Comparison of Artificial Controller Based MRAS Speed Observer for Field Oriented Control of Induction Motor

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Abstract. In many industrial applications, the varying speed of the motor drives has become essential for the fast dynamic load conditions. Therefore, the detailed analysis of Field Oriented Control (FOC) with the sensor-less technique of induction motor is proposed where the reference speed is obtained from the MRAS speed observer, and fuzzy, ANN based controllers control the speed. The FOC not only control the magnitude but also provides the phasor control. The FOC is one of the sensors less technique. The sensor-less invokes the process of estimating the speed; the proposed MRAS speed observer achieves it. The MRAS speed observer gets the inputs such as current and voltage and then it converts to flux to reference speed. The FOC control the torque and flux components independently, and the flux component is obtained by the current. The fuzzy-based control technique is utilized for the control of the speed of the induction motor. In addition to this paper compares the results of fuzzy, and ANN based speed control methods, the results include the settling time, peak overshoot, ripples and accuracy of the speed. The results have been compared in the virtual environment by the MATLAB tool.

Keywords: ANFIS Controller, Field Oriented Controller (FOC), Fuzzy Controller, Induction Motor, MRAS Speed Observer, Settling Time.

1. Introduction
In recent times the application of induction motor with fast varying speed conditions is expanding. The enhancement in speed control requests looking for new control techniques. The typically used controls are scalar and vector control. The scalar control utilizes the Voltage/frequency strategy which invokes the process of controlling the speed by frequency or voltage [1]. The scalar control has the issue of circuit damage when there is confusion in the timing of voltage and frequency control, i.e., voltage and frequency ought to be changed concurrently. The scalar control is mostly used in non-feedback conditions because of its simple structure, financially savvy and error reduction. The feedback condition is also being practicable in scalar control, but it is confounded and produces ambiguity to the control [2]. The feedback condition control only provides control over the torque which is acquired by comparing the motor speed and reference, and they are given through the controller such as PI, PID and advanced controllers to deliver the reference torque [3-4]. The scalar control in the feedback condition has not given authority to control over the flux as well as control over the fast varying speed. To overcome these problems, there is the entry of vector control techniques. The vector control provides the high-quality speed control of induction motor. Both the torque and flux components are controlled individually which builds the intricacy. Thus the FOC and Direct Torque Control (DTC) propelled
control schemes are proposed [5]. The FOC and DTC include in controlling the speed by not only taking out the speed value as a reference and converting them into flux but also uses the stator current values as feedback for the reference. The procedure of control for FOC and DTC is in a similar way, i.e., by controlling the flux and torque components however the considerable contrast is DTC utilises the stator flux while FOC uses the rotor flux and there is also need of converting the three-phase current to two-way components (D-Q) in DTC. Therefore, the DTC is quite simple in structure, but it has the disadvantage of less accuracy during quick speed and loads changing conditions [6]. There are two methods of FOC control one is direct control method, and other is an indirect control method. In FOC the rotor sensors either installed or not needed to detect the rotor position and speed. They can be calculated from any estimation method such as MRAS observer, Kalman filter or adaptive methods. Direct FOC and indirect FOC have a difference in calculating the rotor angle. The indirect FOC calculates the rotor angle indirectly by adding the rotor speed with slip speed and then integrating the sum [7]. The usage of indirect FOC includes complexity and ambiguity. This paper utilizes the sensor-less control of direct FOC technique to enhance the simplicity of the system with the comparison of PI and Fuzzy based speed controller. The sensor-less technique includes the usage of estimation methods for detecting the speed of the rotor. The availability of various estimation methods adds the confusedness of selecting the optimal method for speed estimation [8]. The methods are classified into two main types 1) Based on signal injection 2) based on the model. The signal injection method is hard to install in hardware because it requires separate hardware for signal injection as well as it can be used in low-speed applications. The model-based method consists of MRAS speed observer, Kalman filter, sliding mode observer and adaptive methods. These methods provide quick adaption of parameters during dynamic conditions with reduced computing time and easy implementation in both hardware and software [9]. Among these, the MRAS speed observer is used because this method requires fewer motor parameters with two models for estimating the same parameter with different input parameters for each model. This increases the rejection of error to a greater extent than the other estimation methods.

This paper proposes a novel MRAS speed observer to overcome the drawbacks based on the conventional MRAS observer. The disadvantage of the conventional method includes not having the capability of quality performance in low-speed applications. The performances involve estimating the speed with varying temperature and resistance values. This paper also utilizes either fuzzy or PI controller for the speed control. Both the fuzzy and ANN based control is implemented and their results are compared for the selection of suitable controller. The proposed system of the induction motor based field oriented control for the speed control is compared with [10, 17] through the settling time reduction and minimization in ripples.

2. Literature survey

To improve the induction motor control with the steady state performance and dynamic response, the model predictive controller used. This control method is explained in [11] the relationship in between the stator voltage and the torque are analyzed. In [12] the two axis stationary reference frame based model reference adaptive system (MRAS) is implemented to estimate the speed of the rotor of an induction motor. The speed is controlled effectively but the settling time is more. In [13] loss minimizing strategy is proposed to achieve maximum efficiency operation for torque control. This control system is using the reference of the optimal stator flux and desired torque. The predictive direct torque controller is used to control the induction motor which combines both the predictive control as well as the direct torque control system. The overall performance of the motor is improved using the kalman filter that used for the estimation of the reliable flux [14-15]. The doubly fed induction motor based speed control method is explained in [16] the author describes the two types of control methods that does not relays on inner current loops and it gives direct voltages for rotor that used for the tracking the reference speed profile.

3. Proposed system

In this proposed system consist of mathematical modelling of induction motor with its control techniques are fuzzy and ANFIS based MRAS speed observer with field oriented controller. DC source fed to the
three phase inverter which control motor speed and it’s settling time by proper control pulse to the inverter switches.

3.1. Mathematical model of IM

The three induction motor consists of three types. These types are classified based on the rotor structure. If the rotor looks like squirrel cage and double squirrel cage then it is called squired cage induction motor & double squirrel cage induction motor respectively and it is called as wound rotor when the rotor is in wound type. In this paper we took a squirrel cage induction motor modelling because it have better efficiency, lesser cost, less maintenance, and there is no need of high starting toque. The modelling can be done in both mechanically and electrically. The induction motor modelling can be done by the use of equations presented in upcoming sections.

3.2. Electrical modeling

The electrical modeling of squirrel induction motor is made through the state space model of 4th order. The three phase parameters of stator and rotor are converter to components of dq.

The q and d axis components is given by,

\[ V_{q_{stator}} = R_{stator} * i_{q_{stator}} + \frac{d\psi_{q_{stator}}}{dt} + \omega * \psi_{d_{stator}} \]  \hspace{1cm} (1)

\[ V_{d_{stator}} = R_{stator} * i_{d_{stator}} + \frac{d\psi_{d_{stator}}}{dt} - \omega * \psi_{q_{stator}} \]  \hspace{1cm} (2)

\[ \psi_{q_{rotor}} = R_{rotor} * \psi_{q_{rotor}} + \frac{d\psi_{q_{rotor}}}{dt} + (\omega - \omega_{electrical}) * \psi_{d_{rotor}} \]  \hspace{1cm} (3)

\[ \psi_{d_{rotor}} = R_{rotor} * \psi_{d_{rotor}} + \frac{d\psi_{d_{rotor}}}{dt} + (\omega - \omega_{electrical}) * \psi_{q_{rotor}} \]  \hspace{1cm} (4)

\[ T_{elec \_Mag} = \frac{3}{2} * no.\_of.\_pole (\psi_{d_{stator}} * i_{q_{stator}} - \psi_{q_{stator}} * i_{d_{stator}}) \]  \hspace{1cm} (5)

The fluxes are given by,

\[ \psi_{q_{stator}} = L_{stator} * i_{q_{stator}} + L_{mag} * \psi_{q_{rotor}} \]  \hspace{1cm} (6)

\[ \psi_{d_{stator}} = L_{stator} * i_{d_{stator}} + L_{mag} * \psi_{d_{rotor}} \]  \hspace{1cm} (7)

\[ \psi_{q_{rotor}} = L_{rotor} * \psi_{q_{rotor}} + L_{mag} * i_{q_{stator}} \]  \hspace{1cm} (8)

\[ \psi_{d_{rotor}} = L_{rotor} * \psi_{d_{rotor}} + L_{mag} * i_{d_{stator}} \]  \hspace{1cm} (9)

\[ L_{stator} = L_{stator \_leakage} + L_{mag} \]  \hspace{1cm} (10)

\[ L_{rotor} = L_{rotor \_leakage} + L_{mag} \]  \hspace{1cm} (11)
### 3.3. Electrical Modeling

\[
\frac{d\omega_{\text{mech}}}{dt} = \frac{0.5}{J_{\text{rotor-load}}} \left( T_{\text{elec-Mag}} - T_{\text{rotor-load}} - \omega_{\text{mech}} \right)
\]

(12)

\[
\frac{d\theta_{\text{mech}}}{dt} = \omega_{\text{mech}}
\]

(13)

Where \( R_{\text{stator}} \) and \( R_{\text{rotor}} \) are resistance of the stator and rotor, \( L_{\text{stator-leakage}} \) is the stator and rotor leakage inductor value, \( L_{\text{mag}} \) is magnetizing inductor value, \( L_{\text{stator}} \) is stator and rotor inductance value \( V_{\text{qstator}}, V_{\text{dstator}} \) is stator voltage along \( q \) axis and \( d \) axis respectively, \( i_{\text{qstator}}, i_{\text{dstator}} \) is the stator current along \( q \) axis and \( d \) axis respectively, \( \omega_{\text{mech}} \) is rotor mechanical angular velocity, \( \omega_{\text{electrical}} \) is the rotor electrical angular velocity, \( \omega_{\text{electrical}} \cdot \text{number of poles}, \) \( \theta_{\text{mech}} \) is rotor mechanical angular position, \( T_{\text{electromagnetic}} \) is electromagnetic torque, \( T_{\text{mechanical}} \) is the mechanical torque, \( J_{\text{rotor-load}} \) is the inertia coefficient between the rotor and load, \( F_{\text{rotor-load}} \) is the friction constant between the rotor and load, \( \gamma_{\text{qstator}}, \gamma_{\text{dstator}} \) is the stator flux along \( q \) and \( d \) axis respectively, \( \gamma_{\text{qrotor}}, \gamma_{\text{drotor}} \) is the rotor flux along \( q \) and \( d \) axis respectively.

### 4. Control methods

#### 4.1. Reference frame

The reference frame has to be chosen to modify the three phase input components i.e., \( A, B, C \) to \( d, q \) components and the \( d, q \) components are converted back to three phase output components i.e., \( A, B, C \). \( Q \)-axis and \( D \)-axis of induction motor is shown in the figure. 1 and figure 2. There are three types of reference frame. They are rotor, stationary and synchronous reference frame. The difference between them are based on the angular position and balancing condition of voltages. In this model rotor reference frame is utilized because the stator voltage is in balance condition and rotor voltages are varying. \( \theta \) is taken as rotor is the electrical position of the rotor and \( \beta \) is taken as 0. These may vary for different reference frame. The conversion matrix is given by, Input voltage \( A, B, C \) to \( d, q \):

\[
\begin{bmatrix}
V_{\text{qstator}} \\
V_{\text{dstator}}
\end{bmatrix} = 0.3333 \begin{bmatrix}
2 \cos \theta & \cos \theta + 1.732 \sin \theta \\
2 \sin \theta & \sin \theta - 1.732 \cos \theta
\end{bmatrix} \begin{bmatrix}
V_{\text{a}} \\
V_{\text{b}}
\end{bmatrix}
\]

(14)

\[
\begin{bmatrix}
\gamma_{\text{qrotor}} \\
\gamma_{\text{drotor}}
\end{bmatrix} = 0.3333 \begin{bmatrix}
2 \cos \beta & \cos \beta + 1.732 \sin \beta \\
2 \sin \beta & \sin \beta - 1.732 \cos \beta
\end{bmatrix} \begin{bmatrix}
\gamma_{\text{a}} \\
\gamma_{\text{b}}
\end{bmatrix}
\]

(15)

\[
\begin{bmatrix}
i_{\text{qstator}} \\
i_{\text{dstator}}
\end{bmatrix} = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\cos \theta + 1.732 \sin \theta & -1.732 \cos \theta - \sin \theta
\end{bmatrix} \begin{bmatrix}
i_{\text{a}} \\
i_{\text{b}}
\end{bmatrix}
\]

(16)

\[
\begin{bmatrix}
i_{\text{qrotor}} \\
i_{\text{drotor}}
\end{bmatrix} = \begin{bmatrix}
\cos \beta & \sin \beta \\
-\cos \beta + 1.732 \sin \theta & -1.732 \cos \beta - \sin \beta
\end{bmatrix} \begin{bmatrix}
i_{\text{a}} \\
i_{\text{b}}
\end{bmatrix}
\]

(17)
4.2. Field oriented controller

FOC is one of the vector control strategies which have the ability of controlling the torque and flux separately. The reference torque and flux are generated by the voltage, current and speed parameters from the induction motor. The FOC has two types one is direct FOC and indirect FOC. The direct FOC consists of the sensors fitted to the induction motor which will recognize the speed, position of the rotor as well as flux of the motor. In case of indirect FOC doesn’t need flux sensor which is calculated indirectly by the flux calculating equation. The installing of flux sensors will make system complex and it is not attractive one. Therefore, the indirect FOC bring into act to solve the issue. The mathematical equation based on the current and speed is defined to find the flux. There is also existence of another vector control method which is named as DTC. The DTC is simple, lack of sensors but it has the major drawbacks such as ripples production in current, noise production and can’t be suitable for low speed conditions. The FOC control scheme has been evaluated as sensor-less technique which is major advantage of DTC through the speed observing techniques. This paper utilizes the advantages of indirect FOC by implementing with sensor-less technique. The proposed system invokes the operation of calculating the speed using the speed observer and they are converted to torque and flux reference and there is also hands of Clarke and Park’s transformation. The Indirect FOC block diagram is shown in figure 3.

Figure 1. Q-axis of Induction Motor

Figure 2. D-axis of induction motor

Figure 3. Block Diagram of the IFOC
The indirect FOC process includes the speed is first estimated by using the speed observer. In this paper modified MRAS speed observer is utilized which is discussed in the following section. The estimated speed is then converted as reference torque and flux. The reference torque and flux is converted into dq currents. The q axis current is obtained from torque and d axis current is obtained from flux. Meanwhile \( \omega \) is calculated from the estimated speed for the operation of converting the dq components again to abc components. The conversion of dq current to abc current process is necessary to compare the converted abc current with reference abc current obtained from the motor. The comparison is made and the desired gate pulses to the inverter switches are given which is performed by the current regulator.

4.3. MRAS Speed observer

The proposed FOC utilizes the sensor less technique with the help of MRAS speed observer is represents in the figure 4. The sensor-less technique makes the absence of mechanical sensors has the constraints of less sensitivity and specific range. MRAS speed observer is one of the most commonly used speed observer because of its non-complexity, ease of implementation, less calculations and consistency. MRAS speed observer doesn’t need more number of machine parameters like other methods such as Extended Kalman Filter, Luenberger observer (ELO) and adaptive observer. These methods also require lot of calculations and memory space. Therefore, the MRAS speed observer is became more attractive. It is classified into different groups namely 1) Based on the estimation of speed using the rotor flux 2) Based on the estimation of speed using back EMF 3) Based on the estimation of speed using reactive power 4) Based on the estimation of speed using electromagnetic torque 5) Based on the estimation of speed using stator current. Among all the methods the speed estimation using the rotor flux is the most popular method. This method has some drawbacks such as poor performance during the temperature and resistance variation, offset problem and less efficient on low speed. The proposed MRAS speed observer overcomes these problems and also increases the accuracy in estimating the speed. The proposed method has the two models one is reference model and adaptive model. These models output are compared and the desired results are given to the adaptive mechanism. Both the models are same for the conventional and proposed MRAS speed observer. Only difference is new adaptive mechanism has been developed. The typical reference model and adaptive model equations modeling are as follows equation 18 and 19 belongs to the reference model.

\[
\frac{d\psi_{\text{rotor}}}{dt} = \sigma L_{\text{stator}} \frac{T_{\text{rotor}}}{L_{\text{mutual}} \frac{di_{\text{stator}}}{dt} + \frac{T_{\text{rotor}}}{L_{\text{mutual}}}(V_{\text{stator}} - R_{\text{stator}} \frac{i_{\text{stator}}}{}) \tag{18}
\]

\[
\frac{d\psi_{\text{stator}}}{dt} = \sigma L_{\text{stator}} \frac{T_{\text{rotor}}}{L_{\text{mutual}} \frac{di_{\text{rotor}}}{dt} + \frac{T_{\text{rotor}}}{L_{\text{mutual}}}(V_{\text{stator}} - R_{\text{stator}} \frac{i_{\text{stator}}}{}) \tag{19}
\]

Equation 20 and 21 belongs to the adaptive model

\[
\frac{d\psi_{\text{rotor}}}{dt} = \frac{L_{\text{mutual}}}{Rt} \frac{i_{\text{stator}}}{ - \frac{1}{Rt} \psi_{\text{rotor}} - \frac{1}{Rt} \psi_{\text{rotor}} \frac{di_{\text{rotor}}}{dt} \frac{i_{\text{rotor}}}{}} \tag{20}
\]

\[
\frac{d\psi_{\text{stator}}}{dt} = \frac{L_{\text{mutual}}}{Rt} \frac{i_{\text{stator}}}{ - \frac{1}{Rt} \psi_{\text{stator}} - \frac{1}{Rt} \psi_{\text{stator}} \frac{di_{\text{stator}}}{dt} \frac{i_{\text{stator}}}{}} \tag{21}
\]

The adaptive mechanism is modified by including the torque parameter which is introduced to enhance the stability and response of the system. The adaptive mechanism is given by block diagram. The equation includes,
Figure 4. MRAS based IFOC Controller

\[ T_{elec \_mag} = 1.5 \cdot \frac{P}{2} \cdot \frac{L_{\text{mutual}}}{L_{\text{rotor}}} (i_{\text{stator}} \cdot \psi_{\text{drotor}} - i_{\text{drotor}} \cdot \psi_{\text{stator}}) \]

\[ T_{elec \_mag} = 1.5 \cdot \frac{P}{2} \cdot \frac{L_{\text{mutual}}}{L_{\text{rotor}}} (i_{\text{stator}} \cdot \psi_{\text{drotor}} - i_{\text{drotor}} \cdot \psi_{\text{stator}}) \]

4.4. Controller

The estimated speed is compared with the reference speed and the output from the comparator is given to the controller part. There are several control techniques available for the control operation. The advanced topologies in control technique have been developed in greater way but they have to meet the following constraints such as they should think, evaluate, develop, improve and organize by their own. The conventional PI and PID controller has the drawbacks of steady state and transient problems. To overcome this advanced controller like Fuzzy logic and ANFIS are proposed.

4.5. Fuzzy Logic Controller

Fuzzy logic controller is designed for regulates and reduce the settling of the speed attained from the motor. The error and change in error is the input of the fuzzy system. Then the output is designed by membership function (MF). It includes the property of IF and THEN condition and used the centroid method. Membership function of the fuzzy controller is shown in figure 5, figure 6 and figure 7.
4.6. ANFIS Controller
The Artificial Neural Network Fuzzy Interference system used the property and combines both fuzzy and ANN advantages. The general block diagram for the ANFIS system is shown in Figure 8. It uses the SUGUNO model, which consists of five layers, and this control technique consists of an adaptive
node and a fixed node. Nonlinearity mapping is property of ANFIS framework. The ANFIS incorporates the process towards getting the input values and processing them as per fuzzy rules, and the processed output from the fuzzy rules is again sophisticated through neural network define rules to build the accuracy of the system. The layer 1 includes the input data for processing the purpose of the ANFIS. The layer 2 performs the AND operation based fuzzy rules with input data. The layer 3 performs the same AND operation based NN defines rules for improvement of accuracy. The layer 4 is utilized for adjusting the output parameters and the layer 5 delivers the desired output by processing the input data with given rules.

![Figure 8](image.png)

**Figure 8.** Generalized layered diagram of ANFIS Controller

5. **Simulation analysis**

The proposed three phase voltage source inverter with Fuzzy and ANFIS technique based MRAS speed observer control strategy is executed and their outcome results are evaluated and advantages are confirmed through MATLAB/Simulink. The diagram of overall Simulink setup and Fuzzy, ANFIS based MRAS speed observer with FOC controller is shown in figure 9.
Figure 9. Overall Simulink diagram and Fuzzy, ANFIS with MRAS based IFOC speed controller

The three phase voltage waveform across the load (induction motor) using fuzzy and ANFIS controller is 400V without filter and it represent in figure 10.

Figure 10. Inverter voltage before without filter

Estimated speed is 500rpm and reference speed is obtained from the MRAS speed observer method. Speed of the proposed induction motor using fuzzy controller is 494rpm with the settling time of 1.7sec shown in the figure 11.

Figure 11. Output speed of motor using Fuzzy based MRAS with FOC controller
ANFIS based control the speed control of induction motor is same as fuzzy control, but its settling time is low compare to fuzzy. Estimated speed is 500rpm and reference speed is obtained from the MRAS speed observer method. Speed of the proposed induction motor using fuzzy controller is 494rpm with the settling time of 1.2sec shown in the figure.12. The obtained proposed control method based settling time of the speed is reduced while compared with the reference analysis which is explained in [10].

![Figure 12. Output speed of the IM motor using ANFIS based MRAS with FOC controller](image)

**6. Conclusion**

Compares the results of fuzzy, and ANFIS based speed control methods, the results include the settling time of the speed is proposed in this paper. The results have been compared in the virtual environment by the MATLAB tool. The FOC is one of the sensors less technique. The sensor-less invokes the process of estimating the speed; the proposed MRAS speed observer achieves it. Estimated speed of the induction motor is set at 500 rpm and actual speed of the motor is also 500rpm is obtained with the help of proposed controller fuzzy and ANFIS based MRAS with FOC controller. Settling of the induction motor is less at 1.3sec while using the fuzzy based controller. From this analysis and implementation, controls the motor speed and reduces its settling time by using artificial network based MRAS speed observer with FOC controller with the help of MATLAB/Simulink.

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