An Adaptive Neuro Fuzzy Based Speed Control of an Induction Motor Drive Using Unscented Kalman Filter

I.Sumiya Anjum¹, V.K.Dinesh Prabu², Dr.C.Kumar³

¹PG Scholar, M.E Power Systems Engineering, Dept of EEE, S K P Engineering College, Tiruvannamalai, TamilNadu.
²Research Scholar, AssistantProfessors, Dept of EEE, S K P Engineering College, Tiruvannamalai, TamilNadu.
³Director Academic, S K P Engineering College, Tiruvannamalai, TamilNadu

¹sumiyaaliya@gmail.com
²dineshprabuvk@yahoo.co.in
³drchkumararima@gmail.com

Abstract-This paper presents a robust estimation of speed and rotor flux for sensorless control of motion control systems with an induction motor. A conventional extended kalman filter is replaced, and rotor flux is estimated by means of an unscented Kalman filter, whereas the speed is estimated using adaptive speed estimator technique. Investigations is carried out on a closed loop system which having a low power induction motor system, an adaptive Neuro-fuzzy type controller and the adaptive speed estimation technique, are shown with the aim of confirming the behavior of the whole closed loop control system.

Keywords- Adaptive Speed Estimator, Induction Motor, Sensorless Control, Unscented Kalman Filter

I.  I. INTRODUCTION

Recently, induction motors are starting to be very popular in industrial environment because of its operating performance. Induction motors are relatively smooth and low cost machines. Therefore much interest is given to their control for various applications with informal control requirements. An induction machine, especially squirrel cage induction machine (SCIM), has many advantages when compared with DC machine.

First and foremost, it is extremely low cost. Second, it has very compact design structure and not sensitive to environment. After that, it does not require regular maintenance like DC motors. Moreover, it is highly non-linear and combined dynamic structure, an induction machine need more complex control technique than DC motors. A Conventional open-loop control of the induction machine with variable frequency may not stipulate an acceptable solution. However, when high performance progressive operation is needed, these methods are not satisfactory. Hence, not more unsophisticated control methods are needed to make the behaviour of the induction motor comparable with DC motors. So that to get satisfactory and expected solution, the closed loop control method is used. Presently, improvements in the area of drive control schemes, it made that induction motors replace the DC motors from industry. The most famous induction motor drive control method has been the field oriented control (FOC) in the present paper. Furthermore, the present trend in FOC is towards the use of sensorless techniques that avoid the sensors, for example the use of flux sensor and speed sensor. For this intention, one of the Kalman Filtering techniques which termed as Unscented kalman filter(UKF), are employed to estimate rotor speed and dq-axis rotor fluxes.
Using these techniques, one can obtain very precise flux and speed information as shown in the simulations and experimental results. In this work, it is also shown that the rotor speed estimation performance of these schemes is quite satisfactory in the simulations and Experimental results. Finally, to estimate the rotor flux and rotor flux angle which are directly employed in direct field orientation. EKF is a simple solution derived by direct linearization of the state equation for extending the famous (linear) Kalman filter into nonlinear filtering area. Although it is straightforward and simple, EKF has well-known drawbacks. These drawbacks include: Instability due to linearization and erroneous parameters, Costly calculation of Jacobian matrices. Biasedness of its estimates. Lack of analytical methods for suitable selection of model covariances. UKF is proposed in order to overcome the first three of these disadvantages. The main Advantage of UKF is that it does not need linearization in the computation of the state predictions and covariance. Due to this, its covariance and Kalman gain estimates are more accurate. This accurate gain, at the end, leads to better state estimates. In this study, UKF is introduced into the problem of speed and flux estimation of an induction motor. Neuro-fuzzy controllers (NFCs), which overcome disadvantages of conventional controllers like PI, PID, Fuzzy logic controllers and neural network controllers. To overcome the high computational burden, a Neuro-Fuzzy Controller scheme for the IM drive is proposed in this paper.

II. MATHEMATICAL MODEL

To explain the principle of vector control, an assumption is made that the position of the rotor fluxes linkages phasor $\lambda_r$ is known. $\lambda_r$ is at $\theta_f$ from a stationary reference[4]. $\theta_f$ is referred to as field angle hereafter. and the three stator currents can be transformed into q and d axes currents in the synchronous reference frames by using the transformation

$$ \begin{bmatrix} i_{dq} \\ i_{d} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \sin \theta_f & \sin (\theta_f + \frac{2\pi}{3}) & \sin (\theta_f - \frac{2\pi}{3}) \\ \cos \theta_f & \cos (\theta_f + \frac{2\pi}{3}) & \cos (\theta_f - \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{q} \\ i_{d} \end{bmatrix} $$

from which the stator current phasor is derived as

$$ i_s = \sqrt{(i_{dq})^2 + (i_{d})^2} (2) $$

and the stator phasor angle is

$$ \theta_s = \tan^{-1} \left( \frac{i_{dq}}{i_{d}} \right) (3) $$

Where $i_{dq}$ and $i_{d}$ are the q and d axes currents in the synchronous reference frames that are obtained by projecting the stator current phasor on the q and d axes respectively.

By writing rotor flux linkages and torque in terms of these components as

$$ \lambda_r \propto i_f \quad (4) $$

$$ T_e \propto \lambda_r i_f \propto i_f i_f \quad (5) $$

Crucial to the implementation of vector control, then is the acquiring of the Instantaneous rotor flux phasor position, $\theta_f$. This field angle can be written as

$$ \theta_f = \theta_r + \theta_s \quad (6) $$

Where $\theta_r$, is the rotor position and $\theta_s$ and is the slip angle. In terms of the speeds and time. The field angle is written as

$$ \theta_f = \int (\omega_r + \omega_s) \, dt = \int \omega_r \, dt \quad (7) $$

Vector-control schemes are classified according to how the field angle is acquired. By using terminal voltages the field angle is calculated. Then it is known as direct vector control.
By using the stator-current phasor angle and its magnitude \( \theta_s \) and \( i_s^* \), the required stator-current commands are round by going through the qdo transformation to abc variables:

\[
i_{as}^* = i_s^* \sin(\theta_s)(8)
\]

\[
i_{bs}^* = i_s^* \sin(\theta_s - \frac{2\pi}{3})(9)
\]

\[
i_{cs}^* = i_s^* \sin(\theta_s + \frac{2\pi}{3})(10)
\]

Rotor flux based calculator: Two line-to-line voltages can be measured, from which the phase (line to neutral) voltages can be computed (provided that the voltages are balanced). The q and d stator voltages in the stator reference frames are obtained from the phase voltages as

\[
V_{qs} = V_{a}(11)
\]

\[
V_{ds} = \frac{1}{\sqrt{2}}(V_{cs} - V_{bs})(12)
\]

Similarly, the currents are obtained in the same way; these equations hold true for them, too. From the stator-reference-frame equations of the induction motor, the stator equations an:

\[
V_{qs} = (R_s + L_s P)i_{qs} + (L_m P)i_{qr}(13)
\]

\[
V_{ds} = (R_s + L_s P)i_{ds} + (L_m P)i_{dr}(14)
\]

From which the rotor currents \( i_{qr} \) and \( i_{dr} \) can be computed as

\[
i_{qr} = \frac{1}{L_m}\left[\int(V_{qs} - R_s i_{qs}) \, dt - L_s i_{qr}\right](15)
\]

\[
i_{dr} = \frac{1}{L_m}\left[\int(V_{ds} - R_s i_{ds}) \, dt - L_s i_{dr}\right](16)
\]

\[
T_f = \frac{3}{2}\frac{P}{2}\frac{L_m}{2}(i_{qr}i_{dr} - i_{ds}i_{qr})(17)
\]

The implementation of the scheme requires flux linkages and torque computations, plus generation of switching states through a feedback control of the torque and flux directly without inner current loops.

The stator q and d axes flux linkages are

\[
\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad (18)
\]

\[
\lambda_{dr} = L_r i_{dr} + L_m i_{qs} \quad (19)
\]

\[
\lambda_r = \sqrt{(\lambda_{qr})^2 + (\lambda_{dr})^2} \quad (20)
\]

\[
\theta_f = \tan^{-1}\left(\frac{\lambda_{qr}}{\lambda_{dr}}\right) \quad (21)
\]

Where the direct and quadrature axis components are obtained from the abc variables by using the transformation.

\[
i_{qs} = i_{as}
\]

\[
i_{ds} = \frac{1}{\sqrt{2}}(i_{cs} - i_{bs})(22)
\]

The above mathematical models are useful while estimating the voltage, current, torque, flux. But in this paper the parameters are obtained with the help of estimator, so that the computational time will be reduced.

### III. UNSCENTED KALMAN FILTER

Julier and Uhlmann to replace EKF in nonlinear filtering problems and introduce Unscented Kalman filter (UKF) which is a novel estimation tool[3]. A extended kalman filter (EKF) is a simple solution derived by direct linearization of the state equation to extending in nonlinear filtering area, the famous (linear) Kalman filter is also used. Although it is easy to understand and simple, EKF has famous drawbacks. These drawbacks are as follows:
1. not stable due to linearization and erroneous parameters
2. Costly calculation of Jacobian matrices.

The UKF performs the state estimation by approximating the probability distribution after performing the computation using nonlinear function. A set of deterministic sample points is taken around the last known state and propagated through the real nonlinear function. With these results, a mean and covariance can be approximated using a weighted sample mean and covariance of the transferred sample points.

3.1. Steps in UKF

1. Selection of sigma points.
2. Estimation of next state sigma points.
3. Finding weighted mean and covariance.
4. Predicting the state variables using algorithm
5. Updating to get next state variables.

3.2. UKF flowchart

By using this flowchart how the UKF estimate robust value of rotor flux is explained as follows; first by using present state variables the final state should be estimated. Here, the state is representing the flux position or speed position. Then second step is selecting the sigma points using the equations(24),(25).third step is determined the non-linear transformation of sigma points using the equations(26),(27),(28).then substituted this equations with added and subtracted value of λ we get the equation(29).after that determine the weighted mean and covariance using(32)to(34).in that the Gaussian distribution β must be equal to 2,then only we get optimum solution. Finally the determined values are substituted in the algorithm which having five steps. The algorithm steps contain prediction phase(35) to (37) and correction phase(38) and (39).

3.3. Selection of sigma points

The state space equation for nonlinear system

\[ X_k = X_{k-1} + f(X_{k-1}, u_k) + w_k \] (24)
\[ Y_k = h(X_k) + v_k \] (25)

For an \( n \times 1 \) vector of latent states, a set of \( 2n + 1 \) sigma points are selected

3.4 Prior state sigma points

The priori state sigma points can be determined by using the following equations

\[ S_{k,k-1/k-1} = X_{k-1/k-1} \] (26)
\[ S_{k,k-1/k-1} = X_{k-1/k-1} + \sqrt{(n+\lambda)}P_{k-1/k-1} \] (k = 1, ..., n) (27)
\[ S_{k,k-1/k-1} = X_{k-1/k-1} - \sqrt{(n+\lambda)}P_{k-1/k-1} \] (k = n+1, 2n) (28)

Where,
\[ \lambda = \alpha^2(n+\lambda) - n \]
**International Journal of Emerging Technology and Advanced Engineering**

International Conference on Trends in Mechanical, Aeronautical, Computer, Civil, Electrical and Electronics Engineering (ICMACE14)

The kurtosis of the sigma point distribution usually “0” or “3-n”. \( \alpha \) is a value chosen between 0.0001 and 1 that determines the spread of the sigma points.

3.5. Estimation of next state sigma points

The following equations are used to determine the next state equations:

\[
S_{k,k/k} = [S^*_{k,k/k-1} + \lambda; S^*_{k,k/k-1} - \lambda]
\]

(29)

Where,

\[
S_{k,k/k} \text{ is next state sigma points}
\]

\[
S^*_{k,k/k-1} = f(S_{k,k-1/k-1})
\]

(30)

\[
\lambda = \alpha^2 (n+\kappa)-n
\]

(31)

3.6. Weighted mean and covariance

The following equations are used to determine the weighted mean and covariance:

\[
W^{(c)}_0 = [\lambda/(n+\lambda)] + 1 - \alpha^2 + \beta
\]

(32)

\[
W^{(m)}_0 = [\lambda/(n+\lambda)] + 1 - \alpha^2 + \beta
\]

(33)

\[
W^{(c)}_k = W^{(m)}_k = 1/2(n+\lambda)
\]

(34)

Where \( \beta = 2 \) optimal for Gaussian distribution.

3.7. Algorithm

In algorithm first three step used for prediction, last two step used for correction.

**IV. FIELD ORIENTED CONTROL**

The principle of vector control of electrical drives is based on the control of both the magnitude and the phase of each phase current and voltage. To achieve the more accurate vector controls, the Field Orientated Control method is adopted. It depends on three important points: voltage space vectors, the machine current and the transformation of a three phase speed and time dependent system into a two co-ordinate time invariant system and successful Pulse Width Modulation pattern generation.

The AC machine control, obtain all the greatest advantage of DC machine and it eliminates the mechanical commutation failures. To achieving an accurate steady state and transient control, and carrying the high dynamics performance in both power conversion or response times.
The classic scheme problemsthus solves by the FOC, in the following idea: the lack of difficulty of reaching constant reference (torque component and flux component of the stator current) the lack of difficulty of applying direct torque control for the reason that in the (d,q) reference frame the torque is expressed as:

\[ m \propto \Psi_R \cdot i_{q}(40) \]

By balancing the amplitude of the rotor flux (\( \Psi_R \)) at a fixed value we have a linear relationship between torque and torque component (\( i_{q} \)). Torque can be controlling by the torque component of stator current vector.

V. SPACE VECTOR PULSE WIDTH MODULATION

The best among all the PWM techniques for variable frequency drive applications is, the Space Vector Pulse Width Modulation (SVPWM) method and also it is one of the advanced methods. The PWM method require very short duration for computation. In recent years it has been widely existing application because of its greater typical performance. A novel control technique presented by Satean, which is called as space vector pulse width modulation (SVPWM) method for control of the induction motor. In SCIM an extremely good three-phase bridge inverter which was used with a balanced three phase voltages. They even equipped with a new control technique to control the IMs speed using ANFIS technique.

In two-dimensional (αβ) plane the Space vector modulation for three leg VSI is based on the portrayal of the three phase quantities as vectors. The control variables are presented as rotating frame in field oriented control algorithm. that the torque is directly controls the current vector \( I_{ref} \) and it transformed into a voltage vector by the use of inverse Park transform.

The voltage reference is exhibits in the (αβ) frame. The reference voltage vector and three-phase voltages (VAN, VBN, VCN) are projected in the (αβ) frame using this transformation.

Combine each adjacent vector having modulate time of application and adjacent vectors of the reference voltage when the method used in approximating the desired stator reference voltage with only eight possible states of switches.

VI. OVERVIEW OF ADAPTIVE NEURO FUZZY INFERENCE SCHEME

To recognize the high degree nonlinear system parameter they can be used high accuracy non-linear function. In addition, it have an advantages of ultimately fault tolerate characteristics and fast parallel computation. Not long ago, it has been proposed, the use of neural networks, to identify and control nonlinear dynamic systems due to it can approximate widely with required degree of accuracy of non-linear functions. In speed estimation it has some enquiries in the application of NNs to ac drives with power electronics. This technique gives a fairly good estimate of the speed and is robust to parameter variation.

To get good performance, the neural network various patterns should be trained sufficiently with speed estimator. In the control engineering field, fuzzy logic is one of the intended applications which can be used to control various parameters with the real time systems. This logic combined with neural networks produces very significant results. In addition, it is very difficult to understanding the knowledge learned by neural networks. In another point of view, it uses the structure of IF-THEN rules and linguistic terms based on fuzzy rule models and it is easy to understand. Neural networks can be learning itself, but fuzzy logic not like that. From the areas of statistics, system identification the fuzzy logic systems adopting ideas for learning and identification process.
Thus neural networks can learn, it is natural to combine these two techniques. This combined technique of the NNs with the knowledge representation of FL has created a new hybrid technique, called as the term ‘neurofuzzy networks’. So it also called as universal approximator.

The types of inference operations mainly focused on “if-then rules”, fuzzy inference systems have two types; Sugeno’s system Mamdani’s system. Most widely used method is Mamdani’s, but the Surgeon’s system is also have the advantages such as compact in nature and computationally more efficient; the output in the form of crisp, the time consumption is less and defuzzification operation is mathematically intractable, the use of adaptive techniques (Takagi and Sugeno [37]) is more popular in fuzzy modelling. The root mean square error (RMSE), mean absolute error (MAE), and determination coefficient (R2) criteria are determined for each model which is shown in following three equations. For optimal model condition chosen RMSE and MAE must be minimum, and R2 should be nearer to 1.

\[ R^2 = 1 - \frac{\sum_{j=1}^{N}(Y_{observed,j} - Y_{predicted,j})^2}{\sum_{j=1}^{N}(Y_{observed,j} - \text{mean observed})^2} \]

\[ \text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (Y_{observed} - Y_{predicted})^2} \]

\[ \text{MAE} = \frac{1}{N} \sum_{i=1}^{N} (Y_{observed} - Y_{predicted}) \]

A training data set that the desired input / output data pairs of target systems to be modeled is to be required first to start the ANFIS learning. Any ANFIS controller can be used to design parameter. Checking data sets, Number of data pairs, Training data set &, Fuzzy inference systems for training, Number of epochs to be chosen to start the training, after mentioning the step size learning results to be verified. This structure contains the same components as the FIS, except the NN block.

The structure of the network is composed of a set of units (and connections) arranged into five connected network layers.

**Layer 1:** Input variables (membership functions) in layers 1, which contains input 1 & input 2. Here MF can be used as triangular or bell shaped.

**Layer 2:** Weightsof each MF can be checked in this layer (membership layer).

**Layer 3:** The rule layer called as third layer. Each node (eachNeuron) also the third layer performs the pre-condition matching of the fuzzy rules, i.e., the activation level of each rule compute at each level, the number of fuzzy rules being equal to the number of layers. Each node of these layers calculates the weights which are normalized.

**Layer 4:** The defuzzification layer is called as fourth layer & it provides the output values y resulting from the inference of rules. Connections between the layers 13 & 14 are weighted by the fuzzy singletons that represent another set of parameters for the Neuro fuzzy network.

![Fig: 3 Architecture of ANFIS](image)
Layer 5: The output layer called as layer 5, which sums up all the inputs coming from the layer 4 and it will be transformed into the fuzzy classification results into a binary (crisp).

The ANFIS structure is mainly used for estimation of least-square estimation & the back propagation algorithm. The algorithm shown above is used in the next section to develop the ANFIS controller to control the various parameters of the induction motor. Because of its flexibility, the ANFIS strategy can be used for a wide range of control applications. A controller is a device which controls the device to achieve the stability and also protect the system provides safeguarding protection. In this paper, the development in the control strategy for control of various parameters of the squirrel cage induction motor such as the speed, flux, torque, and voltage, current is presented using the concepts of ANFIS control scheme.

VII. Simulation Results

![Fig 4(a): Rotor speed Vs (i. torque ii. developed power iii. stator current iv. Efficiency )](image)

From figure: 4a the rotor speed versus torque, initially some torque is needed to run the induction motor. When it reaches maximum or rated speed the torque value reduced same as stator current. Then the power and efficiency zero at zero speed gradually increased, when it reaches rated value comes to zero.

![Fig 4(b): Torque waveform](image)

The torque waveform is shown in figure 4b. Initially the torque values are high. For example, initially the speed is 60rpm, it will controlled to 30rpm means, torque also decreased finally compared to initial stage.

![Fig 4(c): Rotor flux](image)

By using unscented kalman filter the rotor flux are estimated in figure 4c. By using unscented kalman filter algorithm flux estimation was done.

![Fig 4(d): Phase current](image)
Three phase current waveform for squirrel cage induction motor was shown in figure 4d.

Fig 4(e): Step speed

the reference speed values was set in the IM, for example initially 60rpm, finally it must come to 30rpm that was shown in figure 4e.

Fig 4(f): Speed Waveform Obtained From Both With Sensor And Without Sensor

By using adaptive speed estimation technique, i.e. without sensors the IM motor speed is estimated, then also obtain same speed value with sensors, from figure 4f without sensors the estimated speed consumes less time when compared with sensor estimation.

VIII. CONCLUSION

This paper discussed how the induction motor speed and rotor flux is estimated and how it is controlled robustly without sacrificing its accuracy. For that the robust estimators are preferred such as unscented kalman filter (UKF), which is mainly used for estimating the rotor flux, and another estimation technique named as an adaptive speed estimation scheme which is used for estimating the speed. In this paper the control strategy is adopted for controlling sensorless control of induction motor, which is termed as an adaptive fuzzy inference scheme (ANFIS). This controller overcome the problems of instability and prevents the system from damages. The SVPWM technique is also used in this paper, it provides pulses. The new concepts implemented in this paper is merging the two techniques such as UKF with ANFIS.

IX. REFERENCES


