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Original Article

Sensorless Speed Control of Induction Machine with Adaptive-Neuro Fuzzy Technique Integrated MRAS Module

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Abstract - *In new electrical power grid technology, advanced control techniques are adopted to control the generation of load parameters better. Artificial intelligence control modules are integrated to stabilize the system at the earliest for a faster response rate. This paper introduces a "sensorless speed control module" with ANFIS in a conventional MRAS estimator module for rapid stabilization of induction motor. The new controller is compared with conventional PI, PID, and fuzzy MRAS control modules. A parametric evaluation and comparison of induction motor speed graphs with all the mentioned controllers determines the best controller among them. Simulation validations of the modules as mentioned above are done using the MATLAB Simulink tool and comparison of graphs concerning peak value generation, ripple, and settling time of speed.*

Keywords - *ANFIS (Adaptive-Neuro Fuzzy Interference System), "MRAS (Model Reference Adaptive System)," PI (Proportional-Integral), PID (Proportional-Integral-Derivative), Fuzzy, MATLAB (Matrix Laboratory).*

1. Introduction

Adapting to new transportation methods like electrical vehicles to avoid environmental damage and reduce climatic disasters is required as electric vehicles are considered to be green energy units that do not generate any gases as do not consume any fossil fuel. These vehicles can be operated using a battery or fuel cell as the source, which needs charging from the grid or hydrogen fuel. These vehicles are driven using electrical motors [1] with good traction capabilities. Generally, these motors will be three-phase AC motors like permanent magnet synchronous motors (PMSM) or induction motors (IM) [2]. These motors operate with high starting torque, overcoming the vehicle mass's inertia and making it respond faster. Among these motors, the induction motor is one of the promising machines with a stable speed and reduced ripple in torque. The speed of the

Various techniques can control a machine [3], including sensor and sensorless controllers. The controller has a speed sensor (tachometer) that measures the motor's speed and is taken as feedback to the controller. However, the sensorless controller estimates the speed of the machine with feedback from inverter voltages and currents.

There are different speed control schemes like direct torque control (DTC), Scalar V/f (voltage/frequency) control, "field-oriented control (FOC)" or vector control, "indirect vector control (IFOC)." Among these techniques, IFOC [4] [5] is considered a less complex controller with better stability in speed and torque of the machine. Therefore, the IFOC speed control technique is adopted for "speed control of three phase IM" [6]. The controller needs the machine's reference and measured speed (or estimated speed) to generate "reference signals to the inverter." The inverter is controlled by the hysteresis loop modulation technique [7], which needs currents as reference signals. The speed of the motor is estimated by the MRAS module, which takes feedback from the inverter's three voltages and currents. The IFOC controller with MRAS speed estimator is shown in figure 1 below.

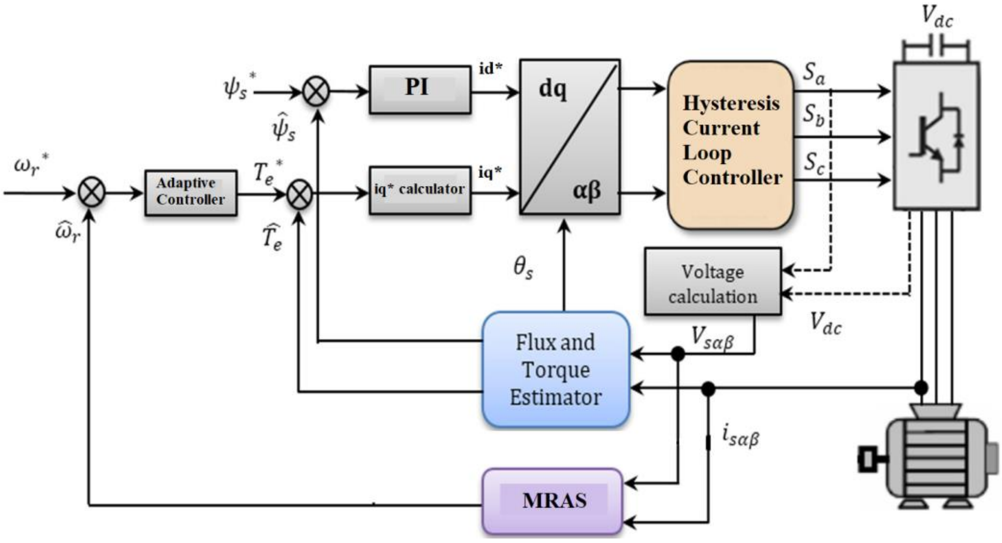

Fig. 1 IFOC control of IM with MRAS module for speed estimation

The speed estimated by the MRAS module, which is considered the measured speed of the motor (w_r), is compared to the "reference speed (w_r*)" given by the user, and a speed error is generated. As per the speed error [8], the values of currents are generated by the IFOC control scheme, which is explained in detail in further sections. A hysteresis current loop control is adopted to control the inverter voltage, which generates pulses for the six-switch inverter operating IM.

In next section II, the internal modeling of the MRAS module with speed reference generation is explained, followed by section III, which includes the ANFIS integrated IFOC control scheme. In section IV, simulation result analysis is carried out on different parameters of the machine and controller. Different parametric comparisons involve peak value generation, ripple, and settling time of speed, determining the optimal controller for speed control in section V, followed by references used in this paper.

2. MRAS Module

The MRAS module [9] included in the control scheme has three units which include the adaptation system, "reference model, and adaptive model" [10]. The MRAS module's input must be in two signal formats (αβ), which can be calculated using Clark's transformation [10]. The three-phase voltage and current signals recorded at the stator terminals of a motor are presented as an example of the conversion.

$$\begin{bmatrix} f\alpha \\ f\beta \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} fa \\ fb \\ fc \end{bmatrix} \ldots\ldots(1)$$

In the above equation, variable 'f' denotes any signal, either voltage (v) or current (i) of the machine. The "internal structure of MRAS [11] module" is shown in figure 2.

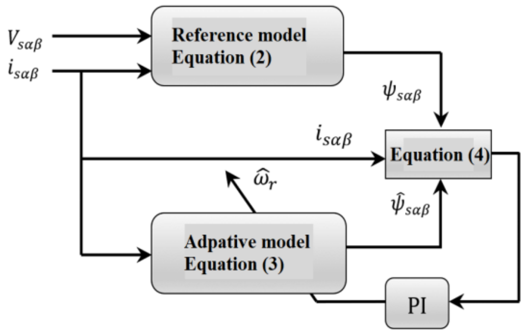

Fig. 2 MRAS machine speed estimator

In the above MRAS module, the inputs taken are αβ components of stator voltage and currents of the machine, which are converted using equation (1). From the two-component [12] voltages and currents, the flux αβ components are calculated and represented as the voltage or reference models. The equation (2) for the generation of reference flux (ψ) components is given as

$$\begin{cases} \psi_{s\alpha} = \int_0^t (V_{s\alpha} - R_{s\alpha} i_{s\alpha}).dt \\ \psi_{s\beta} = \int_0^t (V_{s\beta} - R_{s\beta} i_{s\beta}).dt \end{cases}$$

Similarly, to generate calculated flux ψ* of the machine [12], the current or adaptive model needs feedback from the estimated speed w_r of the machine. The equation to generate the calculated two component flux ψ* of the current model is given as

$$\begin{cases} \psi^*_{s\alpha} = \dfrac{L_r}{R_r + L_{rs}} (\sigma L_s w_r i_{s\beta} + \dfrac{L_s}{L_r} (R_r + \sigma L_{rs}) i_{s\alpha} - w_r \psi^*_\beta) \\ \psi^*_{s\beta} = \dfrac{L_r}{R_r + L_{rs}} (\sigma L_s w_r i_{s\alpha} + \dfrac{L_s}{L_r} (R_r + \sigma L_{rs}) i_{s\beta} - w_r \psi^*_\alpha) \end{cases}$$

Here, "R_r is the rotor resistance of the machine, L_s is the stator inductance of the machine, L_{rs} is the rotor inductance of the machine" [13]. With the above equations, the reference and adaptive flux components are calculated from which speed estimation is done, taking current components also into consideration which is given as

$$\varepsilon = \psi_\alpha \psi_\beta^* - \psi_\beta \psi_\alpha^* - (i_{s\alpha}\varepsilon_\beta - i_{s\beta}\varepsilon_\alpha)\sigma L_s$$

In the above equation the ε_α and ε_β Components are calculated for flux components which are given as

$$\begin{cases} \varepsilon_\alpha = \psi_{s\alpha} - \psi_{s\alpha}^* \\ \varepsilon_\alpha = \psi_{s\alpha} - \psi_{s\alpha}^* \end{cases}$$

From the error value calculated concerning equations, speed estimation of the machine is done when the error signal ε is passed through the PI controller [14] with specific tuned Kp and Ki values. The final speed estimation of the machine is given as

$$w_r = K_p \varepsilon + K_i \int \varepsilon . dt$$

Therefore, here the estimated speed from the MRAS module is fed to the IFOC controller, which calculates the required reference currents for the machine to operate at the desired speed.

3. ANFIS Integration to IFOC Scheme

In the IFOC scheme [9], the controller's reference signals are current signals compared to measured current signals of the stator IM terminals.

The comparisons of the signals are fed to the hysteresis band control unit, which generates signals to the three-phase inverter [10]. The reference current signals ia* ib* ic* are generated by "id* and iq* (d-axis and q-axis) current components," which are determined by torque reference Te* and flux reference ψ*.

The complete structure of the proposed IFOC scheme is represented in figure 3 below.

The flux reference [9] is taken as per the user required value which is always to be '1' ideally.

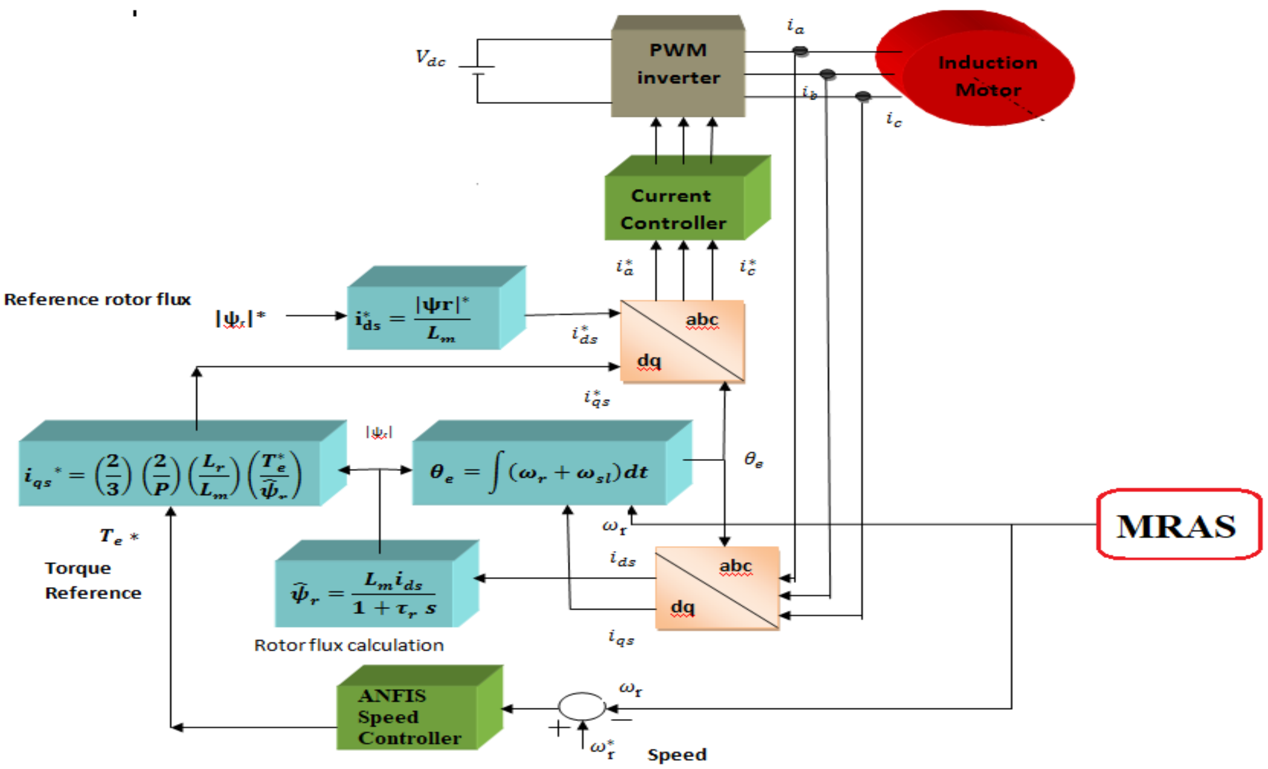

Fig. 3 IFOC control scheme with ANFIS speed controller

From the flux reference ψ*, the id* component is generated as

$$i_d^* = \frac{\psi^*}{L_m}$$

The reference torque Te* is calculated using the ANFIS controller, which takes input from a comparison of estimated speed wr generated by the MRAS module and reference speed wr* given by the user. The modeling of the ANFIS controller [15] with one input and one output variable is discussed further in this section.

As mentioned earlier, the input variable to the "ANFIS controller is speed error signal (E)," and the output variable is reference torque Te*. The input variable E is set with 7 triangular type membership functions [16], as shown below in figure 4.

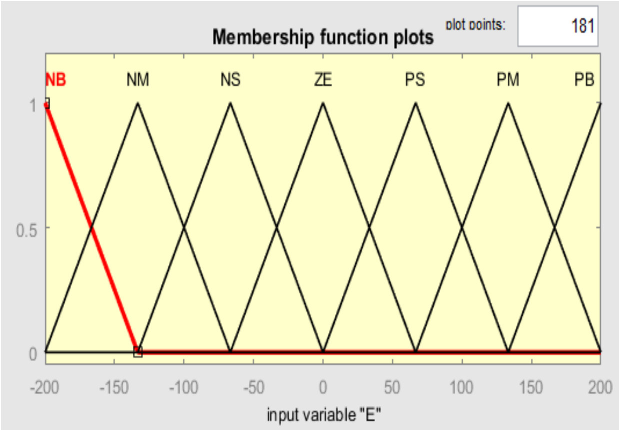

Fig. 4 Input variable E membership functions

The membership functions are defined as "ZE – Zero; PS – Positive Small; PM – Positive Medium; PB – Positive Big; NB – Negative Big; NM – Negative Medium; NS – Negative Small [17]."

The range of the variable is set between -200 to 200. Now the output variable Te* is set with a constant membership function type where the values of each membership function are set by tuning with the trial and error method. The range of the output membership function is set between -10^7 to 10^{7}, which can be seen in figure 5 below.

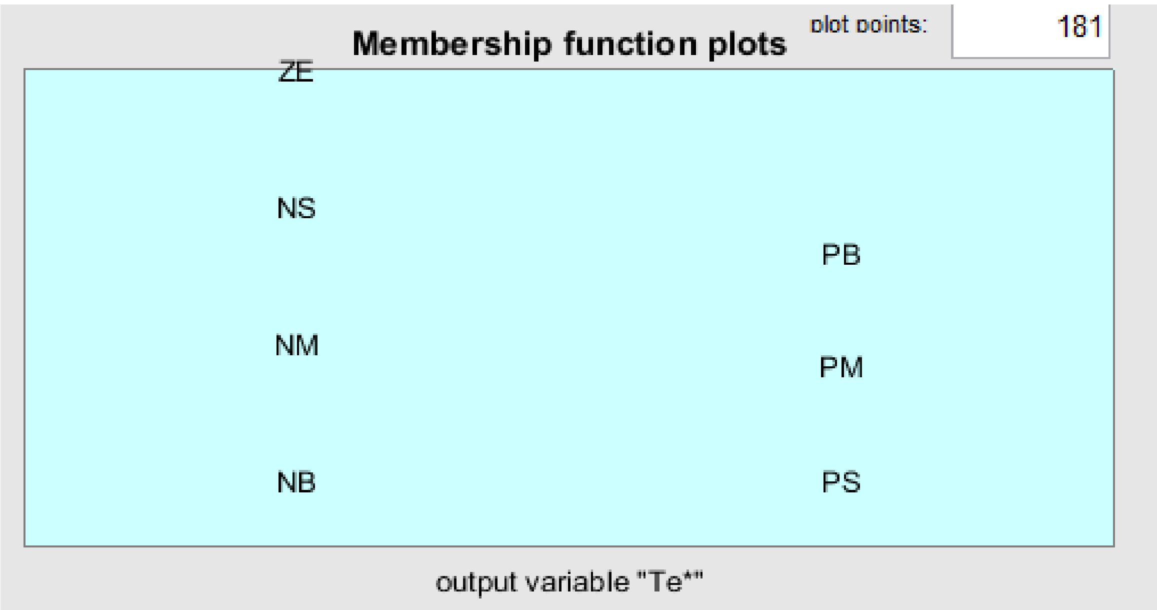

Fig. 5 Output variable Te* membership functions

Now the Sugeno fuzzy membership functions [16] are trained using the ANFIS tool with data taken from PI controller input and output.

The tool's data is imported from MATLAB software's workspace [18], which is needed to train the Sugeno fuzzy membership functions. The loaded training data to the ANFIS tool can be seen below.

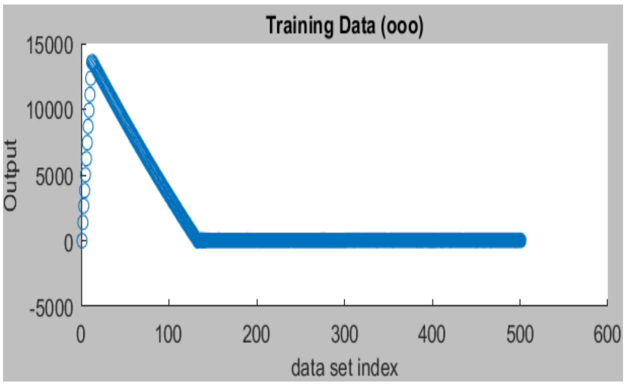

Fig. 6 Training data in the ANFIS tool

With a simple linear rule base, the structure of the ANFIS model [17] can be seen in figure 7. As observed, there are only seven rules where each input variable defines one output variable.

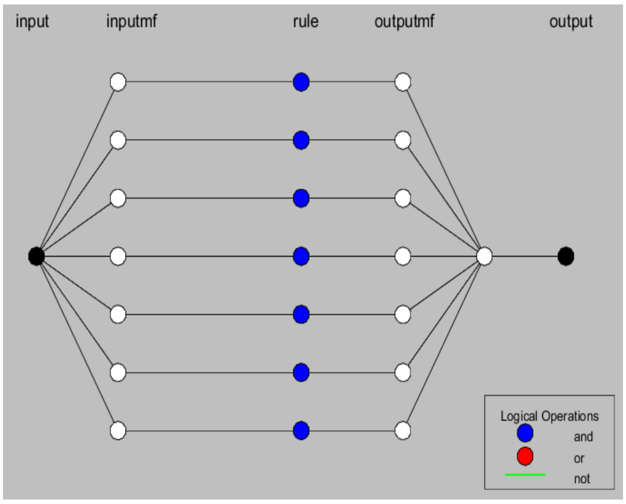

Fig. 7 ANFIS model rule base structure

The training 'hybrid' optimization method is selected, which can also be the 'back-propagation' method per the requirement [15].

The hybrid optimization method shows promising results for the speed controller. After the training of the Sugeno fuzzy structure [16], the new trained data is shown in figure 8.

Fig. 8 New trained data using ANFIS tuning tool

With the new adaptive hybrid algorithm trained FIS file, the structure is imported to the speed controller, generating reference torque Te* for the IFOC controller [9]. From the Te* generation, the q-axis current component (iq*) is determined as

$$i_q^* = \frac{4L_rT_e^*}{3PL_m\psi_r}$$

Here, "Lr is rotor inductance of the machine, P is the number of stator poles of the machine, Lm us the mutual inductance of the machine, ψ_r is rotor flux of the machine," which is given as

$$\varphi_r = \frac{Lm.i_d}{(1+T_{r.s})}$$

With all the above equations and training of the speed controller with estimated speed from the MRAS module [14], the actual speed of the machine is controlled as per the desired reference value of the user. Modeling of the same in the Simulink environment [18] [19] [20] is done with results generated taking time as a reference in the next section.

4. Simulation Result Analysis

Modeling of IM drive through three phases inverter controlled by ANFIS integrated IFOC scheme with speed estimation module MRAS is modeled in Simulink environment of MATLAB software. The simulation of the same can be seen in figure 9. The model is run for 5secs of simulation time, and the results with different operating conditions are recorded. The simulation parameters of the design are given in Table I.

Table 1. Test system configuration parameters

Name of parameter	Value
Vdc	65V
Flux reference	0.1
Speed reference	1000rpm
Induction motor parameters	Prated = 7.8kW, Vrms = 47V, f=52Hz, Rs=3.6mOhms, Ls=0.0301mH, Rr=3.1mOhm, Lr=0.0301mH, Lm = 0.763mH, Inertia J = 0.5kg-mt^2, Number of poles P = 4.

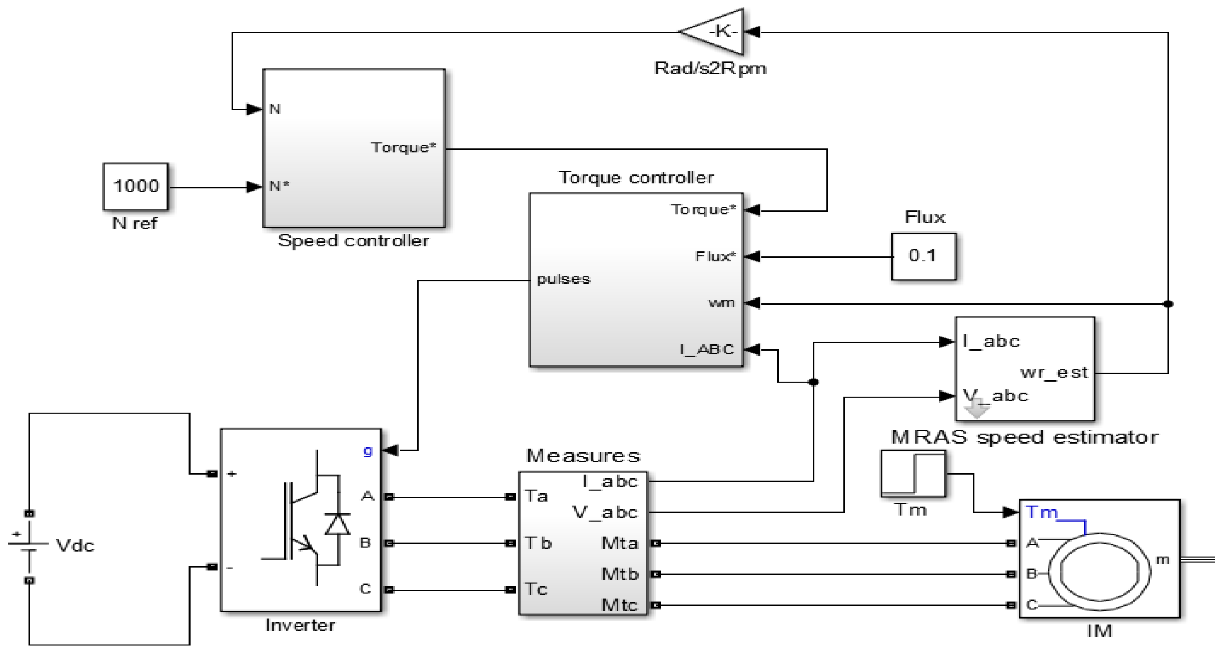

Fig. 9 Simulation modeling of proposed IM drive

The internal modeling of the MRAS speed estimator can be seen in figure 10 with the adaptive model, reference model, and PI controller.

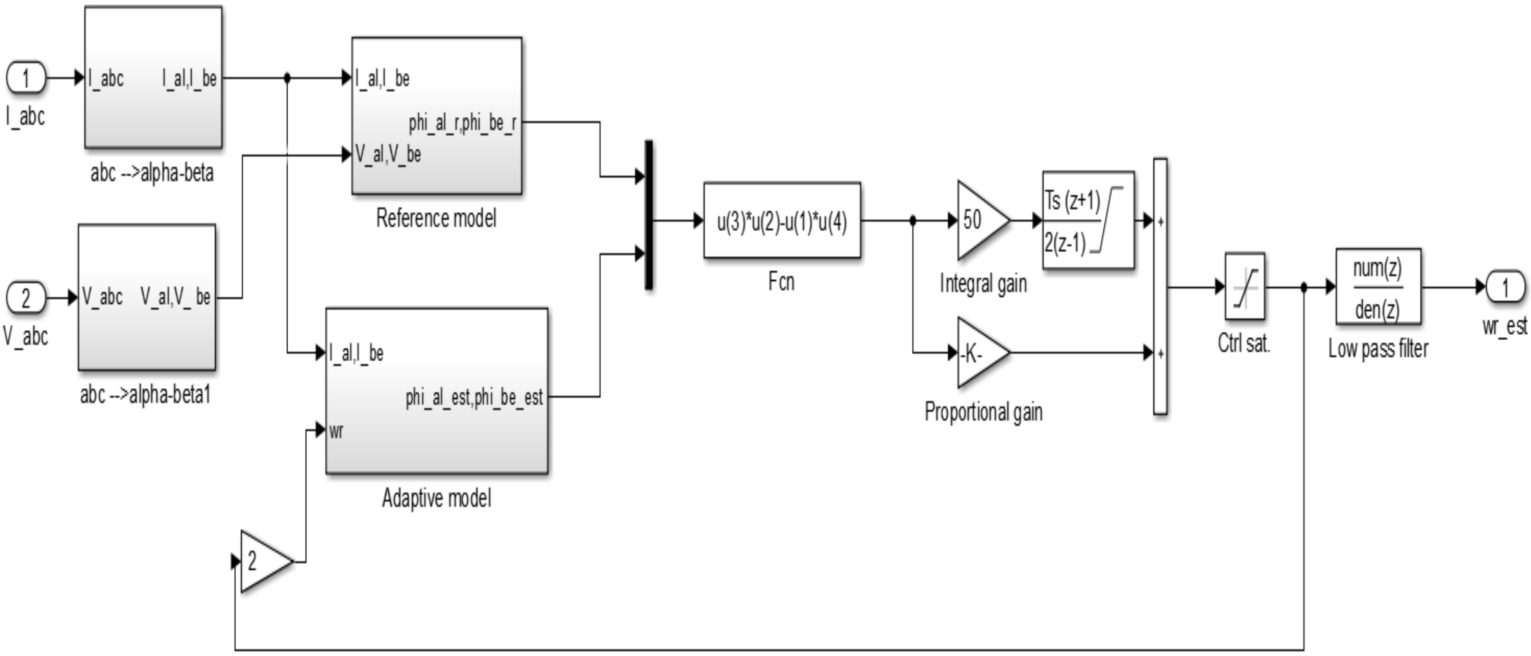

Fig. 10 MRAS speed estimator internal modeling

Torque reference generation with ANFIS controller can be seen below in figure 11. The input to the ANFIS block is the error generated by comparison of reference speed with measured speed. The output will be the machine's reference torque generated concerning the controller's training.

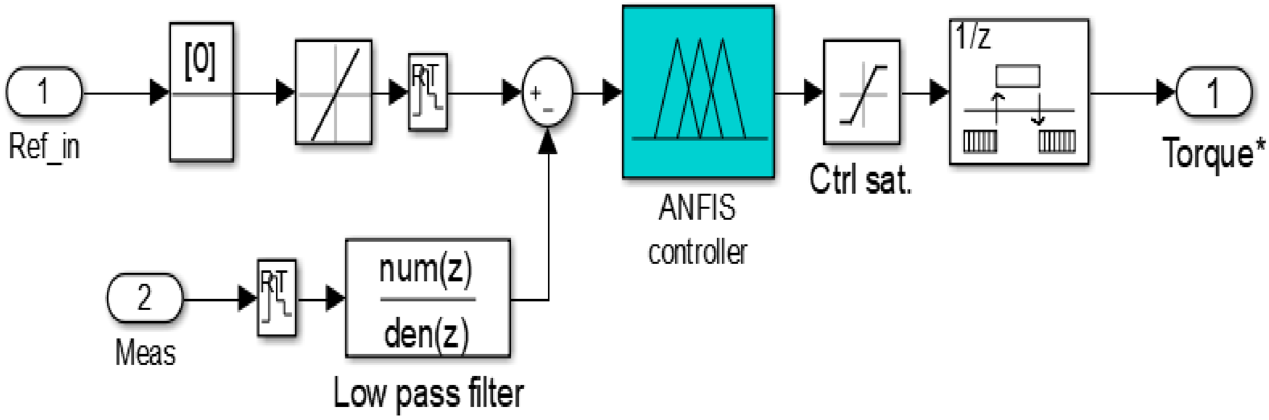

Fig. 11 ANFIS torque regulator

The reference speed of the machine is set to 1000rpm throughout the simulation time of 5sec. The "mechanical torque Tm to the machine is changed from 10N-mt to 15N-mt." Figure 12 shows the MRAS module's estimation of the machine's speed.

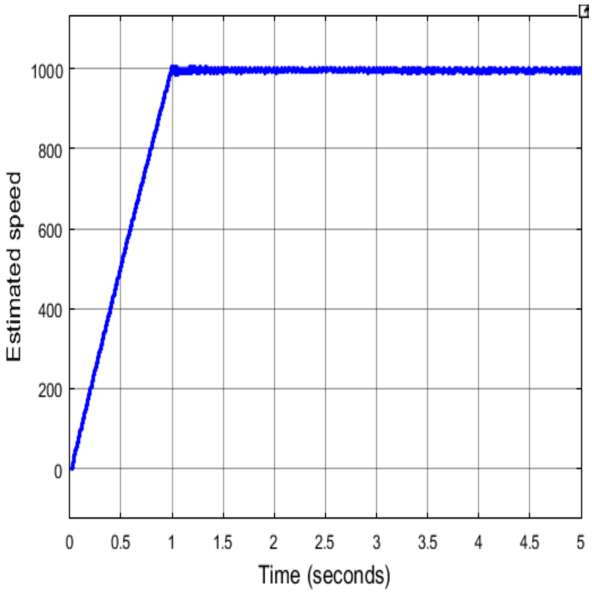

Fig. 12 Estimated speed of MRAS module

The speed is always estimated to be 1000rpm throughout the simulation time of 5sec as per the reference value given by the user. Hence the MRAS speed estimator is in optimal working condition and generating the expected speed of the machine. Reference torque generated by the ANFIS controller integrated speed regulator can be seen in figure 13.

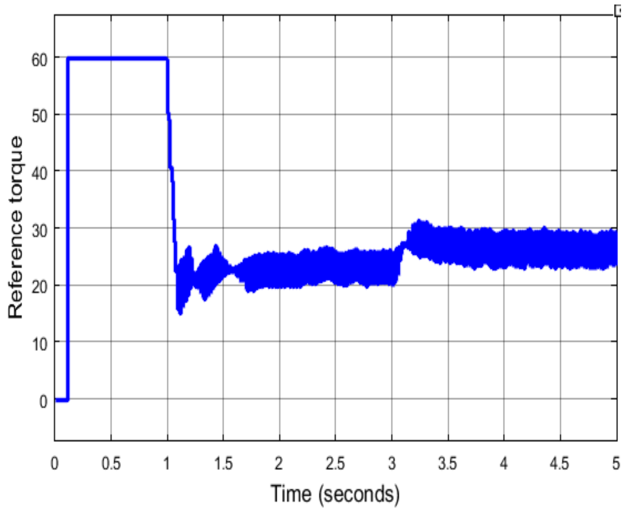

Fig. 13 Reference electromagnetic torque Te*

As per the reference torque generated, reference currents for the hysteresis loop controller can be seen in figure 14. The currents are controlled as per the changes in the dq axis current components of the references generated by the IFOC scheme.

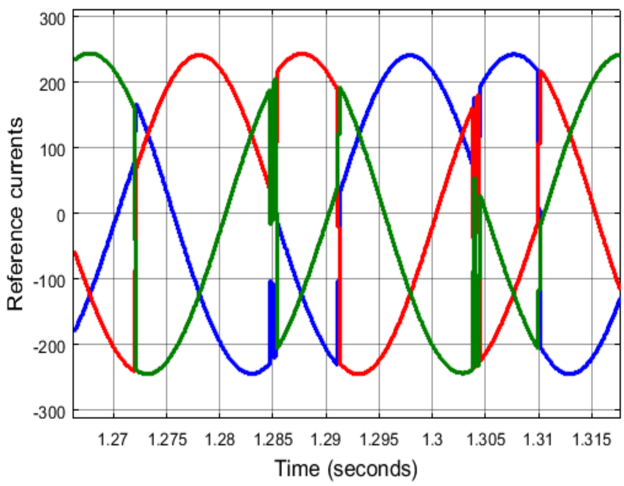

Fig. 14 Reference currents from the IFOC scheme

As per the reference currents generated and comparison of the stator currents of the machine fed to the hysteresis loop controller, the pulses generated for the inverter control the output AC voltage, the measured stator currents, and voltages are shown in figure 15.

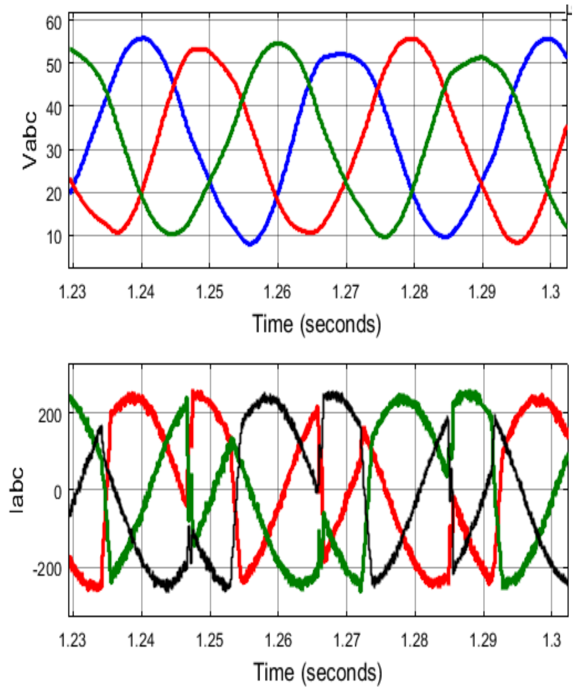

Fig. 15 Stator voltages and currents

As per the simulation references, a comparative measured electromagnetic torque of the machine for all the controllers, including conventional PI, PID controllers, and fuzzy logic controller with ANFIS speed regulator, is given in figure 16.

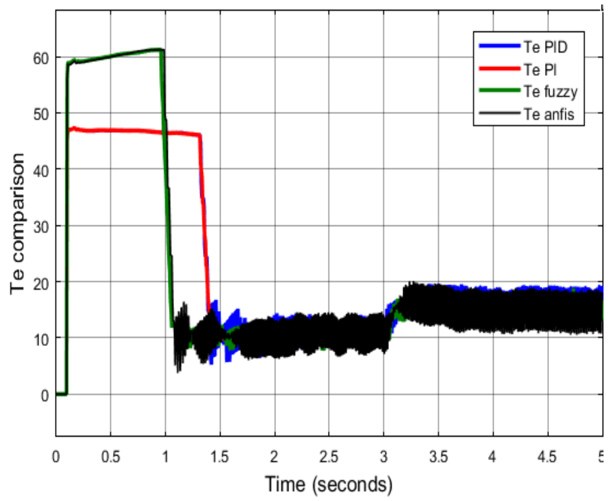

Fig. 16 IM torque comparison of all controllers (PID, PI, fuzzy, and ANFIS)

4.1. Similar comparison of the speed of the machine with different controllers is shown in figure 17.

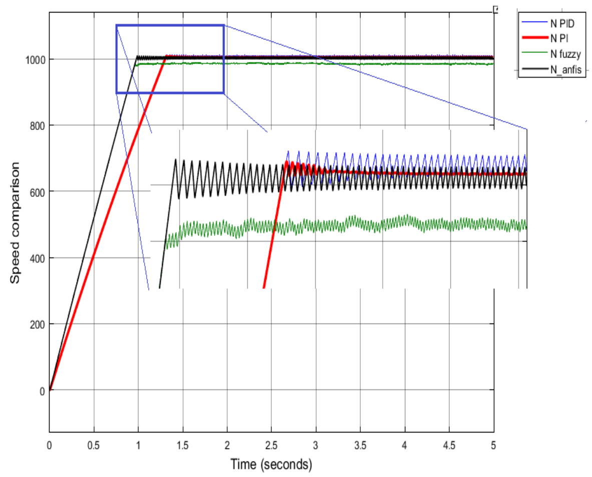

Fig. 17 IM Speed comparison of all controllers (PID, PI, fuzzy, and ANFIS)

5. Conclusion

Complete analysis and design of the proposed "ANFIS controller based IFOC speed control of IM with MRAS speed estimator" is done in this paper. A comparative analysis with conventional controllers like PI and PID is also done, and a "fuzzy logic controller" is also compared to the ANFIS controller. As per the figure, the speed settling time is lowest for ANFIS and fuzzy logic controllers compared to "PI and PID." However, the actual speed of 1000rpm is only achieved by the ANFIS controller, which is not achieved by fuzzy logic. The PI and PID speed regulators have a slower response, for which the speed is settled slower. PI speed regulator has a lesser ripple as compared to all other controllers. A parametric speed comparative table of different controllers is shown below.

Table 2. Parametric comparison table

	Settling time of N	Ripple in N	Settled speed value
PID	1.3sec	0.79%	1007rpm
PI	1.3sec	0.1%	1004rpm
FUZZY	0.96sec	0.5%	985rpm
ANFIS	0.96sec	0.5%	1001rpm

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