Employment of torque-hysteresis controller for DTC based induction motor drive

Payal S. Borse¹, Mohan P. Thakre² & Rakesh Shriwastava³
1 2 Department of Electrical Engineering
1 2 K.K. Wagh Institute of Engineering Education and Research, Nashik-422003.
³MCOE&RC, Nashik, India
mpthakre@kkwagh.edu.in²

Abstract. To acquire high enactment, Direct Torque Control (DTC) is a technique used in AC drive systems. In this paper, based on the hysteresis controller, a very simple improved DTC scheme is proposed for induction motor drive. Owing to its simple assembly & effective enactment, DTC is used for AC as well as DC drive as compared to other controlling schemes. The paper approaches mitigation of the ripples in torque by varying the predictable 3-level torque-hysteresis controller used in DTC. The expansion of distinctive switching approach has been generated for chosen voltage-vector. Based on ripple content simulation results carried out in MATLAB/SIMULINK for torque-hysteresis controller to minimize the ripples.

Keywords: Direct Torque Control (DTC), torque ripple, Induction Motor (IM).

Nomenclature

Acronyms Description
Tₑ Electromagnetic torque (Nm)
λs Flux in the stator (wb)
λsα Flux in stator at α-axis (wb)
λsβ Flux in stator at β-axis (wb)
Vsα Voltage in stator at α-axis (volts)
Vsβ Voltage in stator at β-axis (volts)
Isα Current in stator at α-axis (ampere)
Isβ Current in stator at β-axis (ampere)
Vₛₐ, Vₛₜ, Vₛ₃ 3-φ inverter output voltage (volts)
Vₛₜ Voltage in stator at q-axis (volts)
Vₛ₃ Voltage in stator at d-axis (volts)
iₛₐ, iₛₜ, iₛ₃ 3-φ inverter output current (ampere)
iₛₜ Current in stator at q-axis (ampere)
iₛ₃ Current in stator at d-axis (ampere)

1. Introduction

Besides, commercial processes, the developments of the AC motor control mechanism are crucial. Nowadays, the Induction Motor input frequency, phase, and magnitude have changed using modern high switching frequency power converters [1-3] controlled by microcontrollers, hence the speed of the motor and torque can be controlled. Induction motor drives are controlled by the scalar control approach and the vector control approach. The induction motor module neglects the coupling effect due to just the variation of the control variable in magnitude [4,5]. Such issues have been resolved by vector control approaches, such as Field- Direct-Torque Control (DTC) strategy. Throughout the DTC control system, the electromagnetic torques, as well as the stator flux magnitude, were verifiably estimated with the help of the stator current and voltage. For induction motor drives, a new control strategy is Direct torque control (DTC) that’s recommended by Takahashi [8-10]. The direct self-
control name has been given by Depenbrock. The convenient and practical solution to drive induction motor employing DTC scheme. The realization of DTC is suitable for AC motor drives, i.e., induction motor as well as DC motor drives such as brushless dc motors, etc. [6]. The utilization of the space vector modulation (SVM) technique for DTC schemes has been established to improve the dynamic enactment as compared to [7] conventional DTC schemes. The constant switching frequency helps to activate the SVM scheme and depends on the two adjacent vectors, the inverter voltage vector is procreated in an average sense. In stator current, acquires the low ripples in torque and flux for employing SVM technique with total harmonic distortion (THD) [20]. The PI, predictive, fuzzy controller & neural networks are utilized in DTC-SVM schemes. The defects in conventional DTC are poor flux regulation and present high ripples in torque as well as flux. Reducing efficiency of motor because[16,17] vibration and noise are present in the motor due to high ripple content. Under the dynamic situations, the high torque ripple present in the conventional DTC scheme has been analyzed in a survey paper. The outcome of these ripples existing in the speed of the motor drive.

At very low speed the control of torque & flux is bulky due to high-ripples content in torque as well as current. The occurrence of high-level noise at low speed by varying inverter switching frequency. There are several methods to mitigate the ripple in torque as well as speed-consuming numerous PWM strategies [18,19]. In this paper, the modified 3-level torque-hysteresis controller in the DTC structure has been proposed. On the basis of the assortment strategy of the voltage-vector in terms of torque and flux, the driving behavior has been observed. The dynamic behaviour of the drive is enhanced by the use of the suitable selection of voltage vector strategy along with the minimization of ripple content in the torque and flux. There is no requirement for modular because hysteresis controllers are offered directly switching signals. The behavior of transient response for the motor drive is good via the hysteresis controller in the DTC scheme. The consumption of torque-hysteresis controller has been acquired the constant switching-frequency in the whole speed range with rated load. In this paper, appraisals of the conventional hysteresis controller and modifying hysteresis controller in DTC behavior are carried out in MATLAB-Simulink results.

This article has been organized as follows: the technology of DTC drive has been explained in section 2. The design of the hysteresis comparator is discussed in section 3. The simulation result for torque reverse and current reverse behavior of the Induction Motor & DC Motor is explained in section 4. The conclusion is given in section 5.

2. TECHNOLOGY OF DTC DRIVE

To employed IM In this type of DTC technology, is directly controlled the linkage flux as well as electromagnetic torque and freely by the assortment of optimal inverter voltage-vectors as shown in Figure 1. Inside the relevant flux as well as torque hysteresis comparator, the appropriate selection of voltage vectors is to restrict the flux linkage and electromagnetic torque errors. The availability of feedback is required for estimated values of flux in stator and torque [15,21]. The available feedback is in the form of stator three-phase voltage and current that transforms into a stationary axis. On the type of AC motor, the instantaneous value of torque and flux has been calculated from the flux-torque estimator. To obtain the errors in torque and flux values for the hysteresis controller in real-time can be evaluated by link with the reference input values. The Eq. (1)-(6) seems the relation between torque as well as the flux of the drive:

\[ V_{sa} = R_{s}I_{sa} + \frac{d\lambda_{sa}}{dt} \]  
\[ V_{s\beta} = R_{s}I_{s\beta} + \frac{d\lambda_{s\beta}}{dt} \]
2.1. Estimation of flux and torque

The only use of linkage flux & current in the stator is calculated for electromagnetic-torque through stator flux based on a calculator method. On its evaluation of the motor, the province of mutual and rotor inductance are deserted in it. The linkage flux only considers stator resistance has been employed in the computation of the motor [22,23]. The voltage & current output of 3-phase inverter $V_{as}$, $V_{bs}$, $V_{cs}$, $i_{as}$, $i_{bs}$, $i_{cs}$ respectively are transformed into the 2-phase stationary frame, i.e., d-q axes voltages as well as currents as shown in Eq. (7)-(10):

\[ V_{qs} = V_{as} \]  
\[ V_{ds} = \frac{1}{\sqrt{3}} (V_{cs} - V_{bs}) \]  
\[ i_{qs} = i_{as} \]  
\[ i_{ds} = \frac{1}{\sqrt{3}} (i_{cs} - i_{bs}) \]  
\[ \lambda_{qs} = \int (V_{qs} - R_s i_{qs}) dt \]  
\[ \lambda_{ds} = \int (V_{ds} - R_s i_{qs}) dt \]

\[ \lambda_{sa} = (V_{sa} - R_s I_{sa}) dt \]  
\[ \lambda_{sb} = (V_{sb} - R_s I_{sb}) dt \]  
\[ \lambda_s = \sqrt{\lambda_{sa}^2 + \lambda_{sb}^2} \]  
\[ T_e = \frac{3}{2} p(\lambda_{sa} I_{sb} - \lambda_{sb} I_{sa}) \]
2.2. Control technique of direct flux

According to Figure 2 the magnitude of reference flux is linked with resultant stator flux $\lambda_s$. The given input to the flux hysteresis comparator is the discrepancy between the reference assessment and the estimated assessment offers the error in the flux [10,25]. Within the hysteresis band, the stator flux in DTC is required to observe a circular locus by limiting its magnitude. The selection of a suitable voltage vector can be done by the stator flux touches its upper or lower hysteresis band i.e. to reduce or increase it respectively. Depend on the flux error status $d\lambda_s$ is decide the output of the flux hysteresis comparator. When $d\lambda_s$ is ‘1’ it appeals for an rise in flux and ‘0’ for the drop in flux. The $\lambda_s$ alignment need to be known for the appropriate selection of voltage vectors [8,24]. The distributed six sectors for the stator flux plane take a distinct set of voltage vectors that rise or drop the flux for each sector.

2.3. Direct control technique of torque

The predictable torque beginning with the stator currents and stator flux-linkages in Eq.9 is equated with the command torque [12]. On the side of preferring suitable voltage vectors, the torque can be increased or decreased that depend on the torque error. Within the hysteresis comparator, the torque error in DTC is limited by its magnitude [5,26]. Depend on the torque error status $dT_e$ is decide the output of the hysteresis torque comparator. When $dT_e$ is ‘1’ it appeals for an increase in torque; ‘-1’ to decrease, and ‘0’ to sustain as in torque.
3. DESIGN OF TORQUE HYSTERESIS COMPARATOR

The reference flux in stator $\lambda_s$ and torque $T_e$ significance is associated with the corresponding predictable values, and the hysteresis band controllers are processed through this error. The output of two levels flux controller, while observing the relations given by Eq.13.

$$\Delta \lambda_s = \lambda_s^* - \lambda_s$$  \hspace{1cm} (13)

$|d\lambda_s| = 1; |\lambda_s| \leq |\lambda_s^*| - |\Delta \lambda_s| : $ flux to be rised.

$|d\lambda_s| = 0; |\lambda_s| \geq |\lambda_s^*| + |\Delta \lambda_s| : $ flux to be reduced.

The actual $\lambda_s$ is restricted contained by the hysteresis comparator and trajectories the orientation of flux in a intersect path. There are three levels of the torque control output having the consequent relations in Eq.14

$$\Delta T_e = T_e^* - T_e$$  \hspace{1cm} (14)

$|dT_e| = 1; |T_e| < |T_e^*| - |\Delta T_e| : $ Torque to be rised.

$|dT_e| = -1; |T_e| > |T_e^*| + |\Delta T_e| : $ Torque to be reduced.

$|dT_e| = 0; |T_e| - |\Delta T_e| \leq |T_e^*| \leq |T_e^*| + |\Delta T_e| : $ Torque will not changed.

The stator flux and torque using the decoupled control is achieved by the stator flux linkage space vector in its locus respectively through acting on the radial and tangential modules. For all the possible space vector positions of linkage flux in stator have been the ultimate assortment of switching vectors i.e. 6 positions, resultant to the 6 sectors and 2 null vectors as presented in Figure 4. Figure 4 shows an assortment of the sector for torque-hysteresis controller-based IM drive [27]. The terminal voltage and currents of the machines are estimated from the feedback flux and torque. The Sec(k) defines the sector number in which k fluctuates from 1 to 6 where the flux vector is lies. The Figure4 described that the 60o each other apart six sectors. The requirement of the inverter, switching states, input signals ($dTe, d\lambda_s$) sectors for generating applicable voltage vector. Table 1 designated the switching states using these input signals i.e. $dTe, d\lambda_s$. 

Figure 3. Hysteresis torque comparator.
Table 1: The switching table fed by a 3-level hysteresis controller via DTC

| dα | dTα | S(1) | S(2) | S(3) | S(4) | S(5) | S(6) |
|----|-----|------|------|------|------|------|------|
| 1  | 1   | V4   | V5   | V1   | V1   | V1   | V2   |
| 0  | V0  | V7   | V0   | V2   | V0   | V7   |
| -1 | V1   | V6   | V4   | V4   | V3   | V3   |
| 0  | V4   | V6   | V1   | V2   | V5   | V4   |
| -1 | V3   | V2   | V6   | V4   | V5   | V1   |

4. RESULTS AND DISCUSSION

The conventional DTC and proposed hysteresis-based DTC are compared to execute through simulation in MATLAB/Simulink software. The flux as well as torque of the hysteresis comaprator are set to 0.01 Wb and 0.5 N-m respectively. The torque controller of proportional and integral gain is 100 and 1.5 respectively. The flux controller of proportional and integral gain equivalent values are 4000 and 250. The arrangement of IM parameters used in the simulation is shown in Table 2.

Table 2: Arrangement of IM parameter

| Parameters                  | Value     |
|-----------------------------|-----------|
| Power rating                | 3.6 KW    |
| Torque rating               | 5 Nm      |
| Flux rating                 | 0.3 Wb    |
| Speed rating                | 1400 rpm  |
| Line-line voltage rating    | 415 Volts |
| Frequency                   | 50 Hz     |
| Resistance in stator        | 0.435 Ω   |
| Resistance in rotor         | 0.820 Ω   |
| Inductance in stator        | 2 mH      |
| Inductance in rotor         | 2 mH      |
| Mutual inductance           | 63.16 mH  |
| Inertia                     | 0.089 kg.m2|
| Poles                       | 2         |
On 0.1s, the speed has reduced at 30 rad/sec & it will be constant as seen Figure5. Figure6 described that speed is reduced at 0.1 sec for 20 rad/sec, afterload fluctuation it will be again reduced & constant until 10 rad/sec at 0.1 sec. Figure7 illustrates the flux d-q frame having more ripples as linked with Figure8. As comparing to Figure 9, the torque with ripple content of 50 to 5 Nm and after applied switching performance will be constant 20 Nm at 0.4 sec with reducing the ripple content in Figure10. The behavior of speed as well as torque is shown in table 3.

Figure 5. Behaviour of speed for DTC.

Figure 6. Behaviour of speed for DTC with modifying hysteresis controller.

Figure 7. Behaviour of flux in a d-q frame for DTC.
Figure 8. Behaviour of flux in the d-q frame for DTC with modifying hysteresis controller.

Figure 9. Behaviour of torque for DTC.

Figure 10. Behaviour of torque for DTC with modifying hysteresis controller.

Table 3: Study System Performance of speed & torque

| Parameters                  | DTC                          | DTC with modifying hysteresis controller |
|-----------------------------|------------------------------|-----------------------------------------|
---                           |------------------------------|-----------------------------------------|
| Torque Response (Nm) | ±1.4 Nm  | ± 0.4 Nm |
|----------------------|----------|----------|
| Speed Response (rad/sec) | ±2.0 rpm  | ± 5 rpm  |

5. CONCLUSION

The modified in torque hysteresis band in DTC employing induction motor has been proposed in this paper. At motor speed operation, the proposed DTC does not require variation in its structure, but only modified in torque hysteresis band based on flux error shows better performance. The cost-effectiveness, simplicity, gives less computational time are the main feature of DTC. The dynamic behaviour of the drive is enhanced by the use of the suitable selection of voltage vector strategy along with the minimization of ripple content in the torque and flux. The simulation results help to verify the behavior of various parameters and the effectiveness of the proposed DTC scheme. From the analysis conclude that

- To alleviate the torque as well as flux ripple content.
- Dynamic enactment has improved.
- Speed mechanism of IM can be succeeded.

References

[1] Peter Vas, *Sensorless Vector and Direct Torque Control*, Oxford University Press, 1998.
[2] D. Casadei, G. Grandi, G. Serra and A. Tani, “Effects of flux and torque hysteresis band amplitude in direct torque control of induction machines,” *20th Int. Conf. on Industrial Electronics, Control & Instrumentation (IECON)*, vol. 1, pp.299-304, 1994.
[3] Jun-Koo Kang, Dae-Woong Chung and Seung-Ki Sui, “Direct Torque Control of Induction Machine with Variable Amplitude Control of Flux and Torque Hysteresis Bands,” Int. Conf. on Electric Machines and Drives, pp.640-642, 1999.
[4] H. F. Abdul Wahab, and H. Sanusi, “Simulink Model of Direct Torque Control of Induction Machine”, *American Journal of Applied Sciences*, vol. 5, no. 8, pp. 1083-1090, 2008.
[5] I.Takahashi, T. Nouguchi, “A new quick response and high efficiency control strategy for an induction motor,” *IEEE Trans. Ind. Application.*, vol. 22, no. 5, pp.820-827, 1986.
[6] Marin P. Kazmierdowski, “Improved direct torque and flux vector control of PWM inverter-fed induction motor drives,” *IEEE Trans. Ind. Electronics*, vol. 42, no. 4, Aug. 1995.
[7] Chin-Teng Lin and C. S. G. Lee, “Neural Fuzzy Systems: A Neuro- Fuzzy Synergism to Intelligent Systems,” *NJ: Prentice Hall*, 1996.
[8] Fatiha Zidani and Rachid Na_t Sa_d, “Direct Torque Control of Induction Motor with Fuzzy Minimization Torque Ripple” *Journal of Electrical Engineering*, vol. 56, no. 7-8, pp. 183-188, 2005.
[9] M. P. Thakre and N. P. Matake, "Alleviation of Voltage Sag-Swell by DVR Based on SVPWM Technique," 2020 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS), Chennai, India, 2020, pp. 1-6, doi: 10.1109/ICPECTS49113.2020.9336972.
[10] Hassan Halleh, Meisam Rahmani and Bahram Kimiaghaham, “Direct Torque Control of Induction Motors with Fuzzy Logic Controller” IEEE conf. on Control, Automation and Systems, Oct 14-17, 2008 in CEOX, Seoul, Korea, pp. 345-350.
[11] Ameur Fethi Aimer, Azzedine Bendiabdellah, Abdallah Miloudi, and Cherif Mokhtar, “Application of Fuzzy Logic for a Ripple Reduction Strategy in DTC Scheme of a PWM Inverter fed Induction Motor Drives” *Journal of Electrical Systems*, Special Issue No. 1, pp. 13-17, Nov. 2009.
[12] J. Mane and V. Hadke, “Performance Analysis of SRM Based on Asymmetrical Bridge Converter For Plug-in Hybrid Electric Vehicle,” *Int. Conf.on Power, Energy, Control and*
Transmission Systems (ICPECTS), Chennai, India, pp. 1-6, doi: 10.1109/ICPECTS49113.2020.9337059, 2020.

[13] L. Youb, and A. Craciunescu, “Direct Torque Minimization Torque Ripple” Proceedings of the World Congress on Engineering and Computer Science, San Francisco USA, vol. II, pp. 713-717 October 20-22, 2009.

[14] M. P. Thakre and P. S. Borse, "Analytical Evaluation of FOC and DTC Induction Motor Drives in Three Levels and Five Levels Diode Clamped Inverter," 2020 Int. Conf. on Power, Energy, Control and Transmission Systems (ICPECTS), Chennai, India, 2020, pp. 1-6, doi: 10.1109/ICPECTS49113.2020.9337015.

[15] N. Djagarov, H. Milushev, A. Varganova and J. Djagarova, "Investigation of the Influence of Hysteresis on the Characteristics of Direct Torque Control of Induction Motor," 2021 17th Conf. on Electrical Machines, Drives and Power Systems (ELMA), 2021, pp. 1-4, doi: 10.1109/ELMA52514.2021.9503038.

[16] P. K. Chowdhary and M. P. Thakre, "MMC based SRM Drives for Hybrid EV with Decentralized BESS," 2020 4th Int. Conf. on Electronics, Communication and Aerospace Technology (ICECA), Coimbatore, India, pp. 319-325, doi: 10.1109/ICECA49313.2020.9297508, 2020.

[17] S. S. Hakami, I. M. Alsofyani and K. Lee, "Torque Ripple Reduction and Flux-Droop Minimization of DTC With Improved Interleaving CSFTC of IM Fed by Three-Level NPC Inverter," in IEEE Access, vol. 7, pp. 184266-184275, 2019, doi: 10.1109/ACCESS.2019.2960685.

[18] M. Mirzaei and A. Dastfan, "A Novel Space Vector Modulation Strategy for Direct Torque Control of Induction Motors," 2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC), 2019, pp. 114-120, doi: 10.1109/PEDSTC.2019.8697236.

[19] L. Kumar, H. K. Singh, P. Kumar and S. M. Tripathi, "DTC-SCIM Drive Using Classical Switching Table & SVPWM Methods Based on PI Controller," 2020 IEEE 9th Power India Int. Conf. (PIICON), 2020, pp. 1-6, doi: 10.1109/PIICON49524.2020.9113052.

[20] Rakesh Shrivastava, Mohan Thakre, et.al, “Performance Analysis of CB-SVM Three-Phase Five-Level DCMLI Fed PMSM Drive,” Turkish Journal of Computer and Mathematics Education, Vol. No.12, 887-897, 2021.

[21] M. K. Rahim, A. Jidin, S. A. Tarusan, A. Razi, R. Sundram and H. Ismail, "Constant switching frequency using proposed controller with optimal DTC switching strategy for dual-inverter supplied drive," 2016 IEEE Int. Conf. on Power and Energy (PECon), 2016, pp. 199-204, doi: 10.1109/PECON.2016.7951559.

[22] D. H. Ganatra and S. N. Pandya, "Torque ripple minimization in Direct Torque Control based induction motor drive using a multilevel inverter," 2012 IEEE Students' Conf. on Electrical, Electronics and Computer Science, 2012, pp. 1-5, doi: 10.1109/SCEECS.2012.6184777.

[23] D. S. Maurya, M. P. Thakre, et.al, "A Detailed Comparative Analysis of Different Multipulse and Multilevel Topologies for STATCOM," Int. Conf. on Electronics and Sustainable Communication Systems (ICESC), Coimbatore, India, pp. 1112-1117, doi: 10.1109/ICESC48915.2020.9155708, 2020.

[24] R. Kennel, A. El-refaei, F. Elkady, S. Mahmoud and E. Elkholy, "Torque ripple minimization for induction motor drives with direct torque control (DTC)," Fifth Int. Conf. on Power Electronics and Drive Systems, PEDS 2003., pp. 210-215 Vol.1, doi: 10.1109/PEDS.2003.1282756, 2003.

[25] S. N. Pandya and J. K. Chatterjee, “Torque ripple minimization in DTC based induction motor drive using carrier space vector modulation technique,” Int. Conf. on Power Electronics, Drives and Energy Systems & Power India, pp. 1-7, doi: 10.1109/PEDES.2010.5712444, 2010.

[26] M. Cirrincione, M. Pucci and G. Vitale, "Direct torque control for three-level fed induction
motor drives with capacitor voltage ripple minimization," 34th Annual Conf. of IEEE Industrial Electronics, pp. 3238-3245, doi:10.1109/IECON.2008.4758479, 2008.

[27] T. K. Jadhav, et.al, "Modular Multilevel Converter with Simplified Nearest Level Control (NLC) Strategy for Voltage Balancing Perspective," Innovations in Energy Management and Renewable Resources(52042), Kolkata, India, pp. 1-8, doi: 10.1109/IEMRE52042.2021.9386740, 2021.