Torque Ripple Minimization of Dual Direct Torque Control of Doubly Fed Induction Machine Using Fuzzy Logic

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***Abstract**: In this paper we present a new approach to improve the performance of the dual direct torque control of the doubly fed induction machine. The proposed dual (DTC) is based on fuzzy logic technique. In this application the stator and rotor windings are supplied by two voltage source inverters, witches are linked to two switching tables in order to define the stator and rotor flux vector control. A fuzzy controller is proposed to improve dual (DTC) performance and reduce significantly torque and flux ripples.*
The simulation results illustrate the effectiveness of the proposed control scheme.

***Key words**: Dual direct torque control, Doubly fed induction machine, Switching tables, Fuzzy logic, ripple minimization.*

1. Introduction

The Doubly fed induction machine has found wide range of industrial applications due to its reliability, high performance variable speed drive, generating applications [1] and relatively low cost compared to other machines.

The DFIM is controlled by directing the power flow into and out of the rotor windings. Because the DFIM can operate as either a motor or a generator both at subsynchronous and super-synchronous speeds [2], there are four operational modes in which the DFIM operates.

In application of high performance doubly fed induction machine such as motion control, it is usually desirable that the motor DFIM can provide good dynamic torque response as it is obtained from DC motor drives. Many control schemes have been proposed for this goal, among the vector control has been recognized as one of the most effective methods. It is well known that vector control needs quite complicated to on line coordinate transforms to decouple the interaction between flux control and torque control in order to provide a fast torque control. In recent years an innovative control method, called direct torque control has gained the attraction of researchers.

Direct torque control (DTC) strategy was introduced by Takahashi to give a fast and good dynamic performance and can be considered as an alternative to the field oriented control (FOC) strategy [4]. Therefore, in recent years the industrial application areas of the high performance AC drives based on DTC technique have gradually increased due to the following advantages over the field oriented control technique, such as Excellent dynamic performance, precise and quick control of stator flux and electromagnetic torque, absence of co-ordinate transformation, which reduce the complexity of algorithms involved in FOC, robust against machine parameters variations and no current control loop.

In this study a new Dual-Direct Torque Control scheme is developed with flux model of DFIM. Two Switching Tables (ST) linked to VSI are defined for stator and rotor flux vector control. We propose separate control of stator and rotor flux. In fact, in order to applied DTC strategy to this configuration, we define a first switching table to control the stator flux vector, and a second switching table to control the rotor flux vector. The next part of the control strategy makes possible to control interaction between both flux vectors. Consequently, we are able to control the electromagnetic torque and to regulate the mechanical speed [3]. The performance of such a scheme depends on the error band set between the desired and measured stator and rotor flux values. In this control scheme, the stator inverter switching frequency is changed according to the hysteresis bandwidth of stator flux and stator flux angular position, and the rotor inverter switching frequency is changed according to the hysteresis bandwidth of rotor flux and rotor flux angular position.

The major disadvantage of this control is the steady state ripples in torque and flux. The pulsations in flux and torque affect the accuracy of speed estimation [3]. It also results in higher acoustical noise and in harmonic losses. A fuzzy controller is introduced to allow the performance of DTC scheme in terms of flux and torque ripple to be improved.

1. Mathematical Model of DFIM

With the simplifying assumptions relation to the DFIM, the model of the DFIM expressed in the stationary 'αβ' axes reference frame can be expressed by:

$$\begin{aligned} V_{s\alpha} &= R_s I_{s\alpha} + \frac{d}{dt}\phi_{s\alpha} \\ V_{s\beta} &= R_s I_{s\beta} + \frac{d}{dt}\phi_{s\beta} \\ V_{r\alpha} &= R_r I_{r\alpha} + \frac{d}{dt}\phi_{r\alpha} + \omega_r \phi_{r\beta} \\ V_{r\beta} &= R_r I_{r\beta} + \frac{d}{dt}\phi_{r\beta} - \omega_r \phi_{r\alpha} \end{aligned} \tag{1}$$

$$\begin{aligned} \phi_{s\alpha} &= L_s I_{s\alpha} + \mu I_{r\alpha}, \phi_{s\beta} = L_s I_{s\beta} + \mu I_{r\beta} \\ \phi_{r\alpha} &= L_r I_{r\alpha} + \mu I_{s\alpha}, \phi_{r\beta} = L_r I_{r\beta} + \mu I_{s\beta} \end{aligned} \tag{2}$$

The generated torque of doubly fed induction machine can be expressed in terms of stator and rotor flux vector as:

$$\vec{C}_e = \frac{3}{2}\frac{N_p.\mu}{\sigma.L_s.L_r}.\left(\vec{\phi}_s \wedge \vec{\phi}_r\right) \tag{3}$$

Where C_e is the electromagnetic torque, N_p is the number of Pole pairs, L_s, L_r are the stator and rotor self inductances, μ is the mutual inductance and ϕ_s, ϕ_r are the stator and rotor flux space vectors and $\sigma = 1 - \frac{\mu^2}{L_s L_r}$ is the leakage coefficient. We can use:

$$\left\|\vec{C}_e\right\| = K\left\|\vec{\phi}_s\right\|.\left\|\vec{\phi}_r\right\|\sin(\gamma) \tag{4}$$

γ is the angle between stator and rotor flux as shown in Fig1. This angle is referred as torque angle. The constant K is defined as below: $K = \frac{3N_p\mu}{2\sigma L_s L_r}, k1 = \frac{1}{k\|\phi_s\|\|\phi_r\|}$

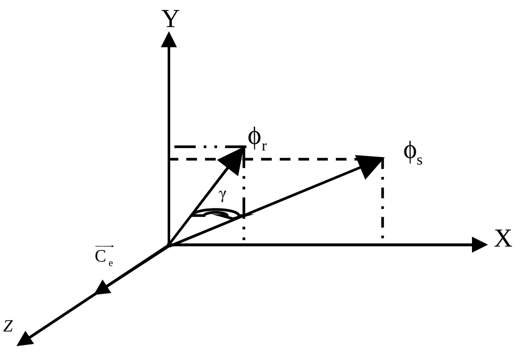

Fig. 1 Flux vector diagram of DFIM.

3. Proposed dual direct torque control strategy

The conventional DTC algorithm using the hysteresis based voltage switching method has relative merits of simple structure and easy implementation. The performance of such a scheme depends on the error band set between the desired and measured torque and stator flux values [5] , the inverter switching frequency is changed according to the hysteresis bandwidth of flux and torque controllers and the variation of speed and motor parameters.

In this paper; we propose separate control of stator and rotor flux. In fact, in order to applied dual DTC strategy to this configuration, we define a first switching table to control the stator flux vector with his angular position, and a second switching table to control the rotor flux vector with his angular position. The next part of the control strategy makes possible to control interaction between both flux vectors. Consequently, we are able to control the electromagnetic torque and to regulate the mechanical speed [3].

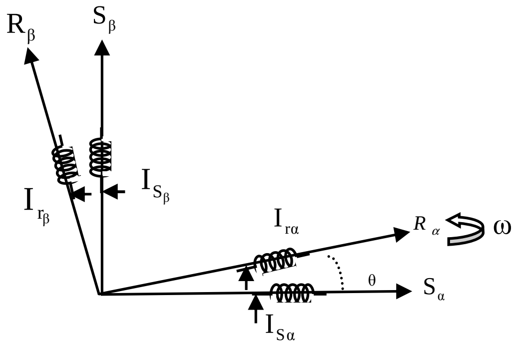

Fig. 2 Two phase reference frame.

Formula (2) can be written as:

$$\begin{bmatrix} \phi_{s_{\alpha,\beta}} \\ \phi_{r_{\alpha,\beta}} \end{bmatrix} = \begin{bmatrix} [L_s] & [\mu(\theta)] \\ [\mu(\theta)]^T & [L_r] \end{bmatrix} \tag{5}$$

Where:

$$\mu(\theta) = \mu_0.\begin{bmatrix} \cos(\theta) & \cos(\theta + \frac{4.\pi}{3}) & \cos(\theta + \frac{2.\pi}{3}) \\ \cos(\theta + \frac{2.\pi}{3}) & \cos(\theta) & \cos(\theta + \frac{4.\pi}{3}) \\ \cos(\theta + \frac{4.\pi}{3}) & \cos(\theta + \frac{2.\pi}{3}) & \cos(\theta) \end{bmatrix} \tag{6}$$

We express the Laplace operator as s and obtain some disturbance terms noted $P_{s\alpha}, P_{s\beta}, P_{r\alpha}, P_{r\beta}$ defined as follows:

$$P_{s_\alpha} = -\frac{\mu}{\sigma.T_s.L_r}(\phi_{r_\beta}\sin\theta - \phi_{r_\alpha}\cos\theta)$$

$$P_{s_\beta} = \frac{\mu}{\sigma.T_s.L_r}(\phi_{r_\alpha}\sin\theta + \phi_{r_\beta}\cos\theta)$$

$$P_{r_\alpha} = \frac{\mu}{\sigma.T_r.L_s}(\phi_{s_\beta}\sin\theta + \phi_{s_\alpha}\cos\theta) \qquad (7)$$

$$P_{r_\beta} = -\frac{\mu}{\sigma.T_r.L_s}(\phi_{s_\alpha}\sin\theta - \phi_{s_\beta}\cos\theta)$$

Where:

$$T_s = \frac{L_s}{R_s}, T_r = \frac{L_r}{R_r}$$

The stator and rotor transmittances terms are defined as:

$$T_\phi^s(s) = \frac{\sigma.T_s}{1+\sigma.T_s.s}$$

$$T_\phi^r(s) = \frac{\sigma.T_s}{1+\sigma.T_r.s} \qquad (8)$$

It can be seen from (5), (7) and (8) that the DFIM in flux mod can be represented as shown in fig.3.

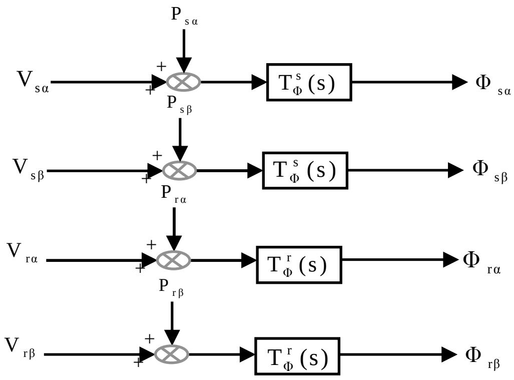

Fig. 3 Bloc diagram of DFIM flux model.

4. Basic DTC principles

From equation (4) it is clear that the DFIM torque can be varied by changing the rotor or stator flux vectors.

The dual DTC uses the hysteresis band to directly control the stator flux and his angular position ρ_s and rotor flux with his angular position ρ_r of the DFIM. When the stator or rotor flux falls out-side the hysteresis band, the inverter switching stator or rotor is changed so that the flux takes an optimal path toward. So VSI outputs (stator and rotor) can be deduced from two estimated and two required values of stator and rotor flux.

In the α,β reference, the stator and rotor flux are obtained by the followings equations:

$$\vec{\phi_s}(s) = \int_0^t (\vec{V_s} - \vec{R_s}.I_s)dt + \vec{\phi_{s0}}$$

$$\vec{\phi_r}(s) = \int_0^t (\vec{V_r} - \vec{R_r}.I_r)dt + \vec{\phi_{r0}} \qquad (9)$$

During the switching interval, $[0, T_e]$ we have:

$V_s >> R_s.I_s$ Et $V_r >> R_r.I_r$ We can express:

$$\phi_s(t) = \phi_{s0} + V_s.T_e$$

$$\phi_r(t) = \phi_{r0} + V_r.T_e \qquad (10)$$

We adopt a "standard" assumption for the considered frequencies. It consists in neglecting the resistive effect in the windings compared with the inductive effect. We can observe that this assumption is especially valid for high power machines. Consequently, we can express [3]:

$$\sigma T_s.S >> 1, \; for: s \to \infty$$

$$\sigma T_r.S >> 1, \; for: s \to \infty \qquad (11)$$

So:

$$T_\phi^s(s) = \frac{\sigma.T_s}{1+\sigma.T_s.s} = \frac{1}{s}, when: s \to \infty$$

$$T_\phi^r(s) = \frac{\sigma.T_s}{1+\sigma.T_r.s} = \frac{1}{s}, when: s \to \infty \qquad (12)$$

A second assumption is used. It consists in neglecting the coupling terms $P_{s\alpha}, P_{s\beta}, P_{r\alpha}, P_{r\beta}$ This can be done because the coupling terms are a low value in relation to the nominal values of the voltages level $V_{s\alpha}, V_{s\beta}, V_{r\alpha}, V_{r\beta}$ If we use the sign n for the nominal value of the considered term, this assumption can be expressed as below[3]:

$$P_{s\alpha} << V_{s\alpha}, P_{s\beta} << V_{s\beta}$$

$$P_{r\alpha} << V_{r\alpha}, P_{r\beta} << V_{r\beta} \qquad (13)$$

According to the equation (12), that the flux expression as the voltage integrals, and by using the two lusts assumption, we can formulate the DFIM global model as shown in fig. 4.

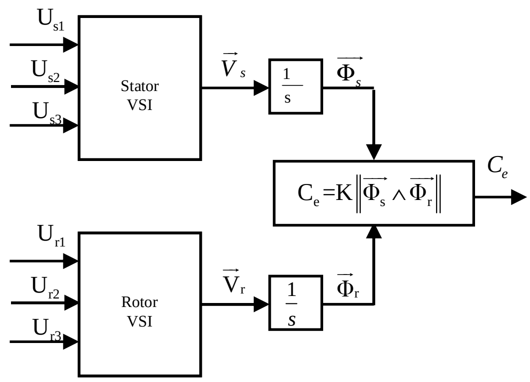

Fig. 4 Block scheme of VSI and DFIM.

A. vectors flux control

The equation (10) can be easy transformed to:

$$\Delta\phi_s = \phi_s - \phi_s(0) = V_s.T_e$$
$$\Delta\phi_r = \phi_r - \phi_r(0) = V_r.T_e \qquad (14)$$

So :

$$\vec{\phi}_{s(t_{n+1})} = \vec{\phi}_{s(t_n)} + T_e.\vec{V}_{s(t_n)}$$
$$\vec{\phi}_{r(t_{n+1})} = \vec{\phi}_{r(t_n)} + T_e.\vec{V}_{r(t_n)} \qquad (15)$$

The voltage vector application time T_e equal to sampling time).Consequently, V_s, V_r remain constant during the interval $[T_n, T_{n+1}]$. Where: $T_{n+1} = T_n + T_e$

$$\vec{\phi}_s^{\,n+1} = \vec{\phi}_s^{\,n} + T_e.\vec{V}_s^{\,n} \qquad (16)$$
$$\vec{\phi}_r^{\,n+1} = \vec{\phi}_r^{\,n} + T_e.\vec{V}_r^{\,n}$$

By neglecting the stator and rotor resistances, (10) implies that the ends of the stator and rotor flux vectors will moves in the direction of the applied voltage vectors as shown in this figure.

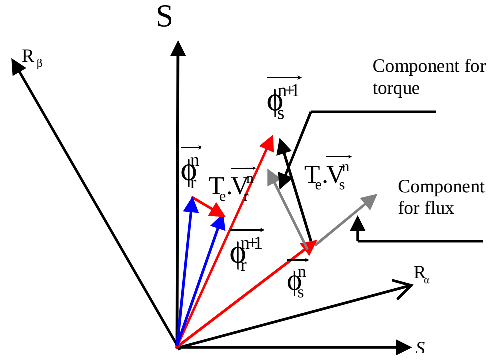

Fig. 5 Stator and rotor flux vector deviation.

The appropriate voltage vector on VSI outputs can be deduced from two estimated and two required values of stator and rotor flux. To select the voltage vectors for controlling the amplitudes of the stator and rotor flux linkage, the voltage vectors plane is divided into six regions, as shown in Figure.5.

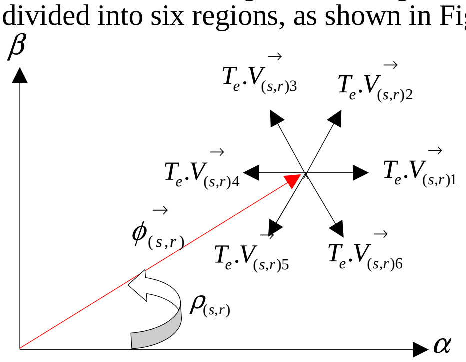

Fig. 6 Applicable voltage vectors for stator and rotor flux vectors control.

In each region, two adjacent voltage vectors, which give the minimum switching frequency, are selected to increase or decrease the flux amplitudes. If $V_{s1,r1}$ is applied, the magnitude of $\phi_{s,r}$ increase. Whereas the angular position $\rho_{s,r}$ of $\phi_{s,r}$ decrease. When a specific voltage vector is applied, the evolution of $\rho_{s,r}$ and the magnitude of $\phi_{s,r}$ can differ according to the $\rho_{s,r}$ initial value. Consequently, if $\phi_{s,r}$ is in the same sector, use of identical voltage vector leads to a similar phase and magnitude evolution of the flux vector. We manage the rotor flux vector in the same way. Thus, the voltage vector to apply depends on:

-The sector number (according to $\rho_{s,r}$),

-The required flux angular position,

- The required flux magnitude evolution.

For instance, vectors are selected to increase and decrease the amplitude of flux vectors and ours angular position as:

if $\vec{V}_{(s,r)i+1}$ is selected then $\phi_{s,r}$ increase and $\rho_{s,r}$ increase;

if $\vec{V}_{(s,r)i-1}$ is selected then $\phi_{s,r}$ increase and $\rho_{s,r}$ decrease;

if $\vec{V}_{(s,r)i+2}$ is selected then $\phi_{s,r}$ decrease and $\rho_{s,r}$ increase;

if $\vec{V}_{(s,r)i-2}$ is selected then $\phi_{s,r}$ decrease and $\rho_{s,r}$ decrease.

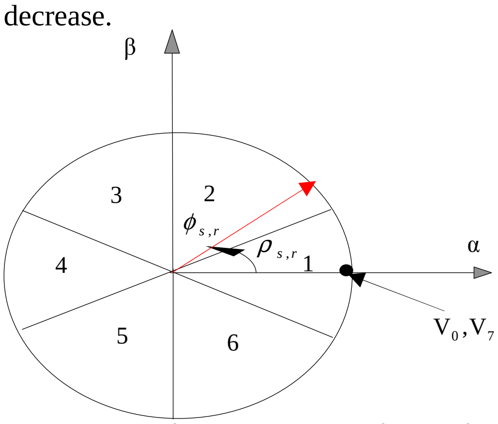

Fig.7 Sector definition in (α, β) reference frame.

B. Stator and rotor flux estimation

The magnitude of stator and rotor flux, which can be estimated as following

$$\overline{\phi_s} = \int_0^t (\overline{V_s} - R_s.\overline{I_s})\,dt \qquad (17)$$
$$\overline{\phi_r} = \int_0^t (\overline{V_r} - R_r.\overline{I_r})\,dt$$

The stator and rotor flux linkage phasors are given by:

$$|\phi_s| = \sqrt{\phi_{s\alpha}^2 + \phi_{s\beta}^2}, |\phi_r| = \sqrt{\phi_{r\alpha}^2 + \phi_{r\beta}^2} \quad (18)$$

The stator and rotor flux linkage phasors positions are:

$$\rho_s = \tan^{-1}\frac{\phi_{s\alpha}}{\phi_{s\beta}}, \rho_r = \tan^{-1}\frac{\phi_{r\alpha}}{\phi_{r\beta}} \quad (19)$$

C. Flux corrector

In this dual DTC we are needed to use for hysteresis comparators: two stator hysteresis comparators in order to control the stator flux magnitude ϕ_s and his angular position .The outputs of these comparators are connected to stator switching table; and two rotor hysteresis comparators in order to control the rotor flux magnitude ϕ_r and his angular position ρ_r. The outputs of these comparators are connected to rotor switching table. The input of these for comparators is the difference between reference values and estimated values of flux magnitudes and angular position; flux magnitude reference values ϕ_{sreff} and ϕ_{rreff} are constant and equal to their nominal values. For the stator flux reference ρ_{sreff}, the flux position value depends only on measured mechanical speed. For the rotor flux reference ρ_{rreff} the flux position value depends on torque angle γ, rotor position θ and stator flux position reference ρ_{sreff} as shown in (10).

The outputs of the comparators with the number of sector at which the stator and rotor flux space vector is located ($\rho_{s,r}$) are fed to a switching tables to select an appropriate inverter voltage vector. The selected voltage vector will be applied to the DFIM at the end of the sample time, as are shown in (7)

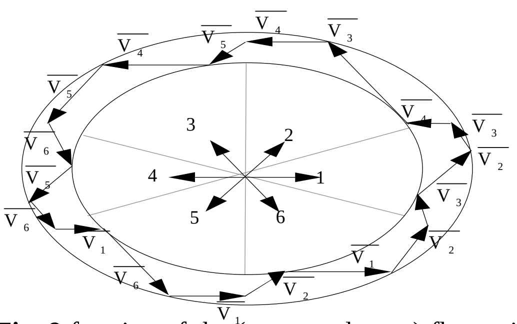

Fig. 8 forming of the (stator and rotor) flux trajectory by appropriate voltage vectors selection.

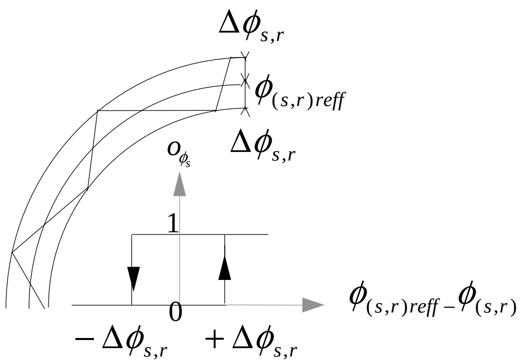

Fig .9 The hysteresis controllers.

D. Stator and rotor flux loci

By analyzing relation (1), it can be noted that the electromagnetic torque depend on stator and rotor flux modulus, and γ the torque angle between stator and rotor flux vectors. Our purpose is to separate the stator and rotor flux adjustment and maintains to their nominal values and to control the electromagnetic torque by adjusting the torque angle γ.Figure 13 shows a new reference frame where ω_s is the stator flux angular speed. An angular relationship can be deduced as:

$$\rho_r = \gamma - \theta + \rho_S \quad (20)$$

According to [2],a ratio K allows to fix the angular velocity degree of freedom ω_s in figure (13).

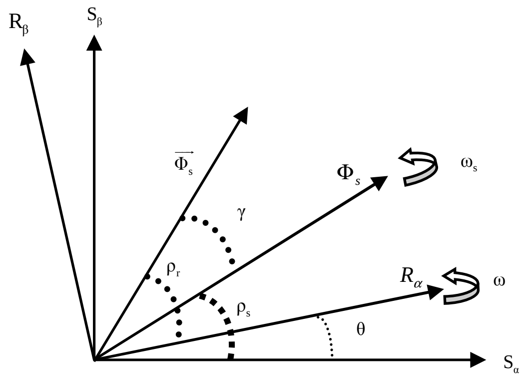

Fig. 10 stator and rotor flux loci

E. Elaboration of the switching table

For the stator and rotor flux vector laying in sector 1 (Fig.7) in order to increase its magnitude the voltage vectors V_2, V_6 can be selected. Conversely, a decrease can be obtained by selecting V_3, V_5 .

For the stator and rotor flux angular position $\rho_{s,r}$ is used therefore, to increase its the voltage vectors V_2, V_3 can be selected and to decrease V_6, V_5. The above considerations allow construction of the selection table as:

		Sector number					
Flux evolution		1	2	3	4	5	6
$\lVert\vec{\phi}\rVert$	ρ	Voltage vector					
↗	↗	V2	V3	V4	V5	V6	V1
↗	↘	V6	V1	V2	V3	V4	V5
↘	↗	V3	V4	V5	V6	V1	V2
↘	↘	V5	V6	V1	V2	V3	V4

Switching table

5. Fuzzy Controller design

The speed controller takes the error signal between the reference and the actual speed and produces the appropriate reference torque value. That means the drive changes mode from torque control to speed control. So, now the mechanical load on DFIM shaft defines the electromagnetic torque of the DFIM. In torque control mode the mechanical load on motor shaft defines the rotor speed. In figure 7 we can see the block diagram of the proposed drive, in speed control mode. A reference speed signal ω_{reff} or, in other words, the speed command is given. The actual speed ω is estimated or measured with a speed encoder .

Two inputs of speed fuzzy controller are chosen, the speed error and its variation.

$$e_{\omega}(k) = \omega_{reff}(k) - \omega(k) \qquad (21)$$
$$\Delta e_{\omega}(k) = e_{\omega}(k) - e_{\omega}(k-1)$$

The output variable C_e is obtained after the inference system, then is defuzzified using the center average method Mamdani operation rule of fuzzy implication is used as inferences method.

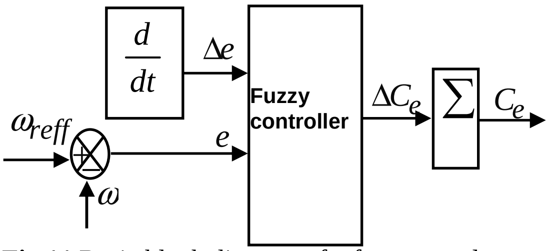

Fig.11 Basic block diagram of a fuzzy speed controller

Fuzzy control rules of proposed fuzzy control scheme are designed to minimize torque and flux ripples .The control rules are formulated using the simulation tests.

The rules sets of fuzzy controller are shown in the following table.

Δe \ e	NG	NM	NP	ZE	PP	PM	PG
NG	NG	NG	NG	NG	NM	NP	ZE
NM	NG	NG	NG	NM	NP	ZE	PP
NP	NG	NG	NM	NP	ZE	PP	PM
ZE	NG	NM	NP	ZE	PP	PM	PG
PP	NM	NP	ZE	PP	PM	PG	PG
PM	NP	ZE	PP	PM	PG	PG	PG
PG	ZE	PP	PM	PG	PG	PG	PG

Inference table

PG: positive high, PM: positive medium, PP: positive small ZE: zero, NG: negative high, NM: negative medium NP: negative small.

The linguistic rules can be expressed by the following example:

If (e_{ω} is PG and Δe_{ω} is NG then the output Δu is ZE)

The membership functions of input/output variables are given in fig (7). The universe of discourse for all variables is Normalized [-1,1] interval.

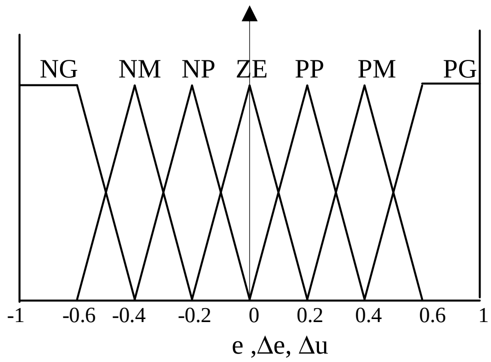

Fig. 12 Membership functions (e ,Δe, Δu)

6. Simulation results

To shown the performance of the proposed fuzzy logic dual DTC. The rotation speed is controlled by a PI compensator; then by a fuzzy logic controller. two Matlab Simulink results are presented in order to examine the difference between the classical dual DTC and the fuzzy logic dual DTC .In all simulation results presented, it can be observed a much better behavior of the fuzzy logic dual DTC performance as compared to classical dual DTC, achieving the objectives of the present work, which was to reduce the torque and flux ripple and consequently improve the DFIM performance.

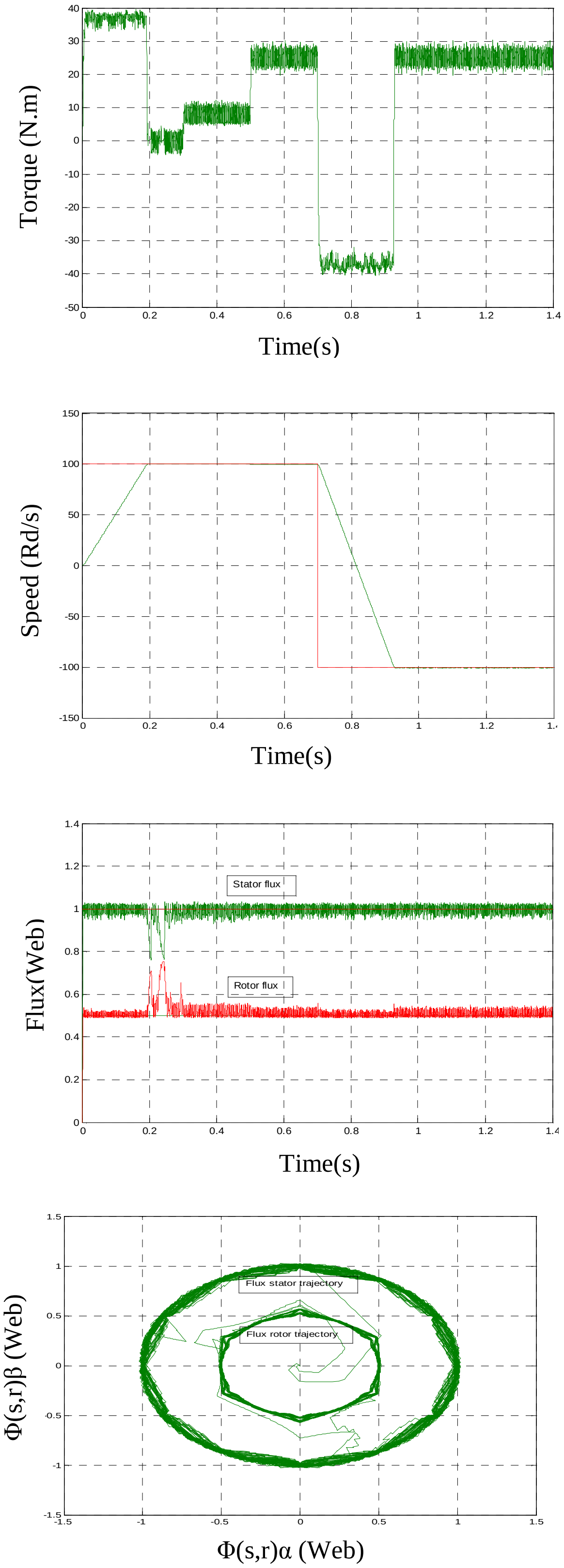

Fig. 13A) Simulation results with PI controller

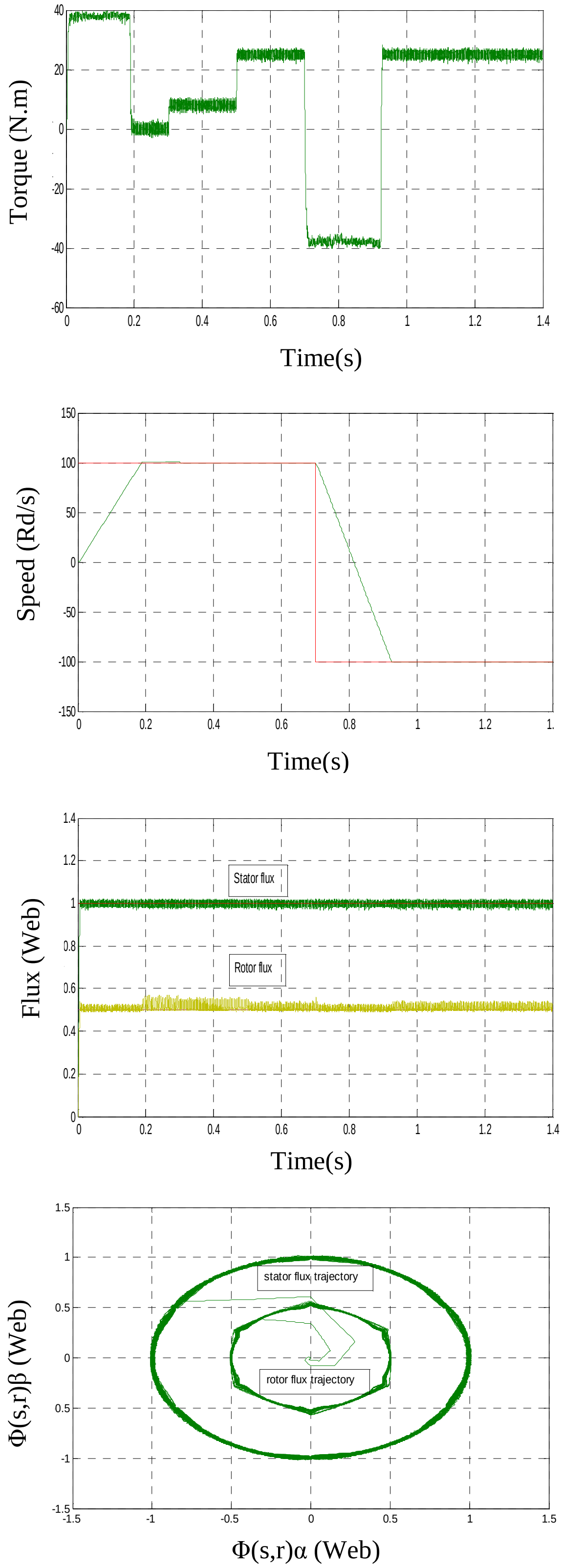

Fig.13B) Simulation results with fuzzy logic controller

7. Conclusion

This paper introduced a new developed algorithm based on fuzzy logic dual direct torque control of doubly fed induction machine. That successfully operates even in cases of rapidly changing conditions. The complete dynamic model of the dual DTC system, with either of the FLC is developed and simulated by using MATLAB-SIMULINK. The FLC is selected to reduce the torque and flux ripples. The simulation results confirm that the fast and good response of the proposed drive system is much better than the corresponding classical drive scheme. The performance in steady state and transient operating conditions are verify and are satisfactory.

DFIM PARAMETRES

Rs	1.2	Ω
Rr	1.8	Ω
Ls	0.1554	H
Lr	0.1568	H
μ	0.15	H
P	2	
J	0.07	Kg .m^2
F	0	Si

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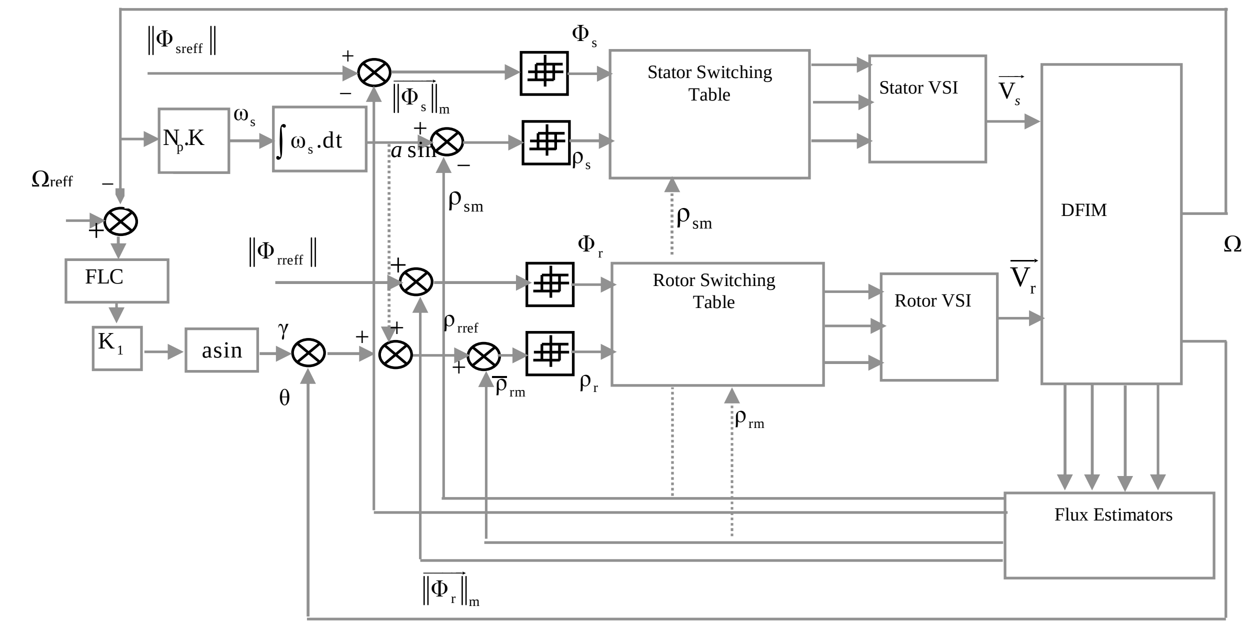

Fig.14. Bloc diagram of DFIM based on fuzzy logic dual DTC