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Fuzzy Direct Torque Control for Induction Motor Sensorless Drive Powered by Five Level Inverter with Reduction Rule Base

***Abstract**. The object of this paper is to study a new control structure for sensorless induction machine dedicated to electrical drives using a five-level voltage source inverter (VSI). However, direct torque control (DTC), known for years, provides high dynamic performance and also fast and robust response for induction motors (IM), classical DTC produces notable torque, flux ripples. In the present paper, fuzzy logic has been suggested to improve the system performance (i.e. gives faster torque and flux responses and also reducing the undesirable torque ripple that can occur in the output torque). In this controller, torque error, flux error and also the position of stator flux are as inputs and the output of it is a suitable voltage vector which should apply to the motor. In this paper to reduce the number of rules and also increase controller's speed, we use particular mapping for the stator flux position. Compared with conventional DTC, this method is easily implemented for induction machine, the ripples of both torque and flux are reduced remarkable. Simulation results proved the superiority of the novel approach.*

Streszczenie.** Celem tego artykułu jest zbadanie nowej struktury sterowania bezczujnikowej maszyny indukcyjnej przeznaczonej do napędów elektrycznych z wykorzystaniem pięciopoziomowego falownika napięcia (VSI). Wiadomo jednak, że bezpośrednia sterowanie momentu obrotowego (DTC), znane od lat zapewnia wysoką dynamikę, a także szybką i solidną reakcję dla silników indukcyjnych (IM), klasyczny algorytm DTC wytwarza znaczny moment obrotowy, tętnienia strumienia. W niniejszym artykule zasugerowano logikę rozmytą, aby poprawić wydajność systemu (tzn. daje szybszą zmianę momentu obrotowego i odpowiedzi strumienia, a także zmniejsza niepożądane tętnienia momentu obrotowego, które mogą wystąpić w wyjściowym momencie obrotowym). W tym regulatorze, błąd momentu obrotowego, błąd strumienia, a także położenie strumienia stojana są jako wejścia, a jego wyjście jest odpowiednim wektorem napięcia, który powinien być zastosowany do sterowania silnika. W tym artykule, aby zmniejszyć liczbę reguł, a także zwiększyć szybkość kontrolera, używamy konkretnego odwzorowania dla położenia strumienia stojana. W porównaniu z konwencjonalnym kodem DTC ta metoda jest łatwo do zastosowania w maszynach indukcyjnych, a tętnienia momentu obrotowego i strumienia są znacznie mniejsze. Wyniki symulacji dowiodły wyższości nowatorskiego podejścia. **Bezpośrednie sterowanie momentem w bezczujnikowym silniku indukcyjnym za pomocą pięciopoziomowego przekształtnika wspomaganegologiką rozmytą

Keywords: Direct torque control (DTC), fuzzy logic, induction motor, fuzzy logic direct torque control (FLDTC), AC Drives.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Introduction

The rapid development of the capacity and switching frequency of the power semiconductor devices and the continuous advance of the power electronics technology have made many changes in static power converter systems and industrial motor drive areas. The conventional GTO inverters have limitation of their dc-link voltage. Hence, the series connections of the existing GTO thyristors have been essential in realizing high voltage and large capacity inverter configurations with the dc-link voltage [1]. The vector control of induction motor drive has made it possible to be used in applications requiring fast torque control such as traction [2].

The Conventional DTC requires no mechanical sensor, no current regulator, no coordinate transformation and depends only on stator resistance. Because of its good dynamic performances and the robustness, it has been widely used despite the inherent drawbacks (e.g., variable switching frequency, high torque ripples at low speed) [3].

Even though DTC has existed for approximately two decades, considerable research effort is still being devoted to the elimination of its inherent disadvantages. One more significant disadvantage of conventional DTC is ripple, which exists in the torque and flux variables. This undesirable ripple is of higher value when the selected state of the inverter remains unchanged for several sampling periods. In DTC method, two hysteresis controllers are used to regulate stator flux and motor electromagnetic torque. The main point in this method is choosing a switching voltage vector to put torque and stator flux in the predetermined bands. Since, hysteresis controller is on-off controller and has two amounts then it's action in facing with torque's large and small errors will be the same. Therefore, a big torque ripple will be produced. Several techniques have been developed to improve the torque performance [4]. In this work, to get a suitable operation, we suggest fuzzy logic method. Generally, in fuzzy logic direct torque control method (FLDTC), torque error is divided to different sectors and in each sector, suitable control signal is used. Also, in this method in spite of conventional DTC, the same voltage vectors for different flux positions in the π/3 region are not used. Above benefits also increases system's speed [5].

Five-Level Inverter Topology

Fig. 1 shows the schematic diagram of neutral point clamped (NPC) five-level VSI. Each phase of this inverter consists of four clamping diodes, eight GTO thyristors and eight freewheeling diodes. Table.1 shows the switching states of this inverter. Since three kinds of switching states exist in each phase, a five level inverter has 61 switching states.

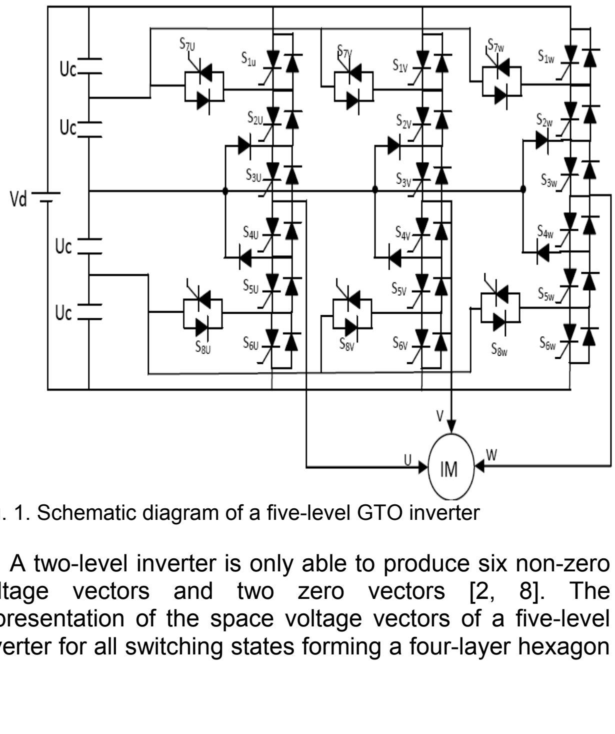

Fig. 1. Schematic diagram of a five-level GTO inverter

A two-level inverter is only able to produce six non-zero voltage vectors and two zero vectors [2, 8]. The representation of the space voltage vectors of a five-level inverter for all switching states forming a four-layer hexagon centered at the origin of the (d, q) plane and a zero voltage vector at the origin of the plane, as depicted in figure 2. According to the magnitude of the voltage vectors, we divide them into nine groups:

(V_0); (V_1, V_{11}, V_{21}, V_{31}, V_{41}, V_{51}); (V_7, V_{17}, V_{27}, V_{37}, V_{47}, V_{57}) ; (V_2, V_{12}, V_{22}, V_{32}, V_{42}, V_{52}); (V_6, V_9, V_{16}, V_{19}, V_{26}, V_{29}, V_{36}, V_{39}, V_{46}, V_{49}, V_{56}, V_{59}); (V_3, V_{13}, V_{23}, V_{33}, V_{43}, V_{53}); (V_8, V_{18}, V_{28}, V_{38}, V_{48}, V_{58}); (V_5, V_{10}, V_{15}, V_{120}, V_{25}, V_{30}, V_{35}, V_{40}, V_{45}, V_{50}, V_{55}, V_{60}); (V_4, V_{14}, V_{24}, V_{34}, V_{44}, V_{54}).

Table 1. Switching states of a five-level inverter

Switching states	S1	S2	S3	S4	S5	S6	V_N
L1	OFF	OFF	OFF	ON	ON	ON	$-2U_c$
L2	OFF	OFF	ON	ON	ON	OFF	$-U_c$
L3	OFF	ON	OFF	OFF	ON	ON	0
L4	ON	OFF	ON	ON	OFF	OFF	0
L5	ON	ON	OFF	OFF	OFF	ON	U_c
L6	ON	ON	ON	OFF	OFF	OFF	$2U_c$

The Zero Voltage Vector (ZVV) has five switching states, the large voltage vector (LVV) have only one [1, 6].

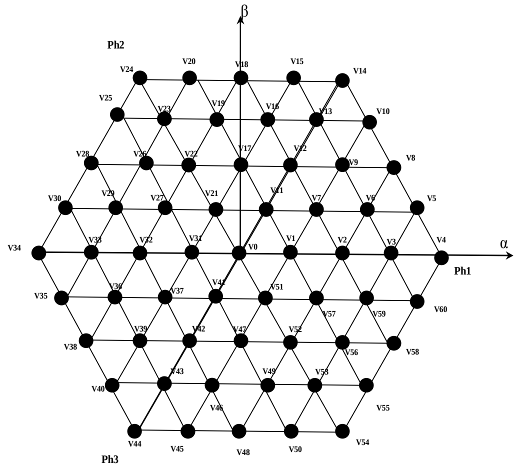

Fig. 2. Topography of the 61 vectors generated by a NPC structured five-level inverter

Dynamic Model of IM and DTC conventional

The state space representation of the induction motor with biphase model in the stationary reference frame is given by (1) in the vector-matrix form. Stator flux, stator currents and rotor speed are considered as the state variable of the system.

$$(1)\quad \begin{bmatrix} \frac{d}{dt}i_{s\alpha} \\ \frac{d}{dt}i_{s\beta} \\ \frac{d}{dt}\psi_{s\alpha} \\ \frac{d}{dt}\psi_{s\beta} \end{bmatrix} = \begin{bmatrix} -\left(\frac{R_s}{\sigma L_s}+\frac{1-\sigma}{\sigma T_r}\right) & 0 & \frac{L_m}{\sigma L_s L_r T_r} & \left(\frac{L_m}{\sigma L_s L_r}\right).\omega_r \\ 0 & -\left(\frac{R_s}{\sigma L_s}+\frac{1-\sigma}{\sigma T_r}\right) & -\left(\frac{L_m}{\sigma L_s L_r}\right).\omega_r & \frac{L_m}{\sigma L_s L_r T_r} \\ \frac{L_m}{T_r} & 0 & \frac{-1}{T_r} & \omega_r \\ 0 & \frac{L_m}{T_r} & -\omega_r & \frac{-1}{T_r} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{s\alpha} \\ \psi_{s\beta} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix}$$

where T_r is the rotor time constant and σ is the leakage coefficient. The electromagnetic torque and the rotor speed are given by:

$$(2)\qquad T_{em} = p\left(\psi_{s\alpha} i_{s\alpha} - \psi_{s\beta} i_{s\beta}\right)$$

$$(3)\qquad \frac{d\omega_r}{dt} = \frac{p}{J}T_{em} - \frac{B}{J}\omega_r - \frac{p}{J}T_l$$

where:

R_s and R_r are the stator and rotor winding resistances;

L_m , L_s and L_r are the stator, mutual and rotor inductances;

p is the number of pole pairs;

ω_e , ω_r and ω_{sl} are the synchronous, rotor and slip speed in electrical rad/s;

$v_{s\alpha}$, $v_{s\beta}$, $i_{s\alpha}$, $i_{s\beta}$, $\psi_{s\alpha}$ and $\psi_{s\beta}$ are stator voltage, stator current and stator flux in Concordia components; T_{em} and T_l are the electromagnetic torque and the load torque respectively;

J and B are the motor inertia and viscous friction coefficient respectively.

The principle of fuzzy direct torque control

The principle of fuzzy direct torque control (DTC) is similar to traditional DTC. To obtain improved performance of the DTC drive during start-up or during changes in the reference flux and torque, it is possible to use a fuzzy-logic-based switching vector selection process. For this purpose, a Mamdani type fuzzy logic system will be used and a rule base has to be formulated, where the different voltage states are selected by using the flux and torque errors and also the position of the stator flux linkage space vector. Thus the goal is to use a fuzzy logic system, which improves the system performance (i.e. gives faster torque and flux responses), and outputs the zero and non-zero voltage switching states (n) and uses three quantities as inputs: the flux error $\left(\varepsilon_\psi\right)$, the torque error $\left(\varepsilon_\Gamma\right)$ and the position of the stator flux space vector $\left(\theta_s\right)$. For this purpose, during start-up, switching states giving a higher increase in stator flux modulus have to be selected by the fuzzy system and during this time, the changes in the torque are small.

When the flux error becomes small, switching states which give faster increase in the torque have to be selected by the fuzzy logic system [5, 6]. The selection of the appropriate rule base of the fuzzy logic system is now discussed.

Switching vector selection using a fuzzy rule base

Each of the rules (in the rule base) can be described by the input variables $\left(\varepsilon_\psi, \varepsilon_\Gamma, \theta_s\right)$ and the control variable, which is in the switching state (n). The general ith rule is as follows:

(4) If ε_ψ is A_i and ε_Γ is B_i and θ_s is C_i then n is N_i

The actual rule can be simply obtained by using physical considerations or simulations of the DTC drive system. The simplest procedure is to obtain these by physical considerations using vector diagrams which show the stator flux linkage space vector at a given instant of time and also the different switching vectors.

Table 2 gives the various rules. It is assumed that for the flux error there are three fuzzy sets and for the torque error there are thirteen fuzzy sets. The angle of the stator flux linkage space vector with respect to the real axis is θ_s , and can be obtained from the direct and quadrature axis stator flux linkages $(\psi_{s\alpha}, \psi_{s\beta})$ expressed in the stationary reference frame as:

$$\theta_s = tg^{-1}\left(\frac{\psi_{s\beta}}{\psi_{s\alpha}}\right) \quad (5)$$

Membership functions shown in Figure.3 which are based on the fuzzy controller's three inputs have been obtained by using trial and error method.

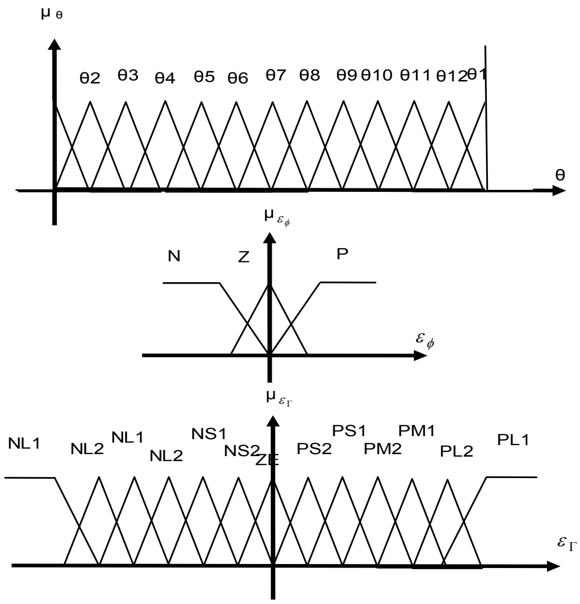

Fig. 3. Memberships of fuzzy controller inputs

By using above flux vector membership, the number of rules will be 468 [7]. So for reducing the number of rules, following membership for flux vector position will be suggested that can only cover the area between $\left[0, \frac{\pi}{6}\right]$, Figure 4.

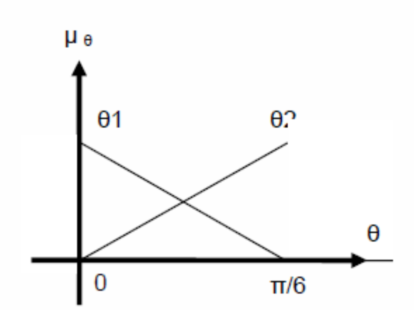

Fig. 4. New member for flux vector position.

According to existing symmetry in inverter voltage vectors and also flux angle in α-β frame, following mapping is suggested till by mean of it, stator flux position from $[0, 2\pi]$ range transfers to $\left[0, \frac{\pi}{6}\right]$

$$\theta = \frac{\pi}{3} rem\left(\frac{\theta'}{\left(\frac{\pi}{6}\right)}\right) \quad (6)$$

where: θ is the input angle of fuzzy logic controller, (rem) is an integer regulator [9].

Fuzzy inference

The goal of the fuzzy system is to obtain a crisp value on its output, which is the appropriate switching state. The inference mechanism is now described briefly. It has been shown above that there are 78 rules, and a general ith rule has the following form (1) thus by using the minimum operator for the fuzzy AND operation, the firing strength of the ith rule (i= 1, 2, 3, …, 78),α_i, can be obtained by considering:

$$\alpha_i = \min(\mu_{A_i}(\varepsilon_\psi), \mu_{B_i}(\varepsilon_{\Gamma e}), \mu_{Ci}(\theta)) \quad (7)$$

Where $\mu_{A_i}(\varepsilon_\psi), \mu_{B_i}(\varepsilon_{\Gamma e}), \mu_{Ci}(\theta)$ are the memberships of fuzzy sets Ai, Bi, Ci of the variables flux error, torque error and flux position respectively. The output from the ith rule is then obtained by using:

$$\mu_{Ni'}(n) = \min(\alpha_i, \mu_{Ni}(n)) \quad (8)$$

Where $\mu_{Ni}(n)$ is the membership function of fuzzy set Ni of the variable n. Hence the overall (combined) membership function of the output n is obtained by using the max operator as:

$$\mu_N(n) = \max_{i=1}^{78}(\mu_{Ni'}(n)) \quad (9)$$

In this case the outputs are crisp numbers, (switching state), and for defuzzification the maximum criteria used. The maximum criterion produces the point at which the possibility distribution of the control action reaches a maximum value.

Table 2. Fuzzy rule base

θ_1

EΓ \ EΦ	P	Z	N
PL1	V14	V17	V24
PL2	V15	V17	V25
PM1	V18	V17	V28
PM2	V13	V11	V23
PS1	V9	V11	V19
PS2	V12	V11	V22
ZE	V0	V0	V0
NS2	V52	V0	V42
NS1	V56	V41	V46
NM2	V53	V47	V43
NM1	V58	V42	V48
NL2	V55	V46	V45
NL1	V54	V43	V44

θ_2

EΓ \ EΦ	P	Z	N
PL1	V14	V17	V24
PL2	V20	V17	V30
PM1	V18	V17	V28
PM2	V13	V11	V23
PS1	V16	V11	V26
PS2	V12	V11	V22
ZE	V0	V0	V0
NS2	V52	V0	V42
NS1	V59	V41	V49
NM2	V53	V47	V43
NM1	V58	V42	V48
NL2	V60	V49	V50
NL1	V54	V43	V44

In this way the value of the fuzzy output, which has the maximum degree of belongingness, is used as the control output. The value of s according to μNi(n), is a fixed and absolute one and based on actual flux position should change to a suitable real voltage vector till can apply to the inverter [10, 11, 12].

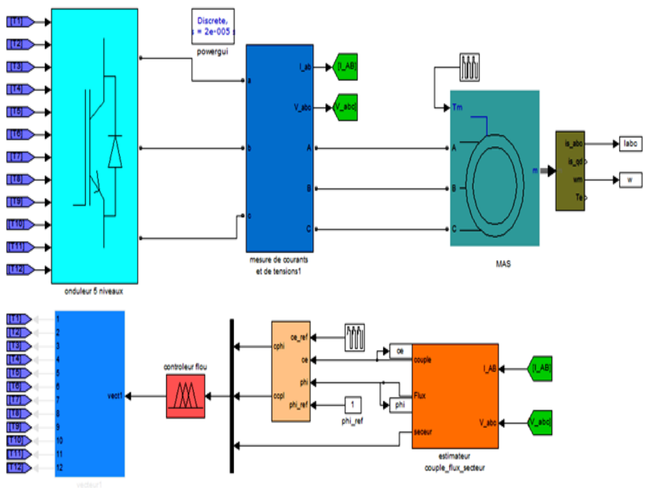

Fig. 5. The structure of the simulation model of proposed DTC based fuzzy logic control

Defuzzification

Usually after fuzzy inference, the output is shown with a fuzzy set which according to conventional methods should change to non-fuzzy set. In this method, the output is a fixed and absolute value which explains one of inverter's 61 vectors, therefore, these values can be directly applied to the inverter. Then, in this paper we don't need defuzzification [12, 13].

Simulation Results

To verify the technique proposed in this paper, digital simulations based on Matlab/Simulink have been implemented. The induction machine used in this system is listed in the Appendix (table 3). To compare with conventional DTC, both proposed Fuzzy DTC and conventional DTC for induction motor are simulated. A step change of reference torque was applied between differents times 0.1 s, 0.25 s, 0.5 s and 0.75 s. Motor started up by no-load then after 0.1 s, a different values of torque are applied respectively 35 Nm, 65 Nm, 50 Nm, -35 Nm and 50 Nm. Torque, flux amplitude, three phase currents and stator voltage according to time are showed in figure 7 and figure 8.

The figure 8 shows that switching states has become more regular and also torque ripple is less in FLDTC.

The simulation results in Fig.9 show that the current's stator ripples with FDTC is significantly reduced compared to DTC conventional Fig.7. The ripple of Torque with FDTC strategy is significantly reduced.

The ripple of stator flux trajectory with FDTC is significantly reduced Fig.13 compared to Fig.10.

It's seen that the statorique currents in FLDTC presented a good THD 12,5% Fig.12 compared with the results obtained with DTC conventional Fig.7.

The Fuzzy direct torque control (FDTC) of an induction machine supplied by five level inverters reduces advantage the harmonics of currents and the ripple of torque and flux.

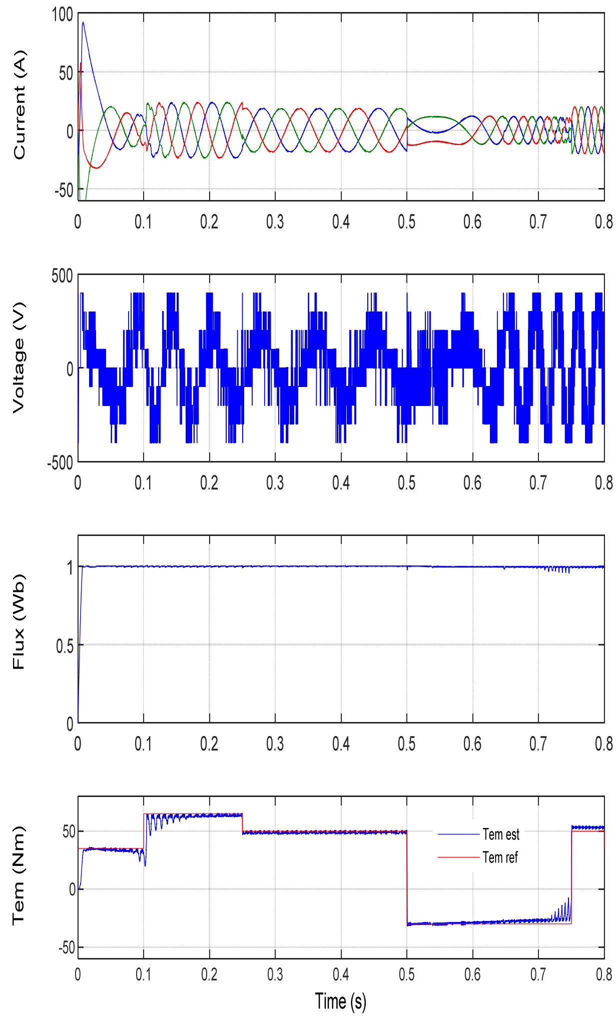

Fig. 6. Simulations results of classic DTC

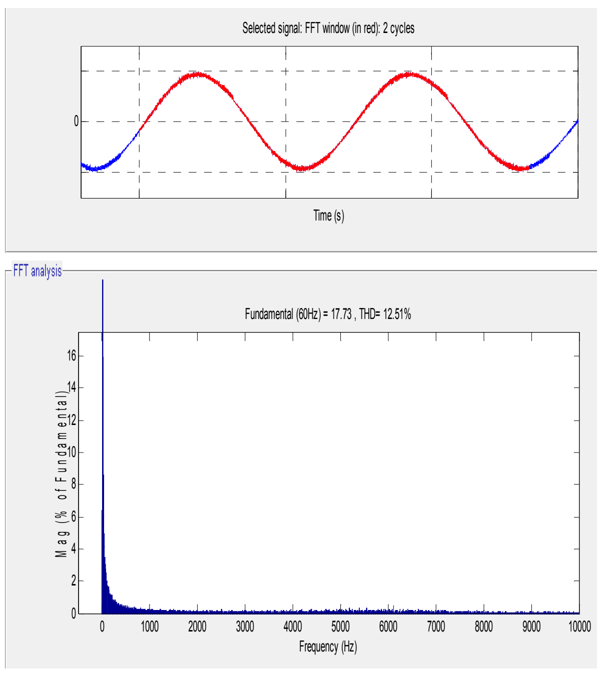

Fig. 7. Spectrum of current (DTC conventional)

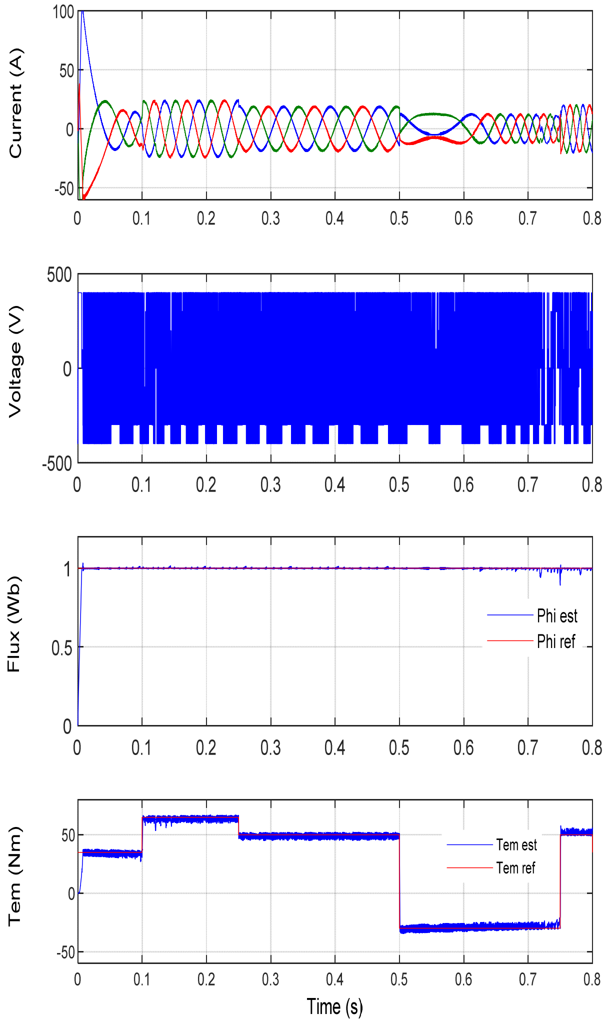

Fig. 8. Simulations results of DTC based Fuzzy logic controllers

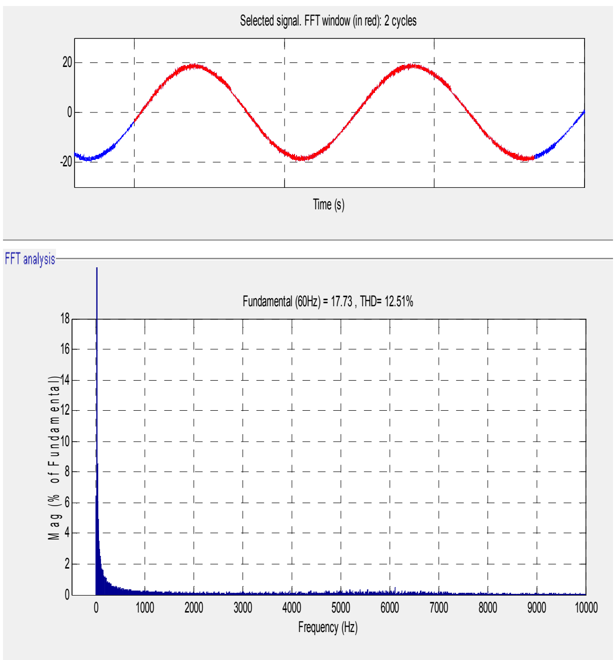

Fig. 9. Spectrum of current (DTC based fuzzy logic)

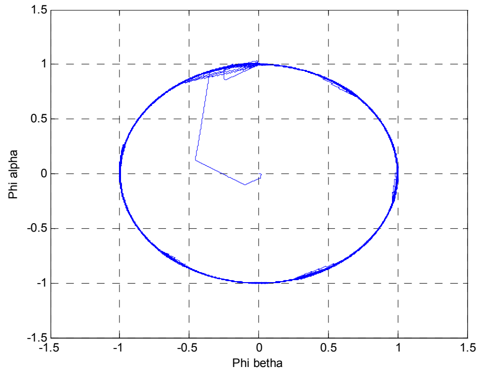

Fig. 10. Stator Flux Trajectory (classical DTC)

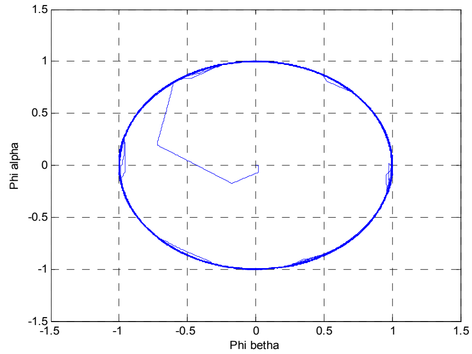

Fig. 10. Stator Flux Trajectory (DTC based fuzzy logic)

Conclusion

In this paper, a novel fuzzy logic direct torque control with five level inverter scheme technique is presented. In DTC method, two hysteresis controllers are used to regulate stator flux and motor electromagnetic torque. The main point in this method is choosing a switching voltage vector to put torque and stator flux in the predetermined bands. Since, hysteresis controller is on-off controller and has two amounts then its action in facing with torque's large and small errors will be the same. Therefore, a big torque ripple will be produced. So we suggest fuzzy logic method to get a suitable operation.

Fuzzy logic controller applied to switching table, therefore, choosing voltage vectors is done with more accuracy. This controller use the torque error, flux error and also the position of stator flux as inputs and the output of it is a suitable voltage vector which should apply to the motor. To reduce the number of rules and also increase controller's speed, we use particular mapping for the stator flux position. By applying this controller not also the quality of system keeps but also its speed increases.

The simulation results suggest that Fuzzy DTC of induction machine can achieve precise control of the stator flux and torque. Compared to conventional DTC, presented method is easily implemented, and the steady performances of ripples of both torque and flux are considerably improved

Appendix

Table 3. Induction Motor Parameters

Components	Rating values
Voltage V	400 V
Sample period T_e	50 μs
Rated power	7.5 kW
Rated voltage	460 V
Rated speed	1760 rpm
Rated frequency	60 Hz
Rotor resistance	0.451 Ω
Stator resistance	0.6837 Ω
Stator inductance	0.004152 H
Rotor inductance	0.004152 H
Magnetizing Inductance	0.1486 H
Number of poles	2
Rotor inertia	0.05 $Kg.m^2$
Friction Coefficient	0.008141 N.m.s/rd

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