

Iranian Journal of Electrical and Electronic Engineering

Journal Homepage: ijeee.iust.ac.ir

Seven-Level Direct Torque Control of Induction Motor Based on Artificial Neural Networks with Regulation Speed Using Fuzzy PI Controller

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Abstract: In this paper, the author proposes a sensorless direct torque control (DTC) of an induction motor (IM) fed by seven-level NPC inverter using artificial neural networks (ANN) and fuzzy logic controller. Fuzzy PI controller is used for controlling the rotor speed and ANN applied in switching select stator voltage. The control method proposed in this paper can reduce the torque, stator flux and total harmonic distortion (THD) value of stator current, and especially improve system good dynamic performance and robustness in high and low speeds.

Keywords: DTC, IM, Seven-Level NPC Inverter, ANN, Fuzzy PI, THD.

1 Introduction

RADITIONALLY, variable speed electric machines were based on DC motors, since the magnetic flux and torque are easily controlled by the stator and rotor current, respectively. For the last two decades, DC motors was replaced by AC motors [1]. The induction machine (IM) known by its robustness, cost, reliability and effectiveness is the subject of several researches [2]. High performance electric drives require decoupled torque and stator flux command. This command is commonly provided through Field Oriented Control (FOC), which is based on decoupling of the torque-producing current component and the stator flux-producing component. FOC drive scheme requires current regulators and coordinate transformations. Current-regulated pulse-width-modulation (PWM) inverter and inner current loops degrade the dynamic performance in the operating regimes wherein the voltage margin is insufficient for the current command, particularly in the field weakening region [3].

The problem of decoupling the stator current in a

Iranian Journal of Electrical & Electronic Engineering, 2018. Paper first received 13 November 2017 and accepted 16 February 2018.

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dynamic fashion is avoided by direct torque control. DTC was introduced in 1985 by Takahashi and Depenbrock especially for the asynchronous and synchronous machines [4]. In DTC the torque and stator flux are directly controlled using the selection of the optimum voltage vector. The switching logic command facilitates the generation of the stator voltage space vector, with a suitable choice of the switching pattern of the inverter, on the basis of the knowledge of the sector and the amplitude of the stator flux and the torque. The DTC scheme is characterized by its simple implementation and its fast dynamic response [5].

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Traditional DTC suffer from disadvantages like high torque and flux ripples under steady state due to presence hysteresis bands, poor performance at starting and low speeds and stator current distortions. These drawbacks of DTC control has been studied in the literature [6, 7]. In past decades researches came out with different type of solutions to improve the performance of the conventional DTC [8]. In order to reduce torque ripples, THD value of stator current artificial intelligence (AI) techniques like neural networks, Fuzzy logic are used to improve the performance of DTC control scheme.

In this paper, two different DTC schemes will be compared with each other. These two schemes are traditional DTC command with seven-level inverter and seven-level DTC-ANN with fuzzy speed regulator. The proposed command scheme is verified by both the simulation results. Simulation results show the clearly

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depicts reduction of stator flux, torque ripples, and THD value of stator current in proposed DTC scheme.

2 Seven-Level Inverter

Multilevel inverter structures have been developed to overcome shortcomings in solid-state switching device ratings so they can be applied to higher voltage systems [9]. In 1980, early interest in multilevel power conversion technology was triggered by the work of Nabae, who introduced the neutral-point-clamped (NPC) inverter topology [10]. The main concept of this inverter is to use diodes to limit the power devices voltage stress [11]. The topology that has been used in this paper is a three-phase full bridge seven levels diode clamped inverter and this topology is shown in Fig. 1 [12]. The voltage across the phase winding of the IM can attain one of the seven levels 6, 5, 4, 3, 2, 1 or 0 depending upon the switching states of the inverters.

The necessary conditions for the switching states for the seven-level inverter are that the DC-link capacitors should not be shorted, and the output current should be continuous [13].

The representation of the space voltage vectors of a seven-level NPC inverter for all switching states is given by Fig. 2 [14].



Fig. 1 Seven-level diode clamped voltage source inverter.



Fig. 2 Space vector diagram of seven-level NPC inverter.

3 Conventional DTC

The basic principle in traditional DTC for induction motors is to directly select stator voltage vectors by means of a hysteresis stator flux and electromagnetic torque command. As it is shown in Fig. 3 [15].

The DTC command is based on applying a switching series, which shall directly eliminate errors, which shall occur in electromagnetic torque, through the reference given as value and the calculated stator flux, to the power switching elements in the inverter. Other vector command methods are mostly based on rotor flux while DTC technique is based on stator flux [16].

The stator flux is estimated by equations [17,18]:

$$\Phi_s = \int_0^t (V_s - R_s \cdot i_s) dt \tag{1}$$

with

...

$$\begin{cases} \Phi_{s\alpha} = \int_0^t (v_{s\alpha} - R_s i_{s\alpha}) dt \\ \Phi_{s\beta} = \int_0^t (v_{s\beta} - R_s i_{s\beta}) dt \end{cases}$$
(2)

The stator flux amplitude is given by

$$\Phi_s = \sqrt{\Phi_{s\alpha}^2 + \Phi_{s\beta}^2} \tag{3}$$

The stator flux angle is calculated by

$$\theta_s = \arctan(\frac{\Phi_{s\beta}}{\Phi_{s\alpha}}) \tag{4}$$

Electromagnetic torque equation is given by

$$T_{e} = \frac{3}{2} p \Big[\Phi_{s\alpha} i_{s\beta} - \Phi_{s\beta} i_{s\alpha} \Big]$$
⁽⁵⁾

The selection of the appropriate voltage vector is based on the switching table given in Table 1 (See Appendix). The input quantities are the stator flux position sector (N) and the digitized output variables Ccpl and Cflx. Thus, the selection table generates pulses Sa, Sb, Sc to control the power switches in the inverter.

In the seven-level DTC control, it employs a pair of hysteresis comparators, one utilizes a three-level hysteresis comparator for controlling the stator flux (Fig. 4) and the other one uses a seven-level hysteresis comparator for controlling the electromagnetic torque (Fig. 5).



Fig. 4 Stator flux hysteresis comparator.

Fig. 5 Torque hysteresis comparator.

4 Seven-Level DTC-ANN with Fuzzy Controller

In order to improve the seven-level DTC performances a complimentary use of neural networks and fuzzy logic regulator is proposed. ANN is part of the family of statistical learning methods inspired by biological nervous system and are used to estimate and approximate functions that depends only on a large number of inputs [19].

A group of artificial neurons, which work in parallel, their inputs and outputs, have the same destination from a layer. Each neural networks must contain at least one layer of neurons but can join as many as someone projects. The layer gathering the neurons which give the output of the neural networks is called output layer. Layers which contain the neurons interposed between the global inputs of the neural network and the inputs of the neurons from the output layer are called hidden layers. Usually, there are used feed-forward NN which contains a hidden layer and an output layer [20]. In the other hand, fuzzy logic is recently getting increasing emphasis in drive control applications. Recent years, fuzzy logic control has found many applications in the past two decades. This is so largely increasing because fuzzy logic command has the capability to command nonlinear uncertain systems even in the case where no mathematical model is available for the command system [21].

The principle of neural networks direct torque command with fuzzy speed regulator is similar to traditional DTC. The difference is using a neural networks controller to replace the switching table and using fuzzy logic to replace the classical PI regulator of speed. As shown in Fig. 6.

4.1 Fuzzy Logic Based Speed Controller

The block diagram for fuzzy based speed regulator (classical PI) is shown in Fig. 7 [22]. The fuzzy regulator design is based on intuition and simulation [23]. The fuzzy logic rules are written by fascinating the performance of the PI regulator. The fuzzy logic rules for the proposed system are given in Table 2.

The Table 3 (See Appendix) shows the parameters of fuzzy regulator.

The block diagram of the fuzzy logic controller of the speed regulation is given by Fig. 8.



Fig. 6 DTC-ANN controls with fuzzy speed controller.



Fig. 7 Fuzzy logic command of speed regulation.

Fig. 8 Bloc diagram of the fuzzy controller.

Table 2 Fuzzy logic rules.

e	NR	NM	NS	FZ	PC	РM	PR
Δe	ND		145	ĽZ	15	1 111	ID
NB	NB	NB	NB	NB	NM	NS	ΕZ
NM	NB	NB	NB	NM	NS	ΕZ	PS
NS	NB	NB	NM	NS	ΕZ	PS	PM
EZ	NB	NM	NS	ΕZ	PS	PM	PB
PS	NM	NS	ΕZ	PS	PM	PB	PB
PM	NS	ΕZ	PS	PM	PB	PB	PB
PB	ΕZ	PS	PM	PB	PB	PB	PB

Here "e" is speed error and (Δe) is change in error. The membership function definition for the input variables "error in speed" is shown in Fig. 9, "change in error" is shown in Fig. 10.

We use the next designations for membership functions:

NB:	Negative Big	NM:	Negative Middle
NS :	Negative Small	PS :	Positive Small
PB :	Positive Big	EZ:	Equal Zero
PM:	Positive Middle		

4.2 Neural Based Switching Table

The ANN has many models, but the usual model is the multilayer feed forward network using the error back propagation algorithm. Such a neural network contains three layers: input layers, hidden layers and output layers. Each layer is composed of several neurons. The number of the neurons in the input and output layers depends on the number of the selected input and output variables. The number of hidden layers and the number of neurons in each depend on the desired degree of accuracy [24].



Fig. 9 Membership functions for error in speed.





Fig. 10 Membership functions for change in error.

The convergence of the network in summer obtained by using the value of the parameters grouped in the Table 4.

In MATLAB command we generated the Simulink block ANN regulator of switching table (Table 1) by (gensim) given this model scheme show in Fig. 11.

The structure of the neural network to perform the seven-level DTC with 36 sectors applied IM satisfactorily was a neural networks with 3 linear input nodes, 30 neurons in the hidden layer, and 3 neurons in the output layer. As shown in Fig. 12. The ANN is composed of two layer, Layer 1 and Layer 2 (Fig. 13 and Fig. 14).



Fig. 11 Simulink block for ANN switching table.







Fig. 13 Structure of layer 1.



Fig. 14 Structure of layer 2.

5 Simulation Results

The simulation results of seven-level DTC-ANN with fuzzy speed controller of sensorless IM are compared with conventional seven-level DTC command. For this end, the commands system was tested under deferent operating conditions such as sudden change of load torque. The performance analysis is done with THD value, sector, speed, stator flux and torque. Fig. 15 show the performances of the seven-level DTC control and Fig. 16 show the performances of the seven-level DTC-ANN with the fuzzy speed controller. The torque and flux references used in the simulation results of the seven-level DTC control and DTC-ANN with the fuzzy speed regulator are 6500 N.m and 3.6 Wb respectively. The machine is running at 1000 rpm. From the simulation results presented in Figs. 15-16 it is apparent that the THD value of stator current for the seven-level DTC with intelligent techniques (Neural network and fuzzy logic) is considerably reduced. Table 5 shows the comparative analysis of THD value for stator current.

Torque response comparing curves are shown in Fig. 17. See figure the torque ripple is significantly reduced when the intelligent techniques is in use.

Fig. 18 shows the stator flux responses of both the conventional and neural seven-level DTC with fuzzy speed controller. It is found that the proposed DTC scheme exhibits smooth response and lesser ripple in flux as compared to the conventional seven-level DTC scheme.



Fig. 15 Performances of seven-level DTC without fuzzy speed controller.



Fig. 16 Performances of seven-level DTC-ANN with fuzzy speed controller.



Fig. 17 Zomm in the torque, a) Seven-level DTC and b) Seven-level DTC-ANN with fuzzy speed controller.

6 Conclusions

In this paper, the 36 sectors DTC principle is presented and it is shown that with intelligent techniques (neural network and fuzzy logic) for a sevenlevel NPC inverter. The simulation results obtained for



Fig. 18 Zomm in the stator flux, a) Seven-level DTC and b) Seven-level DTC-ANN with fuzzy speed controller.

the seven-level DTC with intelligent techniques illustrate a considerable reduction in torque ripple, stator flux ripple and THD value of stator current compared to the traditional 36 sectors DTC utilizing seven-level NPC inverter.

Appendix

a) DTC Switching Table

Table 1 Seven-level DTC switching table with 36 sectors.

	N	1	2	2	4	5	6	7	0	0	10	11	10	12	14	15	16	17
Cflx	Ccpl	1	2	3	4	5	0	/	8	9	10	11	12	15	14	15	10	17
	3	27	28	33	37	40	42	48	49	54	58	61	63	69	70	75	79	82
	2	21	27	28	33	37	40	42	48	49	54	58	61	63	69	70	75	79
	1	19	21	27	28	33	37	40	42	48	49	54	58	61	63	69	70	75
1	0	16	19	21	27	28	33	37	40	42	48	49	54	58	61	63	69	70
	-1	12	16	19	21	27	28	33	37	40	42	48	49	54	58	61	63	69
	-2	7	12	16	19	21	27	28	33	37	40	42	48	49	54	58	61	63
	-3	6	7	12	16	19	21	27	28	33	37	40	42	48	49	54	58	61
	3	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90	91
	2	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90	91
	1	33	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90
0	0	33	37	40	42	48	49	54	58	61	63	69	70	75	79	82	84	90
	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	-2	100	103	105	111	112	117	121	124	126	6	7	12	16	19	21	27	28
	-3	100	103	105	111	112	117	121	124	126	6	7	12	16	19	21	27	28
	3	48	49	54	58	61	63	69	70	75	79	82	84	90	91	96	100	103
	2	47	50	55	59	62	68	68	71	76	80	83	89	89	92	97	101	104
	1	46	46	51	56	56	60	67	67	72	77	77	81	88	88	93	98	98
-1	0	5	8	13	17	20	26	26	29	34	38	41	47	47	50	55	59	62
	-1	26	26	29	34	38	41	47	47	50	55	59	62	68	68	71	76	80
	-2	89	92	97	101	104	110	110	113	118	122	125	5	5	8	13	17	20
	-3	90	91	96	100	103	105	111	112	11/	121	124	126	6	/	12	16	19
10	10	20	21	22	22	24	25	26	07	20	20	20	21	22	22	24	25	26
18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
18 84	19 90	20 91	21 96	22 100	23 103	24 105	25 111	26 112	27 117	28 121	29 124	30 126	31 6	32 7	33 12	34 16	35 19	36 21
18 84 82 70	19 90 84	20 91 90	21 96 91	22 100 96	23 103 100	24 105 103	25 111 105	26 112 111	27 117 112	28 121 117	29 124 121	30 126 124	31 6 126	32 7 6	33 12 7	34 16 12	35 19 16	36 21 19
18 84 82 79	19 90 84 82 70	20 91 90 84	21 96 91 90	22 100 96 91	23 103 100 96	24 105 103 100	25 111 105 103	26 112 111 105	27 117 112 111	28 121 117 112	29 124 121 117	30 126 124 121	31 6 126 124	32 7 6 126	33 12 7 6	34 16 12 7	35 19 16 12	36 21 19 16
18 84 82 79 75 70	19 90 84 82 79 75	20 91 90 84 82 70	21 96 91 90 84 82	22 100 96 91 90 84	23 103 100 96 91 00	24 105 103 100 96	25 111 105 103 100	26 112 111 105 103	27 117 112 111 105 102	28 121 117 112 111 105	29 124 121 117 112 111	30 126 124 121 117	31 6 126 124 121	32 7 6 126 124	33 12 7 6 126	34 16 12 7 6	35 19 16 12 7	36 21 19 16 12 7
18 84 82 79 75 70 60	19 90 84 82 79 75 70	20 91 90 84 82 79 75	21 96 91 90 84 82 70	22 100 96 91 90 84 82	23 103 100 96 91 90 84	24 105 103 100 96 91	25 111 105 103 100 96	26 112 111 105 103 100 06	27 117 112 111 105 103	28 121 117 112 111 105 103	29 124 121 117 112 111 105	30 126 124 121 117 112	31 6 126 124 121 117	32 7 6 126 124 121	33 12 7 6 126 124 121	34 16 12 7 6 126	35 19 16 12 7 6	36 21 19 16 12 7
18 84 82 79 75 70 69 63	19 90 84 82 79 75 70	20 91 90 84 82 79 75 70	21 96 91 90 84 82 79 75	22 100 96 91 90 84 82 79	23 103 100 96 91 90 84 82	24 105 103 100 96 91 90 84	25 111 105 103 100 96 91 90	26 112 111 105 103 100 96 01	27 117 112 111 105 103 100 96	28 121 117 112 111 105 103	29 124 121 117 112 111 105	30 126 124 121 117 112 111 105	31 6 126 124 121 117 112	32 7 6 126 124 121 117 112	33 12 7 6 126 124 121 117	34 16 12 7 6 126 126 124	35 19 16 12 7 6 126	36 21 19 16 12 7 6
18 84 82 79 75 70 69 63 96	19 90 84 82 79 75 70 69 100	20 91 90 84 82 79 75 70 103	21 96 91 90 84 82 79 75 105	22 100 96 91 90 84 82 79	23 103 100 96 91 90 84 82 112	24 105 103 100 96 91 90 84 117	25 111 105 103 100 96 91 90 121	26 112 111 105 103 100 96 91 124	27 117 112 111 105 103 100 96 126	28 121 117 112 111 105 103 100	29 124 121 117 112 111 105 103	30 126 124 121 117 112 111 105 12	31 6 126 124 121 117 112 111 16	32 7 6 126 124 121 117 112 19	33 12 7 6 126 124 121 117 21	34 16 12 7 6 126 126 124 121 27	35 19 16 12 7 6 126 124 28	36 21 19 16 12 7 6 126 33
18 84 82 79 75 70 69 63 96 96	19 90 84 82 79 75 70 69 100	20 91 90 84 82 79 75 70 103 103	21 96 91 90 84 82 79 75 105 105	22 100 96 91 90 84 82 79 111	23 103 100 96 91 90 84 82 112	24 105 103 100 96 91 90 84 117	25 1111 105 103 100 96 91 90 121 121	26 112 111 105 103 100 96 91 124	27 117 112 111 105 103 100 96 126 126	28 121 117 112 111 105 103 100 6 6	29 124 121 117 112 111 105 103 7 7	30 126 124 121 117 112 111 105 12 12	31 6 126 124 121 117 112 111 16 16	32 7 6 126 124 121 117 112 19 19	33 12 7 6 126 124 121 117 21 21	34 16 12 7 6 126 126 124 121 27 27	35 19 16 12 7 6 126 126 124 28 28	36 21 19 16 12 7 6 126 33 33
18 84 82 79 75 70 69 63 96 91	19 90 84 82 79 75 70 69 100 96	20 91 90 84 82 79 75 70 103 103 100	21 96 91 90 84 82 79 75 105 105 105	22 100 96 91 90 84 82 79 111 1105	23 103 100 96 91 90 84 82 112 111	24 105 103 100 96 91 90 84 117 117	25 111 105 103 100 96 91 90 121 121 117	26 112 111 105 103 100 96 91 124 124 124	27 117 112 111 105 103 100 96 126 126 124	28 121 117 112 111 105 103 100 6 6 126	29 124 121 117 112 111 105 103 7 7 6	30 126 124 121 117 112 111 105 12 12 7	31 6 126 124 121 117 112 111 16 12	32 7 6 126 124 121 117 112 19 19 16	33 12 7 6 126 124 121 117 21 21 19	34 16 12 7 6 126 124 121 27 27 21	35 19 16 12 7 6 126 126 124 28 28 28 27	36 21 19 16 12 7 6 126 33 33 33 28
18 84 82 79 75 70 69 63 96 91	19 90 84 82 79 75 70 69 100 100 96 96	20 91 90 84 82 79 75 70 103 103 100 100	21 96 91 90 84 82 79 75 105 105 105 103	22 100 96 91 90 84 82 79 111 111 105 105	23 103 100 96 91 90 84 82 112 111 111	24 105 103 100 96 91 90 84 117 112 112	25 111 105 103 100 96 91 90 121 121 117	26 112 111 105 103 100 96 91 124 124 121 121	27 117 112 111 105 103 100 96 126 126 124 124	28 121 117 112 111 105 103 100 6 6 126	29 124 121 117 112 111 105 103 7 6 6	30 126 124 121 117 112 111 105 12 7 7	31 6 126 124 121 117 112 111 16 12 12 12	32 7 6 126 124 121 117 112 19 19 16 16	33 12 7 6 126 124 121 117 21 21 19 19	34 16 12 7 6 126 124 121 27 27 27 21 21	35 19 16 12 7 6 126 124 28 28 28 27 27	36 21 19 16 12 7 6 126 33 33 28 28
18 84 82 79 75 70 69 63 96 91 91 0	19 90 84 82 79 75 70 69 100 96 96 0	20 91 90 84 82 79 75 70 103 103 100 100 0	21 96 91 90 84 82 79 75 105 105 105 103 0	22 100 96 91 90 84 82 79 111 111 105 105 0	23 103 100 96 91 90 84 82 112 111 111 0	24 105 103 100 96 91 90 84 117 112 112 0	25 111 105 103 100 96 91 90 121 117 117 0	26 112 111 105 103 100 96 91 124 121 121 0	27 117 112 111 105 103 100 96 126 126 124 124 0	28 121 117 112 111 105 103 100 6 6 126 126 0	29 124 121 117 112 111 105 103 7 6 6 0	30 126 124 121 117 112 111 105 12 7 7 0	31 6 126 124 121 117 112 111 16 12 12 12 12 0	32 7 6 126 124 121 117 112 19 16 16 0	33 12 7 6 126 124 121 117 21 19 19 0	34 16 12 7 6 126 124 121 27 27 27 21 21 0	35 19 16 12 7 6 126 124 28 28 27 27 0	36 21 19 16 12 7 6 126 33 28 28 0
18 84 82 79 75 70 69 63 96 96 91 0 33 3	19 90 84 82 79 75 70 69 100 96 96 0 37	20 91 90 84 82 79 75 70 103 103 100 100 0 40	21 96 91 90 84 82 79 75 105 105 105 103 103 0 42	22 100 96 91 90 84 82 79 111 111 105 105 0 48	23 103 100 96 91 90 84 82 112 111 111 0 49	24 105 103 100 96 91 90 84 117 112 112 0 54	25 111 105 103 100 96 91 90 121 121 117 117 0 58	26 112 111 105 103 100 96 91 124 124 121 0 61	27 117 112 111 105 103 100 96 126 126 124 0 63	28 121 117 112 111 105 103 100 6 6 126 126 0 69	29 124 121 117 112 111 105 103 7 6 0 70	30 126 124 121 117 112 111 105 12 12 7 7 0 75	31 6 126 124 121 117 112 111 16 12 12 0 79	32 7 6 126 124 121 117 112 19 16 16 0 82	33 12 7 6 126 124 121 117 21 21 19 19 0 84	34 16 12 7 6 126 124 121 27 21 0 90	35 19 16 12 7 6 126 124 28 28 27 27 0 91	36 21 19 16 12 7 6 333 28 28 0 96
18 84 82 79 75 70 69 63 96 96 91 0 33 33	19 90 84 82 79 75 70 69 100 96 96 0 37	20 91 90 84 82 79 75 70 103 103 100 100 0 40 40	21 96 91 90 84 82 79 75 105 105 105 103 103 0 42 42	22 100 96 91 90 84 82 79 111 111 105 105 0 48 48	23 103 100 96 91 90 84 82 112 111 111 0 49 49	24 105 103 100 96 91 90 84 117 112 112 0 54 54	25 111 105 103 100 96 91 90 121 121 117 117 58 58	26 112 111 105 103 100 96 91 124 124 121 0 61 61	27 117 112 111 105 103 100 96 126 126 124 0 63 63	28 121 117 112 111 105 103 100 6 6 126 126 0 69 69	29 124 121 117 112 111 105 103 7 6 0 70 70	30 126 124 121 117 112 111 105 12 12 7 7 0 75 75	31 6 126 124 121 117 112 111 16 12 12 12 10 79 79	32 7 6 126 124 121 117 112 19 16 16 0 82 82	33 12 7 6 126 124 121 117 21 21 19 19 0 84	34 16 12 7 6 126 124 121 27 21 0 90 90	35 19 16 12 7 6 126 124 28 27 0 91	36 21 19 16 12 7 6 33 33 28 28 0 96 96
18 84 82 79 75 70 69 63 96 96 91 0 33 33 105 5	19 90 84 82 79 75 70 69 100 96 96 0 37 37	20 91 90 84 82 79 75 70 103 100 100 0 40 412	21 96 91 90 84 82 79 75 105 103 0 42 117	22 100 96 91 90 84 82 79 111 105 105 0 48 48 121	23 103 100 96 91 90 84 82 112 111 111 0 49 49 124	24 105 103 100 96 91 90 84 117 112 112 112 54 54 126	25 111 105 103 100 96 91 90 121 121 117 117 58 58 6	26 112 111 105 103 100 96 91 124 121 121 0 61 61 7	27 117 112 111 105 103 100 96 126 124 0 63 63 12	28 121 117 112 111 105 103 100 6 6 126 126 0 69 69 16	29 124 121 117 112 111 105 103 7 6 0 70 70 19	30 126 124 121 117 112 111 105 12 12 7 7 0 75 21	31 6 126 124 121 117 112 111 16 12 12 10 12 10 17 100 79 79 27	32 7 6 126 124 121 117 112 19 16 16 0 82 28	33 12 7 6 126 124 121 117 21 19 19 0 84 84 33	34 16 12 7 6 126 124 121 27 21 0 90 90 37	35 19 16 12 7 6 126 124 28 27 0 91 37	36 21 19 16 12 7 6 33 28 28 0 96 96 40
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b) Parameters of Fuzzy Logic

Table 3 Parameters of fuzzy controller.

Fis type	Mamdani
And method	Min
Or method	Max
Implication	Min
Aggregation	Max
Defuzzification	Centroid

c) Model of Induction Machine

The model of IM in the α , β reference can be written in the following from:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = cx(t) \end{cases}$$

with

$$X = \begin{bmatrix} I_{s\alpha} & I_{s\beta} & \Phi_{s\alpha} & \Phi_{s\beta} \end{bmatrix}^{T}$$

$$U = \begin{bmatrix} v_{s\alpha} & v_{s\alpha} & 0 & 0 \end{bmatrix}^{T}$$

$$T_{r} = \frac{L_{r}}{R_{r}}$$

$$\sigma = 1 - \frac{M^{2}}{L_{s}L_{r}}$$

$$K = \frac{M}{\sigma L_{s}L_{r}}$$

$$\lambda = \begin{bmatrix} \frac{1}{T_{s}} + \frac{M^{2}}{T_{r}L_{s}L_{r}} \end{bmatrix}$$

$$A = \begin{bmatrix} -\frac{\lambda}{\sigma} & 0 & \frac{\sigma}{T_{r}}K & K_{W}r \\ 0 & -\frac{\lambda}{\sigma} & -K_{W}r & \frac{\sigma K}{T_{r}} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_{s}} & 0 & \frac{-1}{T_{r}} & -w_{r} \\ 0 & \frac{M}{T_{r}} & w_{r} & \frac{-1}{T_{r}} \end{bmatrix}$$

$$U = \begin{bmatrix} \frac{1}{\sigma L_{s}} & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

d) Machine Parameters

The parameters of 3 phase induction machine employed for simulation purpose is given below:

Table 6 Implementation parameters
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Parameters	Values
Nominal power	1 Mw
Line to line voltage	791 V
Frequency	60 Hz
Stator resistance	0.228 Ω
Stator inductance	0.0084 H
Rotor resistance	0.332 Ω
Rotor inductance	0.0082 H
Mutual inductance	0.0078 H
Inertia	20 Kg.m ²
Friction	0.008 N.m.s
Number of poles	3

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