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Fuzzy Logic Application for Intelligent Control of An Asynchronous Machine

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Abstract

The aim of this article is propose a method to improve the direct torque control and design a Fuzzy Logic based Controller which can take necessary control action to provide the desired torque and flux of an asynchronous machine. It's widely used in the industrial application areas due to several features such as fast torque response and less dependence on the rotor parameters. The major problem that is usually associated with DTC control is the high torque ripple as it is not directly controlled. The high torque ripple causes vibrations to the motor which may lead to component lose, bearing failure or resonance. The fuzzy logic controller is applied to reduce electromagnetic torque ripple. In this proposed technique, the two hysteresis controllers are replaced by fuzzy logic controllers and a methodology for implementation of a rule based fuzzy logic controller are presented. The simulation by Matlab/Simulink was built which includes induction motor d-q model, inverter model, fuzzy logic switching table and the stator flux and torque estimator. The validity of the proposed method is confirmed by the simulative results of the whole drive system and results are compared with conventional DTC method.

Keywords: *Asynchronous Machine, Direct Torque Control, Fuzzy Logic, Inverter Model, Torque Ripple*

1. Introduction

The asynchronous machine are replacing DC motor in the industry applications, even in the applications where a fast speed and torque response is required [1], the asynchronous machine control system is much more complex and expensive.

Later in the eighties a new control technique named Direct Torque Control is introduced the classical DTC has several disadvantages, such as getting a variable switching frequency , the ripples of the electromagnetic torque [2], flux and the stator current in the transient and permanent regime due to resistive term of use of hysteresis comparators [3] .

The DTC is characterized by its simple structure and fast dynamic response, a torque comparator is used to select whether the inverter output voltage vector should be a torque increasing vector a torque reducing vector [4]. Therefore torque ripples are produced. The torque ripples can be minimized by dividing the torque errors into several intervals on which control action taken. In this paper fuzzy logic based direct torque control is proposed. Since none of the inverter switching vectors is able to generate the exact stator voltage required to produce the desired changes in torque and flux, torque and flux ripples compose a real problem in DTC induction motor drive. Many solutions were proposed to improve performances [2].

On the other hand, intelligent control methods like fuzzy logic have been explored by several researchers for its potential to incorporate human intuition in the design process. The Fuzzy Logic has gained great attention in the every area of electromechanical devices control due to no need mathematical models of systems unlike conventional controllers[3]. A fuzzy logic controller is used to select voltage vectors in conventional DTC in some applications [5].

In this article a fuzzy approach is proposed to reduce torque ripple. The fuzzy control doesn't need accurate mathematical model of a plant, and therefore, it suits well to a process where the systems with uncertain or complex dynamics. Of course, fuzzy control algorithm can be developed by adaptation based on learning and fuzzy model of the plant [5]. For control method, a fuzzy logic controller is used to determine the duration of output voltage vector at

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each sampling period [6]. These fuzzy logic controllers can provide good dynamic performance and robustness.

2. Conventional Direct Torque Control

The DTC scheme is very simple in function; in its basic configuration, it consists of hysteresis controllers, torque and flux estimator and a switching table. The basic concept of DTC is to control directly both the stator flux linkage (or rotor flux linkage, or magnetizing flux linkage) and electromagnetic torque of machine simultaneously by the selection of optimum inverter switching modes [7].

The block diagram for direct torque control is shown in Figure 1. The control stator flux φ s* and torque Te* magnitudes are compared with the respective estimated values, and the errors are processed through hysteresis band controller [8]. With this information, a voltage selector determines the stator voltage that is required to increase or decrease the variables (torque or flux) according to the demands [7]. The selection of the appropriate voltage vector is based on a switching table.

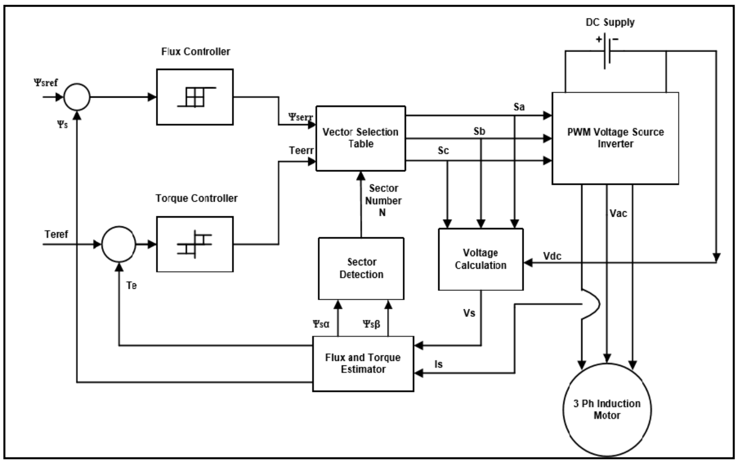

Figure 1. Block Diagram of DTC

2.1. Flux and Torque Estimator

The estimator calculates the stator flux and the electromagnetic torque. The inputs of the state estimator are the stator voltage and current space vectors. The stator flux space vector φ is estimated by integrating the motor voltage space vector [9].

$$\overline{\phi s} = \overline{\phi so} + \int_0^t (\overline{Vs} - Rs\,\overline{Is})dt \tag{1}$$

The stator flux vector is calculated from two components of two-phase axes (α, β) is given:

$$\overline{\phi s} = \phi s\alpha + j\phi s\beta \tag{2}$$

The module stator flux is:

$$\left|\overline{\phi s}\right| = \sqrt{(\phi s\alpha)^2 + \phi s\beta)^2} \tag{3}$$

The electromagnetic torque is proportional to the vector product of two stator and rotor torque.

$$T = \frac{3}{2} \cdot p \cdot (\phi s\alpha \cdot Is\beta - \phi s\beta \cdot Is\alpha) \quad (4)$$

2.2. Flux and Torque Comparator

The error between the estimated torque T and the reference torque T* is the input of a three level hysteresis comparator, whereas the error between the estimated stator flux magnitude Φ and the reference stator flux magnitude Φ* is the input of a two level hysteresis comparator.

2.3. Selection of Stator Voltage

The selection of the appropriate voltage vector is based on the switching table given in Table 1. The input quantities are the flux sector and the outputs of the two hysteresis comparators.

Table 1. Switching Table for the Direct Torque Control Of Asynchronous Machine

Sectors N		(1)	(2)	(3)	(4)	(5)	(6)
dF	dT						
1	1	V2	V3	V4	V5	V6	V1
1	0	V_0	V_7	V_0	V_7	V0	V_7
1	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
0	0	V_7	V_0	V_7	V_0	V7	V_0
0	-1	V5	V6	V1	V2	V5	V3

The aim is to achieve an effective control both steady in transient and this by the combination of different switching. Its depending on the determinate the phase of the estimated flux angle (δ=Arctang(Φβ/Φα)) and the evolution of the magnitude of the flux as well as the evolution of the estimated torque can choose the voltage Vs to be applied so as to respect the references flux and torque. These observed values of the flux and the torque errors are compared to reference the flux and the torque values and the resultant errors are applied to the hysteresis comparators as inputs. Two different hysteresis comparators, as flux and torque comparators, generate other control parameters on the DTC method. According to the hysteresis comparators outputs, the observed angle of flux linkage and using a switching table, optimum voltage vectors are selected and applied to the inverter.

2.4. Voltage Source Inverter Model

The principle is expressed by the sequence imposed on the static switches which perform the modulation width of the pulses of the voltages applied to the stator windings of the machine. By using the switching status (Sa, Sb and Sc) produced by the switching table, the stator voltages in the reference frame are [10].

$$\begin{cases} Vs = Vs\alpha + jVs\beta \\ Vs\alpha = \sqrt{\frac{2}{3}} \cdot Uo \cdot (Sa - \frac{1}{2}(Sb - Sc) \\ Vs\beta = \frac{1}{\sqrt{2}} \cdot Uo \cdot (Sb - Sc) \end{cases} \quad (5)$$

3. Fuzzy Logic Based Direct Torque Control

The torque and flux ripples compose a real problem in DTC induction motor drive [9]. The fuzzy logic has been proved powerful and able to resolve many problems. A fuzzy controller seems to be a reasonable choice to evaluate the amplitude of torque hysteresis band according to the torque ripple level. It is become one of the most successful of today's technology is used to design nonlinear systems in control applications. There are many types of fuzzy logic controller for this particular application. A Mamdani-type fuzzy logic controller, which contains a rule base.

1. A fuzzy controller generally consists of three parts:
2. Fuzzification
3. Fuzzy reasoning
4. Defuzzification

The fuzzification is performed by the membership function. The performance of the fuzzy controller is based upon both the shape of the membership function and the fuzzy reasoning rules [9-11]. The fuzzy reasoning rules in the system are expressed in IF-THEN format; in this fuzzy system the Mamdani's method is employed for the optimal fuzzy reasoning algorithm [11].

The fuzzy controller based on Direct Torque Control is designed to have three inputs and three outputs. The inputs are error of torque, the error in stator and the stator flux angle respectively, the outputs are the switching status (S1, S2 and S3) to get the voltage space vector, replaced the two hysteresis and the switching table, The Figure 2 shows the design of fuzzy logic system in Matlab/simulink and also the configuration of its inputs and outputs as membership functions .

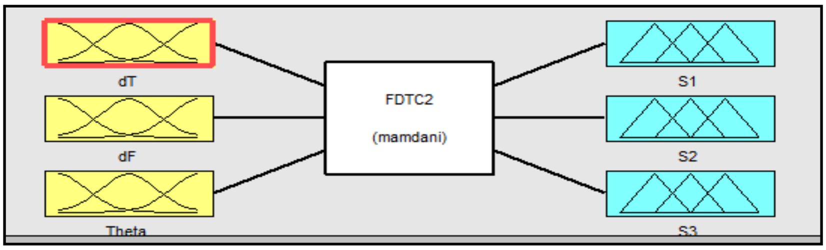

Figure 2. Matlab/Simulink design of the fuzzy logic used in FDTC

Two linguistic values, negative, and positive denoted as N and P respectively are used to fuzzify flux linkage error domain. Three linguistic values, negative, zero, and positive as N, Z, and P respectively are used to fuzzify torque error domain [12].

3.1. The Flux Error Fuzzification

The errors of flux linkage is related value of stator's flux Φs* and real value of stator's Φs, they are subject to equation [13].

$$\Delta\phi = \phi s * - \phi s \qquad (6)$$

For flux linkage error negative value, positive value denoted respectively N and P. Two fuzzy sets are then defined by the delta and trapezoidal membership functions as given by Figure 3.

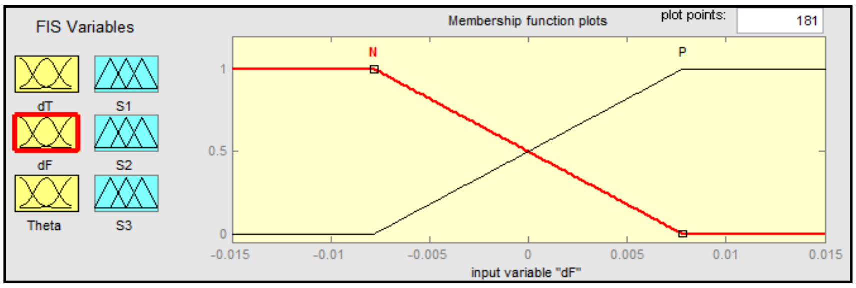

Figure 3. Design of the flux error using fuzzy logic

3.2. The Electromagnetic Torque Error

The electromagnetic torque error ΔTem is related to desired torque value Te_ref and actual torque value Te subject to equation 7 as shown below. The torque error membership function is decomposed in three fuzzy; their membership function's distribution is shown in Figure 4 which is entitled negative error (N), zero error (EZ), and positive error (P).

$$\Delta Te = Te^* - Te \quad (7)$$

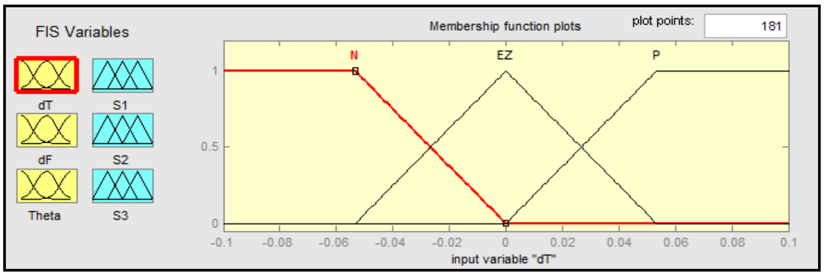

Figure 4. Design of electromagnetic torque using fuzzy logic

3.3. Angle of Flux Linkage θs

The angle of flux linkage θs is an angle between stator's flux Φs and a reference axis is defined by equation 5, fuzzy variable may be described by 6 language value (θ1→θ7), it's the membership function's distribution is shown Figure 5 [10].
The angle θ is equal to:

$$\theta s = arctg(\frac{\phi\beta s}{\phi\alpha s}) \quad (8)$$

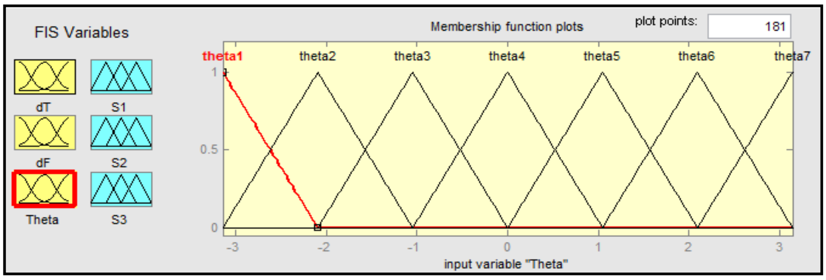

Figure 5. Angle of flux linkage θs

3.4. Fuzzy Logic Rules

The proper activities of fuzzy system are based on derivational (inferential) rules, similarly to expert systems. The benefit of such representation of knowledge is the transparency for users. These rules are of type IF and THEN and are illustrated with the help of Look up table. The total number of rules after their reduction is 42. By analyzing the structure of conventional DTC, the switching table it can be printed as fuzzy rules. The fuzzy system comprises many groups of rules, each of which contains 42 rules. Therefore, a first fuzzy logic-switcher can replace the switching table and the hysteresis controllers [14]. Each fuzzy rule can be described using the three input linguistic variables dF, dT and θ and three outputs are the switching status (S1, S2 and S3) to get voltage vector VS in the direct torque control with fuzzy logic rules base. In this article, Mamdani's fuzzy rule base model is developed to perform the function of proposed Direct Torque Fuzzy Control each one of the rules can be described by the input variables and the control variable, which is the switching state (Si). For example, Table 2 shows various rules as below.

Table 2. Fuzzy Logic Rules

Theta 1				Theta 2				Theta 3				Theta 4			
dT/dF	P	EZ	N	dT/dF	P	EZ	N	dT/dF	P	EZ	N	dT/dF	P	EZ	N
P	V5	V0	V3	P	V6	V7	V4	P	V1	V0	V5	P	V1	V0	V5
N	V6	V7	V2	N	V1	V0	V3	N	V2	V7	V4	N	V2	V7	V4

Theta 5				Theta 6				Theta 7			
dT/dF	P	EZ	N	dT/dF	P	EZ	N	dT/dF	P	EZ	N
P	V3	V0	V1	P	V4	V7	V2	P	V5	V0	V3
N	V4	V7	V6	N	V5	V0	V1	N	V6	V7	V2

3.5. Voltage Vectors

In the conventional direct torque control method, while the stator flux vector rotation, we have to use six active voltage vector to keep stator flux vector in defined error limits [15]. The subset of the fuzzy controller output is assigned to be seven discrete voltage vectors (one zero voltage vector and six non-zero voltage vectors), which makes the defuzzifation unnecessary [11]. The membership functions of the output space voltage vectors are depicted in Figure 6.

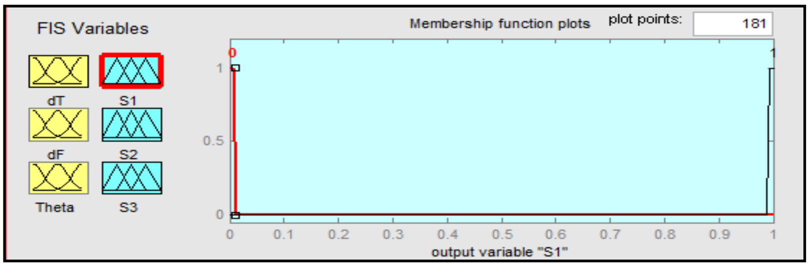

Figure 6. Voltage vector

3. Résults and Simulations

The simulations results were carried out to verify the effectiveness of using direct torque control with fuzzy logic strategy. In order to valid the quality of the drives, a simulation test on 1.5 kW asynchronous machines has been performed [12-14]. The proposed system is shown in Figure 7. The model is done with a Flux reference value and variable Torque reference value with conventional DTC and using fuzzy logic .This model includes subsystems for flux and torque calculations and fuzzy logic controller. The test was carried out during 0.1 second. A step change of reference torque was applied from 8N.m to 18 N.m at t=0.09s while the stator flux reference is maintained at 1.2 Wb.

The implementation of the flux and torque estimators block is used to estimate the flux based on currents and tensions from the asynchronous machine block. To estimate the torque as a function of flux and currents. Based on the formulas mentioned above (1) to (4), a Simulink models for flux and torque estimators have been designed as shown in Figure 8.

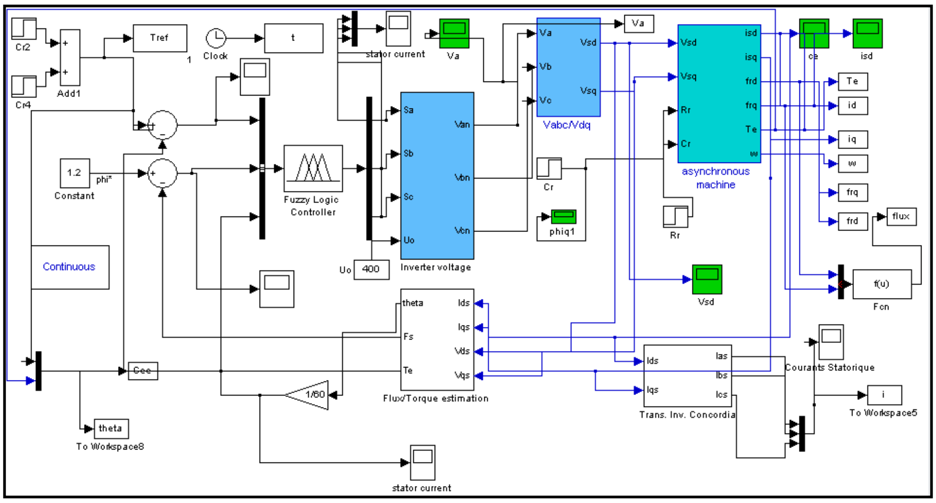

Figure 7. Block diagram of the proposed method

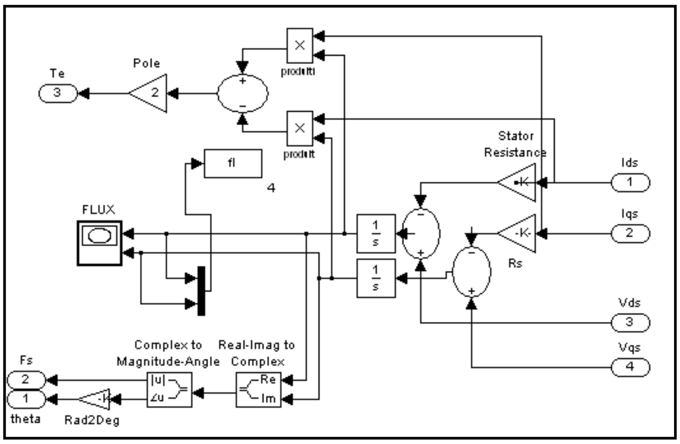

Figure 8. Model of Torque and Flux Estimators

The Figure 9 and 10 show the torque response, the stator flux trajectory using conventional DTC. The torque response which is less than the reference with ripples and the trajectory of stator flux which it is observed that the value of stators flux decreases between the sectors.

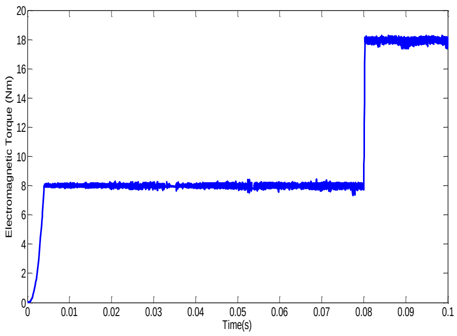

Figure 9. Torque response using DTC

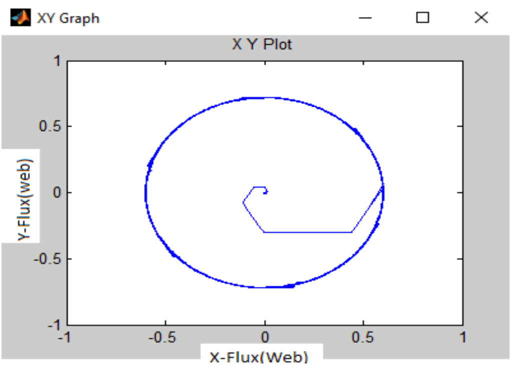

Figure 10. Stator flux trajectory using DTC

The Figure 11 shows the stator current taken by motor which is a sinusoidal in nature. The asynchronous machine takes high current initially and then it becomes a sinusoidal. The Figure 12 presents that when the machine is powered by a voltage inverter controlled, for high torque it takes more current as compared to low torque reference.

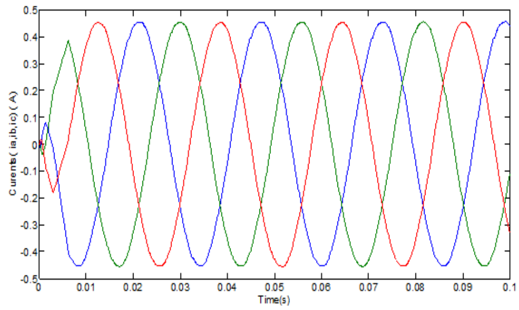

Figure 11. Stator Current using fuzzy logic

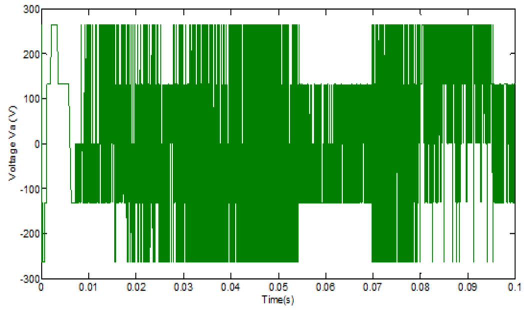

Figure 12. Stator voltage

The Figure 13 shows the steady state torque response of the machine with direct torque control and fuzzy control are employed. Under conventional DTC, the torque ripple rises to an average of 8 Nm with overshoot peaks of up to18 Nm. It can be seen that the fuzzy controller is able to reduce the torque ripple to 2 Nm and also dramatically reduce the overshoot. The ripple of torque with FDTC strategy is significantly reduced Figure 13 compared to Figure 9. The ripple of stator flux trajectory with FDTC is significantly reduced Figure 14 compared to Figure 10.

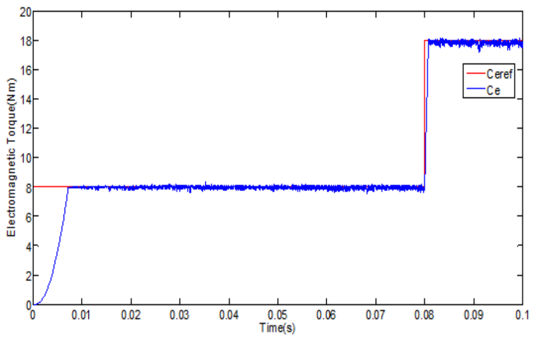

Figure 13. Torque response withfuzzy control

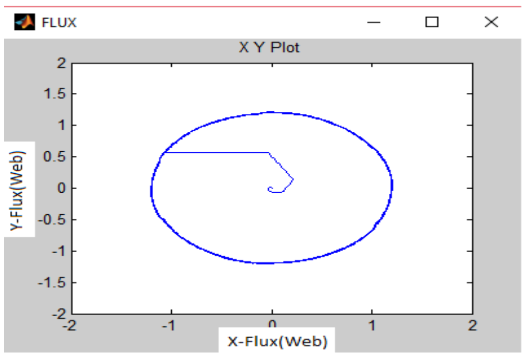

Figure 14. Stator flux trajectory with fuzzy control

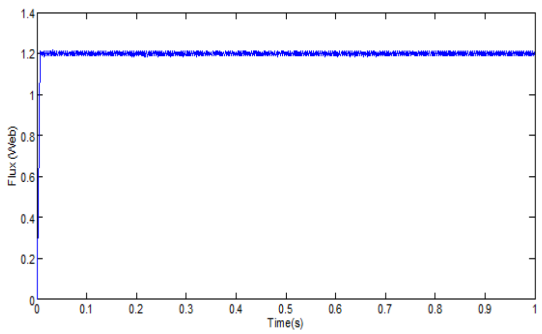

Figure 15. Flux estimator using conventional DTC

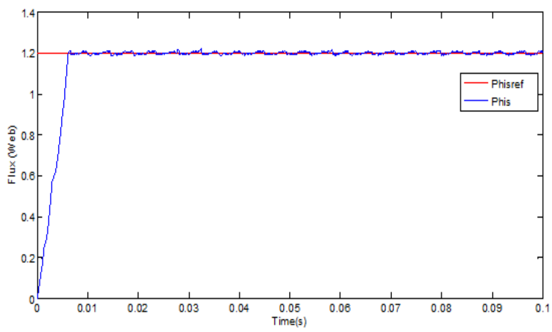

Figure 16. Flux estimator with fuzzy

The Figure 15, 16 shows the estimated flux remains constant and equal to the 1.2 Wb reference value using conventional DTC and DTC with the fuzzy control, respectively. The fuzzy control reduces the stator flux ripple, When the flux vector is in a sector N = i presented in Figure 12, the flux control and torque can be achieved by selecting one of eight voltage vectors Vo to V7.

4. Conclusion

Direct Torque Control is supposed to be one of the best controllers for driving any asynchronous machine. Its main principles have been introduced and deeply explained. It is also demonstrated in this article that the method of DTC also allows the independent and decoupled the torque and the stator flux. A model has been fully developed. From the results it is apparent that DTC strategy is simpler to implement than the flux vector control method because voltage modulators and co-ordinate transformations are not required. Although, it introduces some disadvantages, being the torque ripple one of the worst. The angle of flux linkage θs is an angle between stator's flux Ψs and a reference axis. Though, DTC has high dynamic performance, it has few drawbacks such as high ripple in torque, flux, current and variation in switching frequency of the inverter. The main focus of this article is to minimize the torque pulsations in the conventional DTC. After all the simulation work on conventional DTC done, the proposed control technique using fuzzy control was modeled and simulated in MATLAB/SIMULINK environment. The simulation results proved the superiority of the proposed control technique. The torque ripples of the motor are lesser, in parallel, the flux fluctuations are reduced according to conventional direct torque control technique. Moreover, the hysteresis controllers and switching table that used in conventional method are removed. The use of fuzzy logic control gave satisfactory results and reduces the computation burden by avoiding unnecessary complex mathematical modeling of the nonlinear systems.

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