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# Real-Time Implementation of a Genetic Algorithm Based Fuzzy Logic Controller for Interior Permanent Magnet Synchronous Motor Drive

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***Abstract-***

**This paper presents a novel speed control scheme using a new genetic-based fuzzy logic controller (GFLC) for an interior permanent magnet synchronous motor (IPMSM) drive. The proposed GFLC is designed to have less computational burden, which makes it suitable for online implementation. The parameters for the GFLC are tuned by genetic algorithm (GA). The complete vector control scheme incorporating the GFLC is successfully implemented in real-time using a digital signal processor board DS 1102 for a laboratory 1 hp interior permanent magnet motor. The efficacy of the proposed GFLC based IPMSM drive is verified by simulation as well as experimental results at different dynamic operating conditions such as sudden load change, parameter variations, step change of command speed, etc. The proposed fuzzy logic controller is found to be a robust controller for application in IPMSM drive.**

***Index Terms-*** Interior Permanent Magnet Motor, Vector Control, Real-Time Implementation, Genetic Algorithm, Fuzzy Logic, and Digital Signal processor.

## I. INTRODUCTION

Among ac drives, the permanent magnet synchronous motor has been becoming popular owing to its high torque to current ratio, large power to weight ratio, high efficiency, high power factor and robustness [1]. The interior permanent magnet synchronous motor (IPMSM), which has magnets buried in the rotor core, exhibit certain good properties, such as, mechanically robust rotor construction, a rotor physically non-saliency and small effective air gap. These features allow the IPMSM drive to be operated in high speed mode with better dynamic performance.

Usually, high performance motor drives require fast and accurate response, quick recovery from any disturbances and insensitivity to parameter variations. The vector control scheme is used for the IPMSM drive so that it can be used as a separately excited dc machine, while retaining the general advantages of the ac over dc motors [2].

The design of the conventional proportional-integral (PI), proportional-integral-derivative (PID) controllers and various adaptive controllers depends on accurate machine parameters. Moreover, the conventional fixed gain PI and PID controllers are very sensitive to system uncertainties [3]. Because of nonlinear nature of IPMSM, an intelligent speed controller demands special attention for a high performance IPMSM drive system. To serve that purpose, a simple and new type of fuzzy logic controller (FLC) is developed in the present work.

The mathematical tool for FLC is the fuzzy set theory introduced by Zadeh [4]. In FLC, the system control parameters are adjusted by a fuzzy rule based system, which is a logical model of the human behavior for process control. The main advantage of FLC over the conventional controllers is that the design of FLC does not depend on accurate machine parameters. Some work has been reported recently on the application of FLC for brushless dc, induction and reluctance motors [5-9]. However, the real-time application of FLC has been facing some disadvantages due to its high computational burden. That is why so far the reported works for motor drives [7,8] are based on the simulation results only. Very few works [5,6] are reported with the experimental results at low speed conditions due to the computational burden and hence low sampling frequency which is a major limitation for real-time implementation. Thus, there is a need for successful real-time implementation of fuzzy logic algorithms in practical industrial drives.

The objective of this paper is to develop and implement a genetic based fuzzy logic controller (GFLC) for the interior permanent magnet ac motor drive. The genetic algorithm (GA) is used to optimize the FLC parameters, which makes the design tasks easy. A GFLC for the IPMSM drive is designed and successfully implemented in real-time using digital signal processor board DS-1102. The performance of the proposed GFLC based IPMSM drive is investigated both in simulation and experiment at different operating conditions in order to verify the efficacy of the proposed controller.

## II. IPMSM DRIVE MODEL

The mathematical model of an IPMSM drive can be described by the following equations in a synchronously rotating rotor d-q reference frame as [9]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R+pL_d & -P\omega_r L_q \\ P\omega_r L_d & R+pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ P\omega_r \psi_f \end{bmatrix} \tag{1}$$

$$T_e = T_L + J_m p\omega_r + B_m \omega_r \tag{2}$$

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

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;

$T_e, T_L$ = electromagnetic and load torques; $J_m$ = 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.

## III. Control Principle

According to the motor model given in equations (1-3), it can be seen that the speed control can be achieved by controlling the q-axis component $v_q$ of the supply voltage as long as the d-axis current $i_d$ is maintained at zero. This results in the electromagnetic torque being directly proportional to the current $i_q$. With Since $i_d = 0$, the d-axis flux linkage depends only on the rotor permanent magnets. The resultant IPMSM model can be represented as,

$$pi_q = \frac{1}{L_q}\left(v_q - Ri_q - P\omega_r\psi_f\right) \tag{4}$$

$$v_d = -\omega_r L_q i_q \tag{5}$$

$$T_e = T_L + J_m p\omega_r + B_m\omega_r \tag{6}$$

$$T_e = \frac{3P}{2}\left(\psi_f i_q\right) \tag{7}$$

The machine parameters are given in Table-I. In the following subsections, the FLC and the GA used for tuning of the FLC parameters are explained.

Table-I: Machine parameters

| | |
|---|---|
| Motor rated power | 3-phase, 1 hp |
| Rated voltage | 208 V |
| Rated current | 3 A |
| Rated frequency | 60 Hz |
| Pole pair number ($P$) | 2 |
| d-axis inductance, $L_d$ | 42.44 mH |
| q-axis inductance, $L_q$ | 79.57 mH |
| Stator resistance, $R$ | 1.93 Ω |
| Motor inertia, $J_m$ | 0.003 kgm$^2$ |
| Friction coefficient, $B_m$ | 0.001 Nm/rad/sec |
| Magnetic flux constant, $\psi_f$ | 0.311 volts/rad/sec |

### *A. Fuzzy Logic Control Scheme*

The block diagram of a GFLC based vector control of IPMSM drive is shown in Fig.1. In this figure $i_q^*$ is the control output, which can be defined as,

$$i_q^*(k) = i_q^*(k\text{-}1) + U(k) \tag{8}$$

At time $t$, $u(t)$ is given by,

$$u(t) = U(k) \qquad ; kT_s < t < (k+1)T_s \tag{9}$$

The value of $U(k)$ is determined at each sampling time based on fuzzy logic through the following steps [13]:

*Step 1:* The speed deviation, $\Delta\omega(k)$, is measured at every sampling time, and the acceleration of the machine, $A(k)$, is calculated as follows,

$$A(k) = [\,\Delta\omega(k) - \Delta\omega(k\text{-}1)\,] / T_s \tag{9}$$

*Step 2:* Compute the scaled acceleration, $A_s(k)$, using

$$A_s(k) = A(k)^* F_a \tag{10}$$

*Step 3:* The motor operating condition as shown in Fig.2 is given by the point $C(k)$ where

$$C(k) = (\,\Delta\omega(k)\,,\, A_s(k)\,) \tag{11}$$

*Step 4:* Calculate $R(k)$ and $\theta(k)$ using

$$R(k) = |\,C(k)\,| \tag{12}$$

$$\text{and, } \theta(k) = \tan^{-1}(\,A_s(k) / \Delta\omega(k)\,) \tag{13}$$

*Step 5:* Compute the values of membership functions $N_s(\theta)$ and $P_s(\theta)$,defined as shown in Fig.3(a),

$$N_s(\theta) = \begin{cases} 1 & 0 \le \theta \le \pi/2 \\ 2(\pi - \theta)/\pi & \pi/2 < \theta \le \pi \\ 0 & \pi < \theta \le 3\pi/2 \\ 2(\theta - 3\pi/2)/\pi & 3\pi/2 < \theta \le 2\pi \end{cases} \tag{14}$$

$$P_s(\theta) = \begin{cases} 0 & 0 \le \theta \le \pi/2 \\ 2(\theta - \pi/2)/\pi & \pi/2 < \theta \le \pi \\ 1 & \pi < \theta \le 3\pi/2 \\ 2(2\pi - \theta)/\pi & 3\pi/2 < \theta \le 2\pi \end{cases} \tag{15}$$

*Step 6:* Determine the value of the gain function $G_c(k)$ defined as shown in Fig. 3(b),

$$G_c(k) = \begin{cases} R(k) / D_r & \forall R(k) \le D_r \\ 1.0 & \forall R(k) > D_r \end{cases} \tag{16}$$

*Step 7:* Compute the stabilizing signal $U(k)$ using

$$U(k) = G_c(k)\,[\,P_s(\theta) - N_s(\theta)\,]\,U_{max} \tag{17}$$

*Step 8:* Increase k by 1 and return to step 1.

The main tuning parameters of the proposed GFLC are $U_{max}$, $F_a$, and $D_r$. For the optimal settings of these parameters, following quadratic performance index $J$ is considered:

$$J = \sum_{k=1}^{L} [\,kT_s \Delta\omega(k)]^2 \tag{18}$$

In the above index, the speed deviation $\Delta\omega(k)$ is weighted by the respective time $kT_s$. The index $J$ is selected because it reflects small settling time, small steady state error, and small overshoots. The tuning parameters are adjusted so as to minimize the index $J$.

### ***B. Genetic Algorithms:***

1. Genetic algorithms are exploratory search and optimization procedures that were devised on the principles of natural evolution and population genetics [10]. Typically, the GA starts with little or no knowledge of the correct solution depending entirely on responses from interacting environment and their evolution operators to arrive at optimal or near optimal solutions. In general, GA include operations such as reproduction, crossover, and mutation. Reproduction is a process in which a new generation of population is formed by selecting the fittest individuals in the current population. Crossover is the most dominant operator in GA. It is responsible for producing new offsprings by selecting two strings and exchanging portions of their structures. The new offsprings may replace the weaker individuals in the population. Mutation is a local operator, which is applied with a very low probability. Its function is to alter the value of a random position in a string. Applying GA to the problem of FLC design involves repetitively performing the following two basic steps:

1. The objective function value must be calculated for each of the strings in the current population.
2. GA operations are applied to produce the next generation of the strings.

These steps are repeated until the population has converged. The computational flow of the problem can be shown in Fig. 4. The optimal parameters are as follows: $U_{max} = 3$, $D_r = 10$, $F_a = 7$.

## IV. REAL-TIME IMPLEMENTATION

The proposed GFLC for IPMSM is experimentally implemented using digital signal processor (DSP) board DS1102 through both hardware and software [11]. The DSP board is installed in a PC with uninterrupted communication capabilities through dual-port memory. The hardware schematic for real-time implementation of

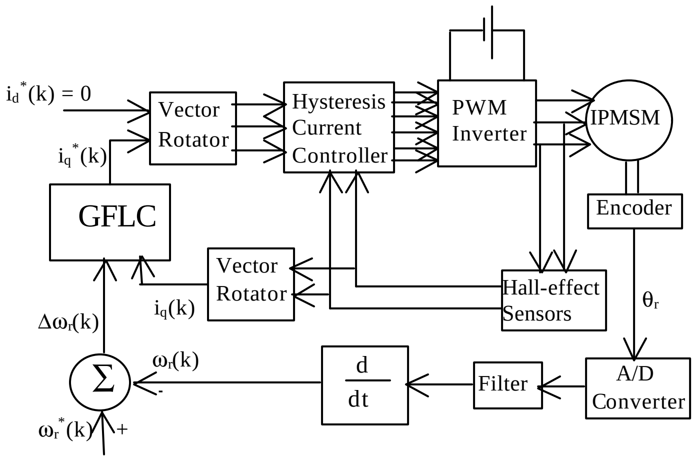


Fig.1. Block diagram of the proposed FLC controller based IPMSM drive.

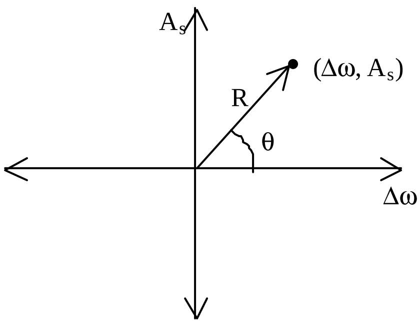


Fig.2. The motor operating point.

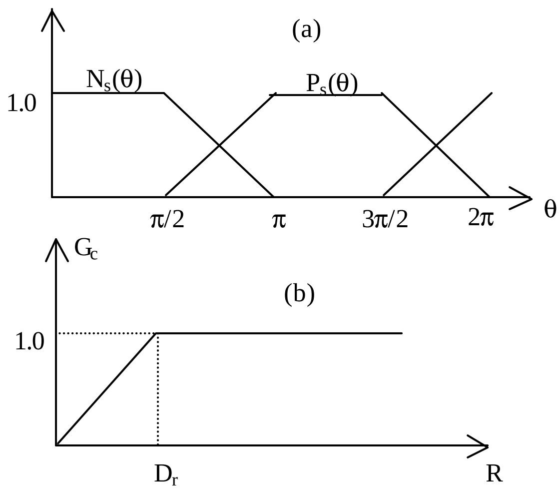


Fig.3. Membership functions for:, (a) θ, and (b) R.

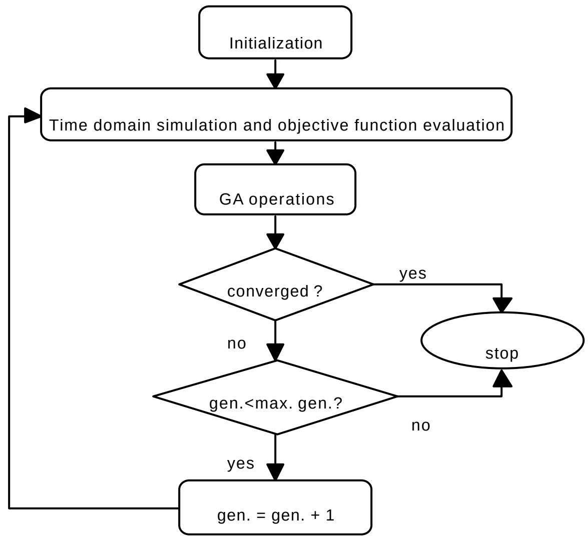


Fig.4. Computational flow chart for GA.

the proposed FLC based IPMSM drive is shown in Fig.5. The DS1102 board is based on a Texas Instrument (TI) TMS320C31, 32-bit floating point digital signal processor. The DSP has been supplemented by a set of on-board peripherals used in digital control systems, such as A/D, D/A converters and incremental encoder interfaces. The DS 1102 is also equipped with a TI TMS320P14, 16-bit micro controller DSP that acts as a slave processor and is sued for some special purposes. In this work, slave processor is used for digital I/O configuration. The actual motor currents are measured by the Hall-effect sensors which have good frequency response and fed to the DSP board through A/D converter. As the motor neutral is isolated, only two phases currents are fed back and the other phase current is calculated from them. The rotor position is measured by an optical incremental encoder which is mounted at the rotor shaft end. Then it fed to the DSP board through encoder interface.

The motor speed is calculated from the rotor position by backward difference interpolation. The calculated actual motor speed is used to calculate the torque component of the current $i_q^*$ using the FLC algorithm. The command a-b-c phase currents are generated from $i_q^*$ using inverse Park's transformation [9]. In order to implement the vector control algorithm,

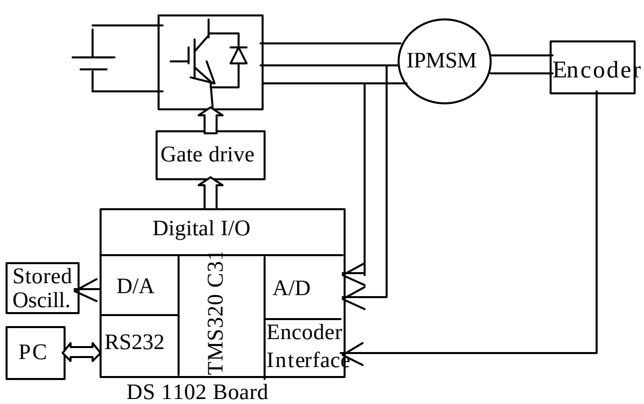


Fig.5. Hardware schematic for real-time implementation.

the hysteresis controller is used as current controllers. The six PWM logic signals are the output of the DSP board and fed to the base drive circuit of the inverter power module. The D/A channels are used to capture the necessary output signals in digital storage oscilloscope.

The 'C' codes are developed for complete IPMSM drive. The program is compiled by the TI 'C' compiler and then it is downloaded to the DSP board. The sampling frequency for experimental implementation of the proposed IPMSM drive system is 10 kHz.

## V. RESULTS AND DISCUSSION

The performance of the proposed GFLC based IPMSM drive is investigated both in simulation and experiment at different operating conditions. Sample results are presented below. The complete drive has been simulated using Matlab/Simulink [12].

The simulated motor speed and current responses are shown in Figs. 6(a),(b) to see the starting performance as well as the response with a load disturbance of the drive. The drive system is started at a constant load of 1 Nm and at t=0.3 seconds, a step increase of load torque of 2 Nm is applied to the motor shaft. It can be seen from these figures that the actual speed converges to the reference value within 0.1 seconds without any overshoot and undershoot and with zero steady-state error. This shows

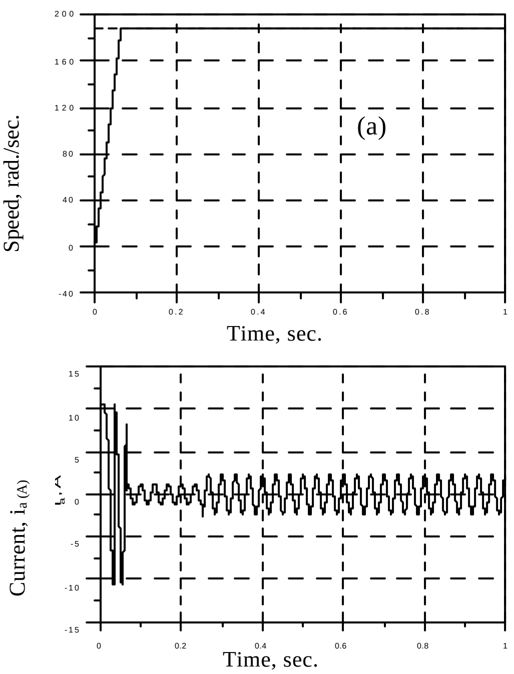


Fig.6. Simulated starting responses of the drive: (a) speed and, (b) current, $i_a$.

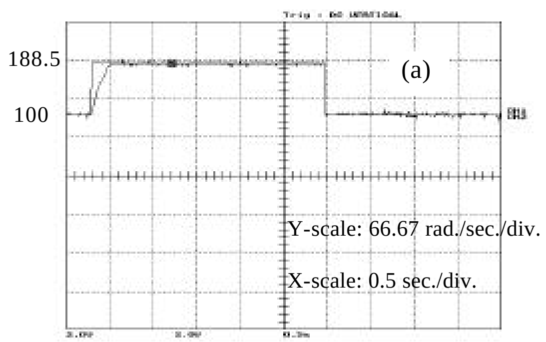


Fig.7. Experimental speed responses of the drive for a sudden change in speed.

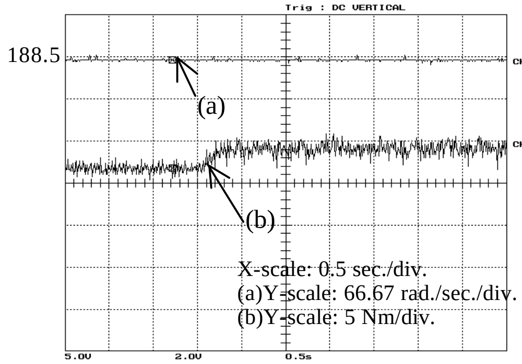


Fig.8. Experimental responses of the drive for a step increase in load: (a) speed, (b) torque.

the capability of new controller to start from standstill condition to the rated speed as well as to reject the disturbance. It is shown from the experimental results in Figs. 7 & 8 that the proposed IPMSM drive is also capable of rejecting the real-time disturbances. Thus, the proposed drive is found robust at different operating conditions.

## V. CONCLUSIONS

The proposed GFLC based vector control of IPMSM drive has been successfully implemented in real-time for a laboratory 1 hp interior type permanent magnet motor. The validity of the proposed control technique has been established both in simulation and experiment at different operating conditions. The unique contribution of this paper is that the developed GFLC parameters were tuned by GA, unlike conventional FLC. The overall control scheme was very simple with low real-time computational burden and hence, found very effective in terms of speed tracking with disturbance rejection.

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