

Assessment of Various Vector Control Schemes for PMSM Drive Application



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Abstract Currently, the operation of Finite Control Set Model Predictive Control (FCS-MPC) schemes in electric motor drives domain is emerging. Its distinguished features are: intuitive, simple and easy insertion of multi-objectives. The application of FCS-MPC in permanent magnet synchronous motor (PMSM) drive has several benefits in terms of improving the performance when compared with direct torque control (DTC)-operated PMSM drive. The FCS-MPC scheme is categorized into two: predictive torque control (PTC) and predictive current control (PCC). This paper deals with comparative evaluation of these control schemes for PMSM drive operation concerning flux and torque ripple, and current THD. Therefore, the gained results are analyzed for PMSM drive highlighting the benefits of FCS-MPC over DTC.

Keywords Direct torque control (DTC) · Finite Control Set Model Predictive Control (FCS-MPC) · Permanent magnet synchronous motor (PMSM) · Predictive current control (PCC) · Predictive torque control (PTC)

1 Introduction

Considering support of fast microprocessor technologies, the AC motor drives are powering the future of industry [1]. Nowadays, PMSM drives are emerging, which is having special advantages in machine point of view [2]. The notable advantages are stated as: high efficiency, high power density and torque-to-weight ratio. To achieve high dynamic performance for motor drives, vector control schemes are

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preferred. The vector control schemes for motor drives started with introduction of field-oriented control (FOC) in the year 1968 [3]. In beginning, it is implemented for induction motor (IM) drives. Later, its application is extended for PMSM drives [4]. The brief features of FOC operation for PMSM drives are: implementation in rotating reference frame necessitates coordinate frame transformations, indirect control of flux and torque through current components and involvement of current PI regulators. Therefore, the FOC operation is stated to be complex for PMSM drive [5]. Continuing the developments in motor drives, in the year 1986, direct torque control (DTC) is introduced. In [6], DTC is implemented for IM drive. Considering the special benefits of PMSM, DTC operation is applied for PMSM drives [7]. Its operational advantages [7] over FOC are provided as: simple, nonappearance of current PI controllers, performance in stationary frame of reference, straight regulation of flux and torque. However, hysteresis controller existence in digital stage of DTC operation consequences poor steady-state response of flux and torque for PMSM drive [5]. The detailed implementation of DTC and its operational results for PMSM drive are analyzed in this paper.

On the other side, FCS-MPC schemes are providing as promising technology in the domain of motor drives [8]. This modeling-based control is accomplished in stationary/rotating reference frame. The vital operational stages in predictive control are considered as [9]: data measuring and estimating, prediction and cost function (CF) evaluation. The FCS-MPC is classified into two [9], which are stated as PCC and PTC. In both of these control techniques, the mentioned operational stages remain same. However, the control variables differ. In PCC technique [10], stator current is considered as basic control variable, whereas in PTC technique, the basic control variables are flux and torque [11, 12]. In this paper, FCS-MPC (i.e., PCC and PTC) technique implementation and operational results are examined for PMSM drive.

The overall conclusions are drawn from various control responses obtained for PMSM drive. Therefore, in this paper detailed investigations are made for the mentioned control schemes applied to PMSM drive.

2 PMSM Drive Operation

The PMSM drive supplied with two-level voltage source inverter (VSI) is presented in Fig. 1a. Voltage space vector (E_s) is indicated based on switching combinations. Its generalized form is given by (1). As it is familiar that the possible switching combinations are 8, and there are overall 8 voltage vectors (VVs). Their realization is depicted in Fig. 1b.

$$E_s = \frac{2E_{dc}}{3} \left(S_a^+ + S_b^+ e^{j(2\pi/3)} + S_c^+ e^{j(4\pi/3)} \right) \quad (1)$$

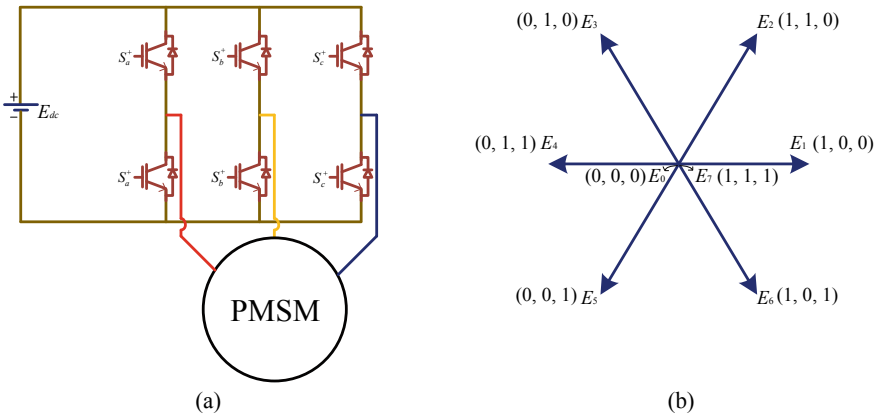


Fig. 1 **a** PMSM supplied from two-level VSI and **b** possible VVs of two-level VSI

2.1 Direct Torque Control (DTC)

PMSM drive is executed with DTC technique in stationary ($\alpha\beta$) reference frame. Its operational block diagram is mentioned in Fig. 2. In first step of its operation, measurement and estimation of PMSM drive variables are required. It is possible to have direct measurement of PMSM speed, current phasor and inverter DC link voltage. The process of present state (k) stator flux estimation is given by (2), where $k - 1$ is previous state data and T_s is sample period. Torque estimation is given by (3), where i_s denotes stator current variable. DTC operation requires stator flux sector information. Among the probable six sectors ($S_1 - S_6$) having 60° span as provided in Fig. 3, the stator flux sector information can be gained by (4). In Fig. 3a, an instant is presented where flux space vector (λ_s) falls in sector 2. The reference flux (λ_s^*) during control operation of PMSM drive is set as rated flux value. With

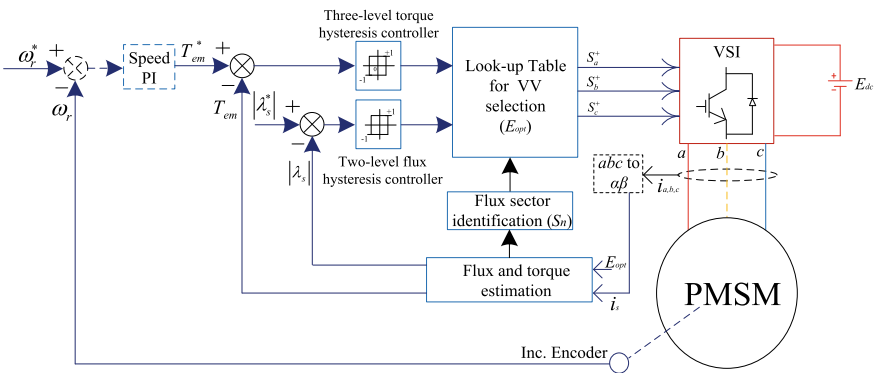


Fig. 2 Block model of PMSM drive operated with DTC technique

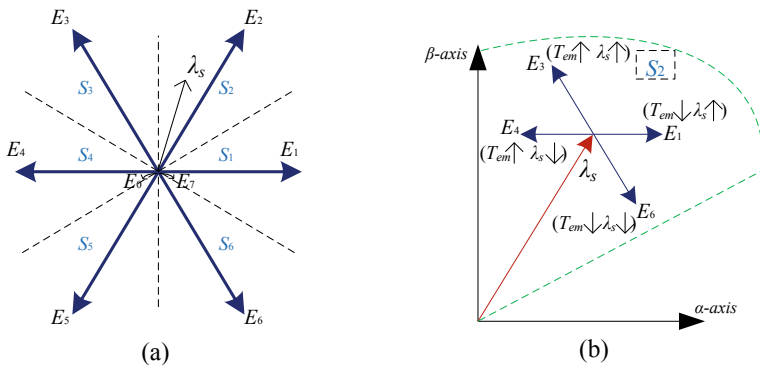


Fig. 3 **a** Possible sectors of voltage space vector plane for two-level VSI and **b** flux space vector in sector-2 and selection of VV for flux and torque control

these, necessary inputs required for operation of DTC technique are fulfilled.

$$\lambda_s(k) = \lambda_s(k-1) + (E_s - R_s i_s) T_s \quad (2)$$

$$T_{em} = 1.5 \frac{P}{2} \text{imag}(\bar{\lambda}_s * i_s) \quad (3)$$

$$\theta = \tan^{-1} \left(\frac{\lambda_{\beta s}}{\lambda_{\alpha s}} \right) \quad (4)$$

During control operation, the speed error (i.e., difference of reference and actual speed) is fed to speed PI controller, which produces required reference torque value (T_{em}^*) to minimize speed error. Torque and flux errors are attained by comparing their reference value with actual.

The torque error is provided to three-level torque hysteresis controller, whose output (H_T) may be -1 or 0 or $+1$, based on its error value crossing boundary conditions. Likewise, two-level flux hysteresis controller is supplied with flux error, whose output (H_λ) may be -1 or $+1$, based on its error value crossing boundary conditions.

The predefined look-up table is framed for VV application in a sample time, which is based on stator flux sector, outputs of flux and torque hysteresis controller. This choice of VV is to reduce errors of flux and torque. In view of flux space vector in sector-2, Fig. 3b shows the effect of VV on flux and torque response. Considering same analysis, Table 1 represents complete look-up table development for application of VV (E_{opt}) in a sample time of DTC operation. Therefore, gaining direct control over flux and torque of PMSM drive.

Table 1 VV selection for flux and torque control in DTC

| Sector identification | Hysteresis torque error (H_T) | | | | |
|-----------------------|---------------------------------------|-------|-------|-------|-------|
| | +1 | | 0 | -1 | |
| | Hysteresis flux error (H_λ) | | | | |
| | +1 | -1 | +1/-1 | +1 | -1 |
| S_1 | E_2 | E_3 | E_0 | E_6 | E_5 |
| S_2 | E_3 | E_4 | E_0 | E_1 | E_6 |
| S_3 | E_4 | E_5 | E_0 | E_2 | E_1 |
| S_4 | E_5 | E_6 | E_0 | E_3 | E_2 |
| S_5 | E_6 | E_1 | E_0 | E_4 | E_3 |
| S_6 | E_1 | E_2 | E_0 | E_5 | E_4 |

2.2 Finite Control Set-Model Predictive Control (FCS-MPC)

At the present time, FCS-MPC techniques drawing more attention in the field of electrical drives. As the control scheme rely on system model, it is essential to deliver system dynamic model during its operation. Therefore, dynamic equations of PMSM used in FCS-MPC operation are given by (5–8), where λ_f is rotor magnetic flux linkage along d -axis, ω_m is mechanical speed of rotor, L_s and R_s are stator inductance and resistance. These dynamic equations are presented in rotating reference frame (dq).

$$E_s = R_s i_s + \frac{d\lambda_s}{dt} + j\lambda_s \omega_r \quad (5)$$

$$\lambda_s = L_s i_s + \lambda_f \quad (6)$$

$$T_{em} = 1.5 \frac{P}{2} \text{imag}(\bar{\lambda}_s * i_s) \quad (7)$$

$$T_{em} - T_l = J \frac{d\omega_m}{dt} \quad (8)$$

As control variables are required to be predicted for next sample intervals, prediction model has to be developed based on PMSM dynamic equations. By means of Euler's methodology, prediction equations for control variables are framed at $(k + 2)$ sample instant. $(k + 2)$ signifies two-step ahead prediction of control variables which obviate sample delay issues during control operation. To execute FCS-MPC, the vital control stages are: measuring and estimation, prediction, and CF optimization. As it is stated that FCS-MPC is categorized into two (i.e., PTC and PCC), the part of first control stage (i.e., measurement) remains same for both. Measuring variables includes PMSM drive speed (ω_r), current phasor (i_s) and DC link voltage (E_{dc}).

The functioning of remaining stages varies based on two subcontrol operations of FCS-MPC. These are presented in detail below.

2.2.1 Predictive Torque Control (PTC)

Using flux and torque as basic control variables, PTC technique for PMSM drive is developed as presented in Fig. 4. PTC functioning is implemented in stationary reference frame to circumvent complexity of coordinate frame transformation. The estimated flux and current phasor at $(k + 1)$ sample are given by (9–10), which are utilized in two-step ahead $(k + 2)$ prediction of flux (11), current (12) and thereby, torque (13) of PMSM drive is attained. Here, e_r signifies back emf which is $\lambda_f \omega_r e^{j\theta}$, where ω_r and θ are electrical rotor speed and angle, respectively. The predictions at $(k + 2)$ are gained with possible 7 (n) VVs of two-level VSI supplying to PMSM drive. Therefore, estimation and prediction of control variables fulfilled two stages of PTC operation.

$$\lambda_s(k + 1) = \lambda_s(k) + (E_{\text{opt}} - R_s i_s(k)) T_s \quad (9)$$

$$i_s(k + 1) = i_s(k) \left(1 - \frac{T_s R_s}{L_s} \right) + (E_{\text{opt}} - e_r) \frac{T_s}{L_s} \quad (10)$$

Prediction of control variables:

$$\lambda_s(k + 2)_n = \lambda_s(k + 1) + ((E_s)_n - R_s i_s(k + 1)) T_s \quad (11)$$

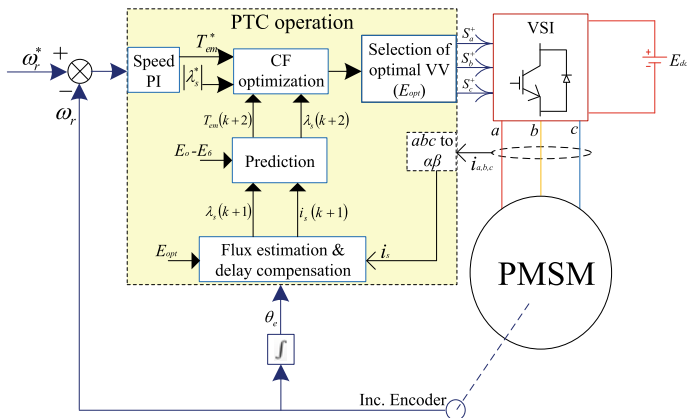


Fig. 4 Block model of PMSM drive operated with PTC technique

$$i_s(k + 2)_n = i_s(k + 1) \left(1 - \frac{T_s R_s}{L_s} \right) + ((E_s)_n - e_r) \frac{T_s}{L_s} \tag{12}$$

$$T_{em}(k + 2)_n = 1.5 \frac{P}{2} \text{imag}(\bar{\lambda}_s(k + 2) * i_s(k + 2)) \tag{13}$$

The final stage involves in CF optimization, which acts crucial role in optimal VV choice. The basic CF design with control objectives of flux and torque is specified by (14). The predicted variables of flux and torque are compared with their references. The optimal VV serving predicted variable closeness to reference ensures the minimum CF value. Hence, CF optimization is achieved. This evaluated optimal VV is chosen for control action, therefore realizing predictive torque and flux control of PMSM drive.

$$X_n = |T_{em}^* - T_{em}(k + 2)_n| + W ||\lambda_s^*| - |\lambda_s(k + 2)_n|| \tag{14}$$

In (14), W is termed as weighting factor, creating relative balance between two dissimilar control objectives (flux and torque).

2.2.2 Predictive Current Control (PCC)

In this control technique, flux and torque of PMSM drive are indirectly controlled by current components in rotating (dq) reference frame. Therefore, basic control variable in PCC is stator current phasor. Its functioning block diagram is presented in Fig. 5. Till the rated speed of PMSM drive, demagnetization of rotor flux is not necessary. Therefore, d -axis reference stator current (i_{ds}^*) is set to zero. The q -axis reference stator current (i_{qs}^*) is set by speed PI controller according to speed error minimization. In first stage, current phasor estimation at $(k + 1)$ is attained by (15).

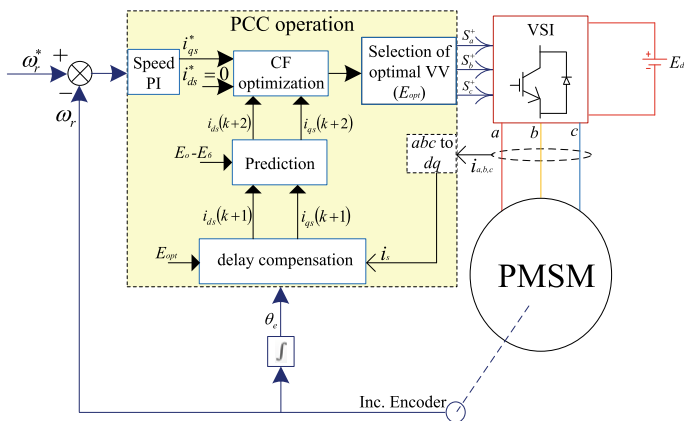


Fig. 5 Block model of PMSM drive operated with PCC technique

With the presented 7 (n) VVs of two-level VSI, measured and estimated data, the current prediction at ($k + 2$) is obtained in second stage as given by (16).

$$i_s(k+1) = i_s(k) \left(1 - \frac{T_s R_s}{L_s} - j\omega_r T_s \right) + \frac{T_s}{L_s} (E_{\text{opt}} - j\lambda_f \omega_r) \quad (15)$$

Prediction of control variable:

$$i_s(k+2)_n = i_s(k+1) \left(1 - \frac{T_s R_s}{L_s} - j\omega_r T_s \right) + \frac{T_s}{L_s} ((E_s)_n - j\lambda_f \omega_r) \quad (16)$$

In PCC, CF (17) is established with elementary control objectives of stator current components. The optimal VV satisfying closeness of predicted current components with their references guarantees minimum CF value and optimization at final stage of PCC operation. The evaluated optimal VV serves predictive current control and thereby, indirect flux and torque control of PMSM drive.

$$X_n = |i_{d_s}^* - i_{d_s}(k+2)_n| + |i_{q_s}^* - i_{q_s}(k+2)_n| \quad (17)$$

From this entire discussion, it is summarized that PMSM drive operation is elucidated with various control techniques such as DTC, FCS-MPC: PTC and PCC.

3 Results and Discussion

Using mathematical analysis presented in part-2, MATLAB/Simulink simulations are conducted on existing PMSM drive whose ratings are listed in Table 2. The discussed control techniques are applied for PMSM drive operation.

Table 2 PMSM drive parameters

| Parameters | Value |
|-------------------------------------|-------------------------|
| Stator resistance (R_s) | 1.12 Ω |
| Stator inductance (L_s) | 10.5 mH |
| Rated stator flux (λ_s^*) | 0.705 Wb |
| Rated power | 5 HP |
| Rated torque | 23.5 N m |
| Poles (P) | 4 |
| Inertia | 0.061 kg m ² |
| Rotor flux (λ_f) | 0.7 Wb |
| Proportional gain | 0.2 |
| Integral gain | 0.05 |

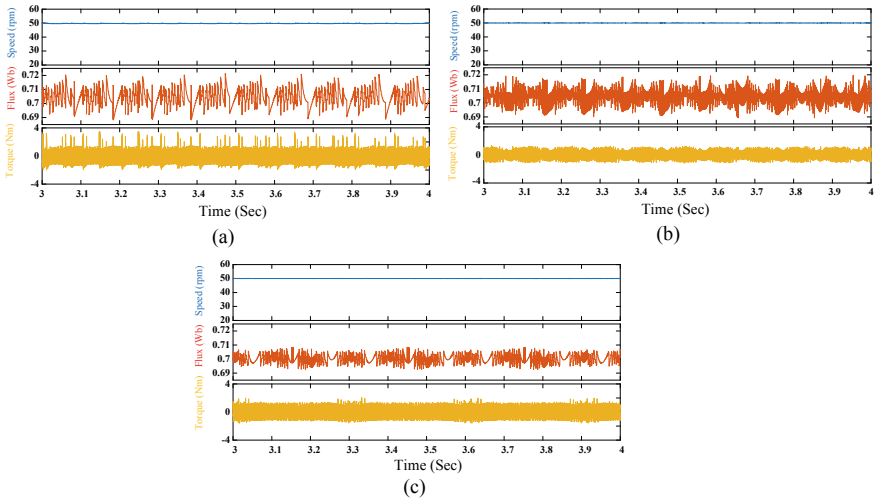


Fig. 6 Response of PMSM drive during low speed (50 rpm) condition **a** DTC, **b** PTC and **c** PCC

In PTC, CF (14) is assigned with weighting factor value of 75, which is designated from heuristic tuning, whereas PCC operation is independent from weighting factor. Considering this simulating environment, various control operation results are presented and discussed in this part of paper.

The simulations are executed on PMSM drive operated with DTC, PTC and PCC techniques. Transition-free response is captured during PMSM drive operation showing speed, flux and torque in Fig. 6. In Fig. 6, low-speed reference (50 rpm) is selected for PMSM drive while observing response of DTC, PTC and PCC techniques. From these tests, it is evident that PTC and PCC techniques exhibits overall improved control response when compared to DTC. In DTC-operated PMSM drive, the existence of hysteresis regulators for flux and torque control is responsible for lack of better response. On the other side, two step ahead prediction, intuitive nature with the consideration of CF optimization in every sample instant made predictive control techniques gaining the benefit of improved motor drive response.

The transition response is analyzed for PMSM drive with sudden variations in speed. In Fig. 7, the reference speed variations are indicated, i.e., from 50 rpm

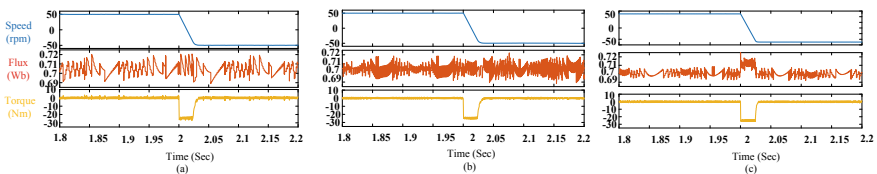


Fig. 7 Response of PMSM drive during speed step change from forward (50 rpm) to reverse (-50 rpm) conditions **a** DTC, **b** PTC and **c** PCC

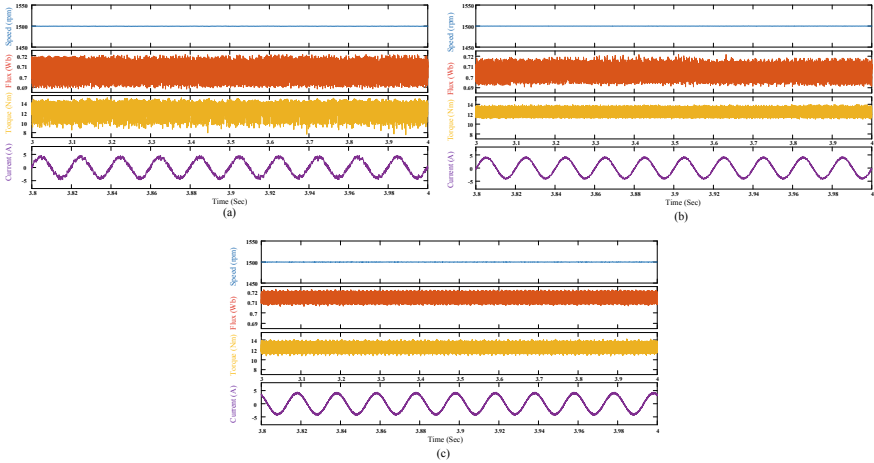


Fig. 8 Response of PMSM drive during loaded condition at 1500 rpm **a** DTC, **b** PTC and **c** PCC

(forward) to -50 rpm (reverse). The executed response of PMSM drive operated with DTC (2 s to 2.023 s), PTC (2 s to 2.023 s) and PCC (2 s to 2.024 s) techniques are presented in Fig. 7. From these, it is verified that all control techniques perform almost similar transition response for PMSM drive. However, PCC-operated PMSM drive has slight variation in dynamic response, i.e., 2 s to 2.024 s, due to indirect control of torque via current space vector.

Under loaded condition (load torque as 12.5 Nm) at rated speed of 1500 rpm, PMSM drive response for DTC, PTC and PCC techniques is presented in Fig. 8. From these tests, it is evident that PTC and PCC techniques exhibit overall improved control response when compared to DTC. The obtained flux and torque ripples (standard deviation values) are presented in Table 3. From this, it is clearly observed that PTC of PMSM drive stands top gaining less torque ripples, followed by PCC and DTC at the end, whereas for current THD observations, PCC stands top with less THD, followed by PTC and DTC at the end. Therefore, in comparison of PTC and PCC techniques, direct involvement of current objective in CF of PCC results less current THD than PTC. While in PTC, CF is structured with flux and torque objectives, which is accountable for less torque ripples than PCC. Flux response is much influenced

Table 3 PMSM drive performance comparison under various control techniques

| Control technique | Flux ripple (Wb) | Torque ripple (Nm) | Current THD (%) |
|-------------------|------------------|--------------------|-----------------|
| DTC | High (0.0067) | High (1.207) | High (15.22) |
| PTC | Low (0.0053) | Lower (0.615) | Low (7.41) |
| PCC | Lower (0.0031) | Low (0.681) | Lower (6.70) |

by direct control of current component (i_{ds}) which is possible in PCC resulting less flux ripples than PTC.

The outcomes of this entire analysis are listed in Table 3, which differentiates among control techniques by quantitative and qualitative data. Thus, PMSM drive operation with various control techniques is studied.

4 Conclusion

In this paper, the concept and operation of different vector control techniques such as DTC, FCS-MPC (PTC and PCC) for PMSM drive application are studied. PMSM drive is operated with these control techniques in simulation platform. The control responses for different operating conditions of PMSM drive are observed. The presented qualitative and quantitative analysis clearly depicts operational differences among them. In comparison of FCS-MPC with DTC, FCS-MPC techniques serves overall better performance for PMSM drive.

References

1. Samir K, Rodriguez J, Wu B, Bernet S, Perez M (2012) Powering the future of industry: high-power adjustable speed drive topologies. *IEEE Ind Appl Mag* 18(4):26–39
2. Behzad A, Rahrovi B (2010) Minimum-copper-loss control over full speed range of an IPMSM drive for hybrid electric vehicle application. In: 2010 IEEE vehicle power and propulsion conference, pp 1–6
3. Felix B (1972) The principle of field orientation as applied to the new TRANSVECTOR closed loop control system for rotating field machines. *Siemens Rev* 34(5):217–220
4. Pradeep K, Dhundhara S, Makin R (2016) Performance analysis of PMSM drive based on FOC technique with and without MRAS method. In: 2016 International Conference on Recent Advances and Innovations in Engineering (ICRAIE), pp 1–6
5. Fatih K, Topaloglu I, Faruk Cakir M, Gurbuz R (2013) Comparative performance evaluation of FOC and DTC controlled PMSM drives. In: 4th international conference on power engineering, energy and electrical drives, pp 705–708
6. Isao T, Noguchi T (1986) A new quick-response and high-efficiency control strategy of an induction motor. *IEEE Trans Industry Appl* IA-22(5):820–827
7. Mino-Aguilar G et al (2010) A direct torque control for a PMSM. In: 2010 20th international conference on electronics communications and computers, pp 260–264
8. Dehong Z, Zhao J, Li Y (2016) Model-predictive control scheme of five-leg AC–DC–AC converter-fed induction motor drive. *IEEE Trans Industr Electron* 63(7):4517–4526
9. Jose R, Kazmierkowski MP, Espinoza JR, Zanchetta P, Abu-Rub H, Young HA, Rojas CA (2013) State of the art of finite control set model predictive control in power electronics. *IEEE Trans Industrial Informatics* 9(2):1003–1016
10. Turker T, Buyukkeles U, Faruk Bakan A (2016) A robust predictive current controller for PMSM drives. *IEEE Trans Industrial Electronics* 63(6):3906–3914
11. Eshwar K, Ravi Eswar KM, Vinay Kumar T (2020) An effective predictive torque control scheme for PMSM drive without involvement of weighting factors. *IEEE J Emerging Selected Topics Power Electronics*. <https://doi.org/10.1109/JESTPE.2020.2989429>

12. Eshwar K, Vinay Kumar T (2020) Effective predictive torque control scheme for four-level open-end winding permanent magnet synchronous motor drive. *Int Trans Electrical Energy Syst* 30(10):e12536