International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 13, No. 4, December 2022, pp. 2207~2215
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v13.i4.pp2207-2215

Torque ripple alleviation of a five-phase permanent magnet synchronous motor using predictive torque control method

Saif Talal Bahar, Riyadh G. Omar
Department Electrical Engineering, University of Mustansiriyah, Baghdad, Iraq

Article Info

Article history:

Received Aug 1, 2022
Revised Sep 12, 2022
Accepted Sep 30, 2022

Keywords:

Current ripple
Electrical drives
Predictive torque control
Switching frequency
Torque ripple

ABSTRACT

The benefits of a five-phase permanent magnet synchronous motor (PMSM) are its compact size, high fault tolerance, low voltage, and high output. The drives of this kind of machines can be enhanced using model predictive direct torque control (MP-DTC) technique. The outcomes of this technique with additional weighting factors are reduces the complexity of calculation, and reduction in current harmonics, which present in harmonic subspace in standard model predictive torque control. Decrease the low-order harmonic constituents of stator currents and alleviation torque ripple can be achieved by optimizing the objective function. Adding current limitations and switching frequency-weighting factor improves the cost function. The suggested technique can provide superior steady-state performance and keep the quick transient performing as a possible characteristic of the MP-DTC scheme. Thus, with the advantageous steady state and dynamic performing obtained concurrently, the most important aspects of the suggested system are the reduced mathematical burden, and with simplified objective functions compared to classic MP-DTC structure. The proposed method reduced the torque ripple from (3.49%) in a traditional method to (0.58%).

Corresponding Author:

Saif Talal Bahar
Department Electrical Engineering, University of Mustansiriyah
Falastin St. Baghdad, Iraq
Email: eema2009@uomustansiriyah.edu.iq

1. INTRODUCTION

Although PMSMs have been around for some time, they have recently been a popular choice for applications that need faster torque to inertia ratios, efficiency, and a great density of power [1]. This is due to their numerous advantages over other conventional three-phase motors, including enhanced fault - tolerant or advantageous reliability, which means fewer stator phase currents and thus lesser converter costs by using semiconductor switches with smaller current ratings [2], and [3]. Because of these advantages, multi-phase devices have prospective applications in marine electric propulsion, electric vehicles (EVs), more electric aircrafts, locomotive tractions, and various power applications [4]. Methods such as field-oriented control (FOC) with pulse-width modulation (PWM) are provided in the literature to improve the steady state and dynamic performances of the interior permanent magnet synchronous motor (IPMSM) drive [5]. Depending on how well the outer and inner control loops function, the FOC-PWM system may be either good or bad. The low bandwidth of this control method is a major negative since it results in poor transient-state control performance [6]. To enhance the dynamic performance of ac machines that need quick transient reactions, an alternative direct torque control (DTC) technique has been presented. By comparing the torque and predicted stator flux linkage values to the directed signals, the standard DTC technique chooses the ideal stator voltage vectors [7]. However, the hysteresis bandwidth places constraints on the magnitude of torque and flux ripples. Recently, it has been shown that model predictive control (MPC) is an effective method for dealing with the constraints and non - linarites of plants with many inputs and outputs. In order to determine a desired switching state, the MPC system uses a straightforward and optimum control structure that reduces control parameter errors. Model predictive direct torque control (MP-DTC) combines this with the standard DTC to provide superior PMSM drive control. In contrast to traditional DTC and FOC with SVM, the MP-DTC technique is founded on the idea of optimum control [8]. The optimal switching states may be obtained by designing an objective function to reduce torque and stator flux control inaccuracy. There has been a lot of interest in MP-DTC owing to its slight control construction and rapid dynamic response [9]. The torque and flux of the motor are used as the control variables in this algorithm. If currents are sampled from each possible voltage vector, then torque and flux may be predicted at a future interval. The computed error values may be utilized to select which voltage vectors have the greatest impact on the cost function. The cost function may be used to select the best nominee voltage vector for the following interval. However, the process of verifying all possible voltage vectors is a computationally intensive one [10]. The cost function's torque and flux terms should be given a weighting factor to account for the two quantities varying sizes. Various weighting factors will have an impact on the performance of the control [11], [12]. Flux and torque errors are included in the cost function and may be used to assess the relative importance of various voltage vector candidates [13]. For the next interval, the voltage vector with the lowest cost function may be picked as the best option. As a result, it requires a lot of computer capabilities to go through all possible voltage vectors [14]. A proper weighting factor should be included to account for the differing lengths of Torque and Flux in the objective function. The performance of a control system may be affected by the weighting factor used. In MP-DTC [15]. Even with this, the test of all voltage vectors is a time-consuming and cumbersome procedure. To make the control group more effective, [16], [17] offered a streamlined technique for doing so. A low-complexity MP-DTC method was presented in [18], [19].

In this paper, an enhanced MPTC approach with reduced computational overhead is suggested for five-phase permanent magnet synchronous motor (PMSM) driving systems. Initially, to get rid of harmonic currents and cut down on computing complexity. Secondly, the suggested MPTC approach may preserve a quick dynamic reaction while further reducing computing complexity by excluding redundant switching states from every control period. Finally, simulation compares the suggested MP-DTC's control performance to that of the conventional MP-DTC schemes.

2. MP-DTC WORKING STEPS AND SYSTEM MODEL

2.1. Five-phase inverter model

Figure 1 depicts the structure of a two-level inverter powering a five-phase PMSM, where the inverter's DC supply voltage (*Vdc*). The leg's switching states are represented by the binary states variables(Sa, Sb, Sc, Sd, Se). These variables indicate the leg switching states in order: leg a (S1–S2), leg b (S3–S4), leg c (S5–S6), leg d (S7-S8) and leg e (S9-S10). To avoid a DC link short, the switches on each leg should operate in tandem. Switches “1” and “0” indicate which switch is on and which is off; “1” indicates the highest switch is on and “0” indicates the lowest switch is off [20], [21]. The voltage vectors that correspond to the varying configurations of switching states are specified [22]. There are 32 voltage vectors in all, containing 30 effective voltage vectors and 2 zero-voltage vectors [23].

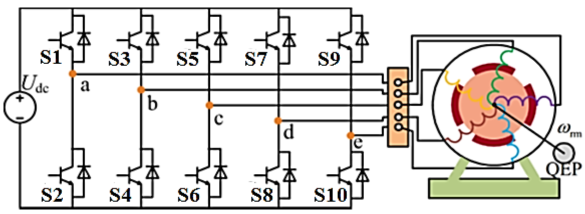
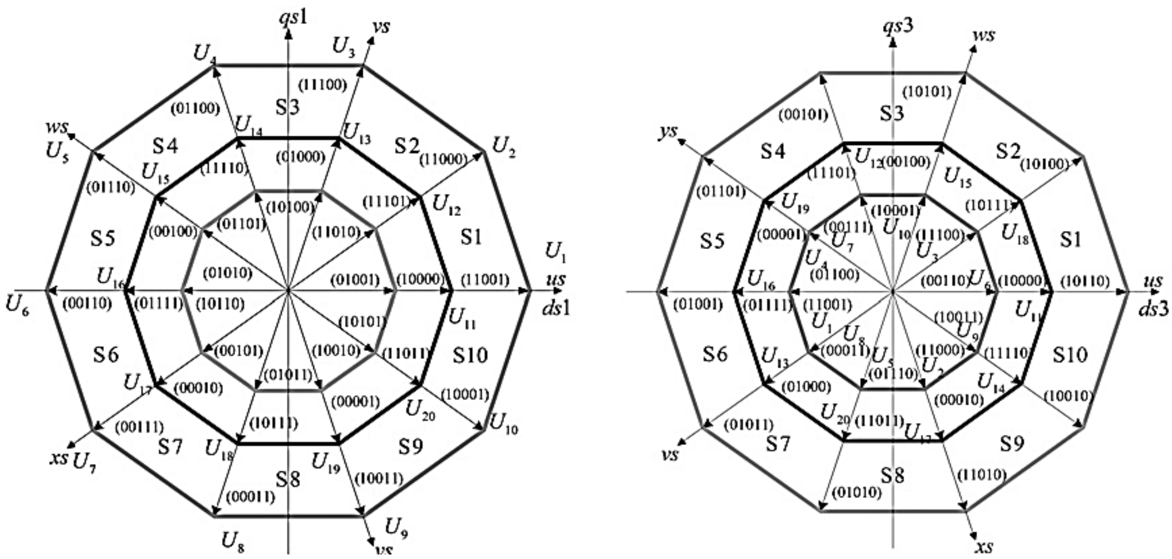


Figure 1. Five-phase inverter

Two zero voltage vectors and thirty active voltage vectors make up the 32 switching states of a five-phase inverter. Both d1-q1 and d3-q3 are 2D subspaces that include all five phases' variables. The 2 subspaces and the corresponding switching vectors are shown in Figure 2. There are 30 voltage vectors in the active space; they are divided into three groups based on their amplitudes: large (U1-U10), medium (U11-U20), and small (U21–U30). Figure 2 displays the space plane design divided into 10 equal sections.



(a) (b)

Figure 2. The 30 effective voltages vector on (a) $(d1 - q1\ axis)$, and (b) $(d3 - q3\ axis)$

2.2. Five-phase PMSM model

It is shown in many literatures that the five-phase PMSM has a good performance due to: minimal core saturation, exclusion of eddy current. The following equations describe the 5- phase surface-mounted PMSM with sinusoidal distributed windings in a synchronous rotating frame [24], [25]:

$$V_{sq1} = R_s * i_{q1} + w_r * \Phi_{d1} + * \frac{d}{dt}\Phi_{q1} \quad (1)$$

$$V_{sd1} = R_s * i_{d1} - w_r * \Phi_{q1} + * \frac{d}{dt}\Phi_{d1} \quad (2)$$

$$V_{sq3} = R_s * i_{q3} + * \frac{d}{dt}\Phi_{q3} \quad (3)$$

$$V_{sd3} = R_s * i_{d3} + * \frac{d}{dt}\Phi_{d3} \quad (4)$$

$$\Phi_{sq} = Lq * iq \quad (5)$$

$$\Phi_{sd} = Ld * id + \Phi_f \quad (6)$$

$$T_e = 2.5 * p * iq * \Phi_f \quad (7)$$

where, Φ_{d1} and Φ_{q1} are the flux in $d1 - q1$ axis Φ_{d3} and Φ_{q3} are the harmonic flux in $d3 - q3$ axis.

2.3. Predictive current

The motor d-q currents can be discretized according to the core idea of predictive control. The sample period Ts is used, at the same time; the $(k + 1)$time current is a prediction of that one at the (k) period. The discrete linear (time-consistent) system is developed in (8) and (9).

$$i_d(k + 1) = \left(1 - \frac{R_s * Ts}{Ld}\right) i_d + \left(\frac{w_r * Lq * Ts}{Ld}\right) i_q + \left(\frac{Ts}{Ld}\right) V_{sd} \quad (8)$$

$$i_q(k + 1) = \left(1 - \frac{R_s * Ts}{Lq}\right) i_q - \left(\frac{w_r * Ld * Ts}{Lq}\right) i_d + \left(\frac{Ts}{Ld}\right) V_{sq} - \frac{w_r * \Phi_{f*Ts}}{Lq} \quad (9)$$

2.4. Predictive torque

To obtain a discrete equation representing the motor torque, another use of the Euler method is utilized. If the sampling time is Ts, and the motor current is predicted at (k+1) time, while the actual one is measured at the instant (k).

$$\Phi_{sq}(k+1) = Lq * i_{sq}(k+1) \quad (10)$$

$$\Phi_{sd}(k+1) = Ld * i_{sd}(k+1) + \Phi_f \quad (11)$$

$$\Phi_s(k+1) = \sqrt{(\Phi_{sd}(k+1))^2 + (\Phi_{sq}(k+1))^2} \quad (12)$$

$$T_e(k+1) = \frac{5}{2}\left(\frac{p}{2}\right)(\Phi_{sd}(k+1) * i_{sq}(k+1) - \Phi_{sq}(k+1) * i_{sd}(k+1)) \quad (13)$$

3. THE CONVENTIONAL MP-DTC METHOD

The model prediction method only affects the system's performance once the prediction model has been established. Because the $(d3 - q3)$ subspace affects the five-phase motor differently from the three-phase one, it is required to regulate the flux not only using the $(d1 - q1)$ subspace, but also using the $(d3 - q3)$ subspace as well. You may use a prediction step to determine which voltage vector will best control the target after establishing the objective function. The full procedures are as follows, with a control block diagram of the traditional MP-DTC system shown in Figure 3. Therefore, in the 5 phase -PMSM system, the objective function (g) will be selected as:

$$g = \left(\frac{Tref - T_e(k+1)}{Tref}\right)^2 + \lambda 1 \,.\left(\frac{\Phi_{ref} - \Phi_{s1}(k+1)}{\Phi_{ref}}\right)^2 + \lambda 2 \,.\left(\frac{\Phi_{ref3} - \Phi_{s3}(k+1)}{\Phi_{ref3}}\right)^2 \quad (14)$$

$\lambda 1 = \frac{Ten}{\psi en}$, $\lambda 2 = \frac{Ten1}{\psi en1}$, Where, λ1, and λ2 are the weight coefficients of flux linkage.

The procedure control of traditional MP-DTC: i) Measure stator currents; ii) Measure rotor speed; iii) Tuning PI controller; iv) Calculate predictive current; v) Calculate predictive torque; vi) Calculate the cost function value for each prediction; and vii) Select the voltage vector that can reduce objective function.

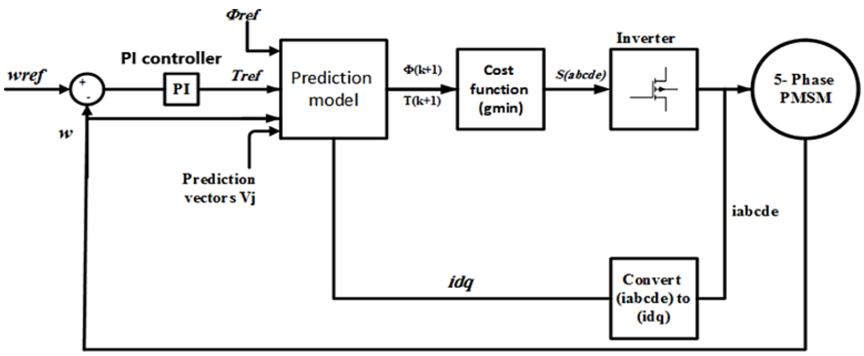


Figure 3. The traditional five-phase motor MP-DTC system

4. THE PROPOSED MP-DTC METHOD

Figure 4 depicts the control circuit for the proposed MP-DTC method. In a sinusoidally wound five-phase permanent magnet synchronous motor (PMSM), only the fundamental components in $(d1 - q1)$ subspace is implicated in the electromechanical energy conversion process, and the voltages in $(d3 - q3)$ subspace will generate enormous harmonic currents, leading to stator current distortion and the additional copper losses. It is possible to get rid of the $(d3 - q3)$ subspace harmonics. As a result, the harmonic terms $(\Phi_{s3}(k+1))$ are no longer obligatory in the cost function. The full procedures are as follows, with a control block diagram of the proposed MP-DTC system shown in Figure 4. Two more constraint on the cost-function are added to these papers as a suggested improvement. The over-current protection term, is represented by the first one (Im), which is current upper limit. The switching frequency weighting factor (Sw) is used to improve the objective function as a second. The final objective function (g) equation is specified in this proposed procedure is:

$$g = \left(\frac{Tref - T_e(k+1)}{Tref}\right)^2 + \lambda 1 \,.\left(\frac{\Phi_{ref} - \Phi_{s1}(k+1)}{\Phi_{ref}}\right)^2 + (i_{dref} - i_d(k+1))^2 + Im + Sw \quad (15)$$

$$Sw = |Sa(k+1) - Sa(k)| + |Sb(k+1) - Sb(k)| + |Sc(k+1) - Sc(k)| + |Sd(k+1) - Sd(k)| + |Se(k+1) - Se(k)| \quad (16)$$

$$Im = \begin{cases} 0, & i_s(k+1) < i_{max} \\ \infty, & i_s(k+1) > i_{max} \end{cases}$$

$i_s(k+1) = \sqrt{i_d(k+1)^2 + i_q(k+1)^2}$ where, $i_s(k+1)$ maximum anticipated stator current, that is permitted. The term Ten is the rated torque, and ψen is the PM flux linkage. $Tref$ Denotes to the torque reference. $T_e(k+1)$Moreover, $\Phi_s(k+1)$ are the predictive electromagnetic torque, and stator flux predictive value. While λ1 is a weighting factor, (Φ_{ref}) represents the reference flux value, i_{dref} is the current reference, and $i_d(k+1)$ represents the predictive current.

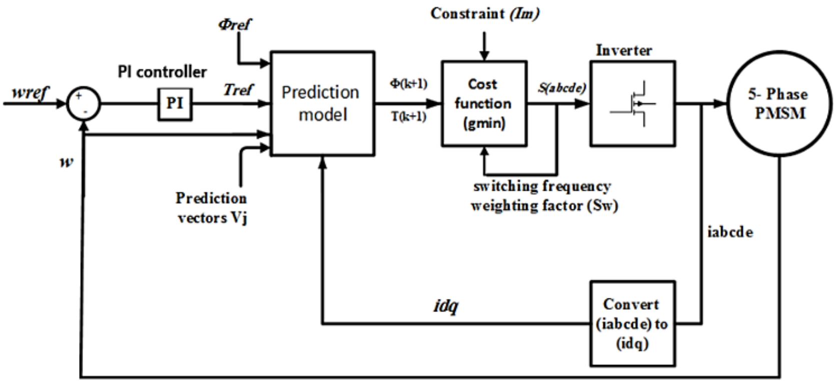


Figure 4. The proposed five-phase motor MP-DTC system

5. RESULTS AND DISCUSSION

The simulation is carried out via MATLAB/Simulink 2021 package. Figure 5 shows the proposed circuit for MP-DTC, the simulation scheme has six principal components: PI control, switching frequency weighting factor, Rotation calculation, predictive torque control algorithm, converter model, and the 5-phase PMSM Model. The system parameters are: rated speed (w_m) = 700 rpm, DC-link voltage = 150 V, p = 4, Ld = 12.4 mH, Lq = 14.3 mH, Rs = 0.5 Ω, load torque = 10 Nm, PM flux = 0.09 wb, frequency = 50 Hz, J = 0.02 $kg.m^2$,Ts = 2µs. The parameters of PI controller proportional gain Kp = 300, integral gain Ki = 2. A MATLAB function linked with the prediction algorithm to execute it. Depending on the system model, this component performs the objective functions of the optimization process. The reference flux, rotor speed, and actual stator currents are all inputs to this sub-system, whereas the gates indications to the converter are the outputs. Figure 6 shown the reference speed and actual speed.

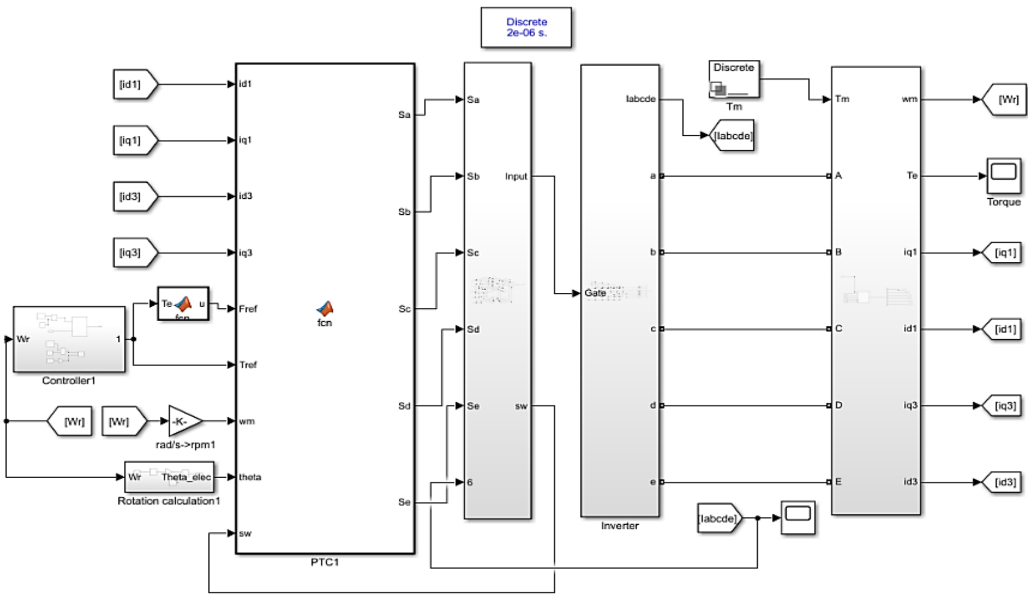


Figure 5. Block diagram of the proposed system

Even though it is incorporated in the cost function, harmonic current with the $(d3)$ and $(q3)$ axes is not adequately reduced when using a conventional MP-DTC. Although the stator current seems to be generally sinusoidal in Figure 7, there is a degree of distortion. As shown in Figure 7, torque exhibits large fluctuations as well show in Figure 8. Figures 9 and 10 shows the improvement in MP-DTC stator current and torque. The $(d3-q3)$subspace may be neglected. In this way, it is evident that the stator current has a perfect sine wave, but its distortion has been nearly completely reduced, resulting in an overall smooth waveform. At the same period, the torque ripple has been much decreased as well.

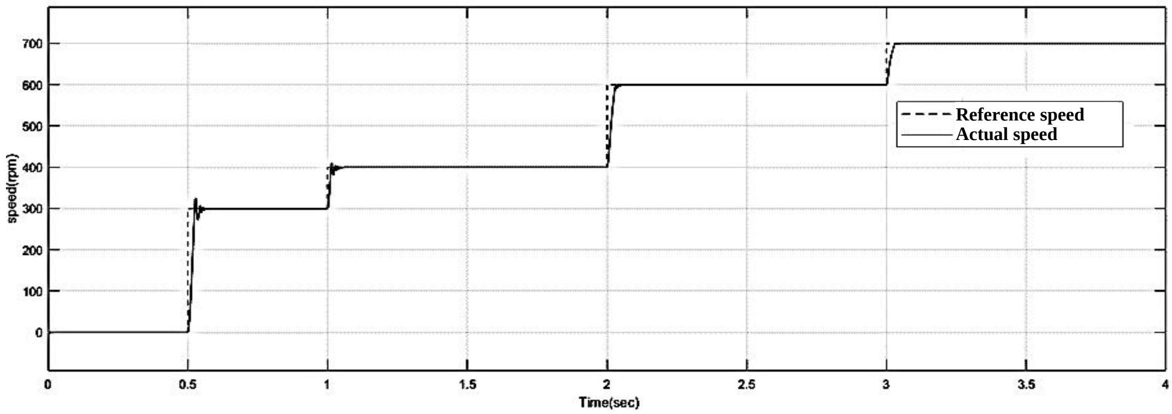


Figure 6. Reference speed and actual speed

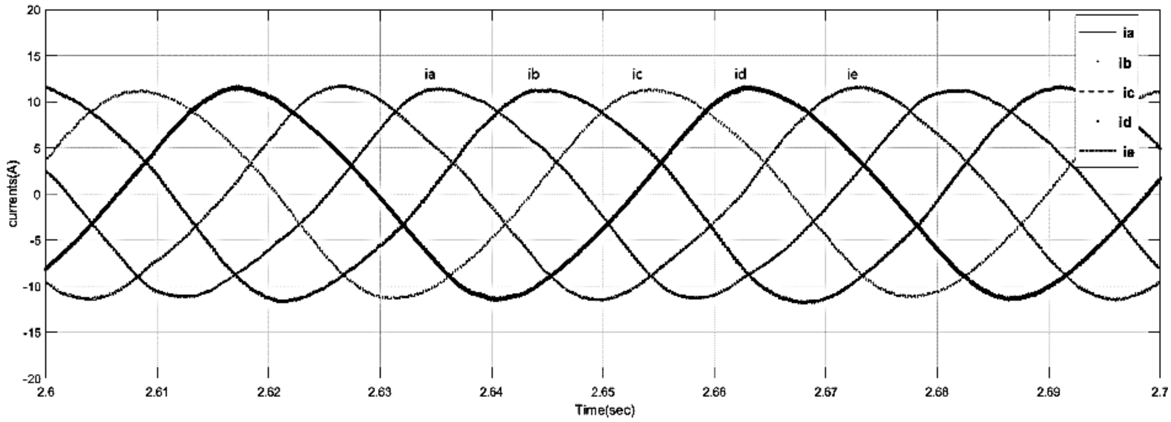


Figure 7. Measured 5-phase motor currents without constraint

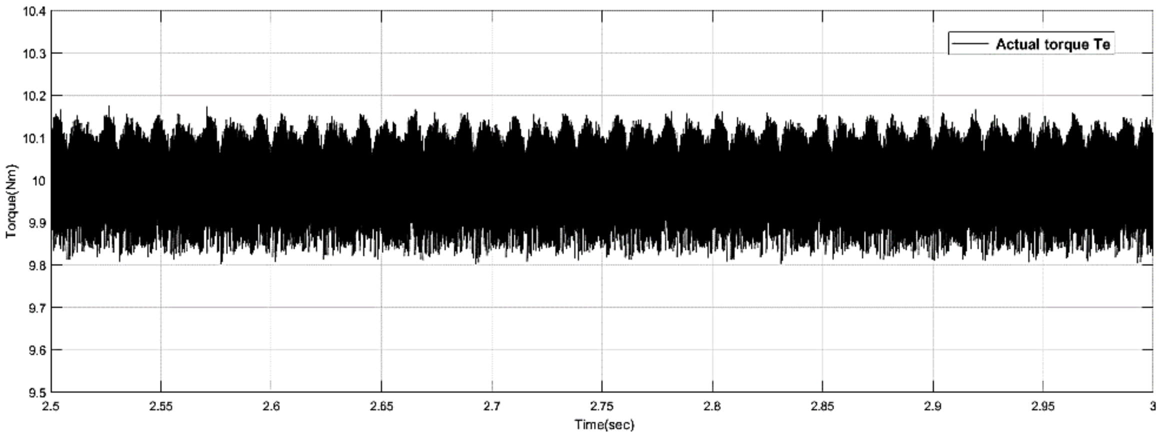


Figure 8. The actual torque in conventional MP-DTC

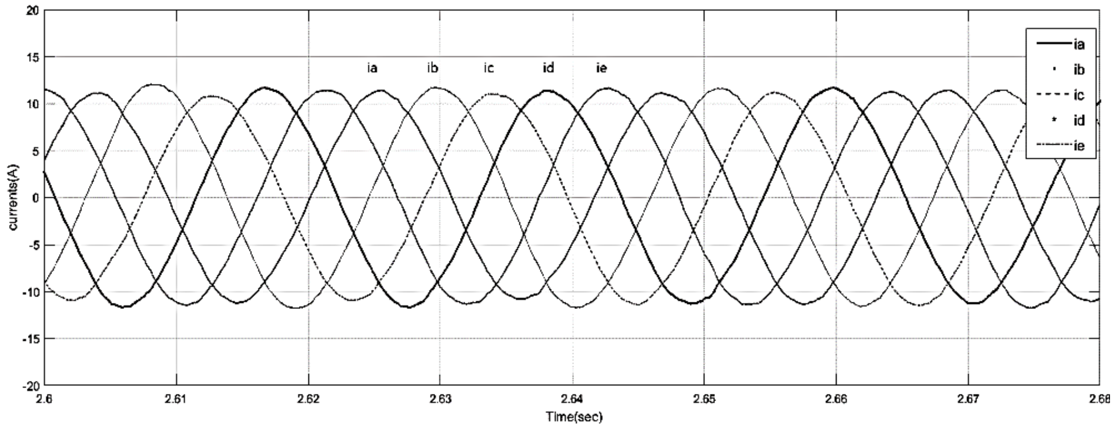


Figure 9. Measured 5-phase motor currents with constraint

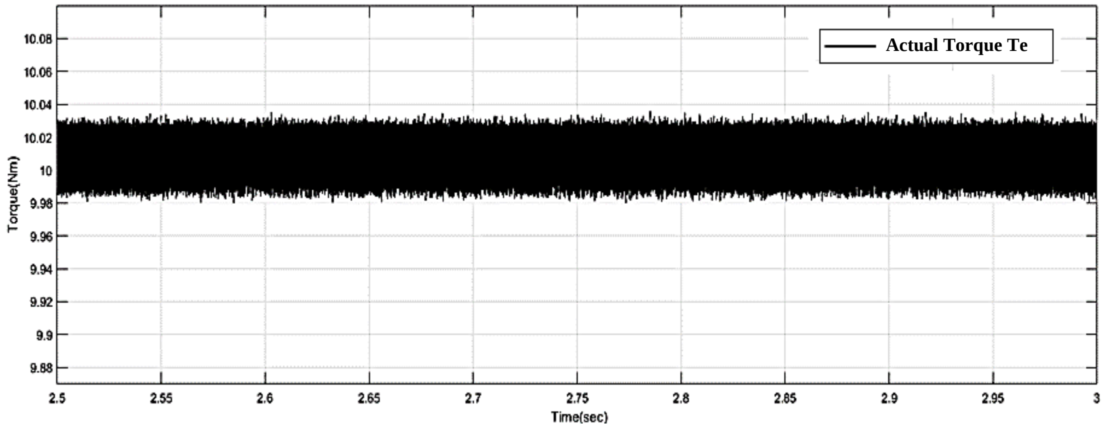


Figure 10. The actual torque in the proposed MP-DTC method

Figures 11 and 12, illustrate the increase in the harmonic currents content represented by total harmonic distortion (THD) when the conventional MP-DTC and decrease THD when the proposed constraint is applied. The proposed method in Figure 5 gives a less ripple in the torque and low THD (7.11%) for current. The result was compared with another reference [26]; the value of ripple in torque is higher than the proposed method. In addition, THD for current is large. The ratio of the difference between the greatest and smallest torque peaks of each control technique and the average torque values are used to determine the torque ripples:

$$Te,rip = \frac{T_{e,max}-T_{e,min}}{T_{e,ave}} \quad (17)$$

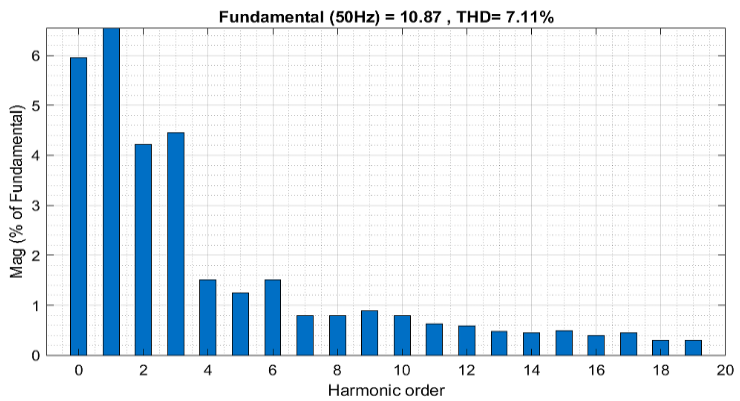


Figure 11. THD for current with constraint

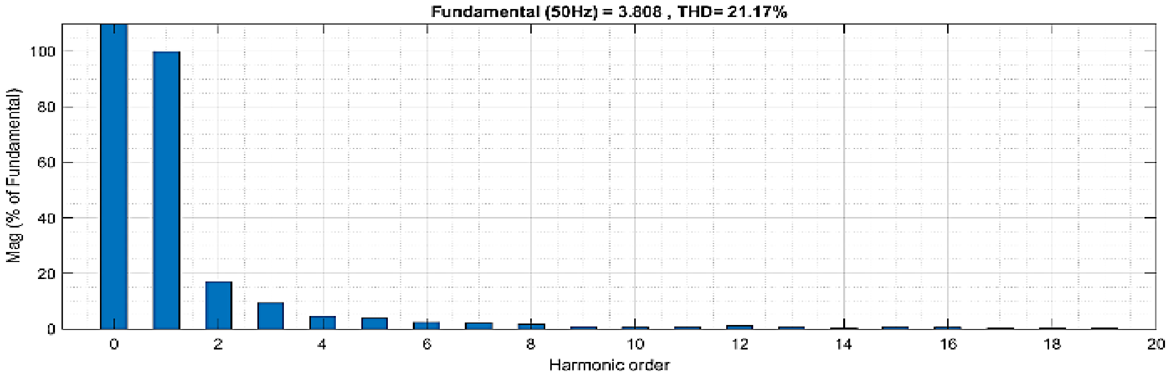


Figure 12. THD for current without constrain

6. CONCLUSION

For applications like aerospace and electric cars, five-phase permanent magnet synchronous motors (PMSMs) include the advantages of rapid fault tolerance and rapid torque per ampere. However, designing a controller for a complicated machine model presents a number of issues. In addition, with Thirty-two voltage vectors with varying impacts on current and torque. This paper presents a low-complexity MP-DTC approach that can produce quick dynamic response and good steady state performance in a 5-phase PMSM drive system. The enhanced MP-DTC may greatly minimize the motor's torque ripple and the distortions in the stator currents. This can be verified in the simulation outcomes. In order to develop the motor performance, the accuracy of the procedure is confirmed. By adjusting the weighting factor SW the importance of the switching frequency can be set. In situations where the switching losses are important SW can be increased to fulfil these requirements. The weighting factor's value must be determined experimentally, via trial and error. The constraints are a safety feature, which limits the current output magnitude. Can be added to the cost function. The benefits of the suggested MP-DTC system may be described in light of a comparison with the conventional MP-DTC method, as follows: The proposed technique has advantageous stator currents, notably for reducing low-order harmonics, it achieves low torque ripple and has outstanding steady-state performance over the whole speed range. Furthermore, it features top-notch dynamic performance and Decrease calculation complexity and it can remove the (d3-q3) subspace harmonics and improve the objective functions.

ACKNOWLEDGEMENTS

To the teachers of Mustansiriyah University, the writers would like to express their thanks for their aid and advice.

REFERENCES

[1] R. G. Shriwastava, M. P. Thakare, K. V. Bhadane, M. S. Harne, and N. B. Wagh, "Performance enhancement of DCMLI fed DTC-PMSM drive in electric vehicle," *Bulletin of Electrical Engineering and Informatics (BEEI)*, vol. 11, no. 4, pp. 1867-1881, 2022, doi: 10.11591/eei.v11i4.3714.

[2] F. Wu and J. Zhao, "A real-time multiple open-circuit fault diagnosis method in voltage-source-inverter fed vector controlled drives," *IEEE Transactions on Power Electronics*, vol. 31, no. 2, pp. 1425-1437, Feb. 2016, doi: 10.1109/TPEL.2015.2422131.

[3] H. Chen, X. Liu, J. Zhao and N. A. O. Demerdash, "Magnetic-coupling characteristics investigation of a dual-rotor fault-tolerant PMSM," *IEEE Transactions on Energy Conversion*, vol. 33, no. 1, pp. 362-372, March 2018, doi: 10.1109/TEC.2017.2747519.

[4] S. Alves de Souza and W. Issamu Suemitsu, "Five-phase permanent-magnet synchronous motor," *IEEE Latin America Transactions*, vol. 15, no. 4, pp. 639-645, April 2017, doi: 10.1109/TLA.2017.7896349.

[5] O. Wallmark, S. Lundberg and M. Bongiorno, "Input admittance expressions for field-oriented controlled salient PMSM drives," *IEEE Transactions on Power Electronics*, vol. 27, no. 3, pp. 1514-1520, March 2012, doi: 10.1109/TPEL.2011.2118231.

[6] S. Sadeghi, L. Guo, H. A. Toliyat and L. Parsa, "Wide operational speed range of five-phase permanent magnet machines by using different stator winding configurations," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 6, pp. 2621-2631, June 2012, doi: 10.1109/TIE.2011.2164771.

[7] Y. Zhang and J. Zhu, "Direct torque control of permanent magnet synchronous motor with reduced torque ripple and commutation frequency," *IEEE Transactions on Power Electronics*, vol. 26, no. 1, pp. 235-248, 2011, doi: 10.1109/TPEL.2010.2059047.

[8] S. S. Yeoh, T. Yang, L. Tarisciotti, C. I. Hill, S. Bozhko and P. Zanchetta, "Permanent-magnet machine-based starter–generator system with modulated model predictive control," *IEEE Transactions on Transportation Electrification*, vol. 3, no. 4, pp. 878-890, Dec. 2017, doi: 10.1109/TTE.2017.2731626.

[9] S. -C. Carpiuc and C. Lazar, "Fast real-time constrained predictive current control in permanent magnet synchronous machine-based automotive traction drives," *IEEE Transactions on Transportation Electrification*, vol. 1, no. 4, pp. 326-335, Dec. 2015, doi: 10.1109/TTE.2015.2482223.

[10] L. Parsa and H. A. Toliyat, "Five-phase permanent magnet motor drives for ship propulsion applications," in *IEEE Electric Ship Technologies Symposium*, 2005., 2005, pp. 371-378, doi: 10.1109/ESTS.2005.1524702.
[11] C. A. Rojas, J. Rodriguez, F. Villarroel, J. R. Espinoza, C. A. Silva and M. Trincado, "Predictive torque and flux control without weighting factors," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 2, pp. 681-690, Feb. 2013, doi: 10.1109/TIE.2012.2206344.
[12] S. Vazquez, J. Rodriguez, M. Rivera, L. G. Franquelo and M. Norambuena, "Model predictive control for power converters and drives: advances and trends," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 2, pp. 935-947, Feb. 2017, doi: 10.1109/TIE.2016.2625238.
[13] J. Rodriguez *et al*., "Predictive current control of a voltage source inverter," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 1, pp. 495-503, Feb. 2007, doi: 10.1109/TIE.2006.888802.
[14] M. Siami, H. K. Savadkoohi, A. Abbaszadeh, D. A. Khaburi, J. Rodriguez and M. Rivera, "Predictive torque control of a permanent magnet synchronous motor fed by a matrix converter without weighting factor," *Power Electronics and Drive Systems Technologies Conference (PEDSTC)*, 2016, pp. 614-619, doi: 10.1109/PEDSTC.2016.7556930.
[15] M. Cheng, F. Yu, K. T. Chau and W. Hua, "Dynamic performance evaluation of a nine-phase flux-switching permanent-magnet motor drive with model predictive control," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 7, pp. 4539-4549, July 2016, doi: 10.1109/TIE.2016.2547858.
[16] Y. Zhang and H. Lin, "Simplified model predictive current control method of voltage-source inverter," *International Conference on Power Electronics - ECCE Asia*, 2011, pp. 1726-1733, doi: 10.1109/ICPE.2011.5944459.
[17] A. Akay, P. Lefley and M. Kansara, "Open-circuit fault-tolerant control for a five-phase permanent magnet synchronous machine drive," *International Conference on Electrical and Electronics Engineering (ICEEE)*, 2020, pp. 150-154, doi: 10.1109/ICEEE49618.2020.9102486.
[18] X. Wu, W. Song and C. Xue, "Low-complexity model predictive torque control method without weighting factor for five-phase PMSM based on hysteresis comparators," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 4, pp. 1650-1661, Dec. 2018, doi: 10.1109/JESTPE.2018.2849320.
[19] W. Zhao, T. Tao, J. Zhu, H. Tan and Y. Du, "A novel finite-control-set model predictive current control for five-phase PM motor with continued modulation," *IEEE Transactions on Power Electronics*, vol. 35, no. 7, pp. 7261-7270, July 2020, doi: 10.1109/TPEL.2019.2954285.
[20] W. Zhao, Z. Li, J. Xu, H. Zhang, and Y. Yuan, "Novel fuzzy direct torque control based on constructed functional transformed grey model," *Journal of Power Electronics*, vol. 21, pp. 901-910, 2021, doi: 10.1007/s43236-021-00236-6.
[21] L. Parsa and H. A. Toliyat, "Sensorless direct torque control of five-phase interior permanent-magnet motor drives," in *IEEE Transactions on Industry Applications*, vol. 43, no. 4, pp. 952-959, July-aug. 2007, doi: 10.1109/TIA.2007.900444..
[22] Y. N. Tatte, M. V. Aware, J. K. Pandit and R. Nemade, "Performance improvement of three-level five-phase inverter-fed DTC-controlled five-phase induction motor during low-speed operation," *IEEE Transactions on Industry Applications*, vol. 54, no. 3, pp. 2349-2357, May-June 2018, doi: 10.1109/TIA.2018.2798593.
[23] R. G. Omar, "Modified FCS-MPC algorithm for five-leg voltage source inverter," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 19, no. 1, pp. 47-57, doi: 10.11591/ijeecs.v19.i1.pp47-57.
[24] A. Hosseyni, R. Trabelsi, M. F. Mimouni and A. Iqbal, "Vector controlled five-phase permanent magnet synchronous motor drive," in *IEEE International Symposium on Industrial Electronics (ISIE)*, 2014, pp. 2122-2127, doi: 10.1109/ISIE.2014.6864945.
[25] C. Xue, W. Song, and X. Feng, "Finite control-set model predictive current control of five-phase permanent-magnet synchronous machine based on virtual voltage vectors," *IET Electric Power Applications*, vol. 11, no. 5, pp. 836-846, 2017, doi:10.1049/iet-epa.2016.0529.
[26] G. Li, J. Hu, Y. Li and J. Zhu, "An improved model predictive direct torque control strategy for reducing harmonic currents and torque ripples of five-phase permanent magnet synchronous motors," in *IEEE Transactions on Industrial Electronics*, vol. 66, no. 8, pp. 5820-5829, 2019, doi: 10.1109/TIE.2018.2870359.

BIOGRAPHIES OF AUTHORS

Saif Talal Bahar received his BSc. degree in Power and Electrical Machine Engineering from Diayla University, Diayla, Iraq. He is currently pursuing his MSc. degree in Electrical Engineering at Mustansiriyah University, Baghdad, Iraq. He was working Electrical Engineer in the Electrical Department of Baquba Technical Institute at Middle Technical University, Baghdad, Iraq. His research interests include Power Electronics & Electrical Machine. He can be contacted at email: eema2009@uomustansiriyah.edu.iq.

Riyadh G. Omar is an Assist. Prof. in the Electrical Engineering Department, Mustansiriyah University, Baghdad-Iraq, for 18 years in Power System Analysis & Power Electronics. He is a member of the electrical engineering department council. He has many publications mainly in power electronics and predictive control. He can be contacted at email: riyadh.g.omar@uomustansiriyah.edu.iq.