Performance Evaluation of speed control using Fuzzy dependent Genetic Algorithm in PMSM

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Abstract. This paper examines the role of the tuning algorithm for speed regulation of the Permanent Magnet Synchronous Motor (PMSM). The picks of the PID regulator normally provide adequate results in the application of a low-force drive, but for high-power application drives, a self PID controller doesn't provide any acceptable performance. Such applications require high-precision, superior and adaptable speed regulators and effectiveness in the cycle and execution of the plan. High-performance applications need some capacity based on High-speed high-reliability regulators, adaptability with maximum torque coefficient, higher rating capacity with minimum ripple torque. So many speed controlling mechanisms are available in the quick world, and these methods vary from the choice of regulator used in the PMSM to the method of programming/use of equipment. In this paper, generous examination is taken to control the speed of PMSM with three unique specialists, ABC based speed control drive, ANFIS controller of PMSM drive and Genetic algorithm based fuzzy controller. The planned regulators are tried through the mathematical reproductions in the MATLAB Simulink Platform. The examination between the reproduction aftereffects of execution measures are introduced toward the end. Hereditary calculation based Genetic algorithm based fuzzy controller gives some better outcome appropriate for the superior applications.

Keywords: Artificial bee colony; ANFIS; Fuzzy Controller; PID controller; Genetic Algorithm; PMSM, Speed regulation.

1. INTRODUCTION.

The development of attractive materials and power electronics devices has rendered the PMSM drive extremely important in various control applications. The PMSM motor is inherently an asynchronous motor where the field is energized by a durable magnet and a sinusoidal EMF. These motors are sufficient to make torque, near to zero rpm by the usage of permanent magnets. For the comparable force produced by induction motors, they have a more manageable packaging size. This makes PMSM machines successful in all types of special operations (e.g., Electrical vehicles and hybrid electrical vehicles, CNC machines, industry robots, ventilating and air conditioning applications). Nevertheless, PMSM sensitivity is highly susceptible to disturbances of external loads and parametric uncertainties in the system. Some
control strategies have been developed, known as intelligent control, sliding mode control and nonlinear control to overcome these problems of speed and position control of PMSMs [1-4]. Current and torque, speed regulation of PMSM electrical drives is periodically recognized by the use of the cascade system model with PI controllers.

Then again, better dynamic characteristics are represented by the controller, with a particular focus on disturbance compensation [6]. A significant downside of controller is identified with tuning measure, that requires determination of all coefficients simultaneously. For complex control frameworks it is by all accounts not a trifling undertaking. The use of inspired algorithms towards adaptive control optimization has been the subject of extensive consideration these days. Traditional (for example State critique or proportional integral derivative controller) and neural network controllers could be used in this technique, in addition to nature-inspired combinatorial optimization for variance. Torque control, rotation speed, quadrant location and low-speed operation, are often needed in commercial processes but are responsive from the perspective of control strategies to reliability [5]. To accomplish superior and high proficiency control, different control strategies are utilized to regulate the speed, position of rotor and torque. This research provided a wide selection of speed control techniques.

The paper is sorted out as the mathematical modelling of PMSM in section II, the exhibition examination of ABC based speed control drive, ANFIS controller of PMSM drive in section III and Fuzzy controller-based genetic algorithm in section IV, PMSM drive model and results are talked about in section V. At last, the conclusion of the paper is sketched out in section VI.

2. PMSM ANALYTICAL MODELLING.

Figure 1 displays a conceptual Schematic Representation of the PMSM Speed control setup. The control drive setup composed of a PMSM motor, a three-phase PWM inverter, speed controller (dependent optimization algorithm for the traditional fuzzy controller or fuzzy controller), a current regulator and a reference current controller for the location encoder and hysteresis band.

![Figure 1. Conceptual Schematic Representation of PMSM Speed Controller Device.](image-url)

The variables used to mathematically model the PMSM drive are just as described on Fig.1:
- $\omega$: actual speed
- $\theta_r$: Position of the rotor
- $i_a^*, i_b^*, i_c^*$ and $i_a, i_b, i_c$ are reference and 120° spacing of real phase current.
- $e$: the speed error
- $\Delta e$: time derivative of $e$
The fuzzy speed controller generates the power current 'Icc' using these two input variables.

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c \\
\end{bmatrix} = 
\begin{bmatrix}
R_{sr} & 0 & 0 \\
0 & R_{sr} & 0 \\
0 & 0 & R_{sr} \\
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
\end{bmatrix} + 
\begin{bmatrix}
L_{ss} - M & 0 & 0 \\
0 & L_{ss} - M & 0 \\
0 & 0 & L_{ss} - M \\
\end{bmatrix}
\frac{di_a}{dt} + \begin{bmatrix}
e_a \\
e_b \\
e_c \\
\end{bmatrix} \\
(1)
\]

Equation (1) express the matrix form of voltage equation of PMSM. Where \( e_a, e_b, e_c \) specifies the electromotive forces (EMFs) of phase windings, \( i_a, i_b, i_c \) are the phase currents, \( V_a, V_b, V_c \) are the phase voltages, \( R_{sr} \) indicates the motor stator resistance. 'Lss-M' in this equation is equivalent to the synchronous inductance of the motor \( L_{sy} \) and is expressed by

\[
L_{sy} = L_{ss} - M = L_t + L_{sl} - \left( -\frac{1}{2} L_{sl} \right) = L_t + \frac{3}{2} L_{sl} \\
(2)
\]

In equation (2),

\( L_{ss} = L_t + L_{sl} \) where,

\( L_t \) phase inductance including leakage inductance.

\( L_{sl} \) self-inductance.

Equation 1 has rearranged in to state- space in eq. (3).

\[
\frac{di_a}{dt} = \frac{1}{L_{sy}} V_a - \begin{bmatrix}
R_{sr} / L_{sy} & 0 & 0 \\
0 & R_{sr} / L_{sy} & 0 \\
0 & 0 & R_{sr} / L_{sy} \\
\end{bmatrix} \begin{bmatrix}
i_a \\
i_b \\
i_c \\
\end{bmatrix} - \frac{1}{L_{sy}} \begin{bmatrix}
e_a \\
e_b \\
e_c \\
\end{bmatrix} \\
(3)
\]

Using the following equation, EMFs produced by the permanent magnet are determined.

\[
\begin{bmatrix}
e_a \\
e_b \\
e_c \\
\end{bmatrix} = -\rho_f \omega \begin{bmatrix}
\sin \theta_r \\
\sin(\theta_r - 2\pi/3) \\
\sin(\theta_r + 2\pi/3) \\
\end{bmatrix} \\
(4)
\]

Where,

\( \rho_f \): flux due to the permanent magnet rotor.

\( \theta_r \): rotor position.

\( T_e \): electrical torque.

\( T_d \) can be expressed as,

\[
T_d = -\rho_f \frac{p}{2} \left( i_a \sin \theta_r + i_b \sin(\theta_r - 2\pi/3) + i_c \sin(\theta_r + 2\pi/3) \right) \\
(5)
\]

Finally, the rotor speed and its direction are given by,

\[
\frac{d}{dt} \omega = \frac{p}{2} \left( T_e - T_L - B \left( \frac{2}{p} \right) \omega \right) / J_e \\
(6)
\]

\[
\frac{d}{dt} \theta_r = \omega \\
(7)
\]

Hysteresis band control is a method of regulating a power converter to produce the required current that retains a actual current waveform and is combined for closed loop device control [7].

3. **ANFIS BASED SPEED CONTROLLER.**

An electronic power converter control system that creates an output current that resembles a waveform of the reference current and is incorporated with a controller [7] is Hysteresis current control.
The two-input $e$ and $de$ and the $du$ output provide the ANFIS edit toolbox as a load \[18,21\]. In order to evaluate the membership features, tuning is performed here. At the initial start of the method, the output and input membership values are normalized. Three positive (P), negative (N) and zero (Z) linguistic values are relegated to input error ($e$), error derivative ($de$) and output current power ($du$). The speed of the engine is controlled by the ANFIS controller, taking into account the rules provided in Table 1. The layout of ANFIS, built through five layers, is shown in Fig. 3.

### Table 1. ANFIS Controller's Rules.

| $e/\Delta e$ | N | Z | P |
|-------------|---|---|---|
| N           | N | N | Z |
| Z           | N | Z | P |
| P           | Z | P | P |

In the PMSM drive, the ANFIS controller was integrated and a traditional PID controller replaces it with the prototype ANFIS controller [8] is shown in Figure 4.
4. **ABC algorithm-based Speed Controller of PMSM.**

A linear plant model, i.e., the PMSM supplied by VSI, is used during synthesis. It should be noted that all state-space variables in the engine can be controlled by a single state feedback controller (SFC) and are calculated directly using accurate sensors and analysis.

A VSI-fed state-space representation of the PMSM will be added to create the SFC. The governing equations will be followed to obtain a definition of the driving structure: (i) a PMSM will be considered with surface-mounted magnets, and thus \( L_d = L_q = L_s \), (ii) the dynamic behavior and nonlinearities of VSI will be ignored, (iii) the load torque of SFC will be viewed as Non-measurable disruption during the synthesis process, (iv) the internal reference signal model will be used, (v) Depending on the hypothesis, a linear model of the PMSM will be determined. [9-10].

The definition utilizes computational equations obtained from the PMSM model's discrete model to measure control signal boundary values that ensure that specified state-space variables are constrained. It was formerly verified that MPAC guaranteed that the q-axis current is properly constrained for each of the controller parameters examined. [11-12] The SFC-MPAC principle is expanded in this approach and the nature-inspired optimization approach is employed to the modification of coefficients if the moment of inertia is variable. For the proposed ASFC, a block diagram with anti-windup direction and MPAC is displayed in Fig. 5, whereas the generalized PMSM drive device block diagram with ASFC was shown in Fig. 6.
The goal of the optimization approach inspired by nature is to reduce the distinction between the outputs of both the MRAS and the control unit. This discrepancy is mostly attributable to a discrepancy between both the variables of the models and the plants. While using the modification of the controller coefficients [19], the difference is decreased. The nature-inspired optimization approach to online optimization is used for this reason. The mathematical model of the suggested ASFC inspired by nature is shown in Fig. 7.
4.1 ABC Algorithm.

The first ABC evaluation is classified into three categories: the working bee stage, onlooker bee stage and the scout stage. The stage of the working bees and the stage of the onlooker bees are comparable. The two phases are looking for another source of food dependent on legitimate sources of food. Working bees search randomly for the food source neighborhood and onlooker bees search for the food source neighborhood in terms of nectar volume. It’s the last stage, the stage of scouts, is responsible for producing another source of food in the place of a source of surrendered food. If the sum of bombed activities reaches the pre-defined limit named limit, a food source is surrendered. The limit of the rate of modification provided to minimize the range of new sources of food obtained in the process and onlooker bee stage. Without a decrease in assembly, the boundary needs a reduction in variety [19].

In a solitary standardizing mode, the first ABC calculation operates. All phases (onlooker stage, employed bees stage & scout stage) are rehashed Y times after the implementation of the state, where Y is a fixed calculation boundary. In disconnected enhancement, this technique is regularly used where the enhancement must be performed once and then it does not require replication, such as separate SFC auto-tuning in PMSM [13]. This is noteworthy that the controller operation depends on the limits of the system and that its enhancements get a significant effect on the response of the control system. In such a case, notwithstanding the shift in boundaries, the repeatability of the reaction of the control system, includes the conversion of control variables. This will be achieved by using an ABC equation that has been updated. The additional level, called "the best food source evaluation" is presented in promoting quality optimization mode in ABC. The accompanying errands could be recognized at this stage: (i) discovery of the limits of the plant shift to run re-enhancement, (ii) expansion of the quest space of impermanent arrangements. The transitory arrangement space of search should be extended after the colony found a significantly better arrangement, so as to explore the least wellness work worldwide. The search space of the transitory configurations is dominated by the colony’s distribution.

5. Speed controller of PMSM using fuzzy controller based on genetic algorithm.

This work hybridizes the genetic algorithm to give ideal contributions to the fuzzy PI controller model. PI-type fuzzy controller is favored because of that it dispenses with the steady state error. The traditional structure of a fuzzy rule-based system (FRBS) by Mamdani is illustrated in Fig. 8. Second, the range of outputs and inputs for the controller should be selected for the preparation of the fuzzy controller [20]. Each universe of conversation is divided at that point into a sufficient number of set theory. It characterizes the most relevant frameworks which measure to inclusion for the set theory of eligibility capabilities. In the following process, standard techniques are set up and a selection list is made on the basis of subjective information, knowledge and instinct. Traditionally, the master knowledge and experimentation strategy [14] has altered the fuzzy variables. Just in Fig. 9, e and de were chosen as the key factors entering the fuzzy controller. This controller’s output is the control current, ΔI*(t).
Figure 8. The fundamental model of the Mamdani FRBS.

Figure 9. Fuzzy-PI controller.

Table 2 The selection table created by both the experimentation approach.

| $\Delta I^*$       | $de_\omega$ | \(NB\) | \(N\) | \(ZE\) | \(P\) | \(PB\) |
|---------------------|-------------|--------|-------|-------|-------|-------|
| $e_\omega$          |             | \(NM\) | \(NS\) | \(NS\) | \(ZE\) | \(PS\) |
| \(NB\)              |             | \(NB\) | \(NM\) | \(NS\) | \(NS\) | \(ZE\) |
| \(ZE\)              |             | \(NS\) | \(NS\) | \(ZE\) | \(PS\) | \(PS\) |
| \(NB\)              |             | \(NB\) | \(NM\) | \(NS\) | \(NS\) | \(ZE\) |
| \(PB\)              |             | \(ZE\) | \(PS\) | \(PS\) | \(PM\) | \(PB\) |
| \(P\)               |             | \(NS\) | \(ZE\) | \(PS\) | \(PS\) | \(PM\) |

The two control parameters, \(e\) and \(de\), and \(\Delta I^* (t)\) are given in Table 1, the option table shown in the traditional fuzzy logic controller is also discussed. In the form, each rule is represented as,

\[
\begin{align*}
R_1 & : \text{If } e_\omega \text{ is } ZE \text{ and } de_\omega \text{ is } P \text{ then } \Delta I^* \text{ is } PS \\
R_2 & : \text{If } e_\omega \text{ is } P \text{ and } de_\omega \text{ is } PB \text{ then } \Delta I^* \text{ is } PM \quad \ldots \quad (8) \\
R_{25} & : \text{If } e_\omega \text{ is } NB \text{ and } de_\omega \text{ is } NB \text{ then } \Delta I^* \text{ is } NB
\end{align*}
\]
In the equation 9, the recognizable increase current in the defuzzification process is calculated as the center of gravity method described.

\[ \Delta I^* = \frac{\sum_{i=1}^{n} u_i \mu(u_i)}{\sum_{i=1}^{n} \mu(u_i)} \] \hspace{1cm} \text{(9)}

- n: number of fuzzy sets,
- \( u_i \): the center of gravity of the \( i \)th fuzzy set,
- \( \mu(u_i) \): membership value corresponding to the output membership function of \( i \)th fuzzy control law.

It is able to get the controller’s final output, as,

\[ I^*(t) = I^*(t-1) + K_u \Delta I^*(t) \] \hspace{1cm} \text{(10)}

The fuzzy logic controller has inevitably been reinforced here, in which the variables of the controller are simultaneously advanced with equal measure. This methodology provides the perfect response based on a pre-characterized multi-target execution file for the output response.

- Genetic Algorithm.

With parameters themselves, genetic algorithms can’t work legitimately. Henceforth the fuzzy controller elements, the collection of rules, membership functions and scaling factors should be condensed into a solitary string that the GA can attempt to upgrade. The performance of the fuzzy controller can be increased in comparison to scaling factors [15] by correctly modifying the fuzzy sets, that are useful for establishing the controller locally. Thus, using genetic algorithms, the focal points for the input and output membership functions are updated.

Let \( cp \) describe the GA-adjusted parameter, and then use the formula given in the following equation to evaluate the midpoints of the triangular membership functions.

\[ \frac{1}{n} \sum_{i=1}^{n} C_p(i) \] \hspace{1cm} \text{(11)}

Where,

\[ n = \frac{(m-1)}{2} \] \hspace{1cm} \text{(12)}

- ‘m’: Number of membership function,
- \( i=1,2,3, \ldots, n \).

The tuning variables connect the input and output parameter values to the discourse universe over which the fuzzy numbers are defined and have a massive effect on the functioning of the controller [16]. For the fuzzy controller, three scaling factors, respectively Ku, Kde and Ke are available. Ku explicitly influences the output ripple of the controller because of the structure of the fuzzy-PI controller. The Ke, Kde optimization search range is [0-500] and is [0-1] for Ku [20], taking this into account.

In each of these works, GA optimizes rule weights and since there are various parameters to change (e.g. in this study), the measure of enhancement turns out to be more worrying. In order to restrict the conditions of growth, this study uses an alternative approach. Fig. 5 reflects the regular two-input base plane.
Figure 10. Generation of rule base.

The required multi-objective output F index is shown for the optimal settings of the fuzzy controller parameters:

\[ F = \int_0^t |e| \, dt + \varepsilon \]  

(13)

The fuzzy controller has 14 parameters, and GA techniques should also be modified. There are 40 chromosomes in the population and is arbitrarily produced by the underlying population. The well-being of each chromosome is measured at any age using Eq (13). As shown by these wellness principles, the populace is arranged from the strongest chromosome to some of the most exceedingly awful chromosome.

These possible parents are selected by the process of rank order selection and 20 offspring are delivered by crossover activity to supplant the disposal of chromosomes in the population. The size of the population subsequently remains constant over the years. Despite natural selection and crossover, the process of the mutation is carried out towards the termination of every other generation. In this analysis, ideology is also used, suggesting that the fittest chromosome in the modern age is spared [17].

6. SIMULATION RESULTS

Three controllers have carried out in speed regulation of PMSM drive, i.e., ANFIS controller, ABC speed control based on the algorithm, and Genetic fuzzy controller based on the algorithm. The simulation process takes place in the framework of MATLAB R2018a and is performed on a PC. The output signal control current concerning the proportional and integral gains is addressed, taking into consideration the three-controller configuration, and based on this the implementation parameters such as rise time, peak time, settling time and Maximum peak overshoot are determined by PMSM controller design. In Table 3, the PMSM variables used during the simulation process are presented.

| PMSM Parameters                          | Parametric values     |
|------------------------------------------|-----------------------|
| Moment of inertia (J)                    | 7 \times 10^{-4} kg m^2 |
| Friction (B)                             | 2 \times 10^{-4} N m  |
| No. of poles                             | 2                     |
| Self-inductance (L_{ai})                 | 1.2 \times 10^{-2} H  |
| Leakage inductance (L_0)                 | 2 \times 10^{-3} H    |
| Back EMF constant (p_{fH})               | 0.111                 |
| Phasor resistance (R_{sr})               | 0.6 \Omega            |
| Maximum current (I_{max})               | 10 A                  |
| Rated Voltage (V)                        | 230V                  |
| Rated Speed (rpm)                        | 1500 rpm              |
| Power rating                             | 3kW                   |

The training phase of each of the three models is initially initiated with the contributions being inputs e and de. At the time of the preparation, the weights and bias of each of the three models are trained using ANFIS, the artificial bee colony algorithm and the genetic algorithm for their optimal values. The technique starts and operates in order to update the Fuzzy PI controller’s membership principles and rules. The preparation of estimates of training error values for kp and ki values is calculated towards the end of
the 100th iteration. When the considered presentation parameter mean square error goes to a virtually conceivable taking into account, the entire algorithmic process is done.

Table 4 PMSM Speed Drive Comparative Study with three different controller types.

| The Controls Designed                      | Tests of control system output |                      |                      |                      |
|--------------------------------------------|--------------------------------|----------------------|----------------------|----------------------|
|                                            | Rise time (s)                  | Peak time (s)        | Peak value (rpm)     | Peak overshoot (%)   |
| Genetic algorithm based Fuzzy Controller   | 0.4041                         | 0.9975               | 1501.7               | 0.1691               |
| ANFIS controller for PMSM drive            | 0.4251                         | 1.0024               | 1504                 | 0.2598               |
| ABC based speed control drive              | 0.4011                         | 0.9953               | 1502.4               | 0.1764               |

Figure 11. Performance characteristics of three controller for PMSM drive.
Figure 12. Variation of PMSM drive speed for load status.

In order to understand the display of the PMSM drive under three controllers, a 3 kW three-phase PMSM drive simulation was performed. Fig. 11 highlights the phase reaction characteristics of the three PMSM drive controllers considered for analysis. Table 4 presents the performance measures for the all controller of PMSM drive system considered for comparison. The results have been dissected and uncover essentialness from various points of uses.

In comparison to the speed control drive based on ANFIS and ABC, the Genetic Algorithm based fuzzy controller technique has been fruitful in decreasing rise time, peak time, peak overshoot and settling time from the study of Table 4.

Figures 12, 13, 14 and 15 display the properties of speed, current, torque and voltage where the genetic algorithm-based fuzzy controller methodology was used in the PMSM drive below 6 Nm load. Since the engine accelerates without load from zero speed to 100 rpm, the speed has just achieved its base speed and the appropriate current frequency is obtained. The motor's starting torque is held at a constant value. From t=0.1 to t=0.2sec, a rapid load of 6 Nm is applied. Then the speed is reversed at 0.25sec. The relating current and torque varieties are appeared in fig.13 and fig.14.
7. CONCLUSION

The correlations of the ABC-based speed control motor, the ANFIS PMSM drive controller and the Genetic algorithm-based fuzzy controller have provided the related realities of the complex PMSM drive reaction in this paper. The findings have been tested and criticality has been discovered from different use points. Inspection and correlation between the enhanced dynamic and static properties are seen under different operating conditions in terms of response time, Maximum peak overshoot and settlement time, which are useful in evaluating the PMSM drive for real modern applications. Genetic algorithm based fuzzy controller technique has been fruitful among the three controllers in reducing the reduction performance parameter as compared to different approaches.

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