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# Novel Fault Tolerant Predictive Control for Analysis of Open Circuit Fault in a PMSM Drive

Warsame H. Ali, Yogita P. Akhare, Penrose Cofie, John H. Fuller, John Attia
*Department of Electrical and Computer Engineering, Prairie View A&M University,*
*Prairie View, TX 77446, USA*
*Corresponding Author: Yogita P. Akhare*

***ABSTRACT :*** *Control system design of Electrical Machine Drives became more significant during last decade as it plays an important role in various industrial applications. Regardless of the fault, relentless operation of the machine drive in various high power and high efficiency applications. Fault tolerant control is an efficacious solution to improve the reliability of the machine drives. Model Predictive Control (MPC) is an optimal control algorithm developed for constrained control of Multi-Input-Multi-Output (MIMO) systems which can assimilate equalities and inequalities constraints. In this paper a fault analysis of a permanent magnet synchronous machine (PMSM) drive using Novel Fault Tolerant Predictive Control (NFTPC) has been discussed.*
***KEYWORDS:*** *Electrical Machine Drives, Model Predictive Control (MPC), MIMO, NFTPC*

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## I. INTRODUCTION

Single phase open circuit fault is usual among the different faults occur in a permanent magnet synchronous machine (PMSM) drive. Due to this the drive operation get stopped because of the maintenance scheduling. This affect the cost and reliability of the operation [1]. Various fault tolerant methods have been employed by different researchers. For multiphase machines with open-circuit faults, various control methods have been proposed [2]. In model predictive control method, the discrete-time system is used to predict the future behaviors of the system according to every possible switch vector (SV). By minimizing a cost function, the best SV is then chosen [3]. The fast response of current control loops is needed for the reliable operation of PMSM drives. Therefore, many advanced current control strategies such as Predictive Current control [4], Hysteresis control [5], and Fuzzy PI control [6] have been proposed by the researchers. Out of all these methods, the predictive current control method has been extensively investigated due to the ability of accurate and rapid current reference tracking. Also, it gives the stable operation by considering the small current harmonic component [7]. PID controller is generally used in order to improve the performance of the system since it has easy structure and few parameters which could be changed by operators. However, it does not provide optimal control inputs which can destabilization of systems [8]. Linear Quadratic Regulator (LQR) has more advanced control approach which provides optimality. It is used to solve an optimization problem of minimization the state and inputs over infinity prediction horizon subject to a linear constraint. Although LQR cannot handle other constraints, but it is applicable to MIMO systems without using any decoupling [9]. As a model-based control, two different MPCs are needed for normal and postfault operations of PMSM drives, which make the whole control method complicated [10]. To the certain extent MPC faces a problem to achieve the robustness against the model mismatches and noises [11]– [13]. Modern MPC algorithms can achieve some specific features such as inclusion of more constraints [14], reduction in online computation [15] and so on. Although there is an open concern to find a computationally efficient and reliable MPC algorithm [16].

To overcome the above-mentioned issues, this paper proposes a novel fault tolerant predictive control (NFTPC) method for a permanent magnet synchronous machine (PMSM) drive considering single phase open circuit fault. The proposed method gives a simple algorithm with less computation, robustness to parameter uncertainties, reduction in total harmonic distortion and low steady state error.

## II. MODEL PREDICTIVE CONTROL (MPC)

MPC is an advanced control technique used to handle the difficult multivariable control problems. It controls MIMO process by satisfying inequality constraints on the input and output variables. If a practicable accurate dynamic model of the process is available, future values of the outputs can be predicted by using model and current measurements. Also, the appropriate changes in the input variables can be calculated based on both predictions and measurements. The changes in the individual input variables can be coordinated by considering the input-output relationships represented by the process model.

The main objectives of MPC:

- Prevent violations of input and output constraints.
- Drive some output variables to their optimal set points by maintaining other outputs within specified range.
- Prevent excessive movement of the input variables.
- Control process variables when a sensor or actuator is not available.
- Maximize a profit function, minimize a cost function, or maximize a production rate.

Fig. 1 shows the MPC strategies applied to power converter and drives. The classification is based on the optimization problem type. Finite Control Set MPC (FCS-MPC) considers the discrete nature of the power converter. Continuous Control Set MPC (CCS-MPC) produces a fixed switching frequency and computes a continuous control signal. An external modulator is not needed in case of FCS-MPC while modulator is needed in CCS-MPC to generate the desired output voltage. FCS-MPC has more computational cost than CCS-MPC since it computes the optimization problem online.

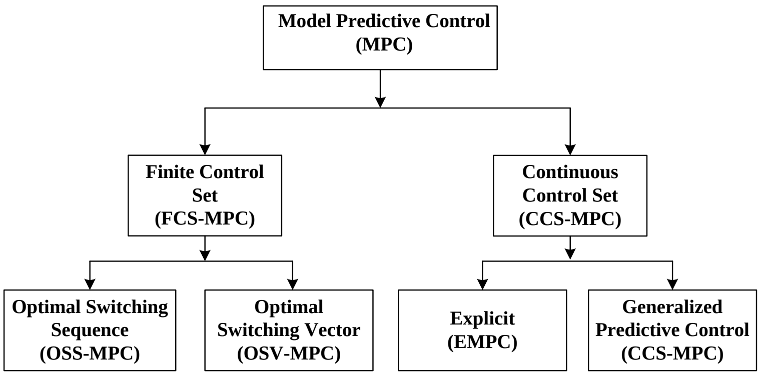



**Fig. 1. MPC strategies applied to power converter and drives.**

## III. STUDIED PMSM DRIVE FOR NFTPC

Fig. 2 shows a three phase PMSM, a three-leg voltage source inverter (VSI) and three fast acting fuses ($f_1, f_2, f_3$). The fuses are connected in series with the stator windings. Three stator windings are controlled by three legs of the VSI respectively. The PMSM has a neutral point n. For fault-tolerance purpose, a fourth leg is added which connects the neutral point through a Triac Tr. During normal operating condition, Tr is turned OFF and the studied drive is just a standard PMSM drive. At the occurrence of single-phase open circuit fault, the faulty leg is first disconnected and then Tr is turned ON.

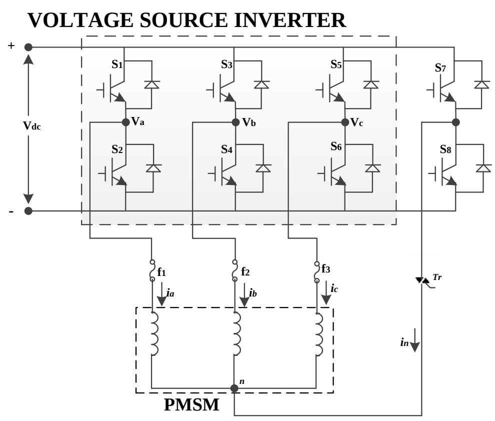



**Fig. 2. Fault Tolerant PMSM Drive.**

Fig. 3 shows the block diagram of the fault tolerant control system. PMSM reference speed, motor actual speed, three-phase currents and the dc bus voltage are the inputs and transistor's and triac's gate signals are the outputs. The PMSM is controlled using the vector control principle under normal operating conditions. The steps involved in the control system are diagnosis of the fault, isolation of the faulty leg, reconfiguration of the hardware and post-fault software control.

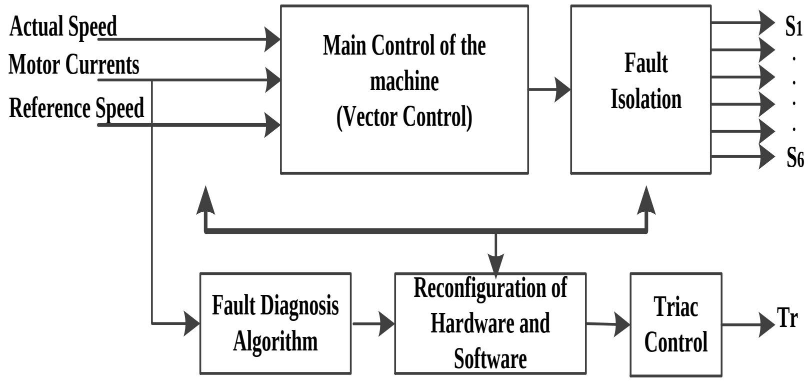



**Fig. 3. Block diagram of the fault tolerant control system.**

## IV. DYNAMIC MODELLING OF PMSM DRIVE FOR NFTPC

When single-phase open circuit fault occurs, consider phase a will get OFF and the current in phase a immediately drops to zero. Let us consider three-phase stator self-inductances be $L_a$, $L_b$ and $L_c$ which are equal to L and three-phase stator mutual-inductances be $M_{ab}$, $M_{bc}$ and $M_{ca}$ are equal to M. $i_b$ and $i_c$ are stator phase currents. Stator flux linkages $\phi_{sa}$, $\phi_{sb}$, $\phi_{sc}$ produced by the stator currents is as shown:

$$\begin{bmatrix}\phi_{sa}\\ \phi_{sb}\\ \phi_{sc}\end{bmatrix}=\begin{bmatrix}M & M\\ L & M\\ M & L\end{bmatrix}\begin{bmatrix}i_b\\ i_c\end{bmatrix} \quad (1)$$

The stator flux linkage vector in abc frame is given by

$$\begin{bmatrix}\phi_a\\ \phi_b\\ \phi_c\end{bmatrix}=\begin{bmatrix}\phi_{sa}\\ \phi_{sb}\\ \phi_{sc}\end{bmatrix}\begin{bmatrix}\phi_m\cos\theta_e\\ \phi_m\cos(\theta_e-120^\circ)\\ \phi_m\cos(\theta_e+120^\circ)\end{bmatrix} \quad (2)$$

$\phi_a$, $\phi_b$ and $\phi_c$ in equation (2) are resultant of stator flux linkages produced by stator currents and rotor magnetic field along a, b and c axes respectively. $\theta_e$ is the electrical rotor angle position and $\phi_m$ is the permanent magnet flux linkage. At the instant of detection of phase a being OFF, triac is turned ON and the stator phase voltages of PMSM given by

$$\begin{bmatrix}v_{bn}\\ v_{cn}\end{bmatrix}=\begin{bmatrix}R_b & 0\\ 0 & R_c\end{bmatrix}\begin{bmatrix}i_b\\ i_c\end{bmatrix}+\frac{d}{dt}\begin{bmatrix}\phi_b\\ \phi_c\end{bmatrix} \quad (3)$$

$$\begin{bmatrix}v_{bn}\\ v_{cn}\end{bmatrix}=\begin{bmatrix}R_b & 0\\ 0 & R_c\end{bmatrix}\begin{bmatrix}i_b\\ i_c\end{bmatrix}+\begin{bmatrix}L & M\\ M & L\end{bmatrix}\begin{bmatrix}\frac{di_b}{dt}\\ \frac{di_c}{dt}\end{bmatrix}-\begin{bmatrix}\phi_m\omega_r\sin\theta_e\\ \phi_m\omega_r\sin(\theta_e-120^\circ)\\ \phi_m\omega_r\sin(\theta_e+120^\circ)\end{bmatrix} \quad (4)$$

where $\omega_r$ is the rotor speed.

Let us consider mutual inductance is one half of the phase inductance L.

$L_d = L_q$ = L+ M = L+(1/2) L = (2/3) L

(5)

Let J, $T_e$, $T_l$, $B_m$ be moment of inertia, electromagnetic torque, load torque, coefficient of damping friction, respectively then the equation for electromagnetic torque is given by

$$J\frac{d\omega_r}{dt}=T_e-T_l-B_m\omega_r-T_s \quad (6)$$

## V. PROPOSED NFTPC FOR PMSM DRIVE

### A. Normal Operating Condition (Pre-Fault)

The discrete-time state-space model of the PMSM drive in pre fault is given by

$$i_{dp}(k+1) = \Delta i_{d0}(k) + \Delta i_{dp}(k) + i_d(k) \quad (7)$$

$$i_{qp}(k+1) = \Delta i_{q0}(k) + \Delta i_{qp}(k) + i_q(k) \quad (8)$$

where $i_{dp}$ and $i_{qp}$ are pre fault d-axis and q-axis currents respectively.

$$\Delta i_{d0}(k) = [L_s\omega_r(k)i_q(k) - R_s i_d(k)]T_s/L_s$$

$$\Delta i_{dp}(k) = [v_{dp}(k)]T_s/L_s$$

$$\Delta i_{q0}(k) = -[L_s\omega_r(k)i_d(k) + R_s i_q(k)]T_s/L_s$$

$$\Delta i_{qp}(k) = [v_{qp}(k)]T_s/L_s$$

$$[v_{dp}(k) \;\; v_{qp}(k)]^T = P_{3/2}v_{dc}(k)[\omega_{a1}(k) \;\; \omega_{b1}(k) \;\; \omega_{c1}(k)]^T \quad (9)$$

where $P_{3/2}$is a Park's transformation matrix and $\omega_{a1} = S_a$ , $\omega_{b1} = S_b$ , $\omega_{c1} = S_c$are the virtual space vectors used to calculate d-axis and q-axis voltages by Park's transformation matrix.

The cost function $C_p$ of NFTPC for pre fault is chosen such that both torque and flux at the end of the cycle is as close as of reference value:

$$C_p(k+1) = [i_d^r(k+1) - i_{dp}(k+1)]^2 + [i_q^r(k+1) - i_{qp}(k+1)]^2 \quad (10)$$

The minimum value of cost function is defined as

$$\text{Min } C_p = |T_e^r - T_e(k+1)| + k_1||\phi_s^r| - |\phi_s(k+1)||$$

$$\text{s.t. } v_s^k \in \{V_1, V_2, \text{----}, V_6\} \quad (11)$$

where $T_e^r$ and $\phi_s^r$ are torque and stator flux reference values. $T_e(k+1)$ and $\phi_s(k+1)$ are predictions for torque and stator flux at $(k+1)$th instant respectively. $V_1$, $V_2$,----,$V_6$ are non zero voltage space vectors generated by three phase inverter before fault. Voltage vectors and the corresponding swithching states of the inverter is as shown in Fig. 5.

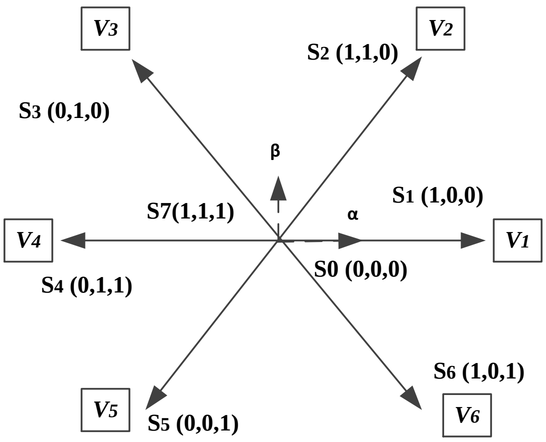



**Fig. 4. Voltage vectors and corresponding switching states of the inverter.**

### B. Post-Fault Condition

The discrete-time state-space model of the faulty PMSM drive is given by

$$i_{df}(k+1) = \Delta i_{d0}(k) + \Delta i_{df}(k) + i_d(k) \quad (12)$$

$$i_{qf}(k+1) = \Delta i_{q0}(k) + \Delta i_{qf}(k) + i_q(k) \quad (13)$$

where $i_{df}$ and $i_{qf}$ are post fault d-axis and q-axis currents respectively.

Let $v_{df}$ and $v_{qf}$ be the d-axis and q-axis voltages:

$$\Delta i_{df}(k) = [v_{df}(k)]T_s/L_s$$

$$\Delta i_{qf}(k) = [v_{qf}(k)]T_s/L_s$$

The cost function $C_f$ of NFTPC for post fault is given by

$$C_f(k+1) = [i_d^r(k+1) - i_{df}(k+1)]^2 + [i_q^r(k+1) - i_{qf}(k+1)]^2 \quad (14)$$

and the minimum cost function value is

$$\text{Min } C_f = |T_e^r - T_e(k+1)| + k_1||\phi_s^r| - |\phi_s(k+1)||$$

$$\text{s.t. } v_{sn}^k \in \{V_{bn1\_cn1}, V_{bn2\_cn2}, \ldots \ldots V_{bn6\_cn6}\} \} \quad (15)$$

where $V_{bni\_cni}$ (i=1, 2, ….,6) represents two stator phase voltages $V_{bn}$ and $V_{cn6}$.

Electromagnetic torque equation is given by

$$T_e\,(k+1) = \frac{3}{2} p[\phi_m(k+1) i_q(k+1) + (L_d - L_q) i_d(k+1)\, i_q(k+1)] \qquad (16)$$

Where p is the number of pole pairs.

### C. Proposed NFTPC Flow chart

Proposed NFTPC Flow chart to obtain minimum cost function is as shown in Fig. 5

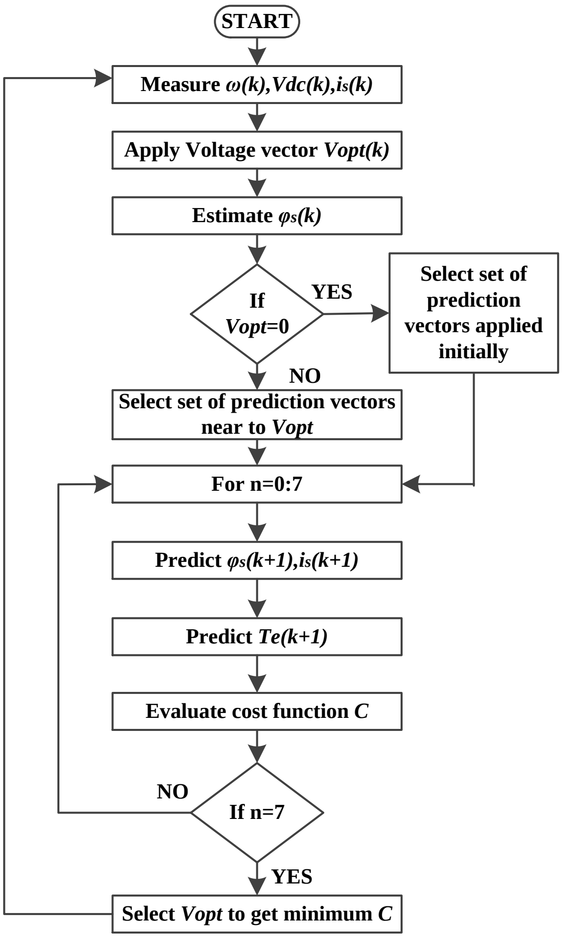



**Fig. 5. Flowchart of proposed NFTPC.**

## VI. SIMULATIONS

Fault Diagnosis simulation has been carried out in MATLAB/Simulink. Parameters of PMSM used for the proposed NFTPC are given in Table I.

TABLE I. PARAMETERS OF PMSM

| **Parameter** | **Symbol** | **Value** |
|---|---|---|
| Armature resistance | $R_s$ | 0.665 Ω |
| Armature inductance | $L_s$ | 7.9 mH |
| Moment of Inertia | J | 1.2677e$^{-4}$ Kg.m$^2$ |
| Permanent magnet flux | $\phi_m$ | 0.0131Wb |
| Number of poles | p | 10 |
| Damping Coefficient | $B_m$ | 2.4857e$^{-4}$N.m/Rad/S |
| Static Friction Torque | $T_s$ | 0.831 N.m |
| Reference Speed | $\omega_r$ | 200 rad/s |

The simulation results for three phase currents, d-axis current and torque for pre and post fault conditions are as shown in Fig.6 and Fig 7.

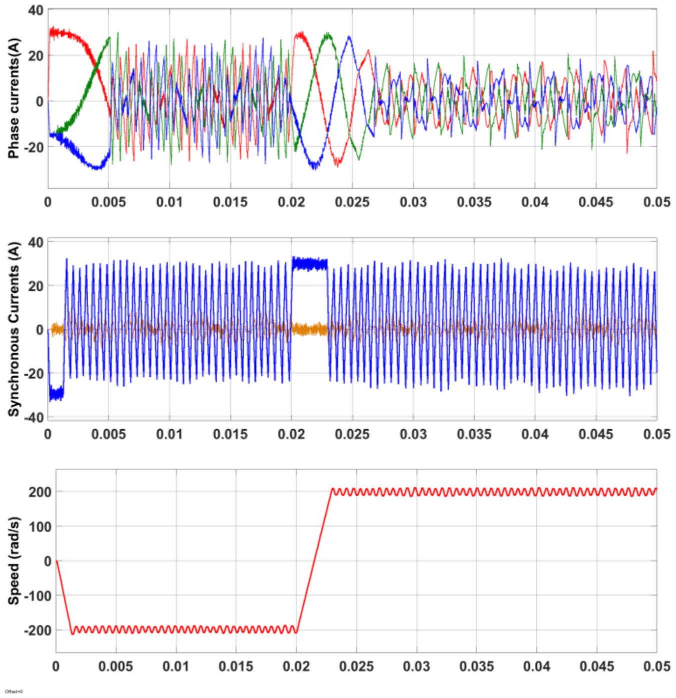



**Fig. 6. Simulation results showing phase currents, synchronous currents and speed for pre fault.**

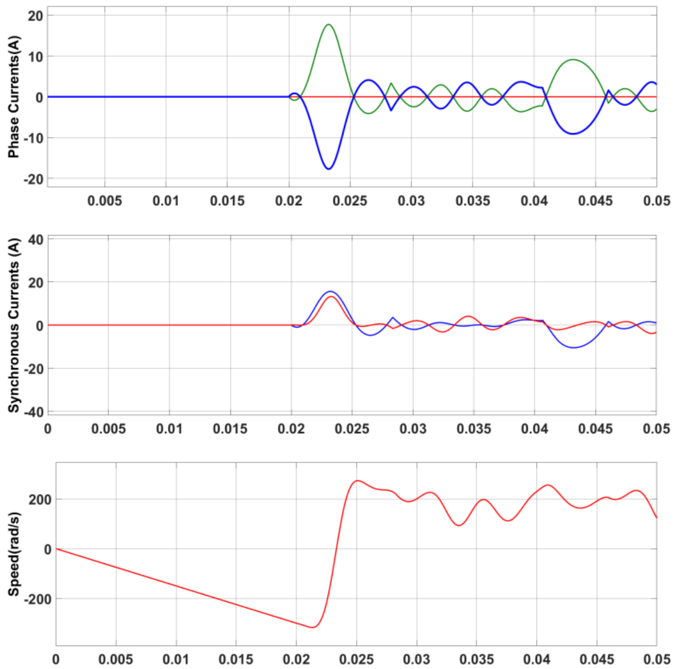
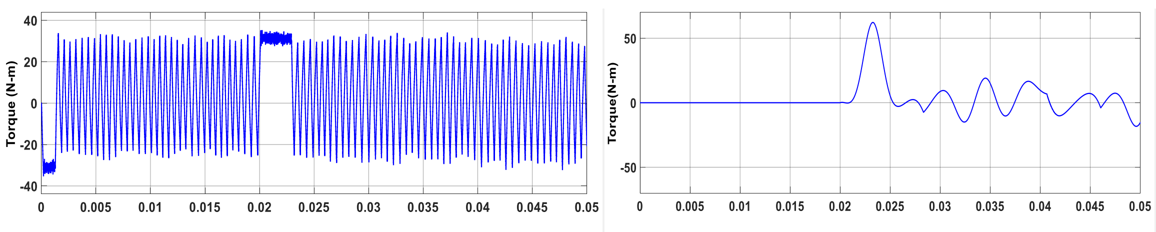
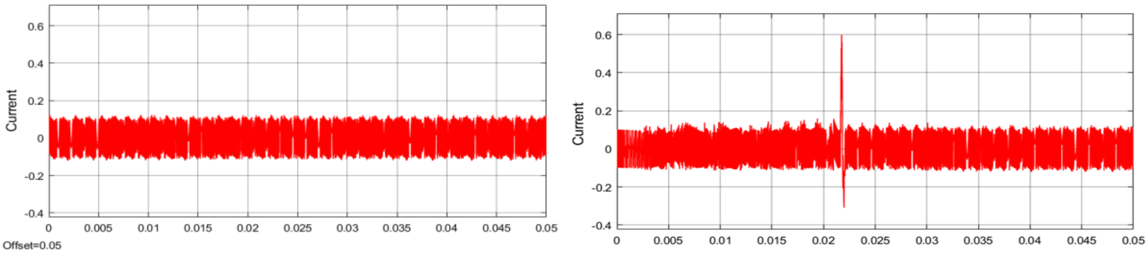



**Fig. 7. Simulation results showing phase currents, synchronous currents and speed for post fault.**




(a) (b)

**Fig. 8. Electromagnetic Torque for (a) pre fault condition and (b) post fault condition.**




(a) (b)

**Fig. 9. d-axis current for (a) pre fault condition and (b) pre fault to post fault condition.**

From Fig. 9 (b) it can be inferred that the fault gets cleared within a very short time (< 0.0005 sec) which is almost 50% less than that of the existing controllers.

## VII. CONCLUSION AND FUTURE WORK

A fault tolerant PMSM drive integrating a real-time fault diagnostic method for single phase open circuit fault of a PMSM drive has been presented in this proposal. The key component of the proposed drive system is the developed fault-tolerant control that incorporates the main control routines regarding the PMSM vector control and the diagnosis and reconfiguration process algorithm. The reconfiguration procedure comprises the inverter faulty phase isolation, by removing the corresponding transistor's gate command signals, and hardware/software modifications. Future work is to implement the proposed algorithm for PMSM drive employing novel fault tolerant predictive control considering circuit faults to validate the theoretical results.

## REFERENCES

[1]. I. Jlassi, J.Estima, S.K.Khill, and N.B.Bellaaj "A Robust Observer-Based Method for IGBTs and Current Sensors Fault Diagnosis in Voltage-Source Inverters of PMSM Drives," IEEE Trans. Ind. Appl., vol. 53, no. 3, pp. 2894–2905, May/June 2017.

[2]. L. Cheng, Y.Sui, P.Zheng, and F.Wu "Implementation of Postfault Decoupling Vector Control and Mitigation of Current Ripple for Five-Phase Fault-Tolerant PM Machine Under Single-Phase Open-Circuit Fault," IEEE Trans. Power Electron., vol. 33, no.10, pp. 8623–8635, Oct.2018.

[3]. J. Rodriguez, R.M.Kennel, J.R.Espinoza, M.Trincado, C.A.silva, and C.A.Rozas, "High-performance control strategies for electrical drives: An experimental assessment," IEEE Trans. Ind. Electron., vol. 59, no. 2, pp. 812–820, Feb. 2012.

[4]. H. A. Young, M.A.Perez, and J.Rodriguez, "Analysis of finite-control set model predictive current control with model parameter mismatch in a three-phase inverter," IEEE Trans. Ind. Electron., vol. 63, no. 5, pp. 3100–3107, Jan. 2016.

[5]. A. Dey, P.P.Rajeevan, R.Ramchand, K. Matthew, and K.Gopakumar, "A space-vector-based hysteresis current controller for a general n-levelinverter-fed drive with nearly constant switching frequency control," IEEE Trans. Ind. Electron., vol. 60, no. 5, pp. 1989–1998, May 2013.

[6]. J.W. Jung, V.Q.Liu, T.D.Do, E.K.Kim, and H.H.Choi, "Adaptive PID speed control design for permanent magnet synchronous motor drives," IEEE Trans. Power Electron., vol. 32, no. 2, pp. 900–908, Mar. 2015.

[7]. S. C. Carpiuc and C. Lazar, "Fast real-time constrained predictive current control in permanent magnet synchronous machine-based automotive traction drives," IEEE Trans. Transport. Electrific., vol. 1, no. 4, pp. 326–335, Oct. 2015.

[8]. R. Cai, R.Zheng, M.Liu, and M.Li, "Robust Control of PMSM Using Geometric Model Reduction and μ-Synthesis," IEEE Trans. Ind. Electron., vol. 65, no. 1, pp. 498–509, Jan. 2018.

[9]. W.H.Ali,M.Gowda, P.Cofie, and J. Fuller, " Design of a speed controller using extended kalman filter for PMSM," in Proc. of IEEE 57th International Midwest Symposium on Circuits and Systems (MWSCAS), Aug.2014, pp. 1101–1104.

[10]. W.Wang, J.Zhang, and M. Cheng, " Common model predictive control for permanent-magnet synchronous machine drives considering single-phase open-circuit fault," IEEE Trans. Power Electron., vol. 32, no. 7, pp. 5862–5872, July 2017.

[11]. R. Sultana and S. K. Sahoo, "Finite control set model predictive current control for a cascaded multilevel inverter" J. Electr .Eng. Technol., vol. 11, no. 6, pp. 1674–1683, Nov. 2016.

[12]. M. P. Akter, "Model predictive control of bidirectional AC-DC converter for energy storage system", J. Electr .Eng. Technol., vol. 10, no.1, pp. 165–175, Jan. 2015.

[13]. Z. Song, Y. Tian, W. Chen, Z. Zou and Z. Chen, "Predictive duty cycle control of three-phase active-front-end rectifiers", IEEE Trans. Power Electron., vol. 31, no. 1, pp. 698–710, Jan. 2016.

[14]. S. Mariethoz and M. Morari, "Explicit model-predictive control of a pwm inverter with an LCL filter," IEEE Trans. Ind. Electron., vol. 56, no. 2, pp. 389-399, Feb. 2009.

[15]. R. Baidya, R. P. Aguilera, P. Acuna, R. Delgado, T. Geyer, D. Quevedo, and T. Mouton, "Fast multistep finite control set model predictive control for transient operation of power converters," Proc. IEEE Ind. Electron. Conf., Florence, Italy, Oct. 2016, pp. 5039–5045.

[16]. S. Vazquez, J. I. Leon, L. G. Franquelo, J. Rodriguez, H. A. Young, A. Marquez, and P. Zanchetta, "Model predictive control: A review of its applications in power electronics," IEEE Ind. Electron. Mag., vol. 8, no. 1, pp. 16–31, Mar. 2014.

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