J. Inst. Eng. India Ser. B (June 2019) 100(3):259–266
https://doi.org/10.1007/s40031-019-00379-y

ORIGINAL CONTRIBUTION

Studies on Direct Torque Control-Based Speed Control of Three-Phase Squirrel-Cage Induction Motor

Pradeep Ranjan Tripathy[1] · **Bibhu Prasad Panigrahi**[2]

Received: 22 February 2018 / Accepted: 16 January 2019 / Published online: 8 February 2019

Abstract Direct torque control (DTC) is the simplest method meant for torque control of a three-phase induction motor. The present study emphasizes speed control by using an external speed loop with DTC controller. The variable torque command is generated from the speed loop using a conventional PI controller which has been implemented in experimental work to validate the simulation results. A fuzzy rule-based speed controller has been developed in this study for comparison purpose. The speed response is faster using conventional PI controller, but fuzzy controller minimizes the ripple content in torque. The design of the speed controller has been made economical by using low-cost discrete electronic hardware components.

Keywords Direct torque control (DTC) · PI controller · Fuzzy PI controller

Introduction

The speed control of three-phase induction motor is challenging due to its nonlinearity, coupled parameters, etc. The invention of field-oriented control (FOC) in 1970s and direct torque control (DTC) in 1980s made the control of the motor less complex [1–3]. In DTC method, the stator flux is added with a differential flux linkage vector or voltage vector to accelerate or decelerate it away from the rotor flux, thereby achieving the required torque both in dynamic and steady-state conditions. Speed performance of induction motor also improves using DTC method, where conventional PI and Fuzzy controllers are used. Fuzzy controller replaces the conventional PI controller to achieve dynamically K_P and K_I adjustment, thereby improving the performance [4–7]. The required switching voltage vector for inverter is derived using the flux and torque controller with knowledge of instantaneous stator flux position. The present study of the DTC method emphasizes implementation of the scheme using a low-cost analog speed controller along with flux and torque controller [8–10]. The PI controller used in the speed controller generates the variable torque command. The scheme has been verified through MATLAB-based simulation using classical and fuzzy PI controllers separately. The experimental setup uses a classical PI controller along with an economical DTC speed controller using discrete hardware components for the use of small-scale industrial sectors. The results obtained in experimentation match those obtained from simulation. A fuzzy rule-based speed controller has also been simulated in MATLAB environment.

Principles of Switching Table-Based DTC (ST-DTC) Scheme with Speed Controller

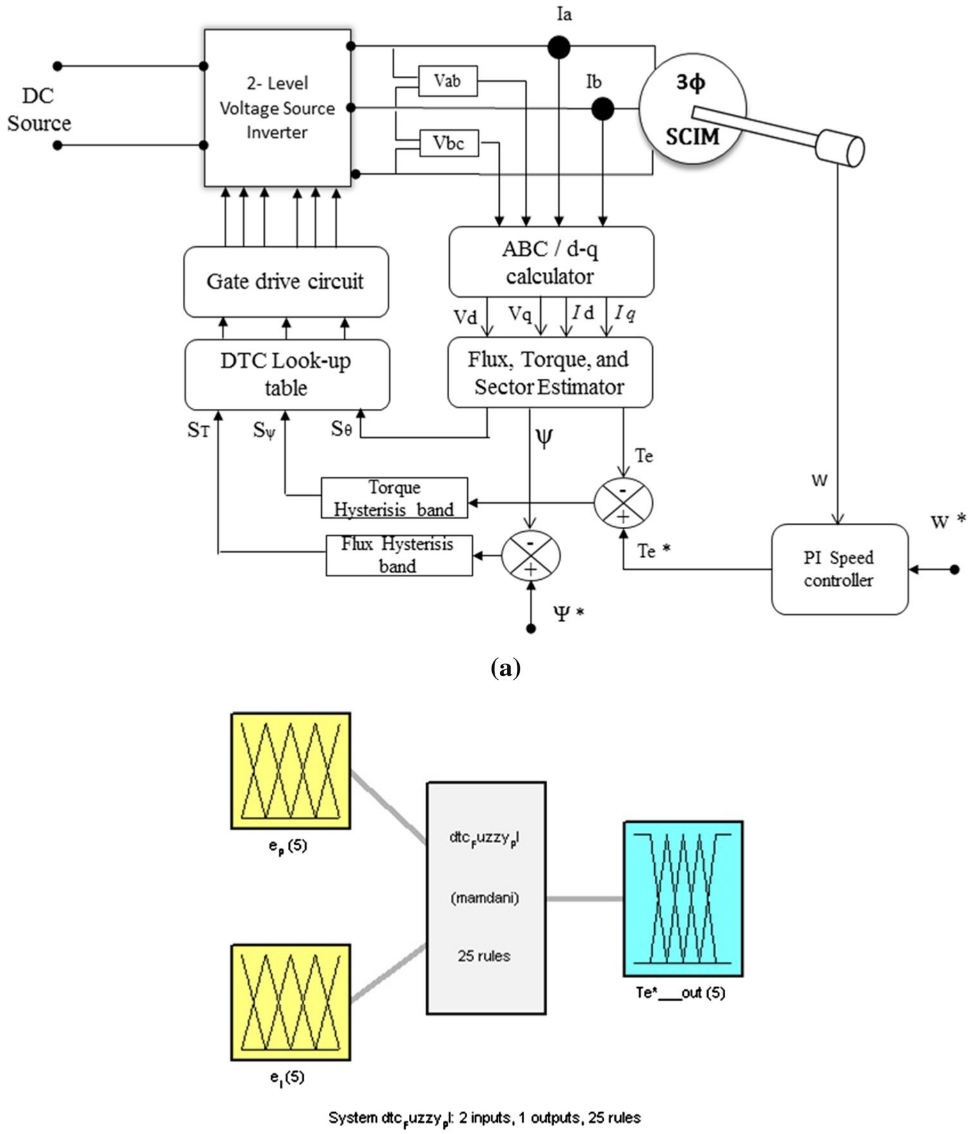
The ST-DTC scheme provides the optimum voltage switching vector for the voltage source inverter (VSI) to yield the fast torque response in the induction motor. Figure 1a shows the schematic block diagram of the

✉ Pradeep Ranjan Tripathy
pradeeptripathy_10@yahoo.co.in

Bibhu Prasad Panigrahi
bibhu89@yahoo.com

[1] Department of Electrical Engineering, KIIT Polytechnic, Bhubaneswar, Odisha 751024, India

[2] Department of Electrical Engineering, Indira Gandhi Institute of Technology, Sarang, Dhenkanal, Odisha 759146, India



(a)

(b)

Fig. 1 **a** Block diagram for DTC of Squirrel Cage Induction Motor (SCIM) using speed controller. **b** Fuzzy interface system in PI speed controller

scheme. The control circuit uses three-phase stator line voltages, current and the rotor speed as its three inputs. The stator voltage and line currents are transformed into d-q axis voltage and currents as per Eqs. 1–4.

$$v_{qs} = \frac{2}{3} v_{ab} + \frac{1}{3} v_{bc} \tag{1}$$

$$v_{ds} = \frac{1}{\sqrt{3}} (-v_{bc}) \tag{2}$$

$$i_{qs} = i_{as} \tag{3}$$

$$i_{ds} = \frac{1}{\sqrt{3}} (i_{cs} - i_{bs}) \tag{4}$$

$$\psi_{qs} = \int \left(v_{qs} - i_{qs} R_s \right) . \mathrm{d}t \tag{5}$$

$$\psi_{ds} = \int (v_{ds} - i_{ds} R_s) \mathrm{d}t \tag{6}$$

$$T_e = \frac{3}{2} P \left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds} \right) \tag{7}$$

The *d*- and *q*-axes flux components ψ_d and ψ_q are obtained integrating the emf (Eqs. 5, 6) after compensating for the corresponding stator resistance drops. The electromagnetic torque T_e is calculated by using Eq. 7. The calculated electromagnetic torque is compared with a two-quadrant torque command generated by PI speed controller to generate three-level torque command S_T from hysteresis torque comparator. The commands + 1 and − 1 denote the increase and decrease in torque demand, respectively, while 0 denotes no change. The absolute flux is calculated from two-axis flux components and compared with the rated flux to process in flux hysteresis comparator. Two-level flux command, S_ψ (1, 0), is the outcome of the comparator which indicates the increasing demand or no change of flux during operation. The instantaneous position of the rotating stator flux in air gap is decided digitally considering the position of two-axis flux components and is denoted by S_θ. The air gap is divided into six sectors [11–13]. A switching table uses the three control signals S_T, S_ψ and S_θ as input and decides the optimum switching voltage vector for the two-level VSI.

Simulation Study of DTC Control Using Speed Controller

The simulation study of the scheme has been carried out in MATLAB/Simulink environment. The parameters of three-phase, 415-V, star-connected, 0.75-kW, 50-Hz SCIM have been determined experimentally. The stator and rotor parameters are determined from no-load test and blocked rotor test. Combined inertia and friction coefficient of induction motor coupled with separately excited DC generator has been determined using retardation test. The same parameters have been used in simulation. The parameters are as follows:

$R_a = 16.575\ \Omega$, $R_r = 5.2183\ \Omega$, $L_{ls} = L_{lr} = 0.0404558$ H, $L_m = 0.5393595$ H, number of poles $P = 4$, combined inertia of motor and coupled load $J = 0.0048742$ kg-m^2, $B = 0.000001$ Nm-s. The motor is loaded with 0.6 times the full load, and the study has been carried out for two-quadrant operation.

Speed Controller Using Classical PI Controller

The discrete expression for classical PI controller in DTC scheme is given by Eq. 8:

$$T_e^*(k) = K_\mathrm{P} e_w(k) + K_\mathrm{I} T \int_1^j e_w(j) \tag{8}$$

where $T_e^*(k)$ is the torque command to achieve the desired torque output, T is the sampling period, e_w is the speed error signal, and K_P and K_I are proportional and integral gains, respectively. Proper tuning of the gains provides the required steady torque and speed response. In present simulation study, the speed of the rotor is sensed and compared with the rated bidirectional speed command. The speed error so obtained is processed in the conventional PI controller to yield corresponding torque command. The present simulation uses the gain value as $K_\mathrm{P} = 3.5$, $K_\mathrm{I} = 5.7$ and sampling period $T_s = 2\mathrm{e}{-6}$ s. The speed command is provided with + 0.6 pu to − 0.6 pu with a zero command in between for the same time interval. The torque generated from PI controller is compared with the estimated electromagnetic torque obtained from DTC controller. The error so obtained is processed in a hysteresis comparator with a band set to ± 0.5% of rated torque to generate the required three-level torque control signals. Similarly, the hysteresis band used for generating flux control signal is set to ± 0.4% of rated flux.

Two control signals along with sector position signal are fed as deciding control signals to the DTC lookup table, and the required switching vector is decided for the VSI that feeds the three-phase input to SCIM for achieving the set speed.

Speed Controller Using Fuzzy PI Controller

The classical PI speed controller DTC gives slow transient response with high torque ripple during starting to a step command. When the motor load is suddenly changed, the speed trajectory along with torque response suffers from over shoot, oscillation, etc. A language-based fuzzy controller studies the sudden variation in load and produces the required set value for the torque, which is able to eliminate the above errors during load change. A fuzzy controller is implemented in place of conventional PI controller.

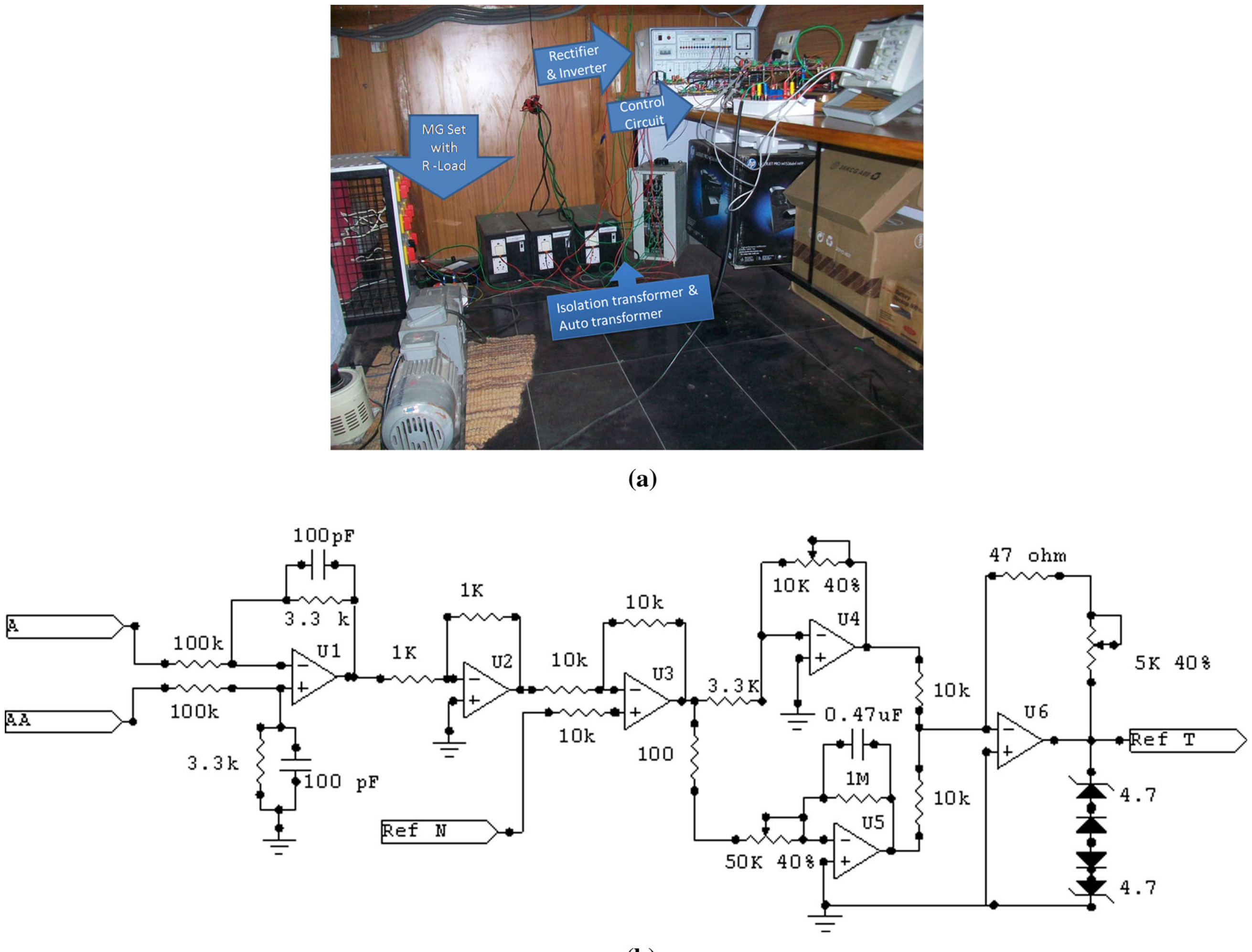
Fuzzy controller uses e_P and e_I as two input variables, where $e_\mathrm{P} = K_1\, w_e$ and $e_\mathrm{I} = K_2\,(w_e{*} + w_e)$ & w_e, $w_e{*}$ are the speed error and unity delay speed error, respectively. The input variables e_P and e_I and the output variable T_out are represented by five triangular membership functions as negative large (NL), negative small (NS), zero (Z or ZE), positive small (PS) and positive large (PL). Twenty-five control rules (Table 1) define the output member in defuzzification using Mamdani-type inference method. So the output of the fuzzy interface system (Fig. 1b) gives a crisp number as a value of the desired torque which is compared in the DTC controller to obtain the required voltage vector for VSI.

Hardware Implementation of DTC Speed Controller

The induction motor is coupled to separately excited DC generator for electrical loading as shown in Fig. 2a. Terminal voltage of DC generator is sensed by low-cost op-amp-based sensors U1 and U2 shown in Fig. 2b. The

Table 1 Fuzzy rule for PI controller

e_I e_P	NL	NS	ZE	PS	PL
NL	NL	NL	NS	NS	ZE
NS	NL	NS	NS	ZE	PS
Z	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PS	PL	PL



(a)

(b)

Fig. 2 **a** Experimental setup. **b** Speed sensor and conventional PI controller

voltage level reduces to 0.033 times the actual generated value. In other words, 1 V of op-amp output represents 30.303 V. The speed scale is determined from this scale. 1 V speed scale represents 252.5 RPM. In reference to the rated speed of the induction motor, the required set value of speed is 5.6 V. A bidirectional speed pattern of maximum value 5.6 with zero value in between is provided as a reference value to obtain the speed error.

The speed error is processed in the PI controller realized with *U*4 and *U*5 op-amps and limited within the rated torque. Tuning of K_P and K_I in the PI controller has been done following *Ziegler–Nicholas* method, and the factors are set to 2.637 and 50.1, respectively. The variable reference torque and constant flux are compared with respective calculated values of analog controller and then processed in their respective analog hysteresis band comparators to determine the control signals for switching table. Sector position as determined digitally from two-axis flux components is provided as the third input to the switching table. Three separate gate pulses are generated for three legs of the VSI producing their complement pulse by means of gate drive circuit.

Result Analysis

The results of both simulations carried out by MATLAB/Simulink and experiment are presented in Figs. 3, 4 and 5. The present study of speed control has been carried out with constant flux, changing speed command. As it is observed in Fig. 3a, b for both simulations, *d*-axis flux component leads *q*-axis flux component during forward motoring and *d*-axis flux lags *q*-axis flux component during reverse motoring. Two-axis flux components behavior during the operations is depicted in Fig. 3c, d for experimental studies. Constant flux operation is verified through the simulation and experiment result. Ripple content in stator flux has been estimated through variance error. The

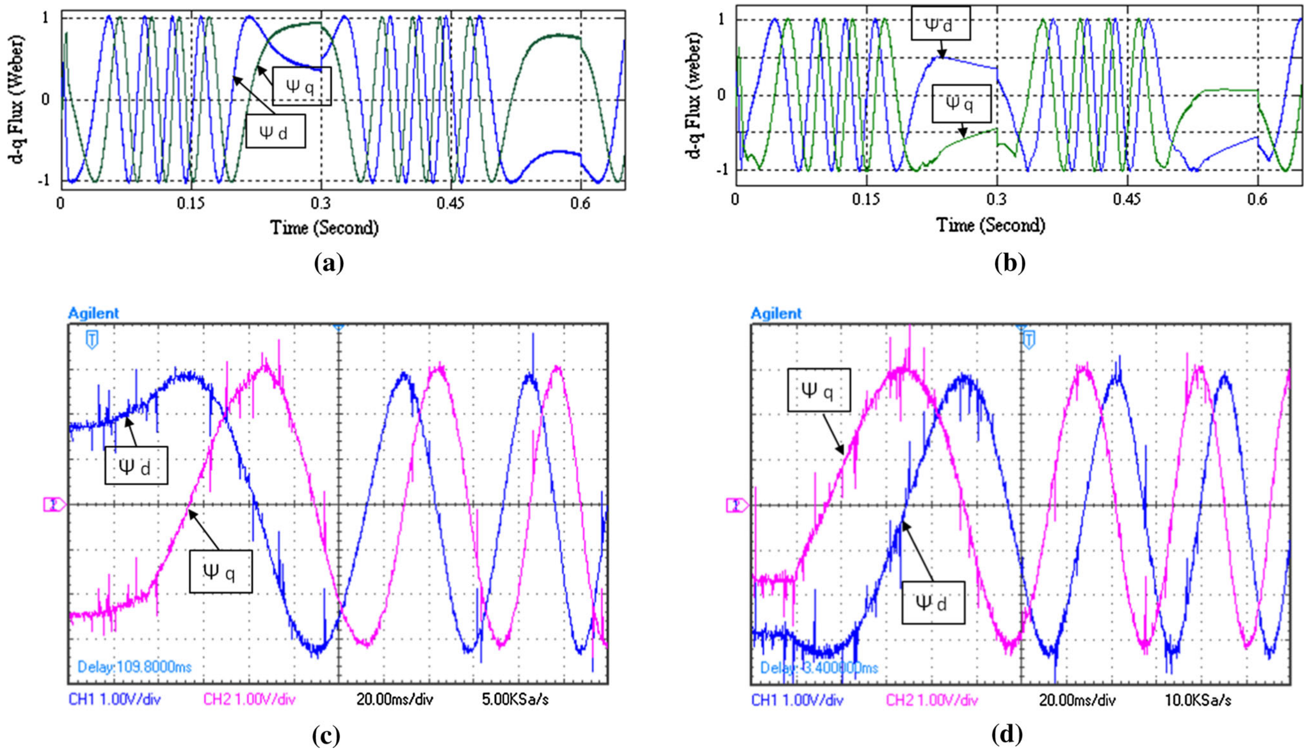


Fig. 3 Superimposed flux ψ_d and ψ_q versus time. **a** Conventional PI controller simulation result. **b** Fuzzy PI controller simulation result. **c** Superimposed flux ψ_d and ψ_q versus time in forward motoring. **d** Superimposed flux ψ_d, ψ_q versus time in reverse motoring

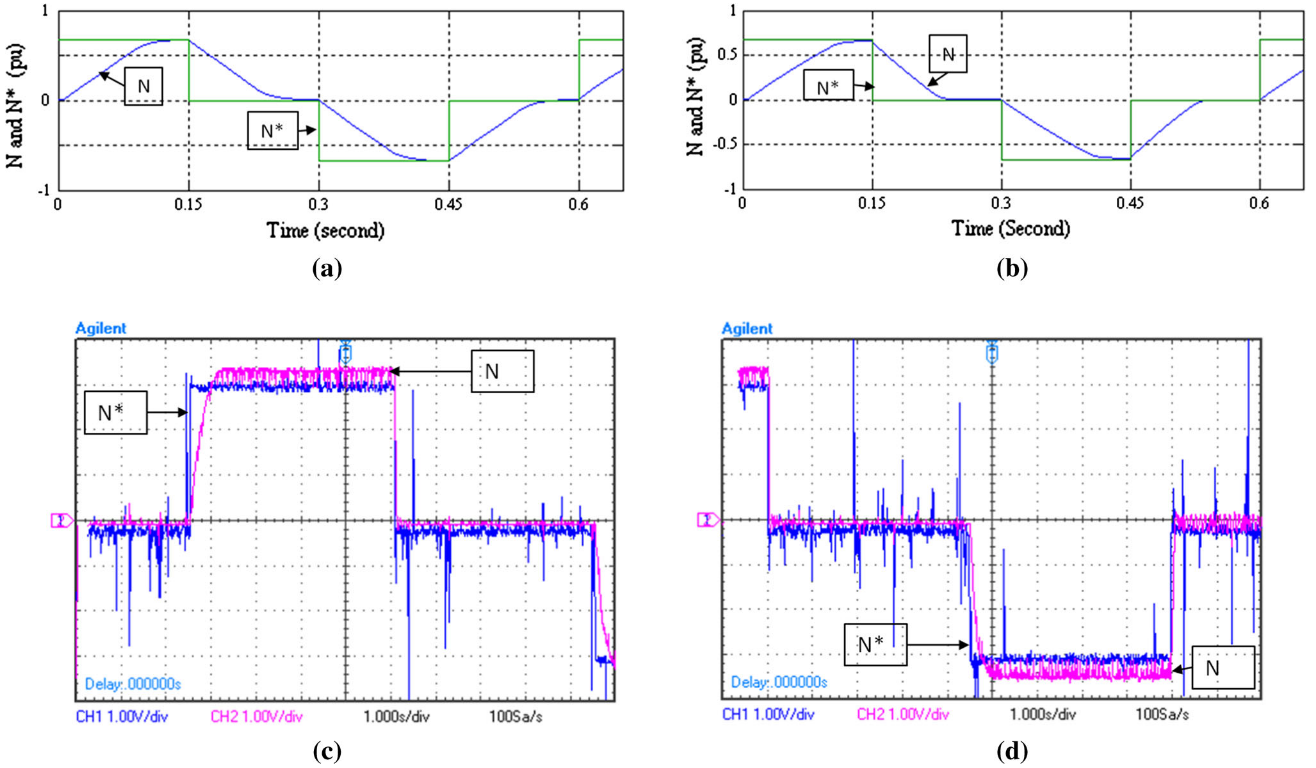


Fig. 4 Superimposed speed response and its command value versus time. **a** Simulation result conventional PI controller. **b** Simulation result fuzzy PI controller. **c** Superimposed speed response and its command value versus time in forward motoring. **d** Superimposed speed response and its command value versus time in reverse motoring

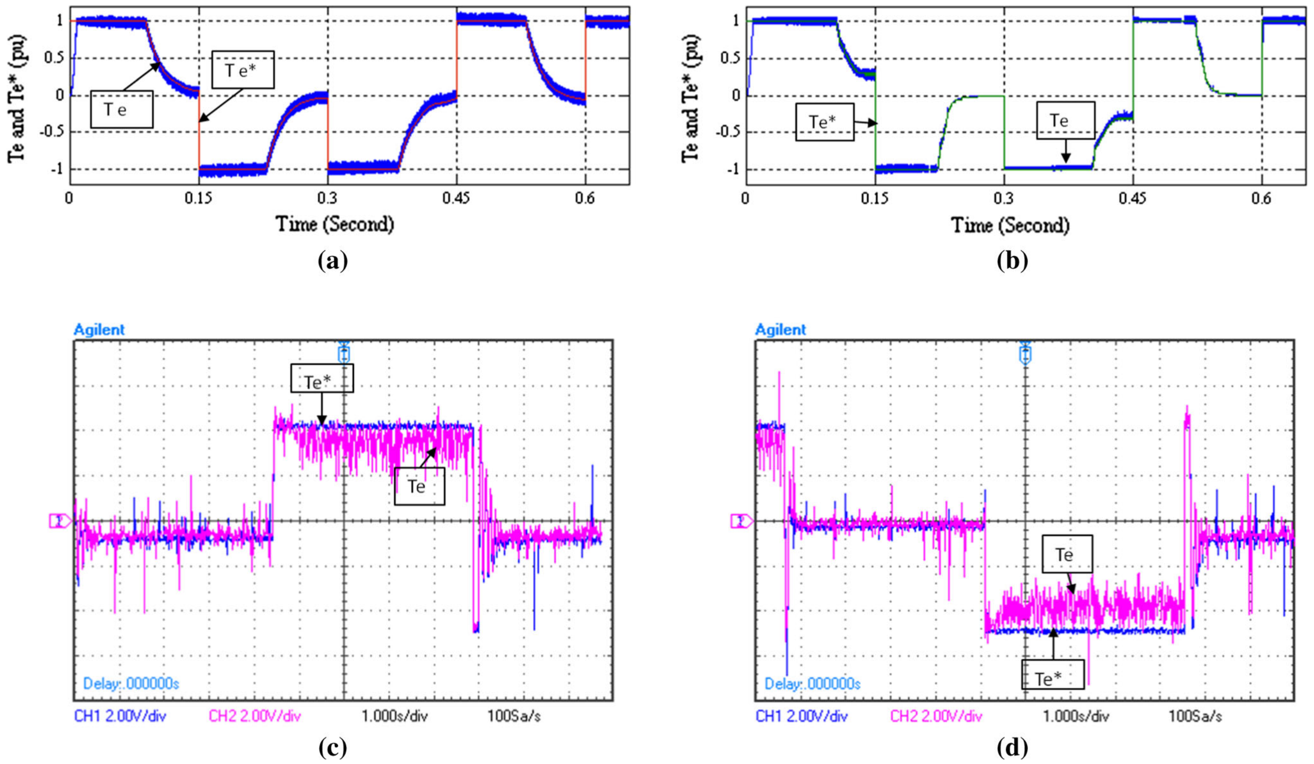


Fig. 5 Superimposed torque response T_e and its command value T_e* versus time. **a** Simulation result conventional PI controller. **b** Simulation result fuzzy PI controller. **c** Superimposed torque response T_e and its command value T_e* versus time in forward motoring. **d** Superimposed torque response T_e and its command value T_e* versus time in reverse motoring

ripple contents can be quantitatively assessed through considering variance of errors [4]. The statistical measure variance, denoted by 'Var,' can be represented by Eq. 9.

$$\mathrm{Var} = \frac{\sum (x_i - \bar{x})^2}{n} \qquad (9)$$

where x_i represents individual error pertaining to speed or torque compared to command value and $\bar{x}$ represents the arithmetic mean of the same in the distribution. In general, a decrease in the variance of errors is obtained in the speed or torque time response obtained through implementing fuzzy rule-based PI speed controller compared to that obtained using classical PI speed control approach. The variance error in classical PI speed control scheme is 0.026581 as against 0.012093 in fuzzy PI speed controller. It implies that the harmonic content is lower in conventional PI controller.

Speed trajectory being superimposed with its command is shown in Fig. 4a, b in simulation study. The stable speed is achieved in 0.6 ms earlier in the case of the conventional speed controller method than in the fuzzy speed controller simulation. Figure 4c, d show the experimental speed response during forward and reverse operations of motor. Assessment of speed response is given in Table 2, considering two simulation studies and experimental study. Settling time of speed to the command value in experimentation is high during motoring mode, but low during braking in either direction of operation. The speed command is distorted with some noises during loading of the motor (Fig. 4c, d). The ripples in speed for both directions and four modes of operation have been measured in terms of variance error. Variance error obtained during experimentation closely matches the simulation results. Smooth change of speed has been obtained in both the quadrants using the DTC scheme for speed control. The speed response obtained using analog-component-based hardware validates the scheme.

The torque response superimposed with its command value is depicted in Fig. 5a, b for both directions of operation in simulation study. The assessment of torque response in both simulation studies is represented in Table 3. Motor torque settles with its command value in 0.48 ms and 0.65 ms, respectively, in conventional and fuzzy logic-based PI speed controller. The ripple content in torque has been measured in terms of variance error. In each step of speed change, a decrease in variance has been observed for entire operation using fuzzy PI control system as compared to conventional PI controller system. A decrease in variance as 31.97%, 22.28%, 14.87% and 27.4% has been noted during forward motoring, forward braking, reverse motoring and reverse braking,

Table 2 Assessment of speed response for DTC speed control scheme

Mode	Conventional PI simulation	Fuzzy PI simulation	Hardware experimentation
Setting time (ms)			
Forward motoring	132.94	132.99	350
Forward braking	129.13	132.98	110
Reverse motoring	138.95	123.13	340
Reverse braking	125.2	126.85	100
Variance (computed from speed ripple)			
Forward motoring	0.051801	0.047226	0.038136
Forward braking	0.047603	0.044304	0.063956
Reverse motoring	0.047894	0.045186	0.059563
Reverse braking	0.048689	0.043324	0.055698

Table 3 Assessment of torque response in DTC speed control simulation

Motoring modes	Torque response parameters	Conventional PI speed controller	FR-based PI speed controller	% improvement
Starting	Settling time	0.00822 s	0.00837 s	− 1.82
Forward motoring	Rise time	0.00048 s	0.00065 s	− 35.42
	Variance	0.00115938	0.00078869	31.97
Forward braking	Decaying time	0.00028 s	0.00035 s	− 25.00
	Variance	0.00209370	0.00162726	22.28
Reverse motoring	Rise time	0.00044 s	0.00069 s	− 56.82
	Variance	0.00245016	0.00208573	14.87
Reverse braking	Decaying time	0.00027 s	0.00035 s	− 29.63
	Variance	0.00218799	0.00158859	27.40

respectively. It signifies that ripple content in torque can be minimized by using fuzzy PI speed control system.

Since the time delay is observed in fuzzy PI system, experimental study has been carried out with conventional PI speed controller. The torque response to its commanded torque, derived from speed controller, is depicted in Fig. 5c, d for forward and reverse operations of motor. The gains for the controller have been used as 2.637 and 50.1 for K_P and K_I, respectively. Overshoot of torque has been suppressed during starting of motoring operation for both directions, whereas it is appreciable in braking instants. The overall torque response in forward and reverse mode operations justifies the feasibility of DTC scheme in controlling the speed of a three-phase induction motor.

Conclusion

The present study justifies that DTC control method can be implemented for speed control purpose by providing additional speed loop to a DTC control circuit. Torque response studied in conventional PI speed controller simulation is 0.17 ms faster than fuzzy PI controller simulation. The experimental setup fabricated as per the proposed model has achieved a speed response of approximately 350 ms for motoring mode and 110 ms for braking mode, during speed control. The result validates the proposed schemes studied in the simulation studies. Results of the proposed model indicate the achievability of low torque ripples with fuzzy PI controller-based speed controller.

Acknowledgements The authors acknowledge with thanks the support received from ‘AICTE, New Delhi,’ for conducting the experimental research work on development of this prototype analog DTC controller.

References

1. M. Depenbrock, Direct self-control (DSC) of inverter fed induction machine. IEEE Trans. Power Electron. **3**(4), 420–429 (1988)
2. I. Takahashi, Y. Ohmori, High performance direct torque control of an induction motor. IEEE Trans. Ind. Appl. IA **25**(2), 257–264 (1989)
3. D. Casadei, F. Profumo, G. Serra, A. Tani, FOC and DTC: two viable schemes for induction motors torque control. IEEE Trans. Power Electron. **17**(5), 779–787 (2002)
4. X. Wei, D. Chen, C. Zhao, Minimization of torque ripple of direct-torque controlled induction machines by improved discrete

space vector modulation. Electr. Power Syst. Res. **72**, 103–112 (2004)

5. F. Zidani, D. Diallo, M.E.H. Benbouzid, R. Nait Said, Direct torque control of induction motor with fuzzy stator resistance adaptation. IEEE Trans. Energy Convers. **21**, 619–621 (2006)
6. T.Y. Abdalla, H.A. Hairik, A.M. Dakhil, Direct torque control system for a three phase induction motor with fuzzy logic based speed controller. In *1st International Conference on Energy, Power and Control* (2010), pp. 131–138
7. T. Ramesh, A.K. Panda, Y. Suresh, S. Mikkili, Direct flux and torque control of induction motor drive for speed regulator using PI and fuzzy logic controllers. In *IEEE-International Conference on Advances in Engineering, Science and Management (ICAESM-2012)*, March 30, 31, 2012 (2012), pp. 288–295
8. B.P. Panigrahi, D. Prasad, S. SenGupta, Digital simulation and PC based implementation of switching table based direct torque control of induction motor drive. In: *Conference, IIT Kharagpur*, Dec 22–24, 2005 (2005), pp. 1–6
9. B.P. Panigrahi, D. Prasad, S. SenGupta, A simple hardware realization of switching table based direct torque control of induction motor. Electr. Power Syst. Res. **77**, 181–190 (2007)
10. D. Prasad, B.P. Panigrahi, S. SenGupta, Digital simulation and hardware implementation of a simple scheme for direct torque control of induction motor. Energy Convers. Manag. **49**(4), 687–697 (2008)
11. P.R. Tripathy, B.P. Panigrahi, Simulation study on DTC based induction motor drives using MATLAB. IEEE Proc. INDICON **1**, 65–68 (2008)
12. P.R. Tripathy, B.P. Panigrahi, Simulation studies on switching table based DTC and fuzzy rule based DTC for three-phase squirrel cage induction motor. Eng. Technol. Appl. Sci. Res. **2**(1), 162–166 (2012)
13. P.R. Tripathy, B.P. Panigrahi, Study of direct torque controlled 3-phase SCIM with two and three-level inverters using ST-DTC and FR-DTC scheme. Eng. Technol. Appl. Sci. Res. **5**(1), 748–752 (2015)