reference speed. In this the actual speed follows the reference speed. Hence under normal speed there is no change in rotor position and actual speed i.e. speed or load is not varied at any point of time. Observe that the PWM 1-3 are motor input speed, PWM 4 gives the reference speed and PWM 5-7 denotes the motor actual speed. If motor exceeds the reference speed the position of the PMSM also get changed. This instant is representing in the waveform PWM 8-10. It can be seen from Fig.5 shows the improvements due to use of the proposed method of theta variation method of speed control. FPGA provides more flexible than microcontroller.

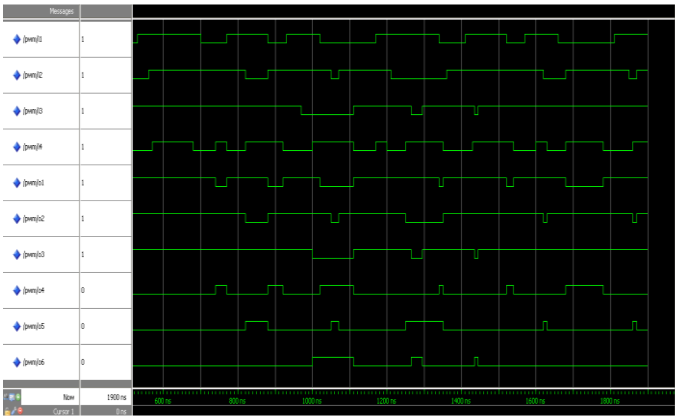


Fig. 5. Simulation Results for Output Speed Waveform of FPGA Based FLC speed control of PMSM

VI. CONCLUSION

FPGA has been used for controlling PMSM. The hardware realization of an AFC and a position control for a PMSM drive based on the FPGA technology is successfully demonstrated in this paper. The proposed control method considers the position error. To guarantee the robustness and to avoid the system nonlinearity or the uncertainty the Fuzzy Logic Control implemented. The simulation results showed that FPGA based speed control performance in real time is comparable to the hardware based speed control in terms of response time and accuracy, with the advantage of flexibility in control scheme implementation.

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