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Speed Control of DTC with Torque Ripple and Flux Droop Reduction Using Sector Alteration Based Adaptive Sliding Mode Control

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Abstract: In this study, an adaptive sliding mode speed controller is Developed for Direct torque Control (DTC) of induction motor drive in accordance with sector alteration strategy. In basic DTC system, the applied voltage vectors are not active during switching sector transition and stator flux drooping occurs at every sector transition. The original sector division is altered slightly to overcome this flux drooping. The Sliding Mode Controller (SMC) developed in this research incorporates adaptive switching gain based on fuzzy logic. The control law of adaptive sliding gain SMC considers the sector alteration in the DTC drive system also. The performance improvement of the developed sector alteration strategy and fuzzy SMC for DTC are verified using performance indices.

Key words: Direct torque control, sector alteration, fuzzy sliding mode controller, speed, India

INTRODUCTION

In variable speed Induction Motor (IM) drives, the DC-AC inverters are used to control the motors for variable frequency and variable voltage. Among them, DTC method of IM drives are controlling the stator flux and torque of the motor by appropriately selecting the inverter switching signals (Vas, 1998). In this DTC method, the electromagnetic torque and stator flux are confined within predefined hysteresis comparator bands (Depenbrock, 1987; Takahashi and Noguchi, 1986). The DTC based IM drives are used predominantly in industries due their ruggedness, less cost and low maintenance. Further, DTC is simple in structure and offers fast torque, flux control and robust to motor parameter variations. The drawbacks of DTC are high torque and flux ripples and variable switching frequency. The switching frequency depends on speed, torque and the bandwidth of hysteresis comparators (Takahashi and Noguchi, 1986; Shyu and Shieh, 1996).

It is generally known that the IM drive system is an online ar system. A Variable Structure Control (VSC) strategy called SMC is used in this paper for controlling the switching frequency and other non-linearity present in the system (Shyu and Shieh, 1996; Barambones *et al*., 2006; Gadoue *et al*., 2007). The VSC comprises of switching surface control mode and sliding surface control mode. Initially, the control action is initiated to ensure that all the states of the control system are confined to be inside the switching hyperplane surface. Then the sliding surface control mode starts and the dynamics of the system are free from non-linearity and disturbances, once the system enters sliding mode (sliding surface) (Shyu and Shieh, 1996). The concept of SMC is used in speed control of IM drives. The SMC needs speed and acceleration of the motor for speed control. A new switching surface sliding mode control is presented (Shyu and Shieh, 1996), it does not require the acceleration of the motor. In SMC method of speed control, the control law is developed such that the sliding gain of the system is adaptive (Barambones *et al*., 2006; Gadoue *et al*., 2009) in order to avoid the upper limit of uncertainties.

Artificial Intelligence (AI) techniques like fuzzy logic, genetic algorithm (GA) and neural networks are incorporated with sliding mode control to improve the performance (Gadoue *et al*., 2007, 2009; Li and Wang, 2010). Four different speed controllers namely two PI speed controllers, a fuzzy speed controller and a hybrid fuzzy SMC are compared for performance improvement in DTC (Gadoue *et al*., 2009). The hybrid fuzzy sliding mode controller is compared with GA tuned PI speed controller

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(Gadoue *et al*., 2007). The fuzzy neural network is used (Li and Wang, 2010) to optimize the control gain matrix of the SMC. The comparison of (Ramesh *et al*., 2014) the conventional SMC with fuzzy speed controller and fuzzy based SMC is performed. In this study, the SMC is developed by a simple fuzzy rule base which varies the sliding gain in accordance with a concept called sector alteration strategy.

The sector alteration strategy was proposed (Mei *et al*., 1999) and the stator flux drooping by conventional methods are investigated (Wong and Holliday, 2004). In basic DTC, the applied voltage space vectors are not effective at the beginning and also at the end of each sectors. By slightly altering the conventional stator flux sectors at the boundaries, the problem of stator flux drooping can be avoided. The reference stator flux value is optimized according to the loading conditions (Kaboli *et al*., 2003; Stojic *et al*., 2015; Ibrahim Mohd Alsofyani and Nik Rumzi Nik Idris). The hysteresis band limits of DTC are self-tuned using neuro-fuzzy controller in order to reduce the torque ripple of IM (Hafeez *et al*., 2014).

In this study, the sector alteration strategy is improved using Pulse Width Modulated (PWM) signals. The angle of alteration is chosen by using trial and error method in accordance with system conditions. The sector alteration is required only during the beginning and end of the sector; hence by properly selecting the duty ratio of the PWM, the performance of the basic DTC is improved. Further, the fuzzy based SMC method is incorporated in the DTC system. The SMC is developed to be adaptive to sector alteration strategy and the other non-linearity present in the system. The fuzzy based SMC adaptive to sector alteration strategy has not been analysed by other researchers. The performance enhancement of the developed DTC system is verified by using performance index called, Integral Square Error (ISE).

MATERIALS AND METHODS

Basic concept of direct torque control: The basic concept of DTC IM scheme shown in Fig. 1, is to choose the optimum voltage vectors from the Voltage Source Inverter (VSI). The applied voltage vectors make the stator flux to rotate for producing the required electromagnetic torque (Vas, 1998).

The VSI chooses switching signals from an optimal switching table shown in Table 1. The switching signals are selected based on the outputs of three level torque hysteresis comparator (dTe) and two level flux hysteresis comparator (dΨs) and stator flux angle (α). In Table 1, the V_0 and $V_7$are zero voltage vectors with switching signals (000) and (111) respectively (Vas, 1998; Bimal, 2012).

The IM stationary reference frame model equation for stator voltage space vector (Vs) is given by Paul (1986), Park (1929) and Stanley (1938):

$$Vs = RsIs + j\frac{d\Psi s}{dt} \quad (1)$$

Based on Eq. 1 the stator flux (Ψs) space vector can be written as:

$$\Psi s = \int (Vs - RsIs)dt \quad (2)$$

If the stator resistance (Rs) value is small, except during low speed operating conditions the IsRs drop can be omitted. Now the proportional relation between the voltage and flux space vectors can be written as:

$$\Delta\Psi s = Vs\Delta t \quad (3)$$

From Eq. 3 it is shown that the stator flux (Ψs) can be changed by applying the voltage space vector (vs).

A two-level three phase VSI produces six non-zero voltage space vectors as shown in Fig. 2. In the same way, the electromagnetic torque (Te) of an IM is related to the stator flux (Ψs) and rotor flux (Ψs) by the following expression:

$$Te = P\frac{Lm}{\sigma LsLr}|\Psi s||\Psi r|\sin(\angle\Psi s\Psi r) \quad (4)$$

Where:

$\angle\Psi s\Psi s$	=	Is the load angle which is in between stator and rotor fluxes
P	=	Is the no of pole pairs. The Leakage factor
(σ)	=	Is defined as
$\sigma = 1 - \frac{L^2}{L_s L_r}$	=	with stator inductance (Ls), rotor inductance

(Lr) and mutual inductance (Lm) respectively. Thus from the Eq. 3 and 4 it is concluded that the stator flux (Ψs) can be changed by applying the voltage vector, and electromagnetic torque (Te) can be changed by controlling the angle between stator and rotor fluxes.

By using Clarke's transformation the abc-dq transformation is done for modelling of induction motor. The actual torque (Te), actual stator flux (Ψs) and the

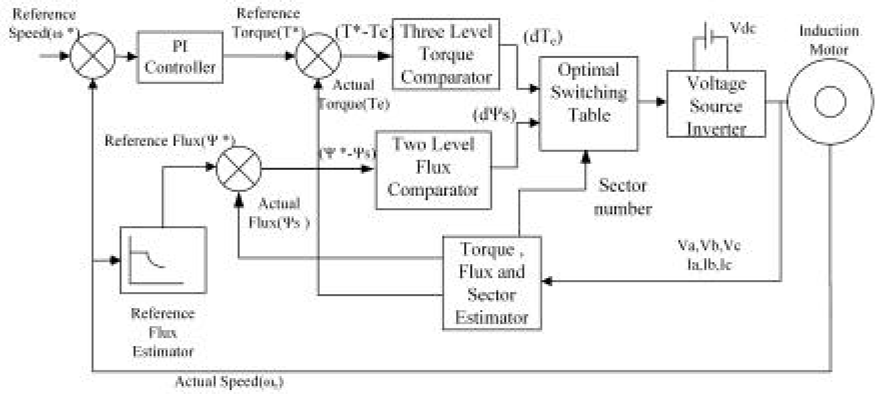

Fig.1: Block diagram of basic DTC IM drive scheme

Table 1: Optimal switching table for inverter switching vectors

dΨs	dTe	α (1)	α (2)	α (3)	α (4)	α (5)	α (6)
1	1	V2	V3	V4	V5	V6	V1
1	0	V7	V0	V7	V0	V7	V0
1	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
0	0	V0	V7	V0	V7	V0	V7
0	-1	V5	V6	V1	V2	V3	V4

stator flux angle (α) are calculated using the equations from 5-7 (Bimal, 2012).

$$Te = \frac{3}{2} * \frac{P}{2} * \left(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}\right) \tag{5}$$

$$\Psi s = \sqrt{\left(\Psi_{ds}^2 + \Psi_{qs}^2\right)} \tag{6}$$

$$\alpha = \tan^{-1}\left(\frac{\Psi_{qs}}{\Psi_{ds}}\right) \tag{7}$$

The sector number α (n) (n varies from 1-6) is calculated based on the stator flux angle (α) as shown in Fig. 2. The reference torque (T*) and reference flux (**Ψ***) are calculated using the actual speed (ω_r) of the IM. The actual speed (ω_r) of the IM is measured using the equation:

$$\omega_r = \frac{1}{J} \int \left(T_e - T_L\right) dt \tag{8}$$

By giving the speed error as input to the PI controller the reference torque (T*) is calculated. The reference flux (**Ψ***) is calculated by reference flux estimator using the actual speed (ω_r) as input. The torque error (T*-Te) is given as input to the three level torque hysteresis comparator and flux error (**Ψ***-**Ψ**s) is given as input to the two level flux hysteresis comparator. The hysteresis comparators use some error band to determine the output. As mentioned earlier, based on the outputs from hysteresis comparators and sector number the switching signals are sent from optimal switching table.

In this study, to improve the performance of the system a control strategy called sector rotation strategy is included in the system. For further improvement, instead of the PI controller, fuzzy based SMC is proposed for reducing the torque and flux ripples in the DTC. The proposed SMC is fine-tuned in accordance with the instantaneous sector rotation angle of the DTC system.

Sector alteration strategy: The inverter voltage space vectors are shown in Fig. 2. The optimal switching table based on d**Ψ**s , dTe and sector no α (n) is give in Table 1. In basic DTC strategy, the stator flux plot is divided into six equal sectors of each with 60 degrees. The applied voltage space vectors for the IM are same at the beginning and end of the sector. From Table 1, when d**Ψ**s is 1, dTs is 1and stator flux angle (α) is in sector number 3, the vector V_4 is to be applied to the stator flux (**Ψ** s(old)) to obtain the resultant (**Ψ** s (new)) as shown in Fig. 3.

The stator flux is located at the end of the sector 3. In Fig. 4 it shown that, if the stator flux plot is slightly altered, then V_5 can be applied to the motor to improve the performance instead of V_4. On comparing the resultant **Ψ** s (new) in Fig. 3 and 4, it is proved that sector alteration yields better performance.

In order to alter the sectors the sector number calculation should be changed to improve the performance (Mei *et al*., 1999) of DTC. The Eq. 9 and 10 are used for sector Alteration (Alt) while modelling the DTC:

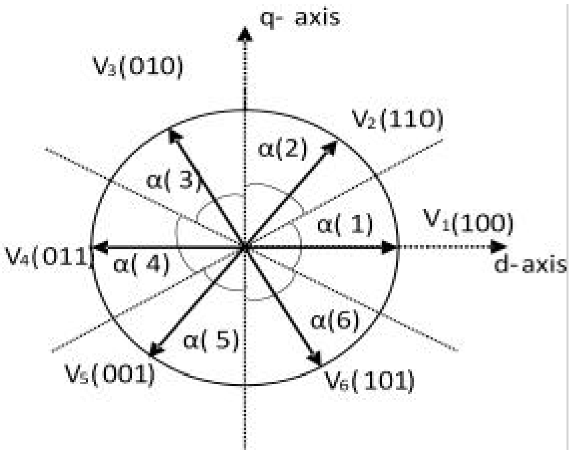

Fig. 2: Sector division of stator flux and inverter voltage space vectors

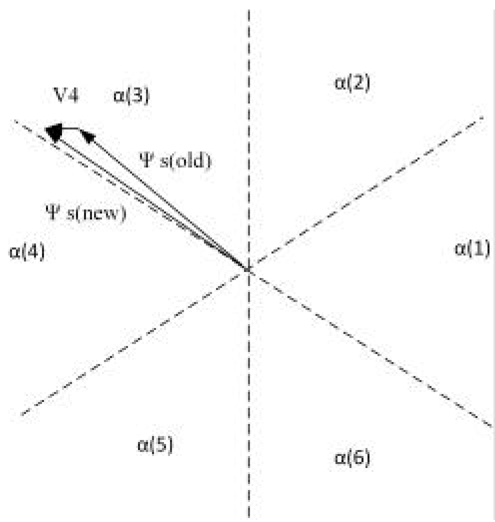

Fig. 3: Stator flux variation from

$$\Delta\theta_{sh} = \theta_{rot} * dTe * dTe \tag{9}$$

$$\alpha^1 = \alpha + \Delta\theta_{sh} \tag{10}$$

where, the $\Delta\theta_{sh}$ is the change in angle required. is magnitude of angle through which the sectors are rotated from their original position (Mei *et al*., 1999; Wong and Holliday, 2004). The sector alteration is required only during the beginning and end of each sector. The usual voltage vectors from the conventional method giving optimum performance is applied during the rest of the period. Therefore, the sector alteration concept is implemented in this work using PWM signal with a change in duty ratio.

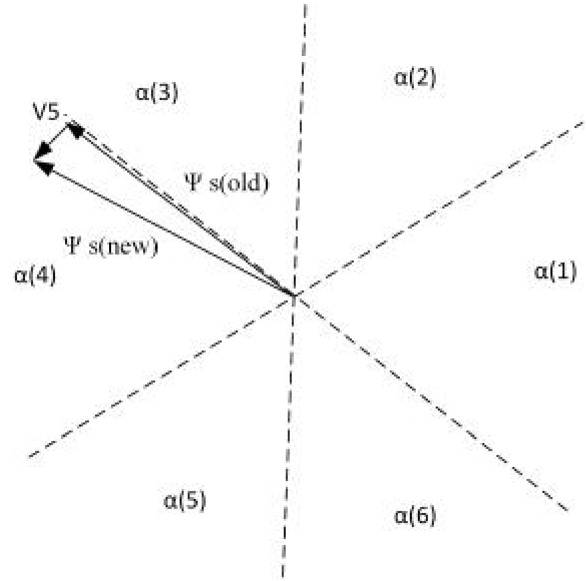

Fig. 4: Stator flux variation for

Designing of speed controller: In basic DTC, PI controller is used as speed controller. The output of the PI speed controller is acting as reference torque (T*) for the DTC system. The speed error is given as input to the PI speed controller. The SMC concept can also be used for designing a speed controller with speed error as input.

Tuning of conventional pi speed controller: The PI speed controller in basic DTC is tuned by manual tuning using trial and error method. The proportional gain (Kp) and integral gain (Ki) values are selected methodically. The Kp value is tuned initially by keeping the Ki value as zero. After amicable improvement in the system, the Ki is increased to improve the steady state error. Using trial and error method both Kp and Ki values are adjusted meticulously to get desired response.

Sliding mode controller with adaptive gain: Normally the IM is represented by the mechanical equation:

$$(J/P)\dot{\omega}_r + T_L = T_e \tag{11}$$

Where:

J = Is the inertia constant of the induction motor
T_L = Is the load torque and
ω_r = Is the angular frequency of the rotor mechanical speed. This equation can be written as:

$$\dot{\omega}_r = (T_e - T_L)(P/J) \tag{12}$$

The system has been assumed of 10% uncertainties in the parameters, so Δx can be considered as bounded uncertainties produced by the system. It should be noted that these uncertainties are unknown. Hence, the specific calculation of these uncertainties are challenging to achieve. The Eq. 12 can be rewritten as:

$$\dot{\omega}_r = (x + \Delta x)T_e + cT_L \quad (13)$$

where, x = (P/J) and c= -(P/J) . The tracking speed error can be taken as:

$$e(t) = \omega_r(t) - \overset{*}{\omega}(t) \quad (14)$$

Taking the derivative of Eq. 14 and substituting from Eq. 13:

$$\dot{e}(t) = xT_e(t) + d(t) \quad (15)$$

where, $d(t) = \Delta xT_e + cT_L$., $d(t)$ is collection of uncertainty terms.

The effect of these uncertainties can be compensated by the proposed SMC strategy. The selection of sliding gain is important in SMC for compensating the uncertainties. For selecting the appropriate sliding gain the boundaries of uncertainties and modelled dynamics should be known. But in reality the precise calculation of these components are very challenging. So the sliding gain should be made adaptive according to the system conditions.

The sliding surface s (t) can be defined as (Shyu and Shich, 1996; Barambones *et al*., 2006):

$$s(t) = e(t) - \int_0^t xke(\tau)d\tau \quad (16)$$

where, k is the constant gain. The error dynamics of the sliding surface s (t) should be made to zero. Then the error dynamics can be written as:

$$\dot{e}(t) = xke(t) \quad (17)$$

Now a variable structure speed controller with adaptive sliding gain can be written as:

$$Te = ke(t) - \beta(sgn(s(t))) \quad (18)$$

where, β is the switching gain and it is made adaptive based on the control law:

$$\beta = \gamma|s(t)| \quad (19)$$

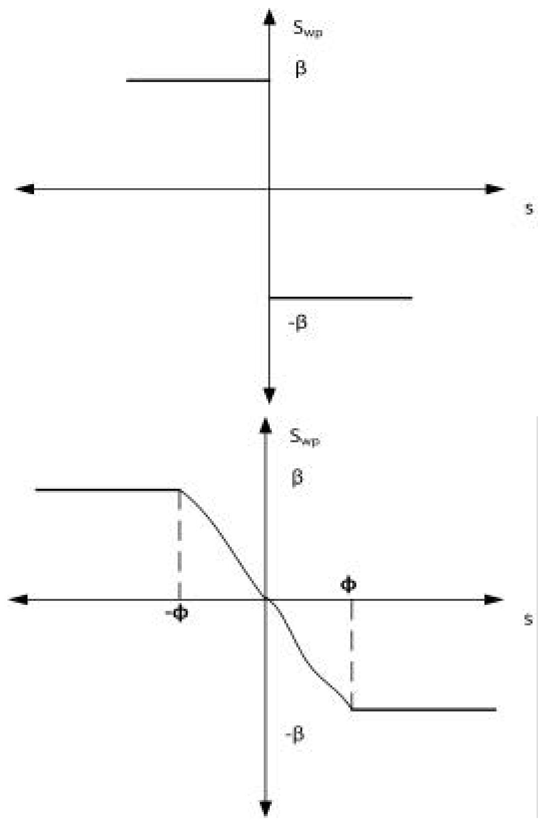

Fig. 5: Switching functions; a) Conventional sliding Mode and b) Fuzzy based sliding mode

where, γ is the positive gain constant i. e., choosing adaptive speed for sliding gain. The sign function is operated as:

$$sgn(s) = \begin{cases} 1 & for \cdot s > 0 \\ 0 & for \cdot s = 0 \\ -1 & for \cdot s < 0 \end{cases} \quad (20)$$

Generally, the control law for the output of SMC is divided into two parts sliding part (S_{lp}) and switching part (S_{wp}). The S_{lp} defines the control logic when the system is in sliding mode and S_{wp} defines the existing condition of the sliding mode:

$$S_{lp} = ke(t) \quad (21)$$

$$S_{wp} = -\beta(sgn(s(t))) \quad (22)$$

The switching control action is defined by Eq. 20. Regrettably, the use of sign function shown in Fig. 5(a,b) gives high frequency chattering. This causes a severe issue, when the system condition is in sliding surface. When this switching control action is used in DTC the problem is further developed because the DTC uses torque and flux hysteresis comparators. To avoid this

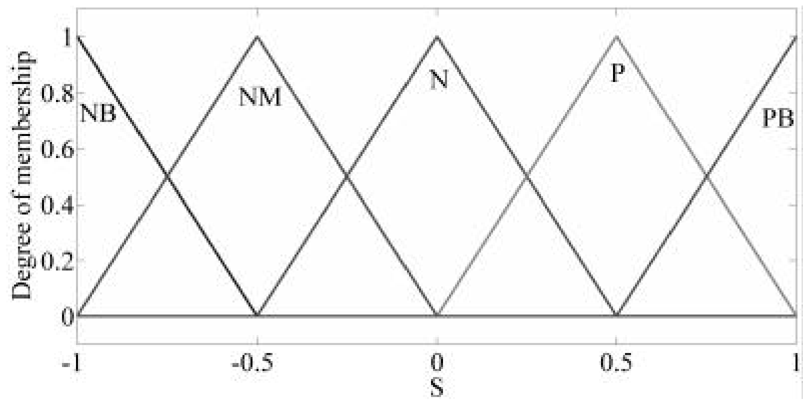

Fig. 6: Input membership functions of fuzzy SMC

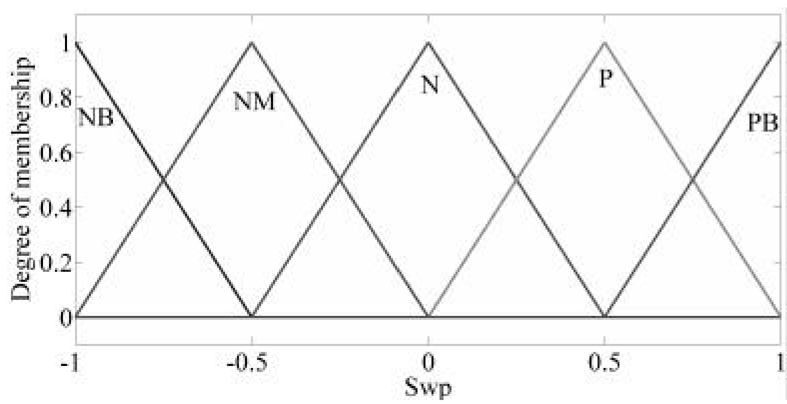

Fig. 7: Output membership functions of fuzzy SMC

issue, the sign function is introduced with a boundary layer around switching surface as in Fig. 5(a,b). The switching part of the control law can now be written as:

$$S_{wp} = -\beta(\mathrm{sgn}(s(t)/\varphi) \tag{23}$$

The ϕ is a measure of boundary layer. The saturation function can be defined as:

$$\mathrm{Sat}(s/\varphi) = \begin{Bmatrix} (s/\varphi) & \cdots\mathrm{for}\cdots|s/\varphi| \le 1 \\ \mathrm{sgn}(s/\varphi)\cdots & \mathrm{for}\cdots|s/\varphi| > 1 \end{Bmatrix} \tag{24}$$

The introduction of saturation region improves the system performance. The thickness of the boundary layer is proportional to the robustness of the system (Gadoue *et al*., 2007, 2009). In this research, the saturation region βsat (s/ϕ) in Fig. 5b is implemented using a fuzzy logic controller.

The input- output membership functions of the fuzzy logic controller are shown in Fig. 6 and Fig. 7. The simple rule base for effective sliding mode control is as follows:

- If S is NB then Swp is P
- If S is NM then Swp is PB
- If S is N then Swp is N
- If S in P then Swp is NB
- If S is PB then Swp is NM

The universe of both input and output membership functions varies from-1-1. The fuzzy inference is divided into five linguistic values {NB = Negative Big, NM = Negative Medium, N = Neutral, P = Positive, PB = Positive Big}.

RESULTS AND DISCUSSION

Simulation results: The performance improvement in DTC due to sector alteration and fuzzy SMC is analysed. The torque, flux and speed responses are investigated

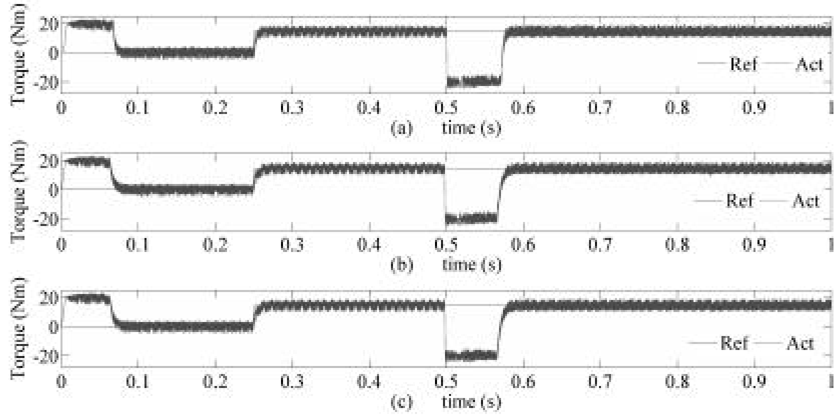

Fig. 8: Torque responses of a) Basic DTC; b) Basic with sector alteration and c) Basic DTC with sector alteration and fuzzy SMC

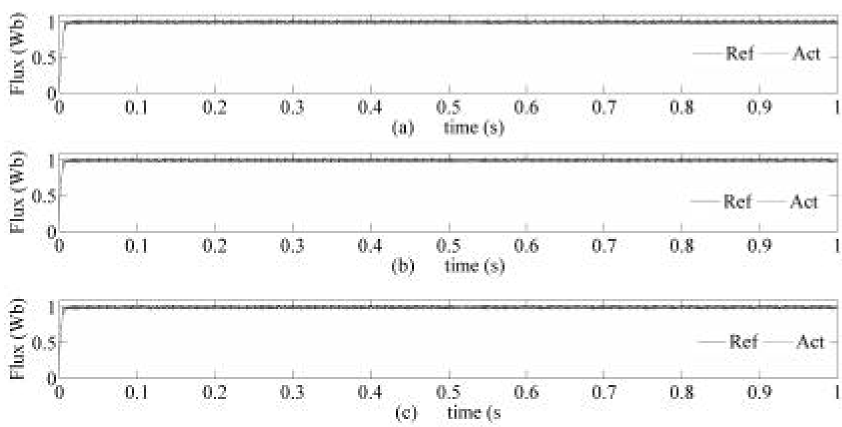

Fig. 9: Flux responses of a) Basic DTC; b) Basic with sector alteration and c) Basic DTC with sector alteration and fuzzy SMC

with the respective reference values with the aid of simulations. The basic DTC scheme shown in Fig. 1 has been developed in MATLAB/Simulink® environment. The induction motor used in this case is of 2.2 kW, 400 V and 4 pole having the following parameters $R_s = 3.67\ \Omega$, $R_r = 2.32\ \Omega$, $L_s = 0.245$ H, $L_r = 0.248$ H, $L_m = 0.235$ H and J = 0.0126 kgm^{-2}.

The induction motor in the developed system is started from standstill with reference speed (Ψ*) of 100 rad/s. Then the reference speed (Ψ*) is changed to -100 rad/s at 0.5 s. The system starts with no-load and at 0.25 s, a load disturbance of 14.6 Nm is given. It is assumed that there is 10% uncertainty in the parameters used. The sliding mode controller parameters used are = 2 and γ = 30. The torque, flux and speed responses of the DTC system with all the control strategies are simulated and given in Fig. 8-10 respectively.

Figure 8 and 9 shows the torque responses of DTC following the reference torque (T*) command in various control strategies. It can be observed that after the transient period the actual torque (Te) follows the reference torque in all the categories. The speed reversal takes place at 0.5 s, so that a slight disturbance is detected. The system overcomes it once the transient period for speed reversal is completed. The actual torque (Te) is chattering around the reference torque (T*) due to error band of torque comparator. The performance improvement due to sector alteration and fuzzy SMC will be verified by using performance indices. Fig. 9 shows the actual flux (Ψs) responses of DTC following the reference flux (Ψ*)

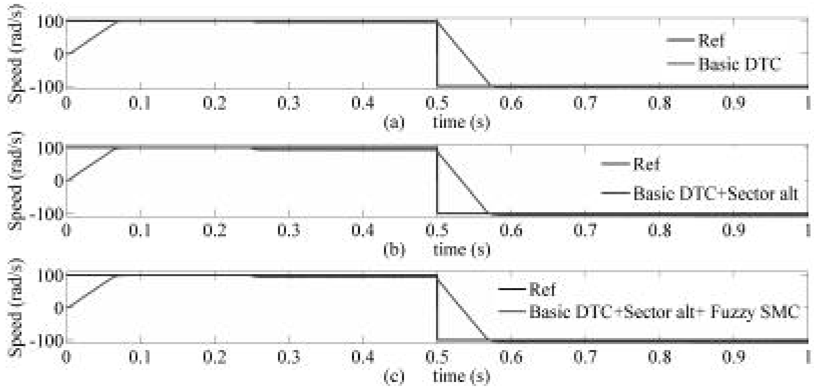

Fig. 10: Speed responses of: a) Basic DTC; b) Basic with sector alteration and c) Basic DTC with sector alteration and fuzzy SMC

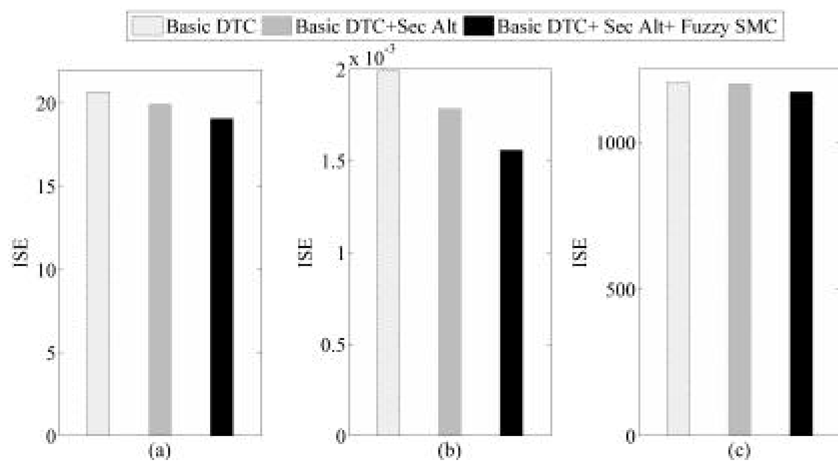

Fig. 11: Performance Index ISE for: a) Torque errorr; b) Flux error and c) Speed error

command in various control strategies. The reference flux (Ψ*) value used is 1 Wb. The reference flux (Ψ*) is maintained constant from no-load to full load and also during speed reversal conditions. Since the reference flux (Ψ*) value is not changed the actual flux (Ψs) will follow the reference flux in all the categories. The actual flux is chattering around the reference flux due to error band of flux comparator.

Figure 10 and 11 shows the speed responses of DTC, where the actual speed (ω_r) is tracking the reference speed (ω^*) during forward and reversal conditions. The fuzzy SMC is applied to overcome the parameter uncertainties and also to eliminate the rotor speed error. The PWM based Duty ratio control is used only in basic with sector alteration strategy. For basic DTC with sector alteration and fuzzy SMC, the PWM duty ratio is not required. The performance improvement in torque, flux and speed responses are computed using the performance index Integral Square Error (ISE) using the Eq. 25. The performance indices are tabulated in Table 2 and 3.

Table 2: Performance index ISE for comparison of DTC with different control strategies

Control Strategy	Torque	Flux	Speed
Basic DTC	20.69	0.001989	1207
Basic DTC and sector alteration strategy	19.94	0.001786	1200
Basic DTC, sector alteration and Fuzzy SMC	19.05	0.001558	1172

Table 3: Induction motor parameters

Parameters	Values
Stator resistance	= 3.67 Ù
Rotor resistance	= 2.32 Ù
Magnetising inductance	= 0.235 H
Stator inductance	= 0.245 H
Rotor inductance	= 0.248 H
Inertia	= 0.0126 Kgm^{-2}
Reference speed	= 100 rpm
Reference torque	= 14.6 Nm

$$ISE = \int_0^t e(t)^2 dt \quad (25)$$

The performance index (ISE) comparison in Table 2 and bar charts in Fig. 11 prove that the fuzzy SMC reduces the torque ripple, flux drooping and also provide a better speed control. By comparing the performances, the basic DTC with sector alteration proves better than basic DTC. The basic DTC with sector alteration and fuzzy SMC proves to be an optimum one than the other two control strategies. Hence, it is concluded that the basic DTC with sector alteration and fuzzy SMC provides optimal speed control with optimal torque and flux ripple reduction.

CONCLUSION

Stator flux drooping of DTC system is improved using sector alteration strategy has been used in this work. The angle of alteration is chosen based on torque and flux hysteresis comparator outputs. To improve the system further, the PI speed controller in basic DTC is replaced with an adaptive fuzzy SMC. The developed fuzzy SMC is having adaptive sliding gain and also the instantaneous sector alteration in the DTC system. The performance improvement of the proposed control strategy is verified using performance index ISE. The results clearly show that DTC system with sector alteration strategy and fuzzy based SMC reduces the flux drooping and torque ripple and also offers better speed control.

REFERENCES

Alsofyani, I.M. and N.R.N. Idris, 2016. Simple flux regulation for improving state estimation at very low and zero speed of a speed sensorless direct torque control of an induction motor. IEEE. Trans. Power Electron., 31: 3027-3035.

Barambones, O., A.J. Garrido, F.J. Maseda and P. Alkorta, 2006. An adaptive sliding mode control law for induction motors using field oriented control theory. Proceedings of the 2006 IEEE Conference on Computer Aided Control System Design and 2006 and IEEE International Conference on Control Applications and 2006 IEEE International Symposium on Intelligent Control, October 4-6, 2006, IEEE, Munich, Germany, ISBN: 0-7803-9797-5, pp: 1008-1013.

Bimal, B.K., 2012. Modern Power Electronics and AC Drives. Prentice Hall, New Jersey, USA., ISBN: 9780130167439, Pages: 711.

Depenbrock. M., 1987. Direct Self-Control (DSC) of inverter-fed induction machine. IEEE Trans. Power Electron., 3: 420-429.

Gadoue, S.M., D. Giaouris and J.W. Finch, 2007. Genetic algorithm optimized PI and fuzzy sliding mode speed control for DTC drives. Proceedings of the World Congress on Engineering, July 2-4, 2007, WCE, London, U.K., ISBN: 978-988-98671-5-7, pp: 475-480.

Gadoue, S.M., D. Giaouris and J.W. Finch, 2009. Artificial intelligence-based speed control of DTC induction motor drives-A comparative study. Electr. Power Syst. Res., 79: 210-219.

Hafeez, M., M.N. Uddin, N.A. Rahim and H.W. Ping, 2014. Self-tuned NFC and adaptive torque hysteresis-based DTC scheme for IM drive. IEEE. Trans. Ind. Appl., 50: 1410-1420.

Kaboli, S., M.R. Zolghadri, S. Haghbin and A. Emadi, 2003. Torque ripple minimization in DTC of induction motor based on optimized flux value determination. Proceedings of the 29th IEEE Annual Conference on Industrial Electronics Society IECON'03, November 2-6, 2003, IEEE, Tehran, Iran, ISBN: 0-7803-7906-3, pp: 431-435.

Li, H. and Q. Wang, 2010. Sliding mode controller based on fuzzy neural network optimization for direct torque controlled PMSM. Proceedings of the 8th World Congress on Intelligent Control and Automation (WCICA), July 7-9, 2010, Jinan, China, pp: 2434-2438.

Mei, C.G., S.K. Panda, J.X. Xu and K.W. Lim, 1999. Direct torque control of induction motor-variable switching sectors. Proceedings of the IEEE 1999 International Conference on Power Electronics and Drive Systems PEDS'99, July 27-29, 1999, IEEE, Singapore, ISBN: 0-7803-5769-8, pp: 80-85.

Park, R.H., 1929. Two-reaction theory of synchronous machines generalized method of analysis-part I. Trans. Am. Inst. Electr. Eng., 48: 716-727.

Paul, C.K., 1986. Solutions Manual to Accompany Analysis of Electric Machinery. McGraw-Hill, New York, USA., ISBN: 9780070354371, Pages: 50.

Ramesh, T., A.K. Panda and S.S. Kumar, 2014. Fuzzy logic and sliding-mode speed control based direct torque and flux control scheme to improve the performance of an induction motor drive. Int. J. Electr. Eng. Inf., 6: 155-180.

Shyu, K.K. and H.J. Shieh, 1996. A new switching surface sliding-mode speed control for induction motor drive systems. IEEE. Trans. Power Electron., 11: 660-667.

Stanley, H.C., 1938. An analysis of the induction machine. Electr. Eng., 57: 751-757.

Stojic, D., M. Milinkovic, S. Veinovic and I. Klasnic, 2015. Improved stator flux estimator for speed sensorless induction motor drives. IEEE. Trans. Power Electron., 30: 2363-2371.

Takahashi, I. and T. Noguchi, 1986. A new quick-response and high-efficiency control strategy of an induction motor. IEEE Trans. Ind. Applic., IA-22: 820-827.

Vas, P., 1998. Sensor Less Vector and Direct Torque Control. Oxford University Press, London, UK., ISBN: 9780198564652, Pages: 729.

Wong, W.S.H. and D. Holliday, 2004. Minimisation of flux droop in direct torque controlled induction motor drives. IEE. Proc. Electr. Power Appl., 151: 694-703.