Speed Control in Fuzzy Direct Torque Control Induction Motor Drives

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Abstract: - A modified fuzzy direct torque control drive is developed in this paper to cope with conventional DTC drive mal-operation during starting and speed reference command changes. Non-zero switching vector selection at starting causes huge increase in torque and current values. So, there is over current problem in conventional fuzzy DTC drive with speed regulator at starting or speed reference changes due to non-zero vector selection. Hence stator current is chosen as the control parameter and its membership functions defined to limit stator current according to stator current reference value. A mamdani type fuzzy direct torque controller is first developed and then rules are modified using stator current membership functions. results show the necessity and effectiveness of this method.

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Key-Words: - Drive-Fuzzy control- Induction motor- DTC- Speed control

1 Introduction

It is well known that the basic concept of direct torque control of induction motor drive is to control both stator flux and electromagnetic torque of machine simultaneously. Torque and flux of a DTC- based drive are controlled in the manner of closed-loop system without using current loops in comparison with the conventional vector-controlled drives. In principle, the DTC-based drives require the knowledge of stator resistance only, and thereby decreasing the associated sensitivity to parameter variations [1,2]. Moreover, the DTC-based drives do not require fulfilling the coordinate transformation between stationary frame and synchronous frame, in comparison with the conventional vector-controlled drives. Since a DTC-based drive selects the inverter switching states using switching table, neither current controllers nor pulse-width modulation (PWM) modulator is required, thereby providing fast torque response [3]. However, this switching-table-based DTC approach is accompanied by some disadvantages; more details are described as follows. If the switching frequency of the inverter is not high the torque and flux pulsation can be high and moreover there is sluggish response during start-up or during a change of reference flux or reference torque [4]. Hence to improve the performance of the DTC drive during start-up or during changes in the reference flux and torque, a fuzzy logic based switching vector process is developed in this paper [5,6,7,8]. In the DTC drives the controller uses feed back control of electromagnetic torque and stator flux linkage. The electromagnetic torque and stator flux linkages are estimated in stator reference frames using the measured stator voltages and currents [9,10]. The machine model is dependent on stator resistance only [11]. The direct torque controlled induction motor drives have been studied in different forms based on how the currents and voltages are measured or estimated [12,13,14]. The stator currents may be obtained using only the dc link current sensor and the motor line voltages can be reconstructed inexpensively utilizing the gate signals [15]. There is problem during start up and at low speed values, like the difficulty in start up current control [16]. is due to the fact that although the switching voltage vectors are determined by the stator flux linkage position and the errors in the

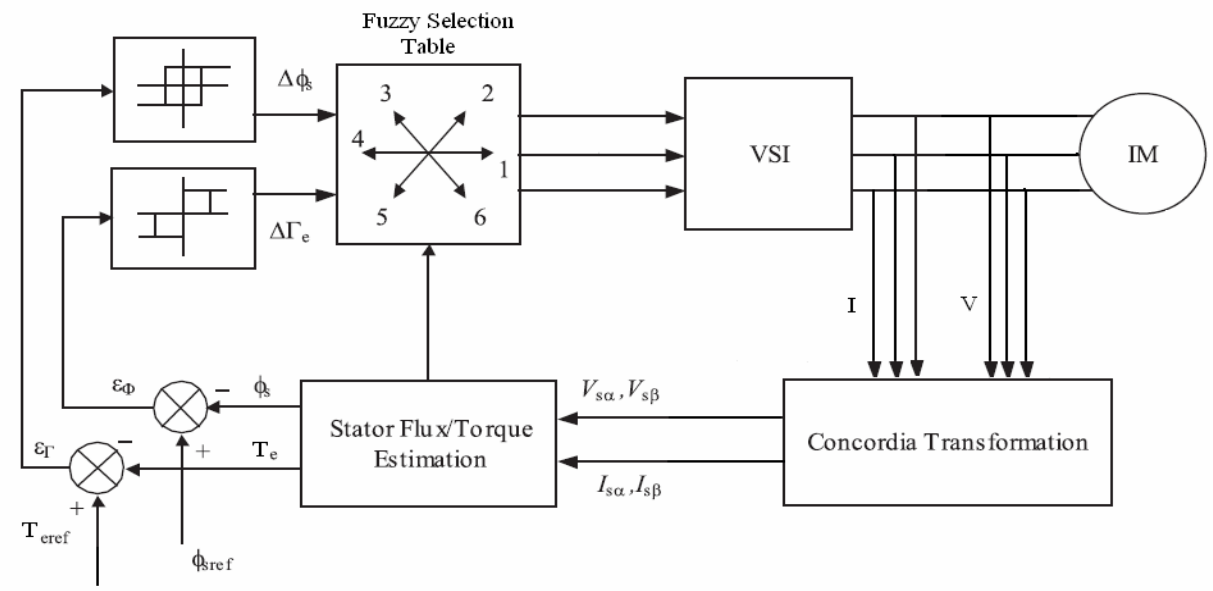

Fig. 1. Block diagram of the fuzzy direct torque control of induction motor drives

electromagnetic torque and modulus of the stator flux linkage space vector, large and small errors are not distinguished. It is possible to choose switching vectors which are in accordance with the range of errors. There are several possible solutions, e.g. it is possible to use a fuzzy logic based system [16].]. In addition to fuzzy strategy, it is also possible to have improvements by using a non-artificial-based scheme, where the stator flux linkage and electromagnetic torque errors are not quantized to two and three levels and where more than six stator flux linkage sectors are used [17]. It is also possible to implement DTC drive schemes in which the required switching voltage vectors are obtained by using predictive algorithms [18]. Duty ratio control is also can be used which estimates the time duration of switching voltage vectors which are adjacent to the reference stator voltage vectors [20]. Most drives are used for speed control of induction motors. In this case there is over current problem in starting and during speed reference command changes. This is due to the fact that the main concept of DTC drives is to control stator flux and electromagnetic torque. Hence, mostly a PI regulator is used to outputs torque reference command dependent on speed inputs value. So there is no control on torque because the speed regulator outputs torque reference value and hence there is an over current due to the over torque problem at starting. A fuzzy direct torque control is developed in this paper and it is modified by current control rules which control stator current.

2 Direct Torque Control

2.1 Conventional DTC Scheme

The schematic of a classical torque controlled (DTC) induction motor drive is shown in Fig. 1, where the induction motor is supplied by a voltage source inverter. The stator flux and electromagnetic torque errors are used together with the position of stator flux linkage space vector directly to select the optimum switching vectors (switching states) [21]. The stator q and d axis flux linkages Φ_{qs}, Φ_{ds} can be obtained through the integration of the difference between the phase voltage and the voltage drop in the stator resistance as,

$$\Phi_{qs} = \int (V_{qs} - R_s i_{qs})\,dt \tag{1}$$

$$\Phi_{ds} = \int (V_{ds} - R_s i_{ds})\,dt \tag{2}$$

and flux linkage phasor is,

$$\Phi_s = \sqrt{(\lambda_{qs}^2 + \lambda_{ds}^2)} \tag{3}$$

stator flux linkage phasor position is,

$$\theta_s = \tan^{-1}\left(\frac{\Phi_{qs}}{\Phi_{ds}}\right) \tag{4}$$

and electromagnetic torque is given by,

$$T_e = \frac{3}{2}\frac{P}{2}(i_{qs}\Phi_{ds} - i_{ds}\Phi_{qs}) \tag{5}$$

In this scheme the stator flux is the controlled flux, i.e. this is a stator-flux-based DTC induction motor drive. Direct torque control involves the separate control of the stator flux and electromagnetic torque through the selection of optimum inverter switching modes. The reference value of the stator flux linkage space vector modulus, Φ_{sref}, is

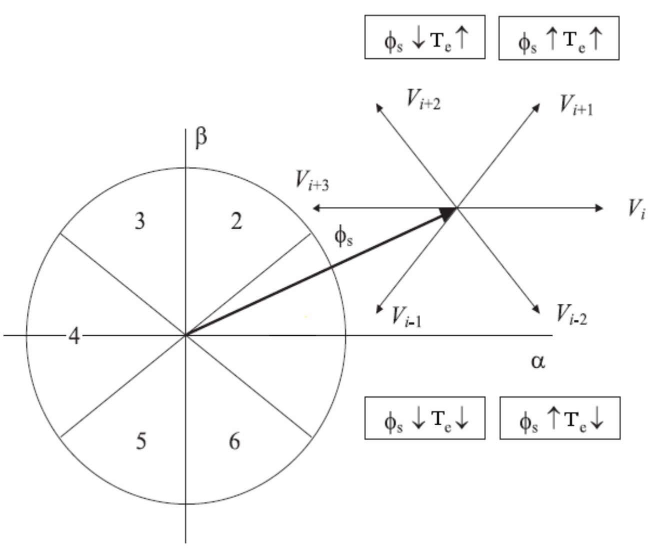

Fig. 2. Change of flux linkage space vectors due to switching vectors

is compared with the actual modulus of the stator flux linkage space vector, Φ_s, and the resulting error is fed into the two-level stator flux hysteresis comparator [15].

Similarly, the reference value of the electromagnetic torque (t_{eref}) is compared with its actual value, (t_e), and the electromagnetic torque error signal is fed into the three-level torque hysteresis comparator. The outputs of the flux and torque comparators ($d\Phi, dt_e$) are used in the inverter optimal switching table (look-up table) which also uses the information on the position of the stator flux linkage space vector. The flux hysteresis band mainly affects the stator current distortion in terms of low-order harmonics, and the torque hysteresis band affects the switching frequency and thus the switching losses [12]. In the conventional implementation of the DTC drive, there are some problems, as follows. The flux and torque pulsation can be high (if the switching frequency of the inverter is not high). There is sluggish response during start-up or during a change of reference flux or reference torque [20,21]. error and flux error and also the flux position. There is no method of distinguishing between very large and relatively small errors [19]. Thus the switching vectors chosen for large errors are the same as the switching vectors chosen for fine control during normal operation. If the switching states are chosen in accordance with the range of the errors, the response at start up and during a change in reference torque or reference flux can be improved [7,11].

2.2 Fuzzy DTC Scheme

TABLE I
OVERLAPS BETWEEN SECTORS

S1	S2	S3	S4	S5	S6
315 - 75	345-45	15-75	45-105	75-135	105-165
S7	S8	S9	S10	S11	S12
135-195	165-225	195-255	225-285	255-315	285-345

TABLE II
FUZZY VECTOR SELECTION IN SECTOR 1

e_Φ / e_t	P	ZE	N
PL	1	2	2
PS	1	2	3
ZE	0	0	0
NS	6	0	4
NL	6	5	5

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 is 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 response), and outputs the zero and non-zero voltage switching states (n) and uses three quantities as inputs which are (e_Φ), the torque error (e_T) and the position of the stator flux space vector(θ_s). 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 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. Each of rules (in the rule base) can be described by the input variables (e_Φ, e_t, θ_s) and the control variable, which is the switching state (n). The general ith rule is as follows:

Rule i: If e_Φ is A_i and e_T is B_i and θ_s is C_i then n is N_i

The actual rules can be simply obtained by using physical considerations or simulations of DTC drive system. These rules are obtained by physical considerations using vector diagrams

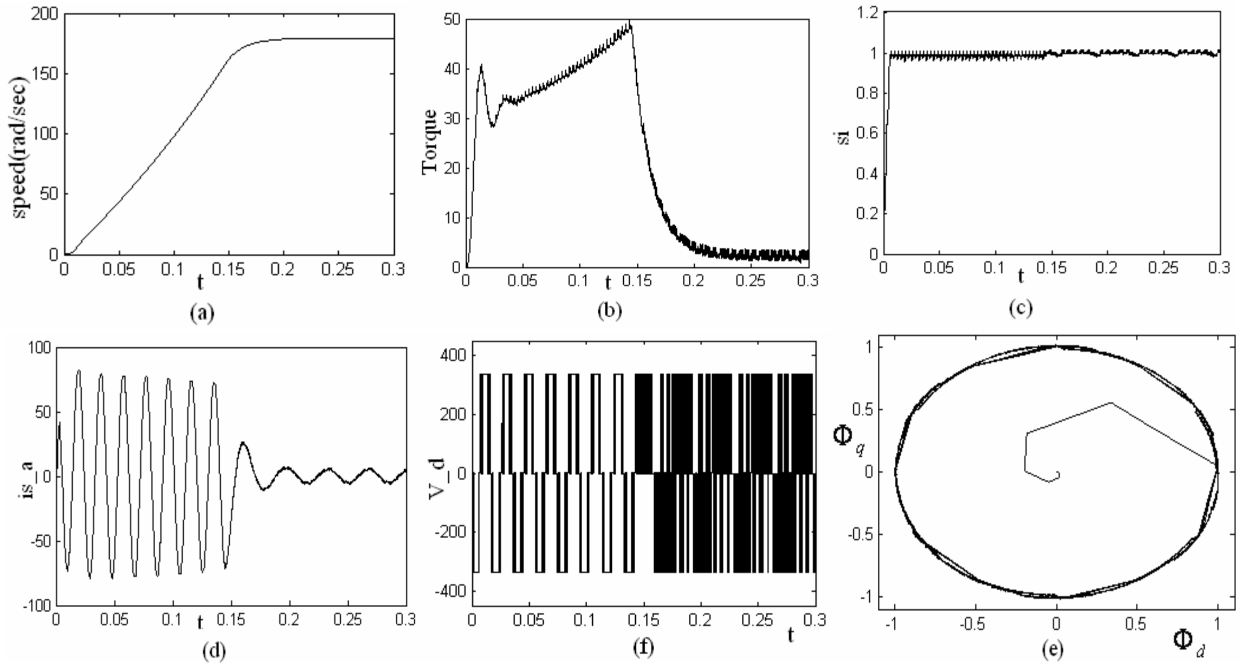

Fig. 3. Direct torque controlled induction machine parameters, (a) speed, (b) torque, (c) flux linkage (d) stator phase current, (e) d-axis voltage, (f) q_axis verse d_axis flux linkage

which show the stator flux linkage space vector at given instant of time and also the different switching vectors.

It is assumed that the stator flux linkage space vector can be located in any of twelve sectors, each spanning a 60 wide region. But there is an overlap between these regions. The various sectors are shown in table 1. According to the Fig.2 the inverter switching states are selected depends on the errors of the torque and the flux, which are indicated by, ΔT_e and $\Delta \lambda_s$, respectively. Noting that,

$$\begin{aligned} \Delta T_e &= T_e^* - T_e \\ \Delta \lambda_s &= \lambda^*{}_s - \lambda_s \end{aligned} \qquad (6)$$

Fig.2 can be used to derive physically the rules for the selection of the appropriate switching voltage vector, when the stator flux linkage space vector is positioned in the 12th sector. Table 2 gives the various rules for sector 1. For every sector there are 15 rules, since it is assumed that for the flux error there are three fuzzy sets and for the torque error there are five fuzzy sets. In particular, the stator flux error (e_Φ) can be positive (P), zero (ZE) and negative (N), corresponding to three overlapping fuzzy sets. The electro- magnetic torque error can be positive large (PL), positive small (PS), zero (ZE), negative small (NS) and negative large (NL), this is due to the fact that it was an intention to make the torque variations smaller, and the thus the universe of the torque is divided into five overlapping fuzzy sets. The various membership functions are shown in Fig.3. Since there are 12 sectors and the total number of rules is 180.Each of the rules can be described by the input variables and the control variable, which is the switching, state (n), for example:

Rule 1: If e_Φ is P and e_T is PL and θ_s is S1 then n is 1
Rule 2: If e_Φ is P and e_T is PS and θ_s is S2 then n is 1
Rule 3: If e_Φ is P and e_T is ZE and θ_s is S3 then n is 0

The goal of the fuzzy system is to obtain a crisp value on its output, which is the appropriate switching state. A general ith rule has the following form:

Rule i: If e_Φ is A_i and e_T is B_i and θ_s is C_i then n is N_i

Thus by using the minimum operation for the fuzzy AND operation, the firing strength of the ith rule, α_i, can be obtained by considering:

$$\alpha_i = \min[\mu_{Ai}(e_\Phi), \mu_{Bi}(e_T), \mu_{ci}(\theta_s)] \qquad (7)$$

Where $\mu_{Ai}(e_\Phi), \mu_{Bi}(e_T), \mu_{ci}(\theta_s)$, are the membership functions of fuzzy sets A_i, B_i and C_i of the variables flux error, torque error and flux position respectively. The output form the ith rule is then obtained by using,

$$\mu_{Ni}(n) = \min[\alpha_i, \mu_{Ni}(n)] \tag{8}$$

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

$$\mu_N(n) = \max[\mu_{Ni}(n)] \tag{9}$$

In this case the outputs are crisp numbers, (switching states), and for defuzzification the maximum criteria used. Fig. 3 shows direct torque controlled three phase induction motor parameters with 180 (rad/sec) reference speed command in no load condition. Comparing to conventional DTC drives fuzzy DTC has less ripple in torque and speed and also smoother starting. There is high starting torque which causes over current during start-up.

3 Speed Control

In the DTC induction motor drive there are over currents in starting and also in speed command changes. In starting mode, motor speed value is zero and the reference value is a nonzero positive value which causes a large error in the PI speed regulator. According to this error the regulator outputs a large positive value of torque command. Hence, only nonzero switching vector are selected to decrease the error of speed reference value and its real one. Therefore, there is an over current at starting due to the nonzero vector selection since there is not any zero switching vector to decrease the current which is shown in Fig.6. There is similar problem in speed reference command changes. As it can be seen from Fig. 3, there is a large increase in torque at the starting moments, because there is no control on the torque in speed control mode. In fact the torque reference command is not the real value of induction machine torque values but the outputs of the speed regulator which depends on the motor velocity. The torque growth continues till the error between the machine real speed value and the reference value becomes small enough. In this moment the regulator output and the real torque value are almost equal, which fire rules with zero or small positive torque membership function. So a zero switching vector is selected which causes a decrease in machine torque. Since time constant of mechanical part which is defined in speed deferential equation is more than that of the electrical part, the machine velocity does not change and continues increasing. So error between speed reference command value and machine velocity is also decreased. A torque increase command is now received by the controller, and torque increase is causes same procedure likes before but this time more zero switching vectors are selected and decrease torque more than before. Hence during this period speed is increases slower than before and this is exactly what happens at the knee of the speed curve. Torque decrease continues till it becomes equal to the load torque value. In this time machine speed reaches its command value and no more torque decrease is desirable. Same inferring explains current behavior in starting and speed reference command changes. Torque growth at starting, causes incremental behavior of current at starting. Torque decreases when speed regulator output becomes equal to real torque value. Since machine internal voltage is a large value, torque decrease command, drops current value. As it discussed before machine speed does not decrease due to its large time constant value. So at the next torque increase value there is slower decrease in torque value and again decrease command is received and larger current drop is occurred at this time and current value drops to its nominal value. Results can be seen in Fig.3.

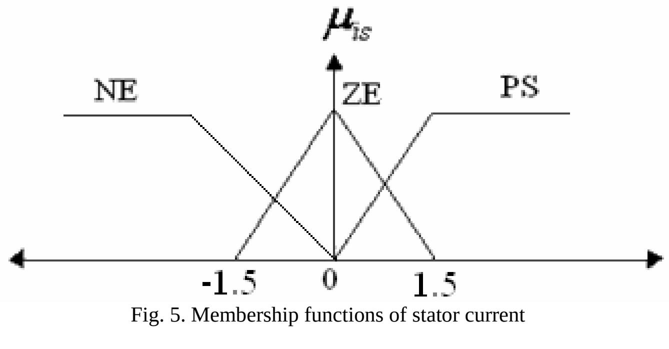

Fig. 5. Membership functions of stator current

4 Current Control

As it is discussed in the previous section over current problem occurs in starting and in speed reference torque command changes. Here a modified fuzzy switching table is developed to overcome this problem. Machine stator current i_s is defined as the fourth input and its membership functions are shown in Fig.7. Stator current is calculated by,

$$i_s = \sqrt{(i_{sq}{}^2 + i_{sd}{}^2)} \qquad (10)$$

Machine stator current is compared with its reference value which is acceptable current value and error is the forth input of the fuzzy controller. Stator current is described by three membership functions. When stator current exceeds its reference value rules belong to PS or NE membership functions fire and zero switching vectors are selected by the controller. So new rules are defines as below:

If e_Φ is A_i and e_T is B_i and θ_s is C_i and e_{i_s} is zero then n is N_i

If e_Φ is A_i and e_T is B_i and θ_s is C_i and e_{i_s} is PS or NE then n is zero

In this method just zero switching vectors are applied when an over current occurs at the stator current. If one of the phase current is used as the input of the controller there will be over current in other phases during starting or during speed reference command changes. Zero switching vector when applied, decreases current value and limit it to its reference value. Therefore, over current problem which is caused by non-zero switching vectors is controlled since zero switching vectors are selected based on stator current value.

Results are being compared in Fig.5. It should be noted that speed rising time increased because of current limitation. Machine is run at 180 (rad/sec) and then the speed reference command increased to 250 and later it is decreased to 200 (rad/sec). As it can be seen there are over currents in at each speed command variations.

5 Conclusion

A fuzzy direct torque control drive is developed for induction machines. There is Start up problem in Conventional fuzzy direct torque strategy with speed control loop. A current input is added and its membership functions defined so it is possible to select zero switching vectors in starting and speed reference command changes. By this method there is not any over current problem in DTC drive. Starting torque is limited by this method to a acceptable value which is defined dependent on machine maximium torque limit. Results show effectiveness of this in DTC drives.

APPENDIX

INDUCTION MOTOR PARAMETERS

Rated value

Power	4	KW
Voltage	480	V
Speed	3000	rpm

Parameter

Stator resistance	1.115	Ω
Rotor resistance	1.083	Ω
Stator self inductance	.005974	H
Rotor self inductance	.005974	H
Mutual inductance	.2037	H
Rotor inertia	.0333	$Kg.m$^2
Friction factor	.00051	$N.m.s$
Poles		

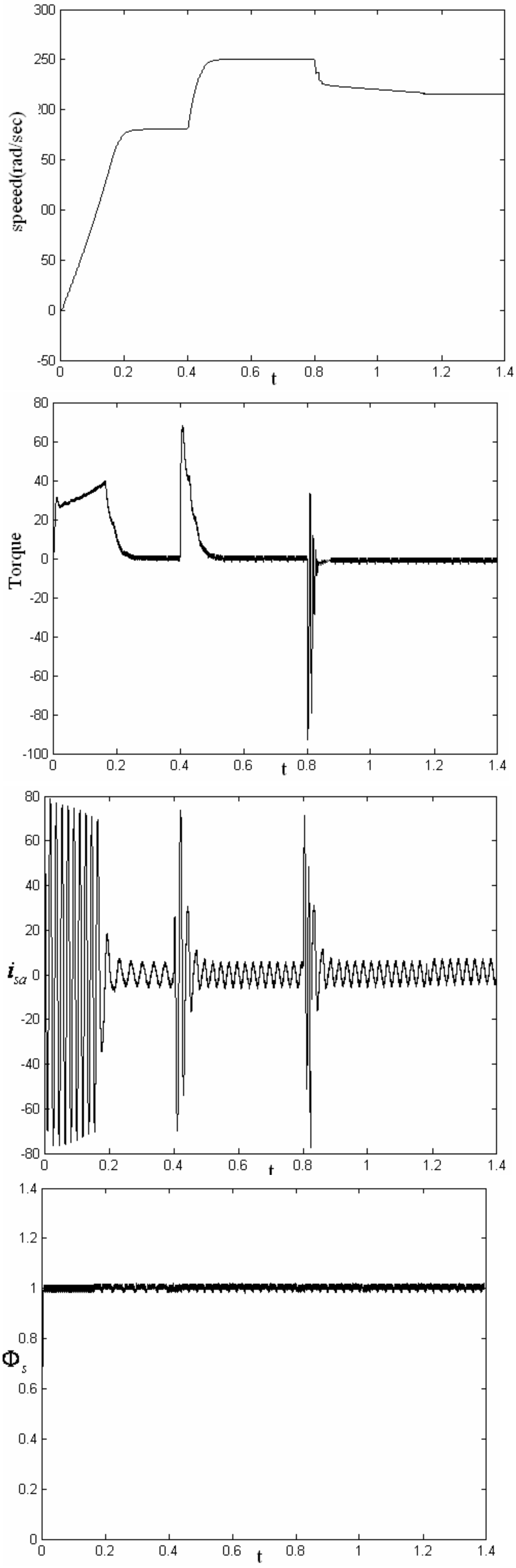

Fig. 5. Conventional Fuzzy direct torque controlled induction machine parameter

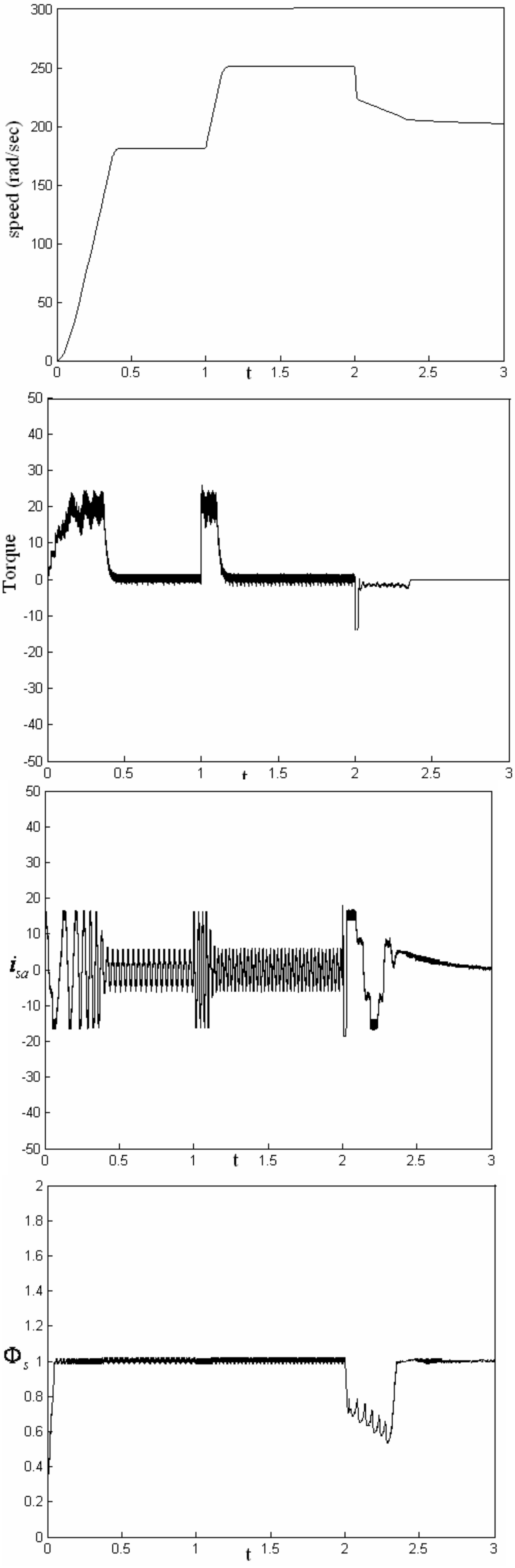

Fig. 5. Modified Fuzzy direct torque controlled induction machine parameter

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