Improved Direct Torque Control Utilizing Model Predictive Control Approach for Permanent Magnet Synchronous Motor

Saif Talal Bahar[*], Deebage Rahman Neama[**]

[*] Department of Electrical Techniques, Baquba Technical Institute, Middle Technical University, Baghdad, Iraq
Email: saif.talal@mtu.edu.iq
https://orcid.org/0000-0001-6799-9259

[**] Department of Renewable Energy Techniques, Baquba Technical Institute, Middle Technical University, Baghdad, Iraq
Email: deebagerahman@mtu.edu.iq
https://orcid.org/0009-0008-2025-3503

Abstract

Permanent magnet synchronous motors (PMSM) are extensively utilized in aerospace industry, transportation, shipping industry, etc., due to their advantages of unpretentious structure, great power density, great efficiency and great torque current ratio. Model predictive control (MPC) has huge potential to be applied in PMSM drives with stable running and high efficiency. In (MPC-DTC), the cost function contains of torque and flux magnitude errors, and they are different in component and greatness. Thus, a suitable weight factor is essential to equilibrium the control execution between torque and flux. The traditional method showed the torque wave by (17.5%) and the torque wave was reduced in the improved method to (2.25%).

Keywords- Model predictive control, Inverter, Permanent magnet synchronous motors, Objective function.

I. INTRODUCTION

Novel (PMSMs) are gaining popularity for a variety of applications, inclusive industrial, home, and transport [1]. With the global movement toward energy conservation, there is a growing demand for electrical drives that are energy efficient, excellent performance, and dependable [2]. Because of their great efficiency, large power output per mass and volume, and excellent dynamic execution, PMSMs are perfect options.

Various different speeds driving techniques and architectures for PMSMs have been actively explored and published lately. The greatest general mechanism systems are field oriented control (FOC) and direct torque control (DTC) [3-4]. DTC's benefits over FOC comprise its unpretentious construction, rapid dynamic restraint, and excellent resilience versus motor parameter fluctuation [5]-[6]. Nevertheless, typical DTC has significant drawbacks, including huge torque and flux ripples, changing switching frequency, and extreme aural sounds. Several solutions have been offered in the literature to address these issues. Approximately of them use interplanetary vector modulation (SVM) to do DTC, which is recognized while SVM-DTC [7]. The switching list in a typical DTC has just a restricted amount of voltage vectors with defined magnitude and places. The SVM method allows for the creation of a random voltage vector with any magnitude and location [8]-[9]. SVM-DTC can create torque and flux more precisely this way. Additional advantage of utilizing SVM is that the sample frequency commanded is lesser than in standard DTC [10]. (MPC) has recently gained popularity in the commercial and theoretical areas [11]-[12]. Inverter with modulation may be treated as a benefit in controller scheme in SVM-DTC [13]. Following the release of this method in the 1960s, the (MPC) principle was established for applications in manufacturing control in the 1970s. The MPC demands a significant amount of computer work and was previously restricted to tardily variable systems such as chemical reactions. With the advent of low-cost great-performance microcomputers and sophisticated digital control methods, MPC may be used to electrical drive systems [14]. In contrast to the use of hysteresis comparison and the switching list le in traditional DTC, the vector choice approach in MPC is constructed on assessing a specified objective function [15].Voltage vector chosen from the standard switching list in DTC may not remain the optimal one for reducing torque and flux wave [16]. Because the 2-level inverter-fed PMSM drives, have a restricted amount of separate voltage vectors, it is feasible to analyze the impacts of apiece voltage vector and pick the one that minimizes the objective function. The definition of the objective function, which is connected to the control goals, is the essential skill of MPC. The torque and flux are of primary interest in PMSM drive applications, and so the objective function is set in such a manner that together the torque and flux at the conclusion of the mechanism time are while near to the orientation standards as feasible.

In order to reduce torque and flux fluctuation, this paper proposes a predictive torque control based on torque and flux model. The current and voltage obtained in the previous cycle are used to estimate the torque to predict the current at the future moment. Then, the possible optimal voltage vector is achieved centered on the current trajectory to reduce the amount of calculation. The duty cycle is optimized using the average torque theory to further reduce the torque fluctuation. Finally, the accuracy and success of the approach suggested in this paper are verified through model.

II. Dynamic Model of the PMSM

The demonstrate in rotor synchronous d-q coordinate is the most commonly used for PMSM because all parameters become continual and torque and currents are decoupled. This will reduce the complexity of the model and make the calculating process easier. PMSM's model may be represented

$$\mathcal{V}_s = R_s * i_s + \frac{d\phi_s}{dt} \quad (1)$$

Where R_s is the stator resistance. The flux (ϕ_s). The voltage formulas that come from the model are provided via [17, 18].

$$\mathcal{V}_q = R_s * i_q + \omega_r * \phi_d + l_q * \frac{d}{dt}\, i_q \quad (2)$$

$$\mathcal{V}_d = R_s * i_d - \omega_r * \phi_q + l_d * \frac{d}{dt}\, i_d \quad (3)$$

Where ω_r is rotor speed and l_q and l_d , d-q stator inductance. i_q And i_d current. Flux remain provided by,

$$\phi_q = l_q * i_q \quad (4)$$

$$\phi_d = l_d * i_d + \phi_f \quad (5)$$

Electromagnetic torque is given by,

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)(\phi_d * i_q - \phi_q * i_d) \quad (6)$$

A 3-phase, 2-level inverter considering an ideal switching state in figure 1, us describe the switching signals Sx (x=A, B, and C) for each phase of SA, SB, and SC.

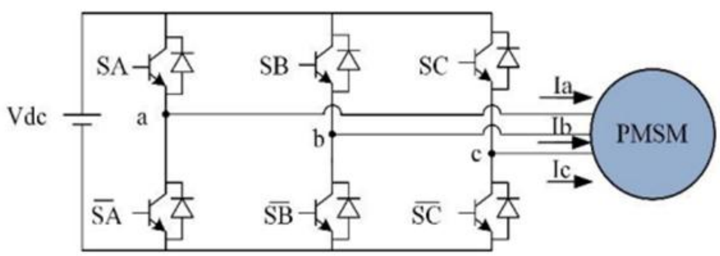

Figure 1. Block diagram of inverter driven motor.

(8) Switching statuses, such as the six not-zero vector states and the 2-zero vector statuses in figure 2,$S = (S_1 , S_2, S_3, S_4, S_5, S_6)$, can thus be created by combining the two states of each phase.

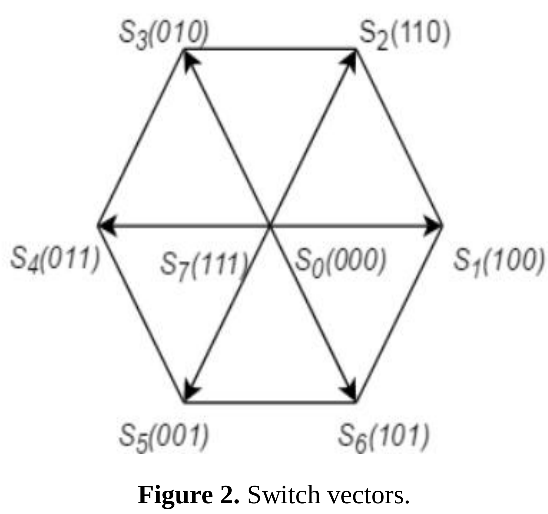

Figure 2. Switch vectors.

III. Direct torque control

Since the output torque of a VC-based PMSM drive system is incidentally organized through the s current, attempts to enhance system execution are primarily directed toward precisely estimating machine feedback and creating an efficient current controller, both of which will regrettably boost calculation load and impede the dynamic response of the system. Direct torque control (DTC) was then suggested as an additional PMSM drive mode [19]. While there is no difference between DTC and induction motor drives, it has been demonstrated that DTC may be utilized for PMSM [20]. Figure 3. Depicts a typical DTC system design [21]. In DTC systems, a PWM comparator replaces the current controller, and the motor characteristics, with the exception of stator resistance, are not employed. The inverter's switching state is only updated once each sample period and remains unchanged unless the output of the hysteresis controller changes statuses [22]. As a consequence, the torque and flux waves are comparatively great as opposed to the vector mechanism motor system. While a lower hysteresis bandwidth can consequence in fewer torque waves, the inverter's switching forfeiture will skyrocket. In addition, the inverter's switching frequency is not continual.

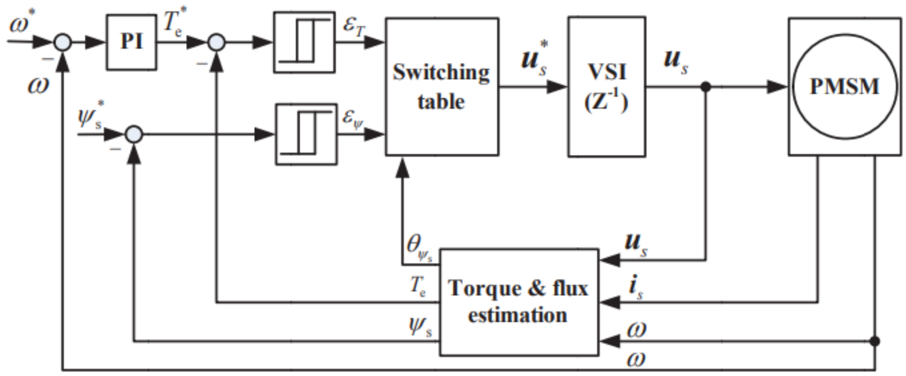

Figure 3. Overall System for DTC's

IV. MP-DTC's of PMSM

Basic principles of DTC, flux, and torque may all be improved by choosing the right voltage vector [23].In PTC, the flux and torque are calculated for the following period. The procedure of predicting variables is performed for each possible switching combination. The minimum value of the objective function determines the voltage vector and switch combination. The result is a switch command that provides the finest reference tracking. Figure 4 depicted the MP-DTC's block diagram.

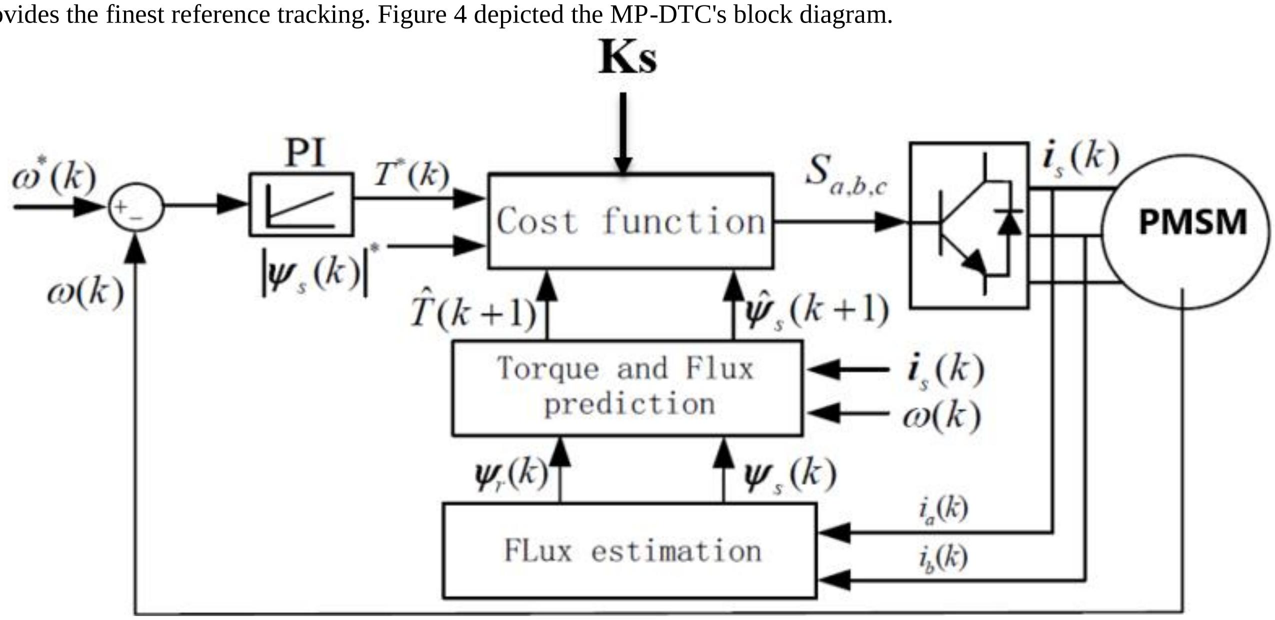

Figure 4. Overall System for proposed MP-DTC's

Discretize the arithmetical model of PMSM to acquire the essential conditions for model prediction. Since the sample time T_s is adequately lesser, the Euler approximation is utilized for the stator current derivative $\frac{di}{dt}$ of the sample time T_s .

$$i_d^{(k+1)} = \left(1 - \frac{R_s * T_s}{l_d}\right) i_d + \left(\frac{\omega_r * l_q * T_s}{l_d}\right) i_q + \left(\frac{T_s}{l_d}\right)\mathcal{V}_d \qquad (7)$$

$$i_q^{(k+1)} = \left(1 - \frac{R_s*T_s}{l_q}\right) \mathrm{i_q} - \left(\frac{\omega_r*l_d*T_s}{l_q}\right) \mathrm{i_d} + \left(\frac{T_s}{l_q}\right)\mathcal{V}_q - \frac{\omega_r*\phi_f*T_s}{l_q} \qquad (8)$$

Then, the future behavior of flux and torque can be calculated by

$$\phi_q^{(k+1)} = l_q * i_q^{(k+1)} \qquad (9)$$

$$\phi_d^{(k+1)} = l_d * i_d^{(k+1)} + \phi_f \qquad (10)$$

$$\phi_s^{(k+1)} = \sqrt{(\phi_d^{(k+1)})^2 + (\phi_q^{(k+1)})^2} \qquad (11)$$

$$\mathrm{T}_e^{(k+1)} = \frac{3}{2}\left(\frac{p}{2}\right)(\phi_d^{(k+1)} * i_q^{(k+1)} - \phi_q^{(k+1)} * i_d^{(k+1)}) \qquad (12)$$

The complication concerning the sample time choice in previous control procedures like SVM by using MPC algorithms. The MPC construction involves a robust computational base and less memorial for storage preceding switching states of the converter. This will remove the most switching state iterations. The switching transitions (K_{sw}) are constrained to one state by

$$K_{sw} = \left|(S_a{}^k - S_a{}^{k+1})\right| + \left|(S_b{}^k - S_b{}^{k+1})\right| + \left|(S_c{}^k - S_c{}^{k+1})\right| \qquad (13)$$

The objective function of torque predictive control consists of the described below:

$$G = (T_e{}^* - T_e{}^{(k+1)})^2 + \mathrm{K}.(\phi_s{}^* - \phi_s{}^{(k+1)})^2 + K_{sw} \qquad (14)$$

Where $T_e{}^*$and $\phi_s{}^*$are orientation values of torque and flux. Where $i_q{}^{(k+1)}$ and$i_d{}^{(k+1)}$ are predictive value of current for the then sample time, T_s is the sample time , $T_e{}^{(k+1)}$ and $\phi_s{}^{(k+1)}$ are predictive standards of torque and flux, correspondingly. K weight factor.

V. SIMULATION AND RESULTS

Figure 5 displays the overall system utilized to model the MPC-DTC with the proposed constraints, which control the three-phase inverter to drive the three-phase PMSM. According to the overall system in figure 4, as shown previously, simulation is done. The system parameters are utilized in the model, which shows in list I. This structure contains of (11) subsystems and (1) MATLAB Function as follows: Constraint, Reference Speed, Speed Calculation, PI Controller, Torque Calculation, Reference Current, Current Calculation, MPC-DTC Function, converter, Flux Calculation, and Load Torque.

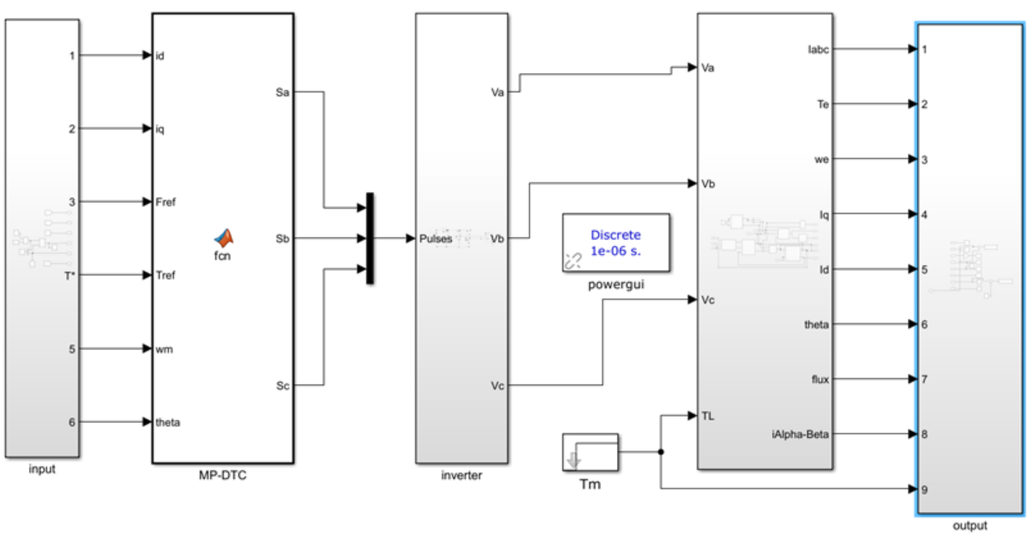

Figure 5. Proposed Model Predictive Torque Control.

Table I system parameters of PMSM

Parameter	Value	Unit
torque	8	N.m
Dc voltage	350	V
p	3	-
R□	1.25	Ω
Lq=Ld	8.5	mH

Figure 6 presents the pursuing of the measured speed to its reference speed. The error among them is presented in figure 7, for DTC approach. The high error values for different speed.

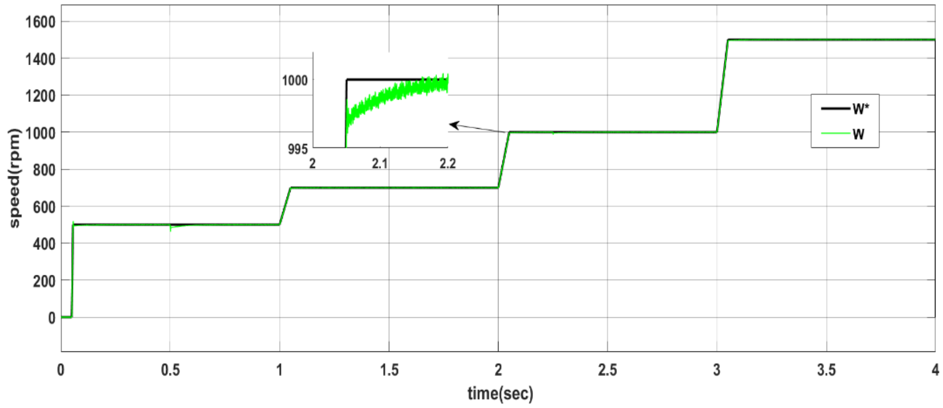

Figure 6. Speed of motor of DTC approach.

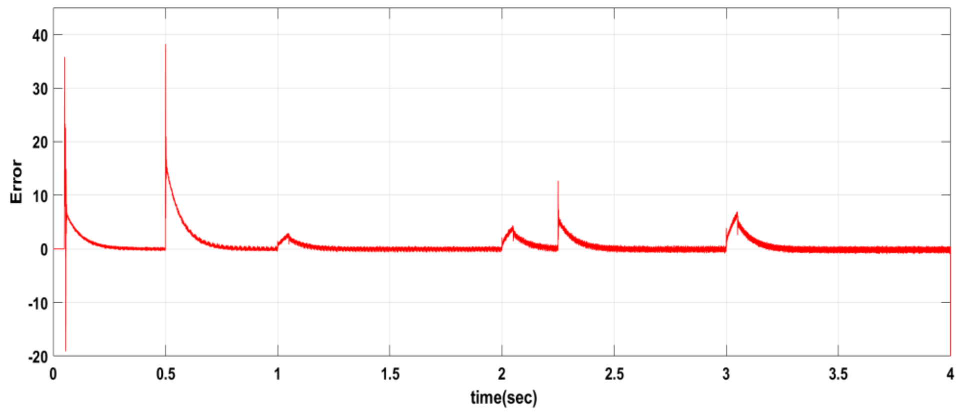

Figure 7. Speed Error of DTC approach.

Figure 8 presents the pursuing of the measured speed to its reference speed. The error among them is presented in figure 9. The small error values for different speed conditions (rise, constant, and reduce), denote the main requirements for an excellent performance in the enhance MP-DTC approach.

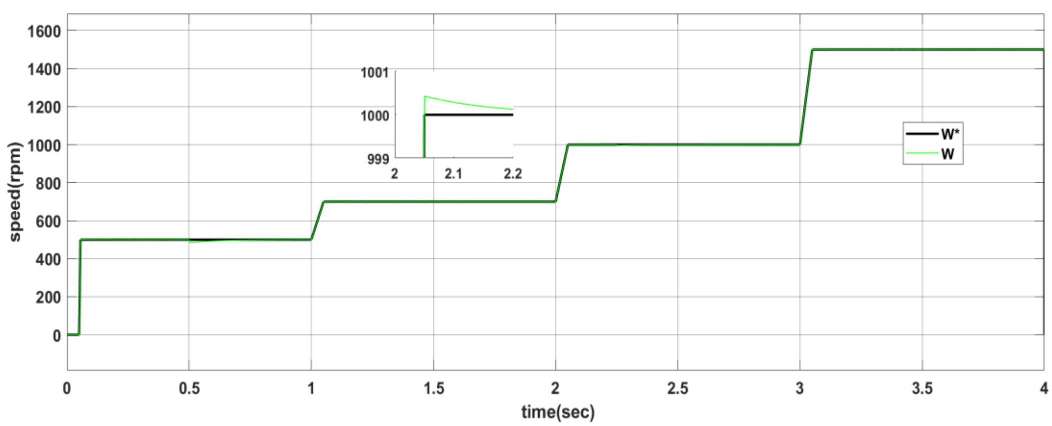

Figure 8. Speed of motor of MP-DTC approach.

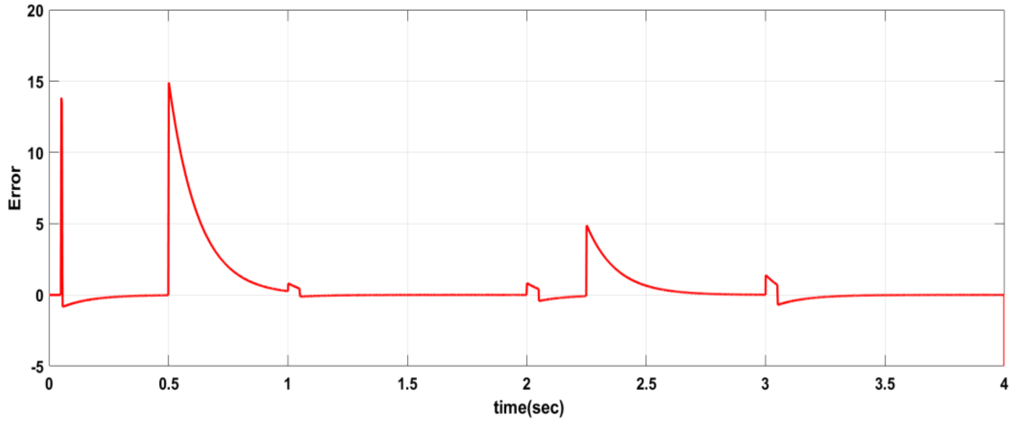

Figure 9. Speed Error of MP-DTC approach.

Figure 10 present the result for torque of DTC approach.

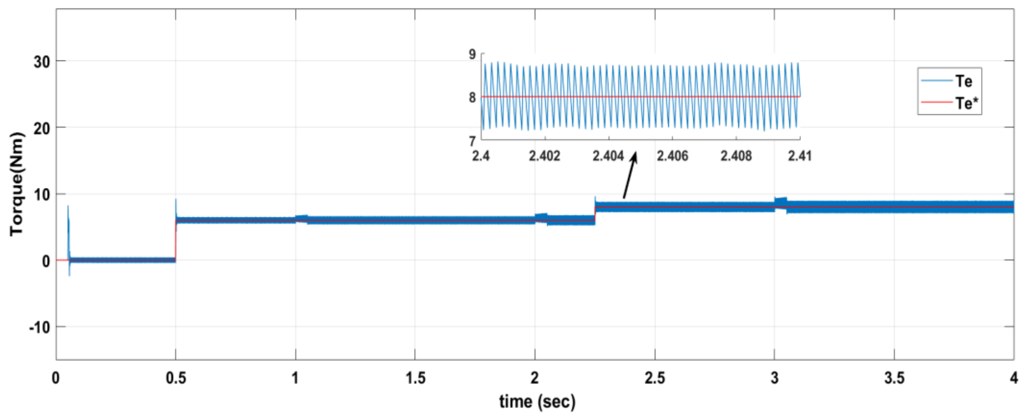

Figure 10. Torque of motor of DTC approach.

Figure 11 showed the stator flux magnitude of DTC approach.

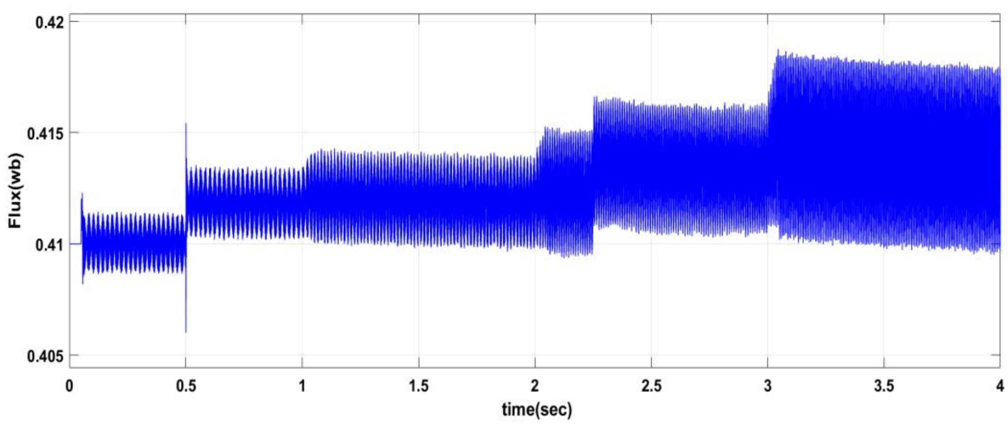

Figure 11. Stator flux of DTC approach.

Figure 12 present the result for torque of enhance MP-DTC approach. In addition, it proves the cogency of the simulation. The calculations displayed the effect of constraint on reducing the torque ripple.

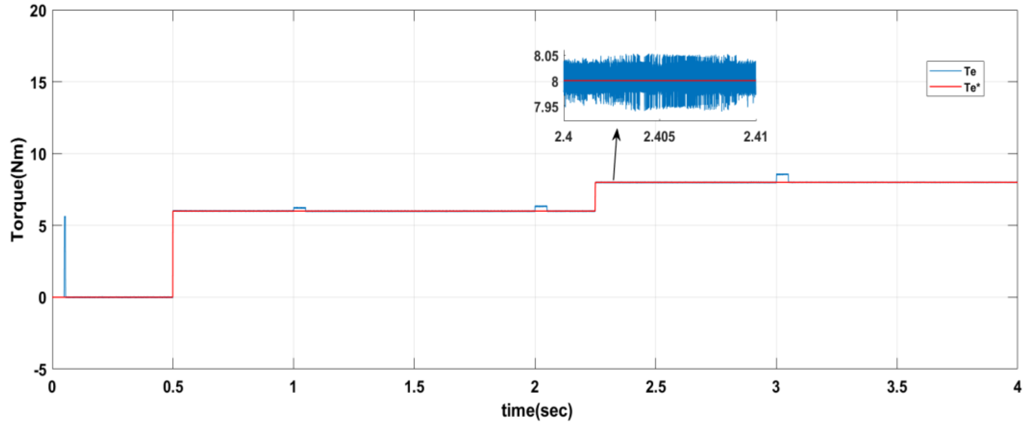

Figure 12. Torque of motor of MP-DTC method.

Figure 13 showed the stator flux magnitude enhance MP-DTC method.

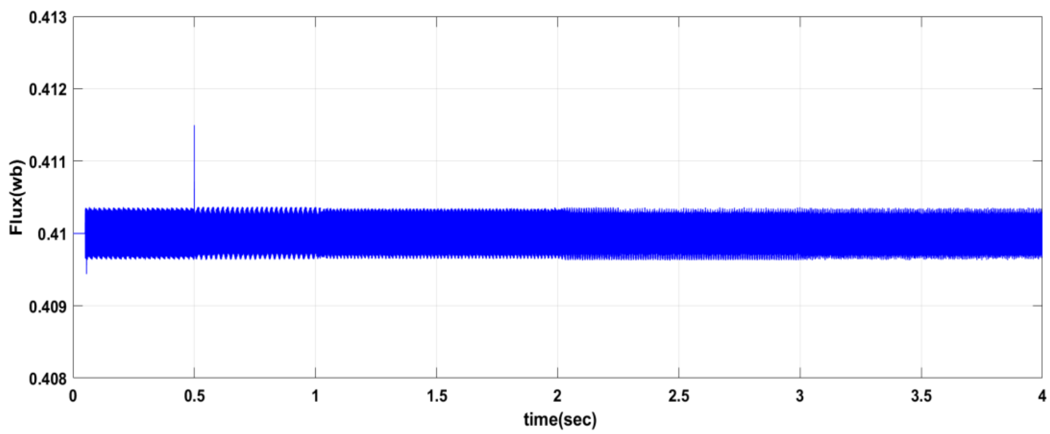

Figure 13. Stator flux of MP-DTC approach.

VI. CONCLUSION

The permanent magnet synchronous motor has a basic design, a broad speed range, large torque output ability, and good operating efficiency. It is widely employed in a variety of industry sectors due to its numerous benefits. Currently, the model predictive torque control approach is employed as an advanced control approach. This developed control strategy has taken a significant role in the control procedure for the (PMSM). The demonstrate (MPC-DTC) predicts reduced torque. It provides good control element working performance, with minimal changes in torque and stator flux. The torque control method and perpetual control set demonstrate predicted the torque control method's control set, predictions demonstrate, and optimum vector. The optimum control law and the unique scheme method of the control technique are obtainable. Depending on the above-mentioned mathematical analysis results, the relevant current challenges in the kind of model prediction torque control technique are further investigated.

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REFERENCES

[1] J. Lee, J. Hong, K. Nam, R. Ortega, L. Praly, and A. Astolfi, “Sensorless control of surface-mount permanent-magnet synchronous motors based on a nonlinear observer,” IEEE Trans. Power Electron., vol.25, no.2, 2010, pp.290–297

[2] SUDHAKAR, Ambarapu, et al. Analysis of fuzzy and neural controllers in direct torque controlled synchronous motors. *Indonesian Journal of Electrical Engineering and Computer Science*, 2023, 32.2: 676-687.

[3] F. Genduso, R. Miceli, C. Rando, and G. R. Galluzzo, “Back EMF sensorless-control algorithm for high-dynamic performance PMSM,” IEEE Trans. Ind. Electron., vol.57, no.6, 2010, pp.2092–2100

[4] Ahmed, Nouir, Zebirate Soraya, and Chaker Abdelkader. "Model predictive control of high voltage direct current based on voltage source converter transmission system." *International Journal of Power Electronics and Drive Systems* 14.1 (2023): 244

[5] Saif Talal Bahar and Riyadh G. Omar, “Torque ripple alleviation of a five-phase permanent magnet synchronous motor using predictive torque control method”, International Journal of Power Electronics and Drive Systems, vol. 13, no. 4, pp. 2207~2215, Nov. 2022

[6] M. Abassi, A. Khlaief, O. Saadaoui, A. Chaari and M. Boussak, "Performance analysis of FOC and DTC for PMSM drives using SVPWM technique," *2015 16th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA)*, Monastir, Tunisia, 2015, pp. 228-233

[7] Y. Wang, L. Geng, W. Hao and W. Xiao, "Control Method for Optimal Dynamic Performance of DTC-Based PMSM Drives," in *IEEE Transactions on Energy Conversion*, vol. 33, no. 3, pp. 1285-1296, Sept. 2018

[8] C. Lascu and A. Trzynadlowski, “A sensorless hybrid DTC drive for high-volume low-cost applications,” IEEE Trans. Ind. Electron., vol.51, no.5, 2004, pp.1048- 1055

[9] Y. Zhang, J. Zhu, W. Xu, J. Hu, D. G. Dorrell, and Z. Zhao, “Speed sensorless stator flux oriented control of three-level inverter-fed induction motor drive based on fuzzy logic and sliding mode control,” in Proc. 36th IEEE IECON, 2010, pp.2926–2931.

[10] T. S. Wang, J. G. Zhu, and Y. C. Zhang, "Model predictive torque control for PMSM with duty ratio optimization," International Conference on Electrical Machines and Systems (ICEMS), 20-23 Aug. 2011

[11] H. Miranda, P. Cortes, J. Yuz, and J. Rodriguez, “Predictive torque control of induction machines based on state-space models,” IEEE Trans. Ind. Electron., vol.56, no.6, 2009, pp.1916–1924

[12] F. Morel, J.-M. Retif, X. Lin-Shi, and C. Valentin, “Permanent magnet synchronous machine hybrid torque control,” IEEE Trans. Ind. Electron., vol.55, no.2, 2008, pp.501–511

[13] K. Drobnic, M. Nemec, D. Nedeljkovic, and V. Ambrozic, “Predictive direct control applied to AC drives and active power filter,” IEEE Trans. Ind. Electron., vol.56, no.6, 2009, pp.1884–1893

[14] G. Papafotiou, J. Kley, K. Papadopoulos, P. Bohren, and M. Morari, “Model predictive direct torque control-part II: Implementation and experimental evaluation,” IEEE Trans. Ind. Electron., vol. 56, no. 6, pp. 1906 –1915, June 2009.

[15] R. Harikrishnan and A. E. George, "Direct Torque Control of PMSM using hysteresis modulation, PWM and DTC PWM based on PI Control for EV - A comparative analysis between the three strategies," *2019 2nd International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)*, Kannur, India, 2019, pp. 566-571.

[16] P. Cortes, M. Kazmierkowski, R. Kennel, D. Quevedo, and J. Rodriguez, “Predictive control in power electronics and drives,” IEEE Trans. Ind. Electron., vol. 55, no. 12, pp. 4312 –4324, Dec. 2008.

[17] Wang, T., Liu, C., Lei, G., Guo, Y., & Zhu, J. (2017). Model predictive direct torque control of permanent magnet synchronous motors with extended set of voltage space vectors. IET Electric Power Applications, 11(8), 1376-1382.

[18 Ha, Vo Thanh, and Pham Thi Giang. "Control for induction motor drives using predictive model stator currents and speeds control." *International Journal of Power Electronics and Drive Systems* 13.4 (2022): 2005.

[19] S. G. Petkar and V. K. Thippiripati, "A Novel Duty-Controlled DTC of a Surface PMSM Drive With Reduced Torque and Flux Ripples," in *IEEE Transactions on Industrial Electronics*, vol. 70, no. 4, pp. 3373-3383, April 2023.

[20] A. Shinohara, Y. Inoue, S. Morimoto and M. Sanada, "Maximum Torque Per Ampere Control in Stator Flux Linkage Synchronous Frame for DTC-Based PMSM Drives Without Using q-Axis Inductance," in *IEEE Transactions on Industry Applications*, vol. 53, no. 4, pp. 3663-3671, July-Aug. 2017.

[21] A. U. Rehman, B. A. Basit, H. H. Choi and J. -W. Jung, "Computationally Efficient Deadbeat Direct Torque Control Considering Speed Dynamics for a Surface-Mounted PMSM Drive," in *IEEE/ASME Transactions on Mechatronics*, vol. 27, no. 5, pp. 3407-3418, Oct. 2022.

[22] N. K. Kumar Reddy and B. T. Geetha, "Enhancement of Output Power in Three Phase Induction Motor Using Torque Controlled Method Compared with Voltage Controlled Method by Controlling the Stator Voltage," *2023 6th International Conference on Contemporary Computing and Informatics (IC3I)*, Gautam Buddha Nagar, India, 2023, pp. 1528-1533.

[23] S. T. Bahar and R. Ghanem Omar, “PERMANENT MAGNET SYNCHRONOUS MOTOR TORQUE RIPPLE REDUCTION USING PREDICTIVE TORQUE CONTROL ”, *J. eng. sustain. dev.*, vol. 27, no. 3, pp. 394–406, May 2023.

AUTHORS

Saif Talal Bahar is an Assist. Lec working in the Department of Electrical Techniques of Baquba Technical Institute at Middle Technical University, Baghdad, Iraq. Received his BSc and MSc degree in Power and Electrical Machine. His research interests include Power Electronics & Electrical Machine, Power System and Renewable Energy. Can be contacted at email: saif.talal@mtu.edu.iq

Deebage Rahman Neama is an Engineer working in the Department of Renewable Energy Techniques of Baquba Technical Institute at Middle Technical University, Baghdad, Iraq. Received his BSc degree in Power and Electrical Machine. His research interests include Power Electronics, Power System and Renewable Energy. Can be contacted at email: deebagerahman@mtu.edu.iq