Direct Torque Control of Three Phase Induction Motor Using Fuzzy Logic

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Abstract

Induction motor drives using field oriented control (FOC) for torque and flux control have been used in high performance industrial applications instead of dc motors for many years. In FOC, torque and flux of an induction motor can be controlled independently by decoupling the stator current into its orthogonal components. The FOC method has achieved a quick torque response. But in order to achieve expected performance from FOC, exact identification of parameters is required. A new torque and flux control scheme called the direct torque control (DTC) has been introduced for induction motors. In DTC the torque and flux of an induction motor can be controlled directly by applying a suitable voltage vector to the stator of an induction motor. However, convectional DTC result in large torque and flux ripples. In this paper, a controller based on fuzzy logic is designed to improve the performance of DTC and reduce the torque and flux ripple.

Keywords

Induction Motor Drives, FOC, DTC, Fuzzy Logic, Orthogonal Components, Torque and Flux ripples.

1. Introduction

The Induction Motor (IM), developed in the last century, is extensively used in AC converters. However, the IM control system is much more complex and expensive. The most common scalar control technique was the Constant Volts per Hertz (CVH) strategy, so called because it adjusts the stator voltage magnitude proportionally to the operating frequency to keep the IM stator flux approximately constant. This is a simple control technique, but it has a limited and non-accurate speed range, particularly at low speeds, and has a poor torque response.

The introduction of the vector control technique partially solves the IM control problem. In the 70's, F. Blaschke developed the IM Field Oriented Control (FOC). In this scheme, torque and flux of an induction motor are controlled independently by decoupling the stator current into its orthogonal components. The FOC method has achieved a quick torque response. In FOC, exact identification of parameters is required.

In the 80's, new IM torque control techniques was developed. Takahasi& Noguchi presented the Direct Torque Control (DTC). It is most convenient for low and medium power applications. In the DTC scheme, the inverter bridge switch connections are directly selected using aqualitative behavior rule set in order to control the stator flux and the torque. The DTC scheme produces a fast torque response while keeping the IM stator flux and torque decoupled. With this scheme the torque and flux presents a high ripple.

The main advantages of DTC are absence of coordinate transformation and current regulator; absence of separate voltage modulation block, common disadvantages of conventional DTC are high torque ripple and slow transient response to the step change in torque during start-up. For that reason DTC using fuzzy logic is used to reduce the ripple in the torque. In this paper all three methods for torque and flux control of induction motor i.e. FOC, DTC and DTC using fuzzy logic are explained.

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. The use of a switching table for voltage vector selection provides fast torque response, low inverter switching frequency and low harmonic losses without the complex field orientation by restricting the flux and torque errors within respective flux and torque hysteresis bands with the optimum selection being made. The DTC controller consists of two hysteresis comparator (flux and torque) to select the switching voltage vector in order to maintain flux and torque between upper and lower limit.The DTC scheme of induction motor drive is explained in detail.

2.1 The Basic Direct Torque Control (DTC) Scheme

The Basic direct torque control scheme is shown below. For implementing the control loop, the actual stator flux (amplitude and orientation) and electromagnetic torque are calculated by an estimator from the statorvoltages and currents. The stator flux is an integral of the stator EMF:

$$\overline{\Psi}_s = \int (\overline{v}_s - R_s \overline{i}_s)dt \qquad (01)$$

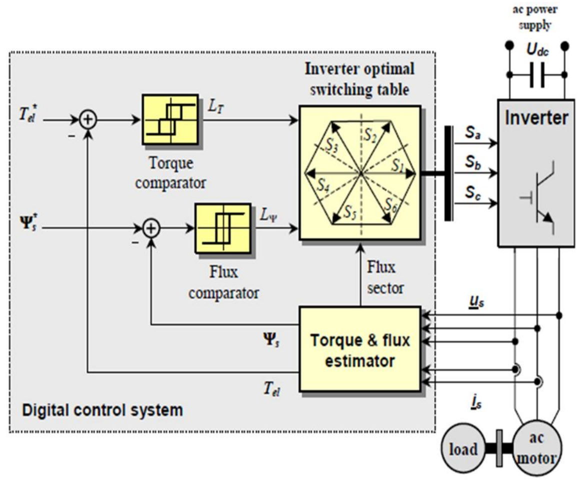

Figure 01: Basic direct torque control scheme

The developed torque is obtained by the product of stator current and flux as shown below

$$T_{el} = \frac{3}{2} p \, \overline{i}_{s.} j \overline{\Psi}_s \qquad (02)$$

In DTC scheme the error between the estimated torque $T_{el}$and the reference torque T_{el}*is the input of a three level hysteresiscomparator defining the error torque state $L_T$in modulus and sign, whereas the error between the estimated statorflux magnitude $\Psi_s$and the reference stator flux magnitude Ψ_s*is the input of a two level hysteresis comparator defining the error flux state L_Ψ. 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. The selection of the appropriate voltage vector is based on a switching table.

3. Direct Torque Control Of Induction Motor Using Fuzzy Logic

Direct torque control (DTC) of induction motor directly controls theelectromagnetic torque and stator flux linkage. It has many good features, such as simple implementation, insensitivity to motor parameters and fast torque response. However, big torque and flux linkage ripples is a main problem associated with the conventional DTC method because of the use of two-value hysteretic controllers for the stator flux linkage. Therefore, the fuzzy logic (FL) method based on the language rules, is employed to solve this nonlinear issue.

3.1 Principle Of Fuzzy Direct Control

The fuzzy controller is designed to have three fuzzy state Variables and one control variable for achieving direct torque control of the induction machine, there are three variable input fuzzy logic controllers, the stator flux error, electromagnetic torque error, and angle of flux stator respectively the output it is the voltage space vector shown in Figure 2.

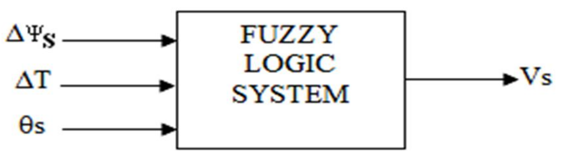

Figure 2: Fuzzy Logic Controller

3.2 Flux Linkage Error

The errors of flux linkage is related to reference value of stator's flux Ψ_{sref} and real value of stator's flux Ψ_s, they are subject to equation,

$$\Delta\Psi_s = \Psi_{sref} - \Psi_s \qquad (03)$$

Voltage vector shall cause different affection to stator's flux in different flux position shown in Figure 3, given that stator's flux θ locates in domain θ1, then V4 will make flux increase rapidly, V3 will make flux decrease rapidly, V5 and V6 will make flux increase slowly; and V1 and V2 will make flux decrease slowly, we use the three following linguistic terms: negative value, zero value and positive value denoted respectively N, Z and P. Three fuzzy sets are then defined by the delta and trapezoidal membership functions as given by Figure 4.

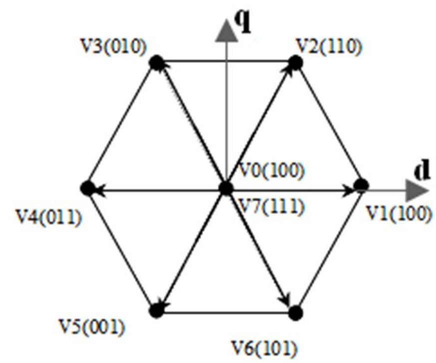

Figure 3: Partition of the d, q Plane into 6 Angular Sectors

Figure 4 is the membership function of flux linkage error i.e. the difference between actual stator flux and reference flux.

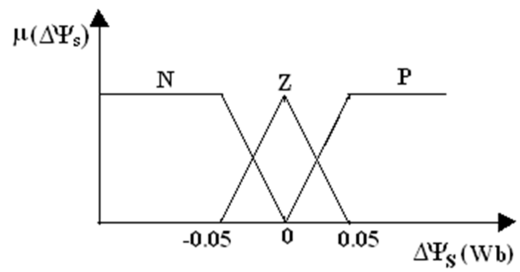

Figure 4: Membership Function of Flux linkage error

3.3 Electromagnetic Torque Error

The electromagnetic torque error $\Delta T_{em}$is related to desired torque value T_{ref} and actual torque value T_{em}subject to equation 04 as shown below,

$$\Delta T_{em} = T_{ref} - T_{em} (04)$$

In domain θ_1, V2 and V6 will make torque increase rapidly, V1 and V5 will make torque increase rapidly, V4 will make torque increase slowly and V3, V0 and V7 will make torque increaseslowly.

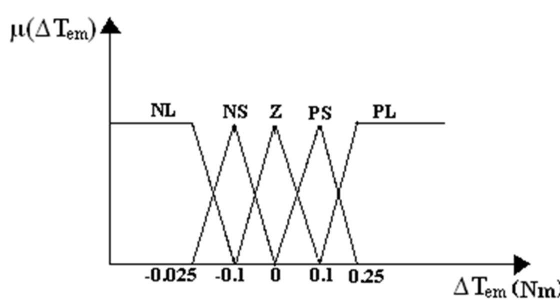

Figure 5: Membership Function for Electromagnetic Torque Error

Therefore, these rules may be described by language variable, i, e. Positive Large (LP), Positive Small (PS), Negative Small (NS), and Negative Large (NL), their membership function's distribution is shown as Figure 5.

3.4 Angle of Flux Linkage (Θ_S)

The angle of flux linkage θ_s is an angle between stator's flux Ψ_s and a reference axis is defined by equation:

$$\theta_s = \arctan \frac{\Psi_{ds}}{\Psi_{qs}} \qquad (05)$$

In (05), (Ψ_{ds}, Ψ_{qs}) are the component of flux linkageΨ_s in the plane (d, q) on the basis of voltage vector shown as Figure 03. The fuzzy variable θ_s may be described by 12 language values ($\theta1 \rightarrow \theta12$), its membership function's distribution is shown Figure 6.

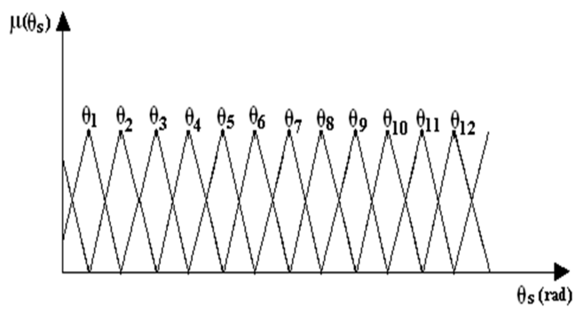

Figure 6: Membership Function for Flux Position

3.5 The Control Variable

The control variable is the inverter switching state (n). In a six step inverter, seven distinct switching states are possible. The switching states are crisp thus do not need a fuzzy membership distribution. Each control rule can be described using the state variables $\Delta\Psi_s$, $\Delta T_{em}$and θ_s and the control variable n (characterizing the inverter switching state). The i_{th} rule R_i can be written as:

R_i: If $\Delta\Psi_s$ is A_i, ΔT_{em} is B_i and θ_s is C_i then n is N_i

These rules are established using Mamdani's procedure based on min-max decision. The membership functions of variables A, B, C and N are given by μ_A, μ_B, μ_C and μ_N respectively. The weighting factor α_i for i_{th} rule can be written as:

$$\alpha_i = \min(\mu_{Ai}(\varepsilon_{\Psi s}), \mu_{Bi}(\varepsilon_{Tem}), \mu_{Ci}(\varepsilon_{\theta s})) \quad \text{- - - - - - - - - -} (06)$$

By fuzzy reasoning, Mamdani's minimum procedure gives:

$$\mu'_{NI}(n) = \min(\alpha_i, \mu_{NI}(n)) \quad \text{- - -} (07)$$

The membership function μ_N of the output n is point given by,

$$\mu_N(n) = \max_{i=1} i = 180 \; (\alpha_i, \mu'_{NI}(n)) \quad \text{- - - - - - - - - -} (08)$$

In this case, the outputs are crisp; the maximum criterion is used for defuzzification. By this method, the fuzzy of output which has the maximum possibility distribution, is used as control output.

$$\mu_{Nout}(n) = \max_{i=1} i = 7 \, (\mu_{Nout}(n)) \quad \text{- - - - - - - - - -} (09)$$

Depending on the membership function values of electromagnetic torque error ΔT_{em}, flux linkage error $\Delta\Psi_s$and stator flux position θ_s, a suitable voltage vector will be applied to the induction motor stator so that errors in electromagnetic torque and stator flux will be minimized as per the following rules tables.

TABLE 01: Fuzzy Logic Rules

	θ_1				
ΔT_{em} / $\Delta\Psi_s$	PL	PS	Z	NS	NL
P	V6	V1	V0	V2	V2
Z	V6	V6	V0	V0	V3
N	V5	V5	V0	V4	V3

ΔT_{em} / $\Delta\Psi_s$	θ_2				
	PL	PS	Z	NS	NL
P	V6	V6	V0	V1	V2
Z	V5	V5	V0	V0	V2
N	V5	V4	V0	V3	V3

ΔT_{em} / $\Delta\Psi_s$	θ_3				
	PL	PS	Z	NS	NL
P	V5	V6	V0	V1	V1
Z	V5	V5	V0	V0	V2
N	V4	V4	V0	V3	V2

ΔT_{em} / $\Delta\Psi_s$		θ_5			
	PL	PS	Z	NS	NL
P	V4	V5	V0	V6	V6
Z	V4	V4	V0	V0	V1
N	V3	V3	V0	V2	V1

ΔT_{em} / $\Delta\Psi_s$		θ_6			
	PL	PS	Z	NS	NL
P	V4	V4	V0	V5	V6
Z	V3	V3	V0	V6	V2
N	V3	V2	V0	V1	V1

ΔT_{em} / $\Delta\Psi_s$		Θ_8			
	PL	PS	Z	NS	NL
P	V3	V3	V0	V4	V5
Z	V2	V2	V0	V0	V5
N	V2	V1	V0	V6	V6

ΔT_{em} / $\Delta\Psi_s$	θ_4				
	PL	PS	Z	NS	NL
P	V5	V5	V0	V6	V1
Z	V4	V4	V0	V0	V1
N	V4	V3	V0	V0	V2

ΔT_{em} / $\Delta\Psi_s$		Θ_9			
	PL	PS	Z	NS	NL
P	V2	V3	V0	V4	V4
Z	V2	V2	V0	V0	V5
N	V1	V1	V0	V6	V5

ΔT_{em} / $\Delta\Psi_s$		Θ_7			
	PL	PS	Z	NS	NL
P	V3	V4	V0	V5	V5
Z	V3	V3	V0	V0	V6
N	V2	V2	V0	V1	V6

		Θ_{10}			
ΔT_{em} / $\Delta\Psi_s$	PL	PS	Z	NS	NL
P	V2	V2	V0	V3	V4
Z	V1	V1	V0	V0	V4
N	V1	V6	V0	V5	V5

		Θ_{11}			
ΔT_{em} / $\Delta\Psi_s$	PL	PS	Z	NS	NL
P	V1	V2	V0	V3	V3
Z	V1	V1	V0	V0	V4
N	V6	V6	V0	V5	V4

		Θ_{12}			
ΔT_{em} / $\Delta\Psi_s$	PL	PS	Z	NS	NL
P	V1	V1	V0	V2	V3
Z	V6	V6	V0	V0	V3
N	V6	V5	V0	V4	V4

4 RESULTS

The results were obtained after performing the test on a 2HP, 400V, 50Hz, Three Phase Induction Motor. The actual torque was being estimated by the controller from sensed values of voltages and currents. The desired torque was given as a reference input to the controller and by comparing the actual and desired value of the torque; the controller selects a particular voltage vector to apply at the stator of the motor so that the desired torque is achieved.

The torque set point was varied as below:

Initially 300N-cm this is achieved by the motor in about 15 seconds. Following this a torque set point is set to 400N-cm at 25 seconds achieved at around 29 seconds. Followed by a new set point of 1000N-cm at 70 seconds and followed by a last set point at 600N-cm. From the graph it is seen clearly that these are achieved in a few seconds of the set point time.

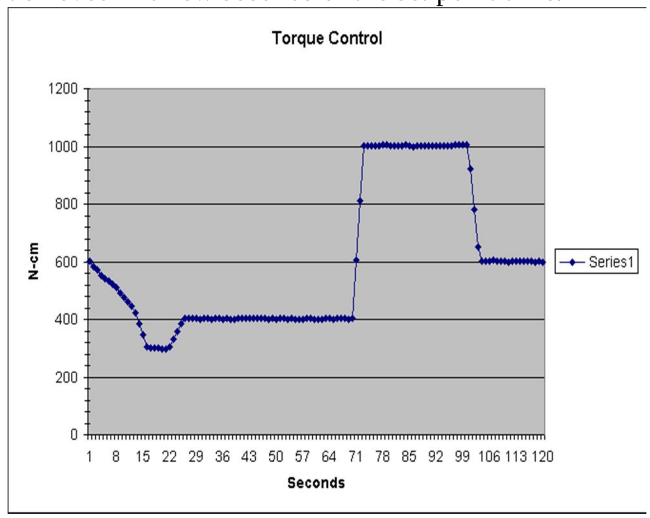

Figure 7: Torque Control

5 CONCLUSION

In this paper, a kind of fuzzy torque control system for induction motor based on fuzzy control technique is presented. Compared to conventional DTC, fuzzy logic control method is easily implemented, and the steady performances of ripples of both torque and flux are considerably improved. The main improvements are:

- Reduction of torque and current ripples.
- No flux droppings caused by sector changes circular trajectory.
- Fast torque response.
- Zero-steady-state torque and flux

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