Design and Tuning of Fuzzy Controller using Human Inspired Algorithm for Speed Control of PMSM

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***Abstract*—designing a decent controller for a speed control of an alternative current (AC) machine, such as the PMSM can be very challenging, the conventional PID and PI controllers are the most used in the industry, but they lack the robustness and the rapid response of A fuzzy controller(FC), the fuzzy controller however needs a very precise scaling of its inputs , outputs, and its membership functions (MFS), this could be done with some serious user experience, or via trial and error technique, which is very time consuming and inconsistent, in this paper a human inspired optimization algorithm called Sewing Training-Based Optimization (STBO) was used to tune the parameters of a specially designed FC ,within an hour of tuning the obtained FC managed to achieve significantly better speed tracking, and produce way less current harmonics than the conventional PID and PI controllers.**

Keywords—component, formatting, style, styling, insert *(key words)*

I. Introduction

Among electrical motors, When putting simplicity performance and robustness into perspective, the PMSM is by far the most preferable choice [1] [2], this motor when modeled using field oriented control (FOC) can get as close as an AC machine can get to linearity [3] [4], in order to perform FOC technique, a set of regulators is needed, two of them controls the direct and quadratic (DQ) axes currents, and one controls the PMSM mechanical speed, these regulators are usually a set of PI controllers or PID controllers, the PI major setback is its noticeable overshoot [5], while the PID is known for its critical derivative kick effect [6], in order to solve this, the mechanical speed regulator could be replaced with a non-classical controller such as the standard fuzzy controller (FC), because they are proven to be more competent than the conventional PI controller [7] [8], the DQ currents could still be controlled with PI controllers.

In the literature, many papers have performed the speed control of PMSM using a FC with FOC technique [9] [10] [11] [12], however these articles didn't provide a clear method to design and tune the FC for various PMSM parameters, in other studies researchers have utilized optimization algorithms to tune FC for many different systems, Rigatos Gerasimog introduced an online tuning of the scaling factors of a FC of an induction motor (IM) [13],Hannan M used Quantum-Behaved lightning search algorithm to tune the scaling and the structure of the membership functions of a FC-PI controller running an indirect FOC of an IM [14].

In this paper, a very capable new metaheuristic algorithm called Sewing Training-Based Optimization (STBO) [15] was used to tune the scaling factor of the output and the range of the inputs MFS of FC running a PMSM with FOC technique, the inputs of this FC were saturated using tuned saturation blocks from Simulink to avoid simulation errors and enhance the performance, the voltages were fed to the motor by a three level inverter controlled with space vector pulse width modulation (SVPWM) [16], the designed FC was later tested against the conventional PI and PID controllers.

II. FOC of PMSM

The model of PMSM based on the dqo frame reference can be represented in [(1),(2),(3),(4)] from [3].

$$v_d = Ri_d - L_d \frac{di_d}{dt} - \omega L_q i_q \tag{1}$$

$$v_q = Ri_q - L_q \frac{di_q}{dt} - \omega L_d i_d + \omega \Phi \tag{2}$$

$$T_e = \frac{3}{2} Pn * [(L_d - L_q) i_d i_q + \Phi i_q] \tag{3}$$

$$j \frac{d\omega_r}{dt} = T_e - T_l - B\omega_r \tag{4}$$

Respectively $v_d, v_q, i_d, i_q, L_q, L_d, \omega, \omega_r, Pn, \Phi, T_e, T_l, B, j$ are direct and quadratic voltages and currents, quadratic and direct axis inductances, motor mechanical and electrical velocity, number of pair of poles ,the permanent magnet induced flux ,electromagnetic torque, load torque, motor viscous friction and inertia.

Applying FOC reduces the produced torque equation to (5).

$$T_e = \frac{3}{2} Pn * i_q \Phi \tag{5}$$

III. Fuzzy speed controller Design

Based on Mamdani inference system a fuzzy speed controller is constructed with two inputs and one output each has five MFS, three scaling factors and two saturation blocks for the two inputs, the saturation blocks and the scaling factors are tuned using STBO algorithm, the output of the controller is T_e which used to deduct the i_q reference as in(6) :

$$i_q = T_e * 2/3(Pn * \Phi) \tag{6}$$

The FC Simulink block is depicted in Fig(1)

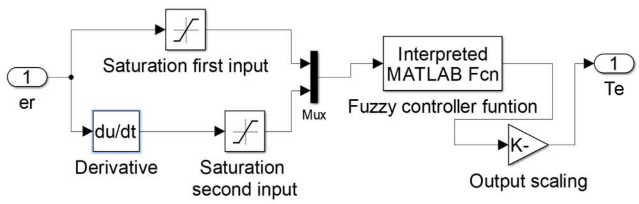


Figure .1 FC speed controller

The output is scaled using Output scaling gain however the inputs are saturated with tuned saturation blocks

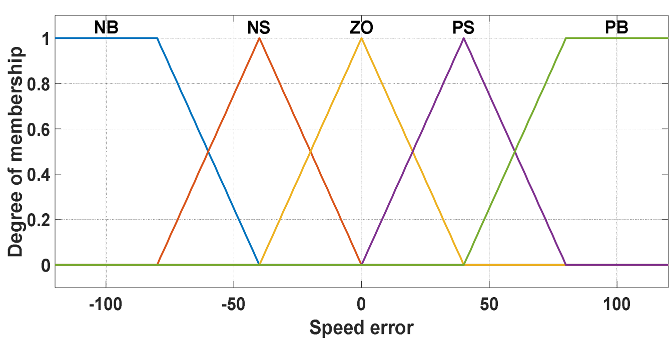
The inputs range is tuned in the Interpreted MATLAB Fcn fuzzy controller code from Fig(1) using scaling(1) and scaling(2) as in Fig(2) from

```
% MF for input1
tfc = addmf(tfc,'input',1,'NB','trapmf',scaling(1)*[-3 -3  -2   -1])
tfc = addmf(tfc,'input',1,'NS','trimf',scaling(1)*[-2 -1 0]);
tfc = addmf(tfc,'input',1,'ZO','trimf',scaling(1)*[-1 0   1]);
tfc = addmf(tfc,'input',1,'PS','trimf',scaling(1)*[0    1 2]);
tfc = addmf(tfc,'input',1,'PB','trapmf',scaling(1)*[1 2 3 3   ]);
% MF for input2
tfc = addmf(tfc,'input',2,'NB','trapmf',scaling(2)*[-3 -3  -2   -1])
tfc = addmf(tfc,'input',2,'NS','trimf',scaling(2)*[-2 -1 0 ]);
tfc = addmf(tfc,'input',2,'ZO','trimf',scaling(2)*[-1 0   1]);
tfc = addmf(tfc,'input',2,'PS','trimf',scaling(2)*[0    1 2]);
tfc = addmf(tfc,'input',2,'PB','trapmf',scaling(2)*[1 2 3 3  ]);
```

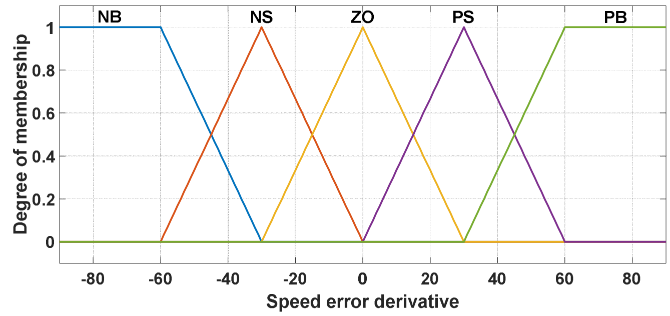
Figure 2.inputs of the FC

This makes five tunable parameters of FC which are [scaling(1), scaling(2), output scaling gain, saturation interval first input, saturation interval second input].

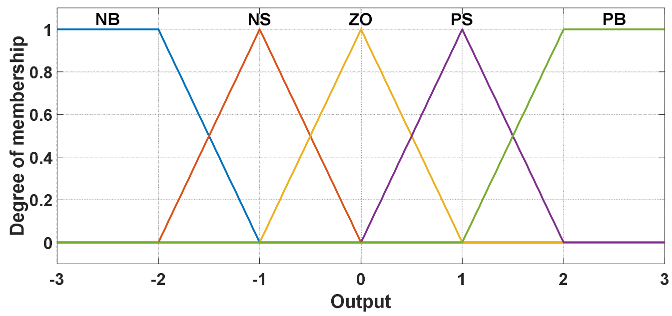
post tuning which will be presented in later section we got scaling(1) = 40.97, scaling(2) = 35.5, the inputs and the output MFS can be represented as in Fig (3).



(a)



(b)



(c)

Figure .3.(a).Input[1]. (b).Input[2]. (c).Output.

Note that unlike the inputs, the output uses the output scaling gain for scaling.

The rules set of FC is represented in Table I.

Table I. Rules set

Control signal		Speed error				
		NB	NS	ZO	PS	PB
Derivative of error	NB	NB	NB	NB	NS	ZO
	NS	NB	NB	NS	ZO	PS
	ZO	NB	NS	ZO	PS	PB
	PS	NS	ZO	PS	PB	PB
	PB	ZO	PS	PB	PB	PB

IV. Sewing training-based optimization

In this section the idea and the mathematical model of STBO are explained.

STBO is an algorithm that mimics the work relation between a sewing trainee and a sewing instructor, each sewing trainee or instructor represents a search agent X_i ,each has a set of parameters and a fitness value , the parameters are values assigned for the system tunable knobs, the fitness value can be obtained when simulating the system with the current search agent parameters, every search agent is an instructor to all search agents with worst fitness than the latter.

Phase one: Training (exploration). In first phase every search agent chooses a random instructor , the chosen instructor X_j helps the trainee X_i acquire new sewing skills using (7)

$$X_i^P = X_i + r_i * (X_j - I_i * X_i) \tag{7}$$

Where X_i^P is the potential new position of the trainee, r_i is a random number from the interval [0,1], I_i is also a random number from the set {1,2}.

The search agent updates its position base on (8).

$$X_i = \begin{cases} X_i^P, F_i^P < F_i; \\ X_i,\ else; \end{cases} \tag{8}$$

Where F_i^P and F_i are the new and the old fitness values respectively.

Phase two:**Imitation of the instructor skills (partial exploration).** In this phase each search agent tries to mimic a specific set of skills by exploring a calculated number of a random instructor position vector dimensions m_s, the number of explored dimensions increases over the course of iterations to keep a steady exploration. m_s can be calculated based (9).

$$m_s = 1 + \frac{t}{2*maxiter} \tag{9}$$

Where t is the current iteration and $maxiter$ is the maximum number of iterations.

The potential new position of the trainee represented in (10).

$$X_{i,m_s}^P = X_{im_s} + r_{im_s} * (X_{jm_s} - I_{im_s} * X_{im_s}) \tag{10}$$

Search agent updates position based on (11).

$$X_{i,m_s} = \begin{cases} X_{i,m_s}^P, & F_{i,m_s}^P < F_{i,m_s}; \\ X_i, & else; \end{cases} \tag{11}$$

Phase three: Practice (exploration). In this phase each search agent tries to improve it self by exploiting nearby possible solutions.

Using (12) The new position can be calculated.

$$X_i^P = X_i + (lb_i + r_i * (ub_j - lb_i)/t) \tag{12}$$

lb_i and ub_j and the upper and lower bounds of the search area.

The search agent position updates according to (13)

$$X_i = \begin{cases} X_i^P, F_i^P < F_i; \\ X_i,\ else; \end{cases} \tag{13}$$

For more in-depth explanation check out [15].

V. TUNING PROCESS.

The fuzzy controller is known for its long simulation time in MATLAB Simulink, however in this system many modifications have been applied to speed up the process, one of which is replacing the SVPWM and the inverter blocks with saturation blocks that limits the DQ voltages fed to the motor to the interval [-200v;200v], this way singularity errors can be avoided and a way faster tuning process achieved.

The FC and PI controllers of Iq and Id currents were all tuned simultaneously

In this system 300 search agents and 35 iterations were chosen to obtain FC optimal parameters which took around 3400seconds to achieve.

Parameters of the motor are in Table II.

Table II. Motor parameters

Parameter	Value
R (Stator resistance).(ohm)	1.4
Ld (inductance of direct axis).(H)	0.0066
Lq (inductance of quadratic axis).(H)	0.0058
Pn (number of pair of poles)	3
Flux (permanant magnet flux linkage).(Wb)	0.1546
B (viscous friction).(Nm/ rad/s)	0.00038
J (motor inertia). (kg-m^2)	0.00176

FC and PI currents controllers optimal parameters are in Table III.

Scaling(1)	Scaling(2)	Saturation(1)	Saturation(2)	Output gain
40.97	35.5	[-120;120]	[-0.292; 0.292]	84.3003
$k_p(i_q)$	$k_i(i_q)$	$k_p(i_d)$	$k_i(i_d)$	
61.964	143.489	79.5	54.46	

VI. PERFORMANCE ANALYSIS.

This section compares the performance of FC compared to the conventional PID and PI controllers.

During 4seconds of simulation the setpoint values of speed and load charge goes as:

- At 0 sec speed reference (SR) is **100 rad/sec** and load charge (LC) is **0 N*m**.
- at 0.5 sec SR is **100 rad/sec** and LC is **4N*m**. at 2sec LC is back to **0N*m**.
- at 2.5sec SR is **-100 rad/sec** and LC is **0N*m**.
- at 3sec SR is **50 rad/sec** and LC is **0N*m**.
- at 3.5sec SR in **150 rad/sec** and LC is **0N*m**.

Fig (4) depicts the speed tracking performance of the three controllers, from Fig(4).a.c.d.e we can see a significant over shoot and undershoot with PI controller and a very apparent derivative kick effect with PID controller, FC achieves the best speed tracking between the three controllers , in Fig (4).b due to the lack of an integrator FC steady state error is slightly higher than other controllers when under charge however its doesn't affect the overall performance.

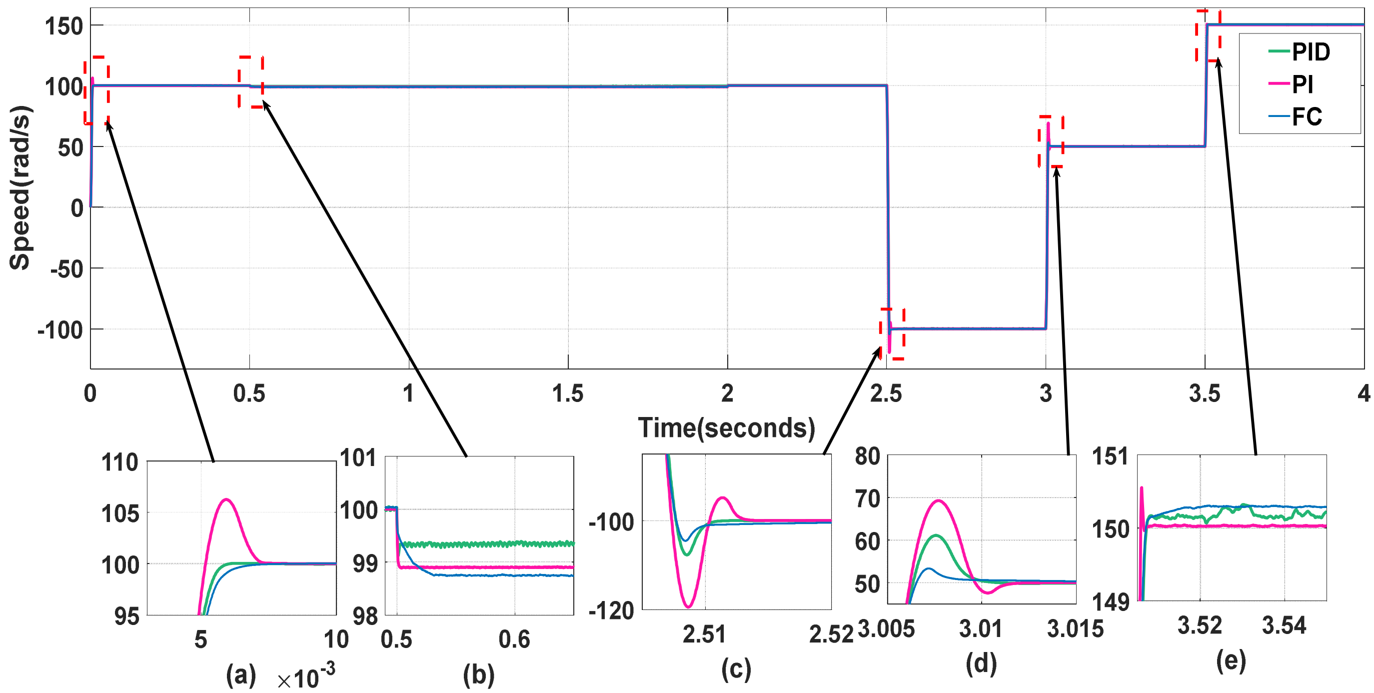


Figure 4.Speed tracking results

Fig (5) presents the Id current regulation, FC significantly outperforms PID and PI regulators managing to keep its direct axis current the closest to zero under various speed set points and charge loads.

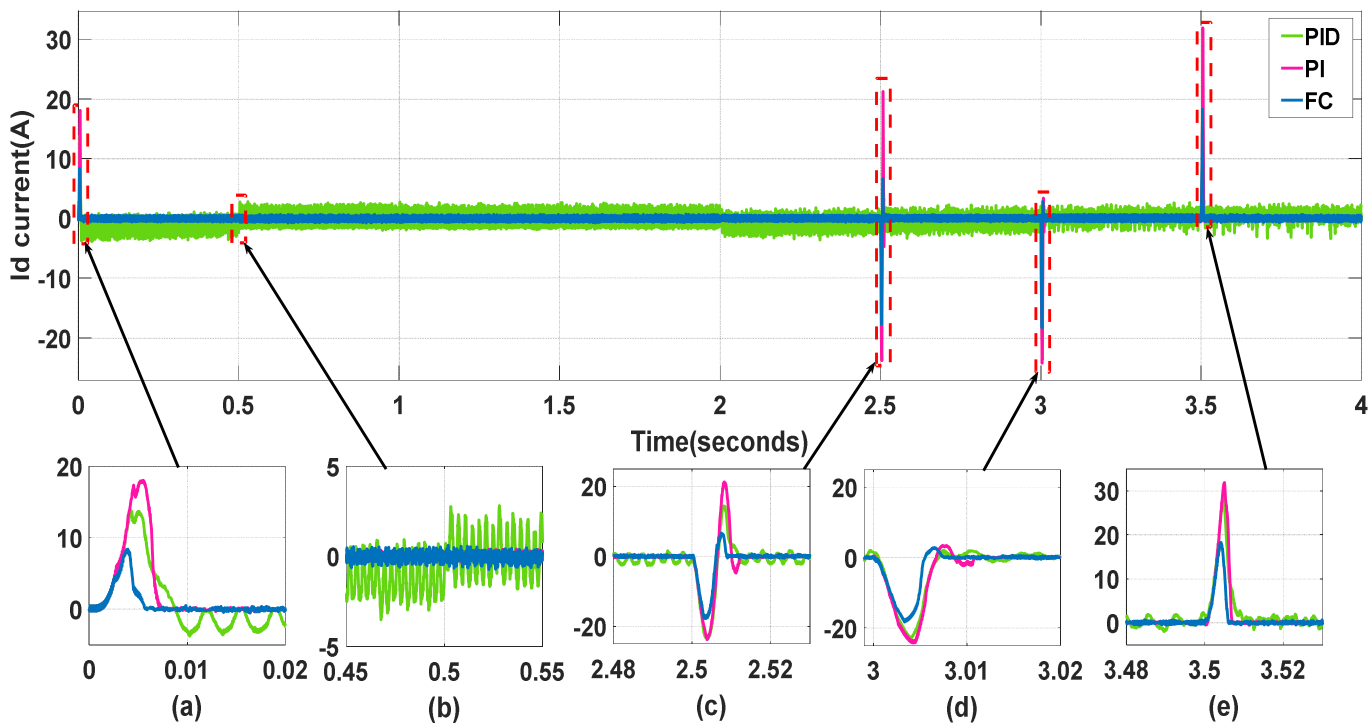


Figure 5 Id current

The electromagnetic torque produced with each controller is depicted in Fig (6), judging by the results we can see that the best results are achieved with the designed FC , FC managed to generate the demanded torque with less over and under shoot and way less oscillations compared to the conventional PID and PI.

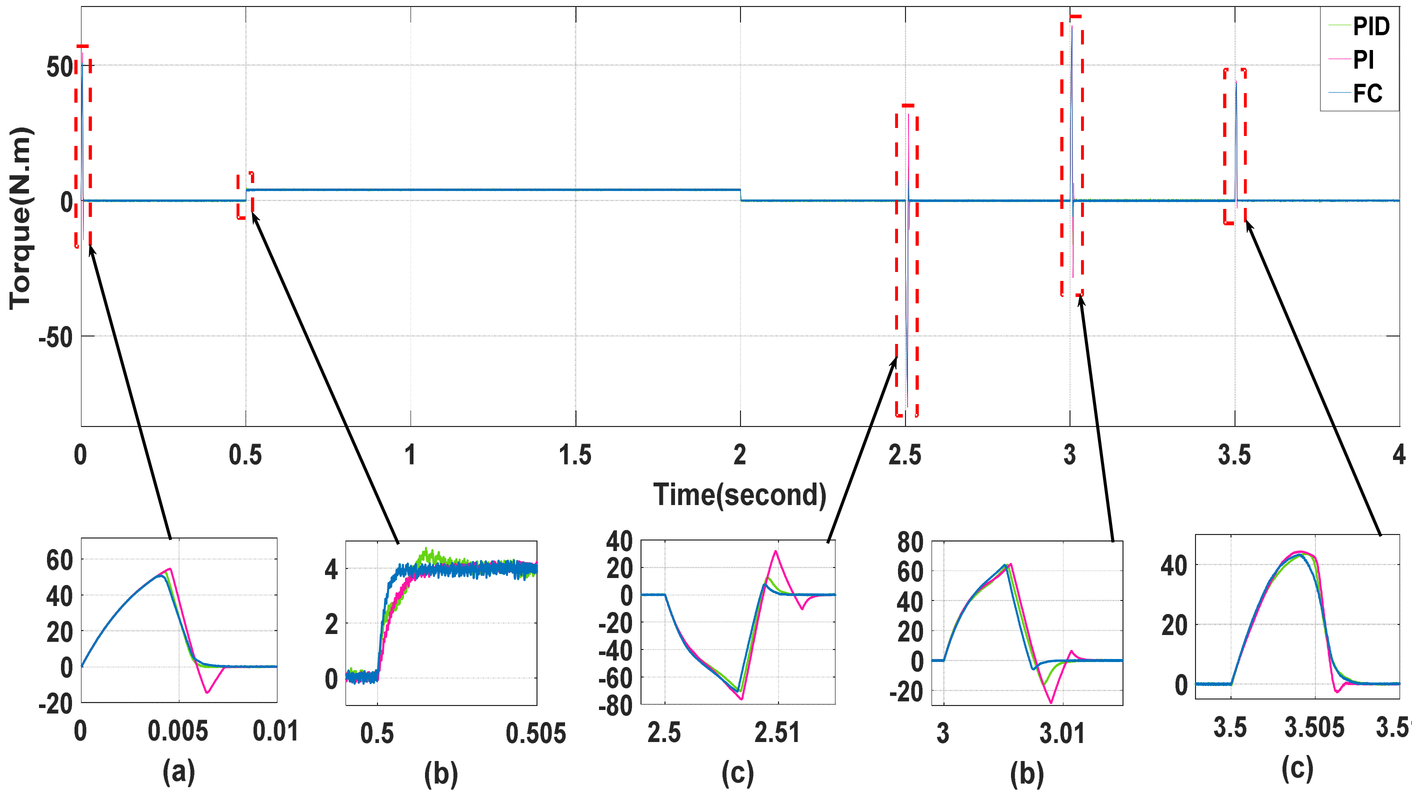


Figure 6 induced torque

VII. CONCLUSION.

In this article, a FC was designed and tuned using STBO optimization algorithm for speed control of PMSM , the design of the controller was presented in detail, then with few tweaks applied to the tuning Simulink model, the algorithm managed to get optimal parameters for the FC in less than an hour, the obtained FC was later compared to the conventional PID and PI controllers , the speed and torque tracking and currents induction results proved the supremacy of the designed FC over the other controllers.

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