FUZZY LOGIC BASED STATOR RESISTANCE ESTIMATOR FOR A DIRECT TORQUE CONTROLLED THREE-PHASE INDUCTION MOTOR

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Abstract:

Direct torque control (DTC) of three phase induction motor uses the motor stator resistance to estimate the stator flux. The variation of stator resistance due to changes in temperature or frequency deteriorates the performance of DTC controller by introducing errors in the estimated flux linkage and the electromagnetic torque. A fuzzy based stator resistance estimator during the operation of the motor is proposed. By means of comparing the actual current and the reference current, the change of stator resistance can be estimated. The estimation method is implemented using fuzzy logic control schemes. Simulation results obtained clearly demonstrate the effectiveness of the estimator in estimating the stator resistance and improving performance of DTC.

تخمين مقاومة الجزء الساكن باستخدام التحكم المضبب لمنظومة التحكم المباشر بالعزم لمحرك حثي ثلاثي الطور

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الخلاصة:

التحكم المباشر بالعزم (DTC) للمحرك ألحثي ثلاثي الطور يستخدم مقاومة الجزء الساكن R_s لتخمين قيمة فيض الجزء الساكن. تغيير مقاومة الجزء الساكن نتيجة لتغير الحرارة أو التردد يؤدي إلى تدهور خصائص DTC عن طريق زيادة الخطأ في القيمة المخمنة للفيض والعزم الكهرومغناطيسي. تم اقتراح التخمين باستخدام المنطق المضبب لمقاومة الجزء الساكن خلال العمل للمحرك. عن طريق مقاومة القيمة الحقيقية للتيار مع القيمة المرجعية، التغير في مقاومة الجزء الساكن يمكن تخمينه . طريقة التخمين تم بنائها باستخدام التحكم المضبب. نتائج المحاكاة المستخلصة أوضحت فعالية المخمن في تخمين مقاومة الجزء الساكن وتحسين خصائص منظومة التحكم المباشر بالعزم DTC.

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1. Introduction:

Direct torque control (DTC) of three phase induction motor has many advantages when compared with vector control such as less machine parameter dependence, simpler implementation and quicker dynamic torque response [1]. i.e. DTC requires no mechanical sensor, no current regulator, no coordinate transformation, and depends only on stator resistance[2].

Although DTC is getting more and more poplar, it is also has some drawback, such as high torque ripple and flux ripples and stator resistance variation [3].The variation of induction machine parameters and its effect on the performance of induction motor drives have long been recognized[4]. DTC uses stator resistance to estimate the stator flux. Thus the variations of stator resistance with any disturbance (such as temperature rising, or defect part of stator coil) will cause error in flux estimation. This problem become serious in drive behavior at low speed or standstill where stator flux estimation becomes strongly dependant on stator resistance.

2. Theory

The fundamental principles of DTC based on the direct control of stator flux and stator voltage. The estimation of stator flux is based on the induction motor voltage model in stator flux reference is determine from

$$\overline{V_s} = R_s \bar{I}_s + j\frac{d\varphi}{dt} \qquad \text{……(1)}$$

the stator flux space vector is determined by integrating the motor back-e.m.f. space vector

$$\overline{\varphi_s} = \int\left(\overline{V_s} - R_s \bar{I}_s\right)\cdot dt \qquad \text{……(2}$$

The stator flux estimator from Eq.(2) become critical at low speed. To achieve good performance at stand still and at low speed, integration drift due to the dc offset or measurement noise must be eliminated by introduction of a low-pass filter with a cutoff frequency [3]. The flux estimator output becomes

$$\overline{\varphi_{sf}} = \frac{\overline{V_s} - R\bar{I}_s}{j(w_s - w_f)} \qquad \text{……(3)}$$

At low speed, the resistive term becomes preponderant and therefore the stator resistance is greater than the actual one, the time constant of the following differential equation , obtained from Eq.(2), become negative, leading to instability

$$\frac{d\overline{\varphi_s}}{dt} + \frac{\left(R_s - \hat{R}_s\right)}{\delta L_s}\cdot\overline{\varphi_s} = \frac{d\overline{\hat{\varphi}}}{dt} + \frac{L_m\left(R_s - \hat{R}_s\right)}{\delta L_s L_r}\cdot\overline{\varphi_r} \qquad \text{…..(4)}$$

Where L_s is the stator winding inductance

The stator flux estimator is determined by integrating the difference between the input voltage and the voltage drop across the stator resistance, as mentioned in Eq.(2). At high speed, the stator resistance drop is $R_s \bar{I}_s$ is small and can be neglected. At low speed this drop becomes dominant compared to the input stator voltage Vs, therefore any changes in stator resistance give wrong estimation of stator flux and consequently of the electric torque and the stator flux position. The effect of stator resistance change on the stator flux linkage and electrical torque can be explained by the following analysis [5].

If the stator resistance have no change during the operation of the machine, the actual stator flux φ_{sa}, estimated stator flux φ_{se}, the actual electromagnetic torque T_{ea}, and the estimated electromagnetic torque T_{ee} are given by

$$\varphi_s = \varphi_{sa} = \varphi_{se} = \int \left(V_s - R_s \bar{I}_s \right) dt \qquad \ldots\ldots(5)$$

$$T_e = T_{ea} = T_{ee} = \frac{3}{2} \cdot n_p \cdot \left(i_{qs}\varphi_{ds} - i_{ds}\varphi_{qs} \right) \qquad \ldots\ldots(6)$$

where R_s is the stator resistance V_s input stator voltage, n_p pole pairs and $\varphi_{ds}, \varphi_{qs}$ are the direct and quadrature flux linkage components [6].

Now it is assumed that stator resistance changes by ΔR_s, which cause a change Δi_s in stator current vector i_s. The corresponding changes in d and q axis currents are Δi_{ds} , and Δi_{qs} . The estimator uses the unchanged value of resistance whereas the stator resistance changes, then the actual variables in the motors are

$$\varphi_s + \varphi\Delta\varphi_{sa} = \int \left[\left(V_s - \left(i_s + \Delta i_s \right)\left(R_s - \Delta R_s \right) \right) \right] \cdot dt \qquad \ldots\ldots (7)$$

$$T_e + \Delta T_{ea} = \frac{3}{2} n_p \begin{bmatrix} (i_{qs} + \Delta i_{qs})(\varphi_{ds} - \Delta\varphi_{dsa}) - \\ (i_{ds} + \Delta i_{ds})(\varphi_{qs} + \Delta\varphi_{qsa}) \end{bmatrix} \qquad \ldots.. (8)$$

Estimated variables in the controller are

$$\varphi_s + \Delta\varphi_{se} = \int \left[\left(V_s - (i_s + \Delta i_s)(R_s - \Delta R_s) \right) \right] \cdot dt \qquad \ldots\ldots(9)$$

$$T_e + \Delta T_{ee} = \frac{3}{2} n_p \begin{bmatrix} (i_{qs} + \Delta i_{qs})(\varphi_{ds} - \Delta\varphi_{dse}) - \\ (i_{ds} + \Delta i_{ds})(\varphi_{qs} + \Delta\varphi_{qse}) \end{bmatrix} \qquad \ldots\ldots(10)$$

The error in the estimated stator flux linkage and electromagnetic torque from the actual values of stator flux linkage and torque in the motors are given by equations

$$\Delta\varphi_s = \Delta\varphi_{se} - \Delta\varphi_{sa}$$

$$= \int \left(\Delta i_s R_s + i_s \Delta R_s + \Delta i_s \Delta R_s\right) \cdot dt - \int \Delta i_s R_s dt$$

$$\int \left(i_s + \Delta i_s\right) R_s dt$$

$$\Delta T_e = \Delta T_{ee} - \Delta T_{ea}$$

$$= \frac{3}{2} n_p \Delta R_s \begin{bmatrix} \left(i_{ds} + \Delta i_{ds}\right) \\ \int \left(v_s \left(i_{sq} + \Delta i_{qs}\right) dt - \right) \\ (i_{qs} + \Delta i_{qs}) \int \left(v_s - (i_{ds} + \Delta i_{ds}\right) dt \end{bmatrix}$$

Equation (13) and (15) show that there are errors in stator flux linkage and electromagnetic torque due to the change in stator resistance. These will deteriorate the overall performance of DTC system. The problem is worse at low speed because the input voltage is $i_s R_s$ small and the voltage drop can be comparable with the input voltage V_s. The error in stator flux linkage vector position is more important because it make the controller select a wrong switching state, which can result in unstable operation. It has been clarified that the variation in stator resistance will cause a change of stator current, thereby the change in current will cause the variation in flux linkage and torque [7] . The change in current and flux will affect the torque further according to Eq.(15) , and as explained in Fig.(1).

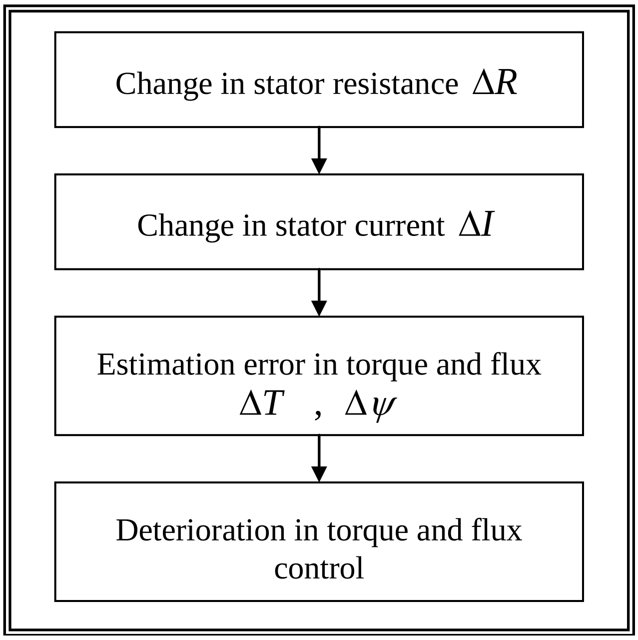

Fig.(6.1) The effect of change stator resistance

Fuzzy Logic Based Stator Resistance Estimation Scheme :

The whole block diagram for direct torque control with fuzzy stator resistance is shown in Fig.2. Where the input of fuzzy logic circuit is the estimated stator flux and the filtered one, the estimated value of stator resistance is used in estimation stage of torque and stator flux.

Figure 2 shows the configuration of the proposed fuzzy logic stator resistance estimation system, this approach is based on the phase error between the estimated flux and filtered one. The fuzzy logic identifier (FLI) input variable is the phase error of stator flux this variable is used as input for fuzzy logic controller (FLC) [8]. The internal structure of the fuzzy logic stator resistance estimation is chosen similar to that of a fuzzy logic controller, which consists of fuzzification, inference engine, and defuzzification. for the k^{th} sampling interval we have

$$e(k) = phase(\overline{\varphi}_{sf}) - phase(\overline{\varphi}_s$$

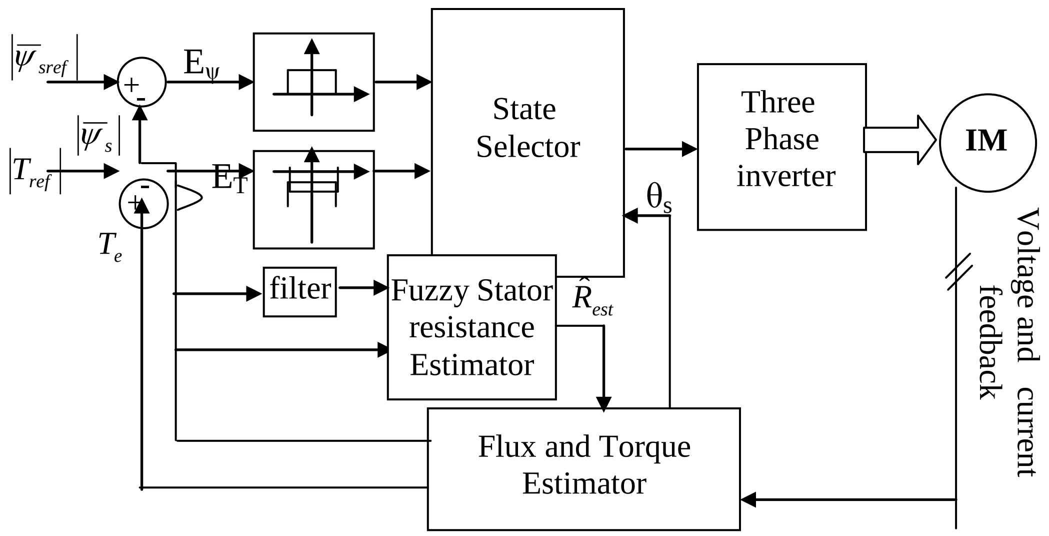

Fig. (6.2) Block diagram of the DTC with fuzzy logic based stator resistance estimator.

Fuzzification Stage :

The phase error of flux is fuzzified in fuzzification stage, the crisp variable are converted into fuzzy variable using triangular membership functions as shown in Fig.3. The input membership functions are used to transfer crisp inputs into fuzzy set [9].

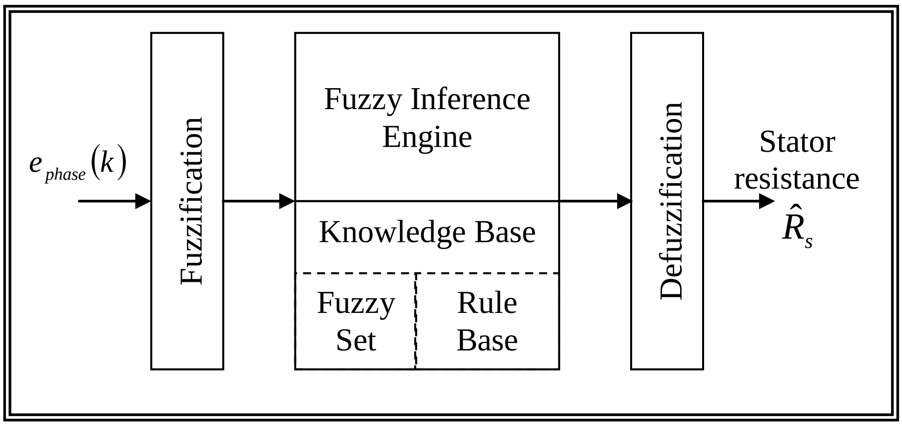

Fig.(3) Proposed fuzzy logic based stator resistance estimator

The fuzzy logic identifier (FLI) output variable is the rate of change that is generated through fuzzy inference and defuzzification. The crisp output is integrated in such a way that the estimated stator resistance is given by

$$\hat{R}(k) = \hat{R}(k-1) + \Delta\hat{R}_s(k) \quad \text{……(17)}$$

The output membership functions is shown in Fig. 4.

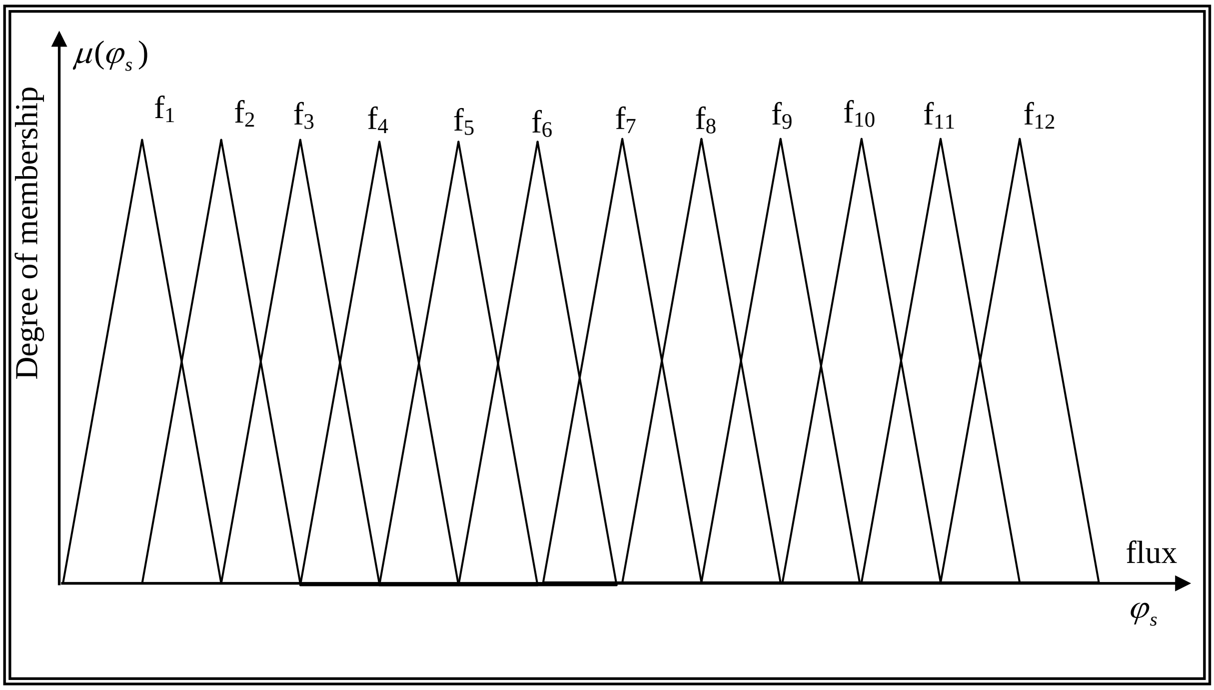

Fig. (4) Membership functions for phase error of stator flux

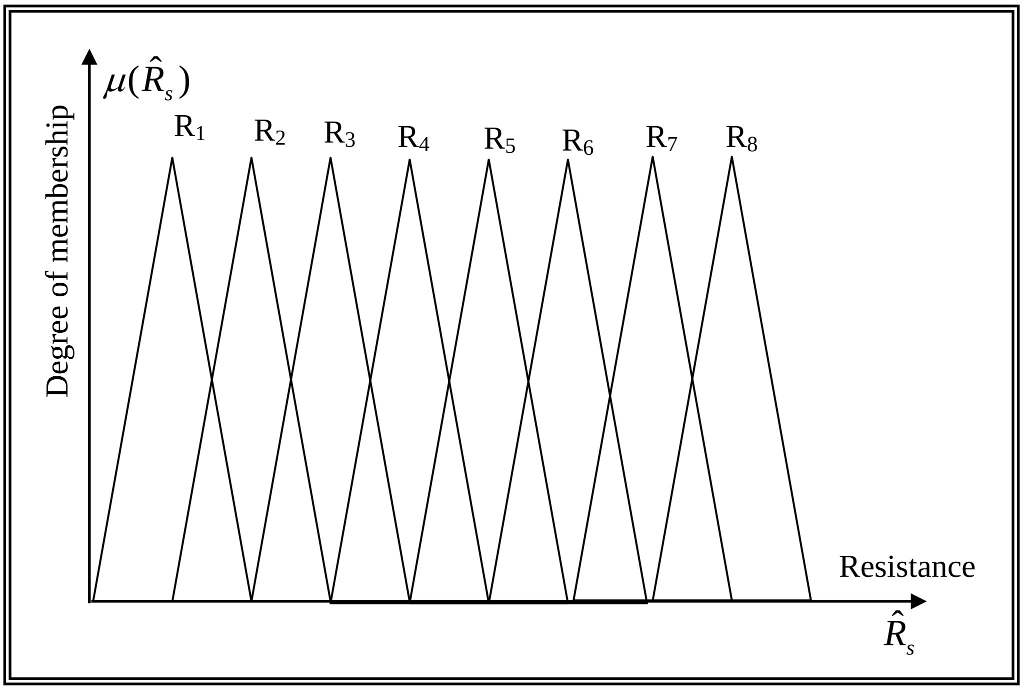

Fig. (5) Stator resistance membership functions

The expert's experience is incorporated into knowledge base with 16 rules. This experience is synthesized by the choice of the input-output (I/O) membership functions of the rule base. Then, in the second stage of the FLC, the inference engine, based on the input fuzzy variable phase error of stator flux, uses the appropriate IF-Then rules in the knowledge base to imply the final output fuzzy sets [10].

The Defuzzification Stage:

The implied fuzzy set is transformed to a crisp output by the centre of gravity defuzzification technique as given by the

$$\Delta\hat{R} = \frac{\sum_{i=1}^{n} R_i \cdot \mu(R_i)}{\sum_{i=1}^{n} \mu(R_i)}$$

where Ri is the numerical output at the i-th number of rules is the corresponding value of the fuzzy membership function at the i-th number of rules. The summation is from one to n , where n is the number of rules that apply for a given fuzzy input [4].

Simulation Results:

Simulink model of the three phase induction motor drive by direct torque control with fuzzy stator resistance estimation is shown in Fig. 6.

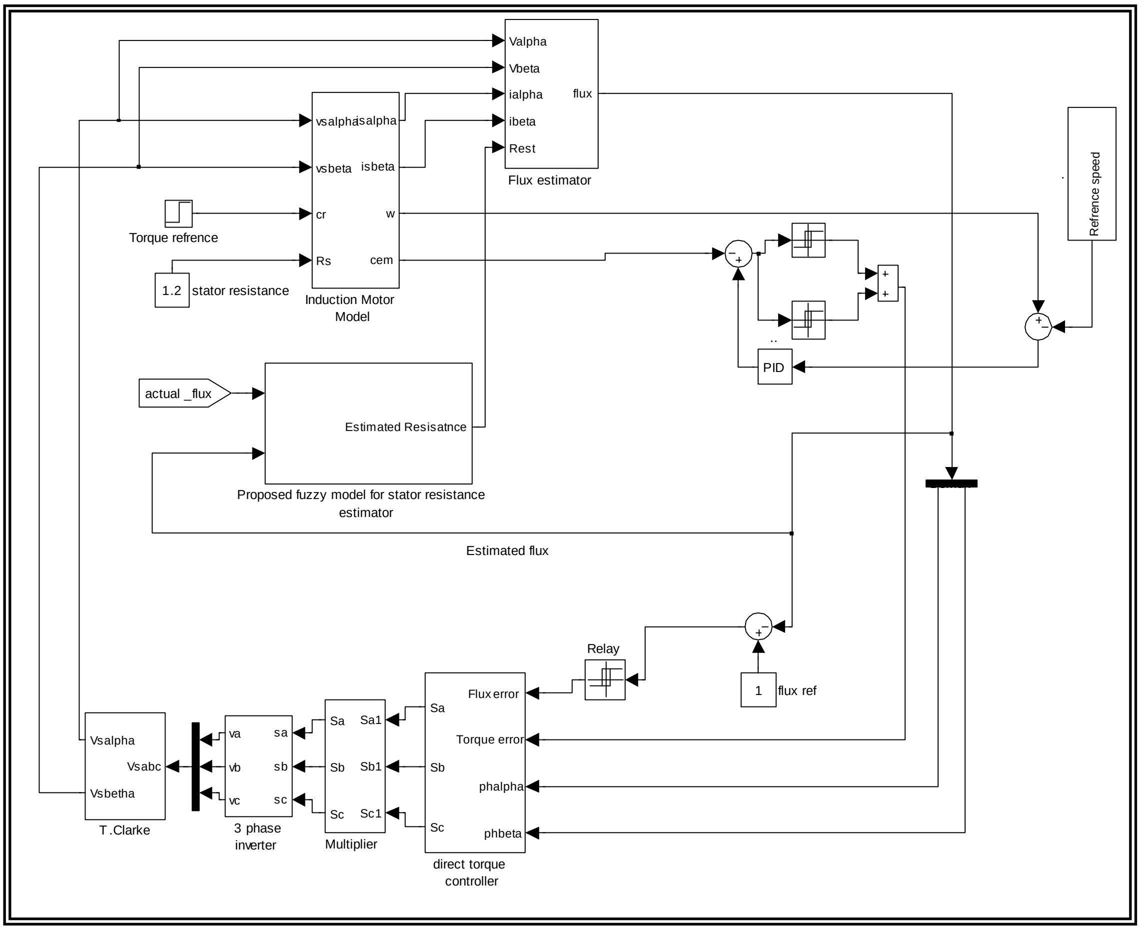

Fig. (6) Implemented simulink model for the direct torque control with fuzzy logic based stator resistance estimation

The structure of the fuzzy scheme is explained in Fig.7 where phase error is obtained from subtract the estimated flux phase from the actual flux phase, this error is fed to root mean square circuit to obtain smooth variation for this phase error, this error is used as input to the fuzzy logic controller circuit to estimate the stator resistance during operation., The implemented simulink model for the proposed scheme is shown in Fig.8.

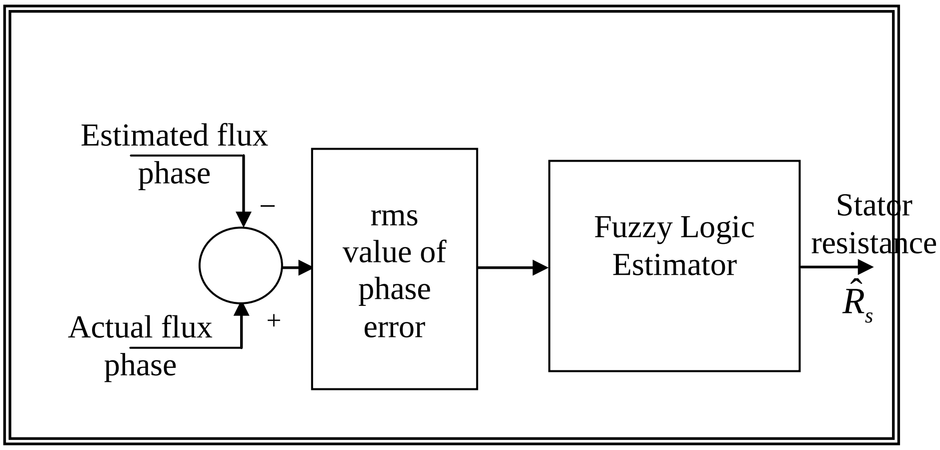

Fig. (7) Block diagram of the fuzzy logic based stator resistance estimator

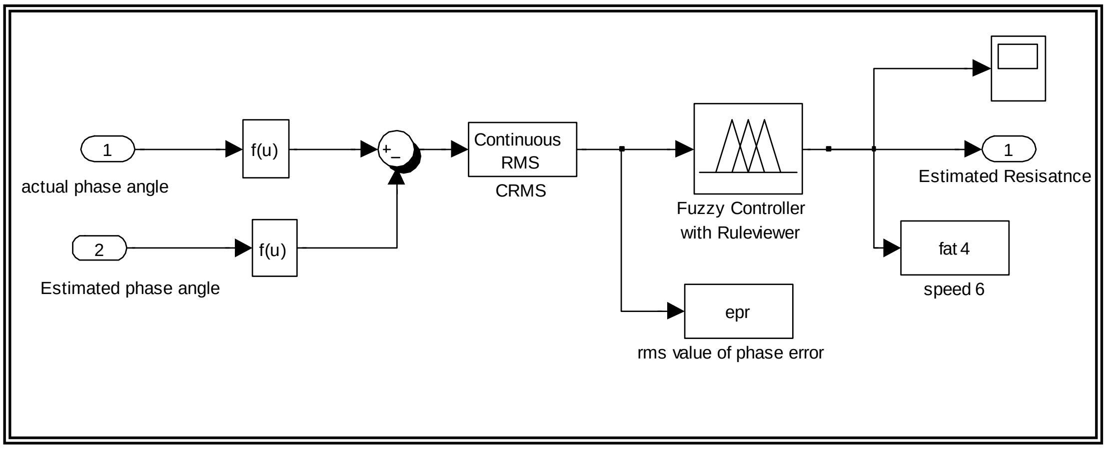

Fig. (8) Implemented simulink model of the fuzzylogic based stator resistance estimator

First variation case is shown in Fig.(9) in this figure the stator resistance variation is from 1.2Ω to 1.4Ω, after one second the actual stator resistance reach 1.4Ω and the estimated resistance coincide with it.

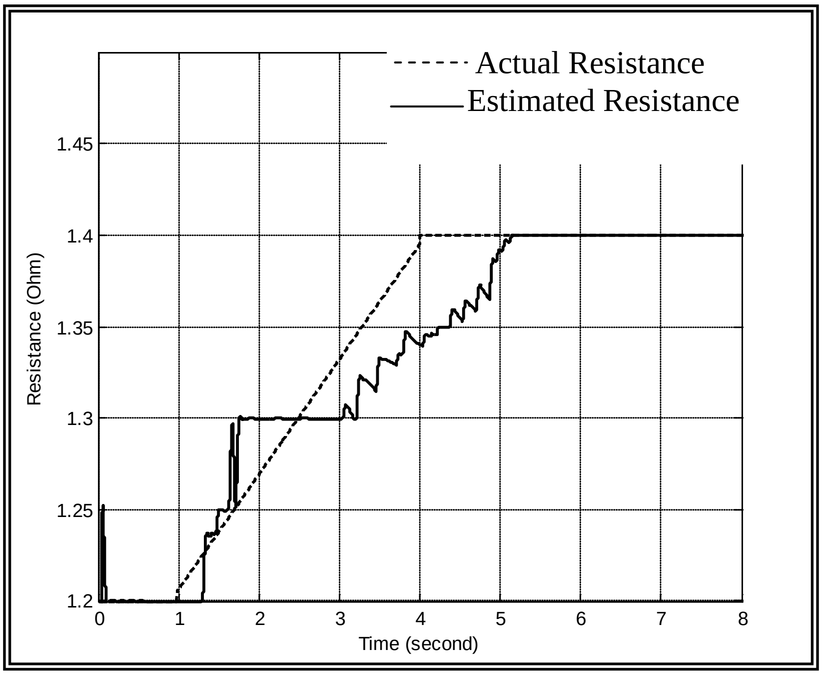

Fig.(9) Actual and the estimated stator resistance for a ramp change from 1.2Ω to 1.4Ω

The second stator resistance variation case is shown in Fig.(10), the final value of stator resistance is considered to be 1.6Ω, the properties of this estimator as in the previous case the estimated resistance coincides with the actual one.

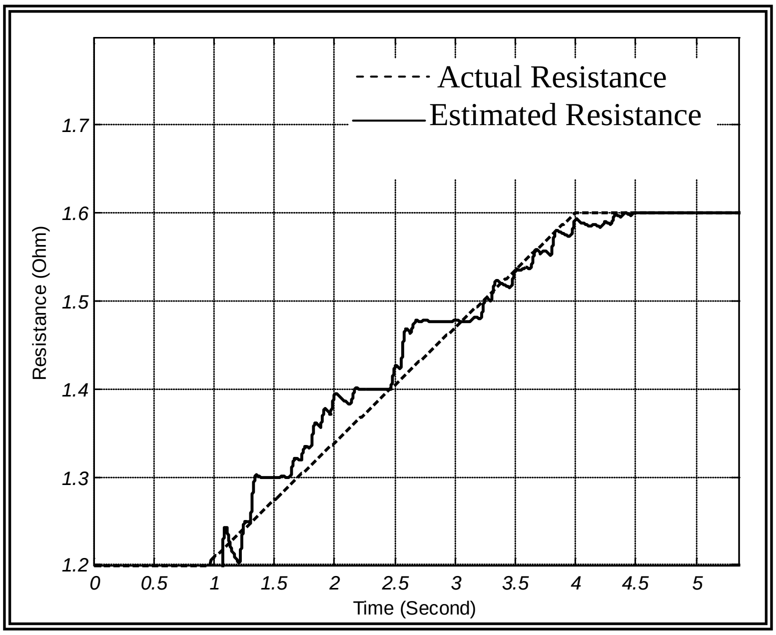

Fig.(10) Actual and estimated stator resistance for a ramp change from 1.2Ω to 1.6Ω

The stator resistance variation case is shown in Fig.(11) in which the stator resistance changes from 1.2 Ω to 2Ω, with duration of 5 second.

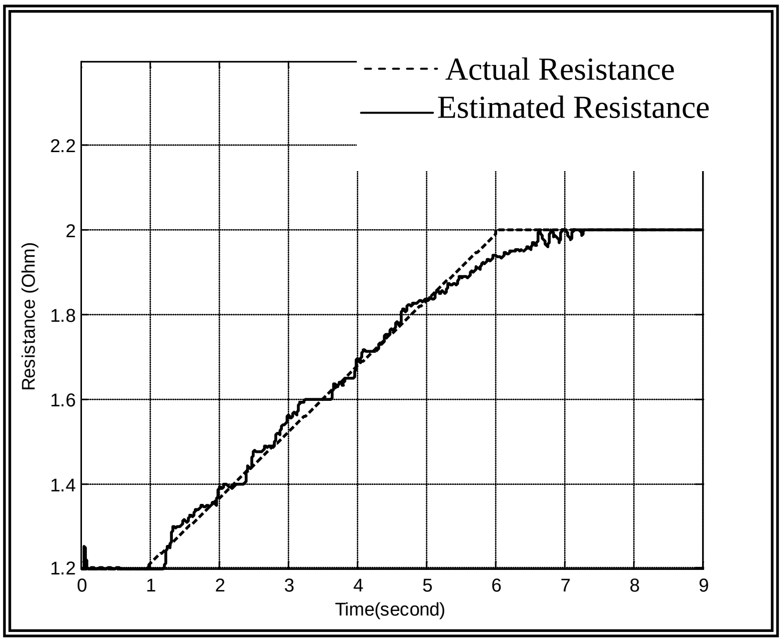

Fig.(11) Actual and estimated stator resistance for a ramp change from 1.2Ω to 2Ω

Three-phase induction motor driven by DTC scheme is tested first with no stator resistance estimation; then with fuzzy stator resistance estimation. For both cases the stator resistance is assumed to be changed from 1.2 Ω to 2.2 Ω as shown in Fig. (12), which is considered as practical variation case of stator resistance due to temperature rising.

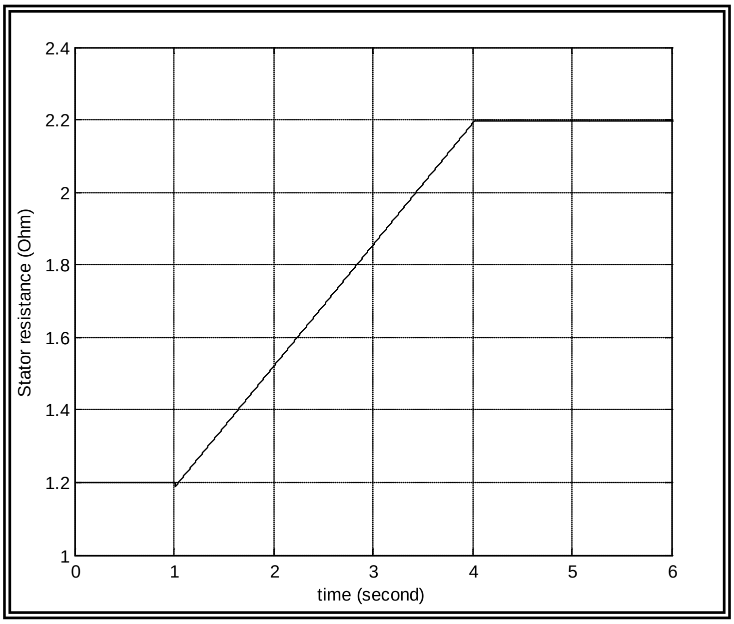

Fig.(12) Stator resistance variation for a ramp change from 1.2Ω to 2.2Ω

The developed electromagnetic torque of the three-phase induction motor which is driven by DTC scheme but with no stator resistance estimation is shown in Fig.(13), from this figure the decreasing of the developed electromagnetic torque can be well noted.

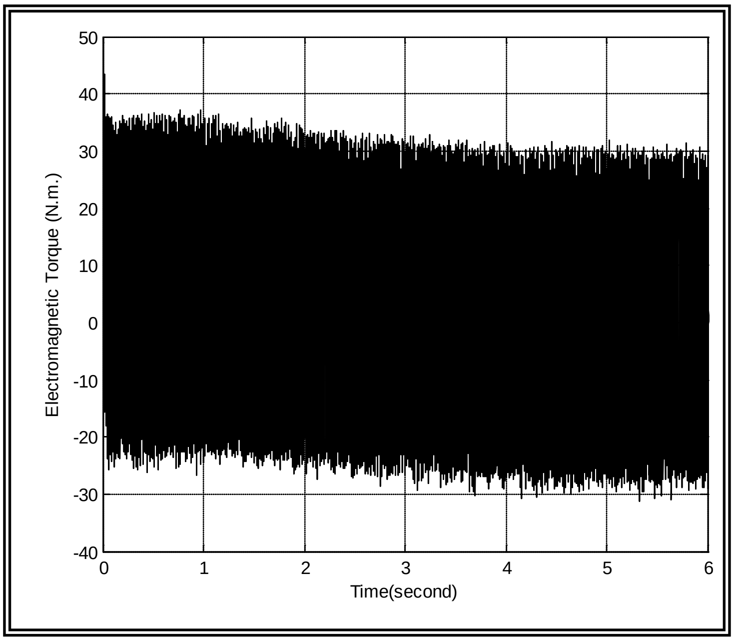

Fig.(13) Electromagnetic torque with no stator resistance estimation for a ramp change of stator resistance from 1.2Ω to 2.2Ω

Now by using the fuzzy estimator the electromagnetic torque have almost a constant value as shown in Fig.(14).

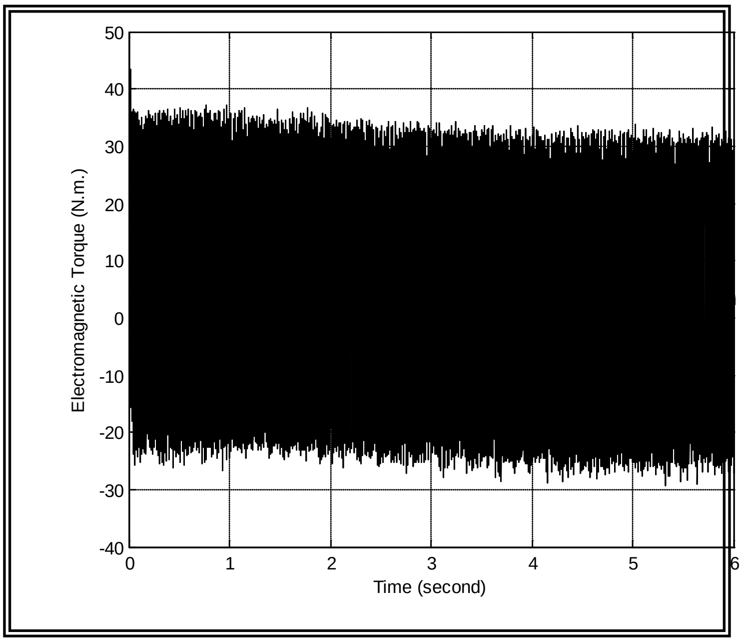

Fig.(14) Electromagnetic torque with fuzzy stator resistance estimation for a ramp change of stator resistance from 1.2Ω to 2.2Ω

For the same variation of stator resistance the speed profiles of the drive system are shown in Fig.(14) and Fig.(15) the first one shows the speed response without stator resistance estimation, the other represents the response but with fuzzy stator resistance estimator which represents a good enhancement in the speed profile.

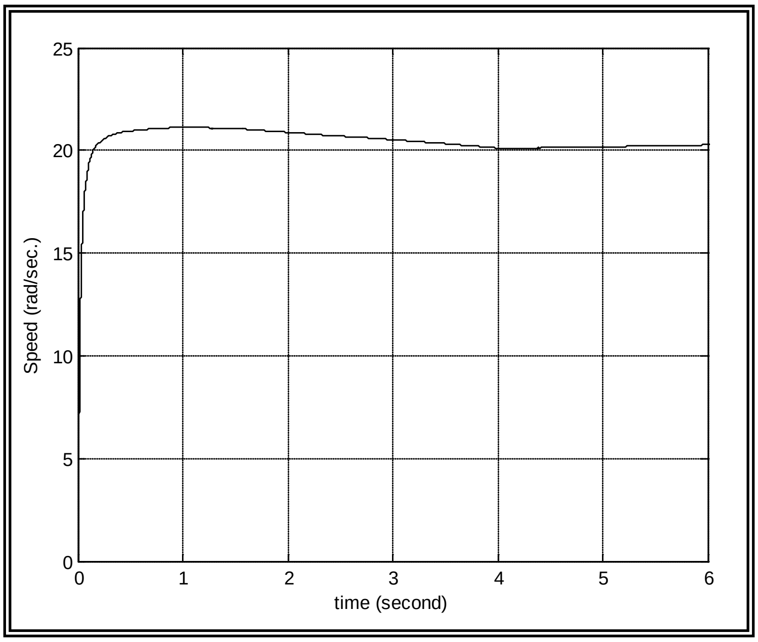

Fig.(14) Speed response with no stator resistance estimation for a ramp change of stator resistance from 1.2Ω to 2.2Ω

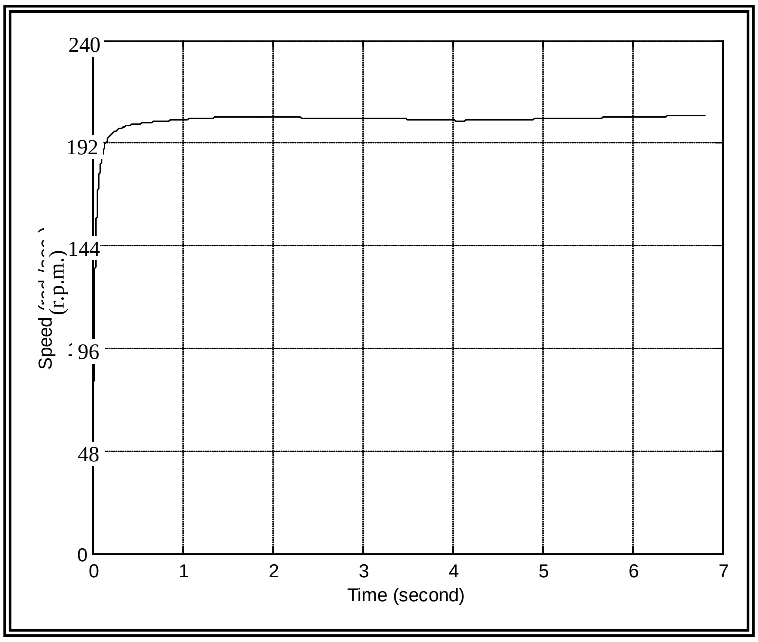

Fig.(15) Speed response with fuzzy stator resistance estimation for a ramp change of stator resistance from 1.2Ω to 2.2Ω

The change in stator current magnitude can be noted in Fig.(16) which represent the case with no stator resistance estimation. With adding fuzzy stator resistance estimator to the DTC induction motor drive system the stator current profile will be as shown in Fig.(17).

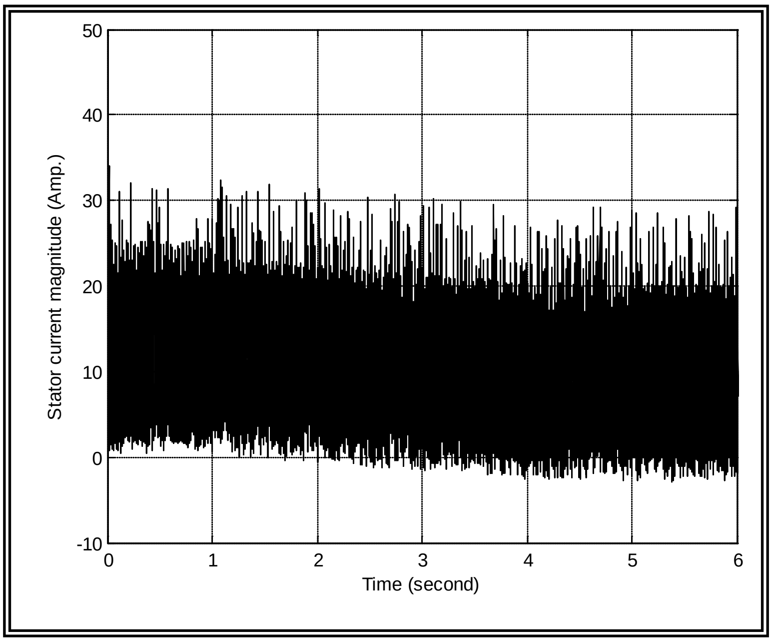

Fig.(16) Stator current magnitude with no stator resistance estimation for a ramp change of stator resistance from 1.2Ω to 2.2Ω

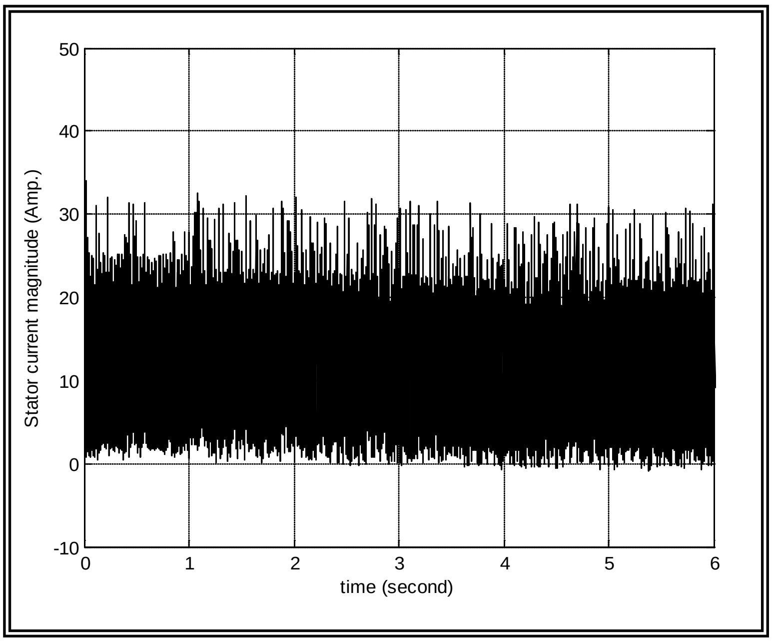

Fig.(17) Stator current magnitude with fuzzy stator resistance estimation for a ramp change of stator resistance from 1.2Ω to 2.2Ω

Conclusions :

The variation of stator resistance has an important effect on the performance of direct torque control. There are two major effects concluded by the analysis of stator resistance:

(i) Destroying the decoupled condition for flux and torque, hence, deteriorating the dynamic performance of the system.

(ii) Deviation of the flux from the actual value.

Therefore, the on-line estimation of the stator resistance is important for high performance of DTC drive system. The proposed method of the on-line estimation for establishing the exact value of stator resistance of an induction motor has been described and simulated using the Matlab/Simulink software package. The simulation results represents a good agreement with the theoretical calculations of the detuning in stator resistance.

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