Fault Analysis of Electrical Machine Drives Employing Novel Model Predictive Control

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ABSTRACT

Electrical machine drives play a crucial role in various industrial applications. Therefore, its control system design became more significant in the last decades. Numerous high powers and high-efficiency machine drives require faultless continuous operation. Fault-tolerant control is a productive solution for the improvement of 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. MPC can handle MIMO systems and can incorporate several constraints in the form of equalities and inequalities. A Novel Model Predictive Control (NMPC) method for a Synchronous Servo Motor Drive (SSMD) integrating a real-time fault diagnostic method for Insulated Gate Bipolar Transistor (IGBT) faults in an inverter have been presented in this paper. NMPC ensures the system's better performance and minimal fault clearanc.

Key Words: Novel Model Predictive Control (NMPC), MPC, Synchronous Servo Motor Drive (SSMD), Insulated-Gate Bipolar Transistor (IGBT).

1. INTRODUCTION

Nowadays, Servo drives are used for numerous production facilities and are employed where the dynamic, automatic variable speed drives are necessary. Servo drives consist of a permanent-magnet synchronous motor (PMSM) provide with an inverter unit [1]. Synchronous servo motor drives (SSMD) are extensively used in the control system to turn the electrical signal to a motor's mechanical displacement [2]. A variable frequency inverter in controlled speed synchronous motor drives provides synchronous speed to overcome the fixed speed limitation resulting from the mains constant frequency [3]. Among all the faults of synchronous servo drives, a single-phase open circuit (SOCF) fault as usual, in which one phase winding disconnected from the VSI [4]. The performance of the motor does not remain valid under short circuit fault condition. For this cause, some researchers have studied their proposed model using MATLAB /Simulink and validated experimentally to detect the effects of faults in an electrical machine [5-7]. Various control methods proposed for multiphase machines with open-circuit faults [8]. For predicting the system's future behavior and cost function minimization, MPC is presented [9]. Researchers proposed many advanced current control strategies such as Predictive current control [10-17], Hysteresis control [18], and Fuzzy PI control [19] to find the rapid response of the current control loop. PCC method tracks the current reference rapidly and accurately by taking both stability and small current harmonic components into account [20]. PID controllers have easy structure and few parameters that operators could change to improve the controller's performance. PID controllers do not provide optimal control inputs [21]. A more advanced control approach is a Linear Quadratic Regulator (LQR), which offers optimality. LQR solves an optimization problem of minimization of the state and inputs over the infinity prediction horizon subject to a linear constraint, which is the system’s linear model. LQR cannot handle other constraints, but it applies to MIMO systems without decoupling [22]. Two different MPCs needed for routine and post fault operations of PMSM drives as a model-based control, making the whole control method complicated [23-26]. To a certain extent, MPC faces a problem in achieving the robustness against model mismatches and noises [27-30]. Modern MPC algorithms can perform some specific features such as more constraints [31-33], reduction in online computation [34]. However, there is a concern to find a computationally, reliable, and efficient MPC algorithm [35].
A novel model predictive controller (NMPC) is designed for synchronous servo motor drive (SSMD) considering single-phase open-circuit fault (SOCF), short circuit fault (SCF), and demagnetization fault (DF). First, the mathematical modeling of SSMD for the pre-fault and post-fault operation has been introduced, followed by the advancement of the NMPC. The NMPC then employs for the prediction of current in a discrete-time calculation. The phase current can be estimated at the next sampling step to compensate for the current errors, with the modification of three-phase currents of the motor. The machine's speed responses using traditional control methods compared with the NMPC under different load and speed references for various fault conditions. The experiments conducted on the Lucas Nulle servo drive system for all the faults occur in machine drive to validate the simulation results. The complete analysis and the simulation and experimental results show that with the adoption of NMPC, fault clearance time for all the different types of faults occurs in the servo drive system is intensively low compared to the conventional controllers.

2. MODEL PREDICTIVE CONTROL

2.1 Recent control and modulation schemes for industrial drive

Control and modulation schemes for industrial drives used recently are listed below:

- **Direct Torque Control (DTC):**
  Analysis of PMSM shows that electromagnetic torque is proportional to the angle between the stator and rotor flux linkages. The stator flux linkage's rotating speed needs to increase for the direct torque control method's fast torque response. Compared to vector control methods, the direct torque control has a simple structure that allows the easy implementation to the digital signal controller. Also, DTC has high robustness and minimal torque response time due to which a high dynamic performance of the drive can be achieved [36-37].

- **Direct Power Control (DPC):**
  In this method, active and reactive powers are regulated in a fixed switching frequency with a space vector modulation (SVM) technique. DPC-SVM has a unique feature in active and reactive power with a continuous switching frequency and low ripples [38].

- **Field-Oriented Control (FOC):**
  In this scheme, an orthogonal current vector component controls the position of a servo motor. The stator currents are considered two different vectors: the torque and the motor's magnetic flux [39].

- **Voltage-Oriented Control (VOC):**
  VOC has a cascaded control structure with an outer dc-link voltage control loop and an inner current control loop. A minimum dc-link voltage is necessary to obtain undistorted current waveforms for the proper operation of the rectifier. All the six diodes need to be polarized negatively at all the ac-voltage supply values for the rectifier's full control [40].

- **Carrier-Based Pulse Width Modulation (CB-PWM):**
  CB-PWM is the modulation process used in most communication systems to encode a signal's amplitude into a pulse width, usually a carrier signal, for transmission [41].

- **Space Vector-Pulse Width Modulation (SV-PWM):**
  SV-PWM is the final step in the field-oriented control technique to generate the motor's desired three-phase voltages. In this technique, a steady-state DC-voltage is provided to the inverter's six switches to create a frequency and amplitude adjustable sinusoidal waveform [42].

- **Volts Per Frequency (V/f) Control with Optimized Pulse Patterns (OPPs):**
  MV converter systems mostly use OPPs. Optimized pulse patterns (OPPs) allow minimizing the current distortions for a given switching frequency [43].

- **Model Predictive Control (MPC):**
  MPC is an advanced control technique that controls the multi-input multi-output (MIMO) process satisfying inequality constraints impacted by the input and output variables. Model and current measurements predict the outputs' future values if a feasible and accurate dynamic model of the process is available. The predictions and measurements are used for calculation of the appropriate changes in the input variables [44].

2.2 Comparison of MPC with other control methods

Figure 1. shows the comparison of MPC with other control methods. MPC combines the advantages of DTC or DPC during transients with the benefits of offline computed OPPs during steady-state operation. The bandwidth (response time for changing input command) is fast for MPC, and it has very low distortion and switching losses.
2.3 Fundamental Structure of MPC
The objective of an MPC is to prevent violations of input and output constraints. It drives some output variables to their optimal set points while maintaining other outputs within specified ranges. In addition to this, it prevents excessive movement of the input variables. MPC can control as many process variables as possible when a sensor or actuator is not available. MPC’s main objective is to maximize a profit function while minimizing a cost function or maximizing a production rate [46]. Figure 2 shows the fundamental structure of the MPC.

2.4 Working Principle of MPC
The future outputs are predicted at each sampling instant t considering the dynamic output of the plant for the prediction horizon N. These predicted outputs y (t+ k) depends on the known values up to instant t (past inputs and outputs) and the future control signals u (t + k). A model is used to predict future plant outputs based on past and current values and the proposed optimal future control actions [47]. The optimizer's actions are calculated considering the cost function and the constraints, as shown in Figure 3.
The economic optimization based on a steady-state model of the process calculates the control action set points. The current measurements and predictions of the future values of the outputs determine the MPC calculations are based. The MPC control calculations’ objective is to select a sequence of control moves (manipulated input changes) so that the predicted response optimally moves to the set-point [48]-[49].

3. FAULT-TOLERANT CONTROL AND DYNAMIC MODELLING FOR NMPC

3.1 Fault-Tolerant Control of PMSM Drive

Figure 4 shows the fault-tolerant control analogy. The PMSM neutral point N connected to the mid-point of the DC bus capacitor link. This analogy mitigates both open circuits as well as short circuit fault. It comprises a conventional three-phase drive and three fast-acting fuses connected in series with the stator windings. A triac TRn is used for the control of open circuit fault and triacs TRa, TRb, and TRc are used for the short circuit fault. The triacs remains OFF during the normal operating condition of the drive. When a fault occurs, the faulty leg will be isolated first, and then the triac will be turned ON. Triacs turned OFF during the normal operating condition of the drive. When a fault occurs, the faulty leg will be isolated first, and then the triac will be turned ON. The neutral point is needed to control the currents' amplitude and phase in the remaining two healthy phases. The currents in the remaining two healthy phases should be regulated to a magnitude of $\sqrt{3}$ times their original value, and phase-shifted 60° with respect to each other to maintain the torque and the motor's performance.
3.2 Dynamic Modelling of SSMD for NMPC

Considering single-phase open-circuit fault occurs in phase $a$, it will get OFF, and the current immediately drops to zero. Now consider the three-phase stator self-inductances be $L_a, L_b$ and $L_c$ to $L$ and three-phase stator mutual-inductances be $M_{ab}, M_{bc}$ and $M_{ca}$ to $M$. Stator phase currents $i_b$ and $i_c$[44]

$$\begin{align*}
\lambda_{sa}, \lambda_{sb}, \lambda_{sc} \text{ be the stator flux linkages produced by the stator currents are as shown:} \\
\begin{bmatrix}
\lambda_{sa} \\
\lambda_{sb} \\
\lambda_{sc}
\end{bmatrix} =
\begin{bmatrix}
M & M \\
L & M \\
M & L
\end{bmatrix}
\begin{bmatrix}
i_b \\
i_c
\end{bmatrix}
\end{align*}$$

(1)

The stator flux linkage vector equation in $abc$ frame:

$$\begin{align*}
\dot{\lambda}_a &= \lambda_m \cos \theta_e \\
\dot{\lambda}_b &= \lambda_m \cos(\theta_e - 120^\circ) \\
\dot{\lambda}_c &= \lambda_m \cos(\theta_e + 120^\circ)
\end{align*}$$

(2)

The resultant of stator flux linkages produced by stator currents and rotor magnetic fields along $a$, $b$, and $c$ axes are $\lambda_a, \lambda_b$ and $\lambda_c$ respectively. The electrical rotor angle position is $\theta_e$ and the permanent magnet flux linkage is $\lambda_m$. At the instant of phase $a$ being OFF, the triac gets turned ON. The stator phase voltages vector of PMSM given by:

$$\begin{align*}
\begin{bmatrix}
v_{bn} \\
v_{cn}
\end{bmatrix} &= \begin{bmatrix} R_b & 0 & \frac{i_b}{\lambda_m} \\
0 & R_c & \frac{i_c}{\lambda_m}
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
\lambda_b \\
\lambda_c
\end{bmatrix} \\
\dot{\lambda}_b &= \lambda_m \cos(\theta_e - 120^\circ) \\
\dot{\lambda}_c &= \lambda_m \cos(\theta_e + 120^\circ)
\end{align*}$$

(3)

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

(4)

$\omega_r$ ------ the speed of the rotor.

Here it is assumed that 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 us consider the moment of inertia, electromagnetic torque, load torque, coefficient of damping friction be $J, T_e, T_l$ and $B_m$ respectively.

The electromagnetic torque equation is given by

$$J \frac{d\omega_r}{dt} = T_e - T_l - B_m \omega_r - T_s$$

(6)

3.2.1 Proposed NMPC for PMSM Drive for Normal Operating Condition (Pre-Fault) [44]

The state-space(discrete-time) model of the PMSM drive before the occurrence of fault (pre-fault) is given by

$$i_{dp}(k + 1) = \Delta i_{dp}(k) + \Delta i_{qp}(k) + i_q(k)$$

(7)

$$i_{qp}(k + 1) = \Delta i_{qo}(k) + \Delta i_{qp}(k) + i_q(k)$$

(8)

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

$$\Delta i_{dq0}(k) = \begin{bmatrix} L_s \omega_r(k) i_q(k) & -R_s i_q(k) \end{bmatrix} T_s / L_s$$

$$\Delta i_{dp}(k) = \begin{bmatrix} v_{dp}(k) \end{bmatrix} T_s / L_s$$

$$\Delta i_{qo}(k) = \begin{bmatrix} -L_s \omega_r(k) i_d(k) & +R_s i_d(k) \end{bmatrix} T_s / L_s$$

$$\Delta i_{qp}(k) = \begin{bmatrix} v_{qp}(k) \end{bmatrix} T_s / L_s$$

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

(9)

where $P_{3/2}$ is a Park’s transformation matrix

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\( \omega_{a1} = S_a, \omega_{b1} = S_b, \omega_{c1} = S_c \) ------ the virtual space vectors which are used to calculate d-axis and q-axis voltages by Park’s transformation matrix.

The cost function \( C_p \) of NMPC for pre-fault must be chosen so that both torque and flux is as close as of reference value:

\[
C_p(k + 1) = \left[ i_d^p(k + 1) - i_{dp}(k + 1) \right]^2 + \left[ i_q^p(k + 1) - i_{qp}(k + 1) \right]^2
\]  

(10)

The minimum value of cost function is defined as

\[
\text{Min } C_p = [T_e^f - T_e(k + 1)] + k_f [\lambda^f_0] - [\lambda_e(k + 1)]
\]

s.t. \( V_i(k) \in \{ V_1, V_2, ..., V_6 \} \)  

(11)

\( T_e^f \) and \( \lambda^f_0 \) ------ torque and stator flux reference values.

\( T_e(k + 1) \) and \( \lambda_e(k + 1) \) ------ predictions for torque and stator flux at \( (k + 1) \)th instant, respectively.

\( V_1, V_2, ..., V_6 \) ------ non zero voltage space vectors generated by a three-phase inverter before the fault.

Voltage vectors and the corresponding switching states of the inverter is as shown in Figure 6.

\[
\begin{align*}
V_1 & \rightarrow S_0(0,0,0) \\
V_2 & \rightarrow S_1(1,0,0) \\
V_3 & \rightarrow S_2(1,1,0) \\
V_4 & \rightarrow S_3(0,1,0) \\
V_5 & \rightarrow S_4(0,1,1) \\
V_6 & \rightarrow S_5(0,0,1) \\
V_7 & \rightarrow S_6(1,0,1) \\
V_8 & \rightarrow S_7(1,1,1)
\end{align*}
\]

3.2.2 Proposed NMPC for PMSM Drive for Faulty Condition (Post-Fault)

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

\[
i_{df}(k + 1) = \Delta i_{d0}(k) + \Delta i_{df}(k) + i_d(k)
\]

(12)

\[
i_{qf}(k + 1) = \Delta i_{q0}(k) + \Delta i_{qf}(k) + i_q(k)
\]

(13)

\( i_{df} \) and \( i_{qf} \) ------ post fault d-axis and q-axis currents, respectively.

Let \( v_{df} \) and \( v_{qf} \) be the d-axis and q-axis voltages:

\[
\Delta i_{df}(k) = \left[ v_{df}(k) \right] T_e/L_s
\]

\[
\Delta i_{qf}(k) = \left[ v_{qf}(k) \right] T_e/L_s
\]

The cost function \( C_f \) of NMPC for the post-fault is given by

\[
C_f(k + 1) = \left[ i_d^f(k + 1) - i_{df}(k + 1) \right]^2 + \left[ i_q^f(k + 1) - i_{qf}(k + 1) \right]^2
\]

(14)

In the NMPC algorithm, while evaluating cost function, the stator phase voltages \( (V_{bn} \text{ and } V_{cn}) \) are directly employed instead of voltage space vector.

The minimum cost function value is

\[
\text{Min } C_f = [T_e^f - T_e(k + 1)] + k_f [\lambda^f_0] - [\lambda_e(k + 1)]
\]

s.t. \( V_{bn}(k + 1) \in \{ V_{b1,1}, V_{b2,2}, ..., V_{b6,6} \} \)

(15)

where \( V_{bn}(i, j) \) represents two stator phase voltages \( V_{bn1} \text{ and } V_{bn6} \).

In NMPC, the phase currents predicted in abc reference frame instead of d-q. Therefore equation (4) can be rewritten as

\[
\frac{di}{dt} = \frac{1}{i^2-M^2} \left[ MV_{bn} - MV_{cn} + MR_{cl} I_c - R_b I_b + L\omega_r \sin(\theta_e - 120°) - M\omega_r \sin(\theta_e + 120°) \right]
\]

(16)

\[
\frac{di}{dt} = \frac{1}{i^2-M^2} \left[ MV_{cn} - MV_{bn} + MR_{bl} I_b - LR_{cl} I_c + L\omega_r \sin(\theta_e + 120°) - M\omega_r \sin(\theta_e - 120°) \right]
\]

(17)

The prediction of stator current at next sampling instant based on given stator voltages \( V_{bn}(k), V_{cn}(k) \) and measured currents \( i_b(k), i_c(k) \) at the current sampling instant.

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\[ i_b(k+1) = i_b(k) + \frac{Ts}{2\pi M} [L V_{bn}(k) - M V_{cn}(k) + M R e i_c(k) - R_b L i_b(k)] \\
+ L \lambda_m(k) \omega_r(k) \sin(\theta_c(k) - 120^\circ) - M \lambda_m(k) \omega_r \sin(\theta_c(k) + 120^\circ) \] \tag{18}

\[ i_c(k+1) = i_c(k) + \frac{Ts}{2\pi M} [L V_{cn}(k) - M V_{bn}(k) + M R e i_b(k) - R_c L i_c(k)] \\
+ L \lambda_m(k) \omega_r(k) \sin(\theta_c(k) + 120^\circ) - M \lambda_m(k) \omega_r \sin(\theta_c(k) - 120^\circ) \] \tag{19}

where \( i_b(k+1) \) and \( i_c(k+1) \) are predicted values for the stator currents for the next sampling period, \( Ts \).

After getting \( i_b(k+1) \) and \( i_c(k+1) \) both the torque and flux at the \((k+1)\)th instant can be estimated.

3.2.3 Torque Estimation

The electromagnetic torque equation is given by

\[ T_e(k+1) = \frac{3}{2} p [\lambda_m(k+1) i_q(k+1) + (L_d - L_q) i_d(k+1) i_q(k+1)] \] \tag{20}

\( p \) is the number of pole pairs.

3.2.4 Flux Estimation

Flux linkage expression can be given by

\[ \begin{bmatrix} \lambda_d(k+1) \\ \lambda_q(k+1) \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} + \begin{bmatrix} \lambda_m(k+1) \\ 0 \end{bmatrix} \] \tag{21}

\( L_d, L_q \) and \( i_d, i_q \) are d-q system inductances and currents, respectively.

Using Park and Clarke transformations, \( i_d \) and \( i_q \) can be calculated as

\[ \begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} = \begin{bmatrix} \cos \theta_e(k+1) & -\sin \theta_e(k+1) \\ \sin \theta_e(k+1) & \cos \theta_e(k+1) \end{bmatrix} \begin{bmatrix} -1/2 & -1/2 \\ \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_b(k+1) \\ i_c(k+1) \end{bmatrix} \] \tag{22}

Finally, the stator flux linkage is given by

\[ \lambda_s(k+1) = \sqrt{[\lambda_d(k+1)]^2 + [\lambda_q(k+1)]^2} \] \tag{23}

The desired reference stator flux linkage obtained by maximum torque per ampere algorithm

\[ \lambda_s^* = \sqrt{[T_e^* L_q \lambda_d^*/(2 \pi M \lambda_m)]^2 + [i_d^* L_d + \lambda_m]^2} \] \tag{24}

Where \( i_d^* \) is assumed to be zero

Hence, \( \lambda_s^* = \sqrt{[T_e^* L_q \lambda_d^*/(2 \pi M \lambda_m)]^2 + \lambda_m^2} \) \tag{25}

4. ANALYSIS OF SSMD FOR NMPC

Analysis of SSMD for NMPC carried out using the LUCAS NULLE servo drive system.

4.1 Specification of synchronous servo motor used for the analysis of proposed NMPC

Table 1 shows the parameters of the synchronous servo motor for the proposed NMPC.

| Parameter                | Symbol | Value   |
|--------------------------|--------|---------|
| Armature resistance      | \( R_s \) | 4.74Ω   |
| Armature inductance      | \( L_s \) | 8.6 e^-3 H |
| Moment of Inertia        | \( J \)   | 0.33 Kg.cm² |
| Permanent-magnet flux    | \( \lambda_m \) | 0.089Wb |
| Number of poles          | \( P \)   | 8       |
| Standstill current       | \( I_o \) | 2.99 A  |
| Peak current             | \( I_{\text{omax}} \) | 12 A   |
| Reference Speed          | \( \omega_r \) | 1000 rpm |
4.2 Experimental Set-up
Figure 7 shows the experimental set-up of the Lucas Nulle servo drive system for NMPC. It comprises a self-commutated converter, MATLAB interface for power electronics, three-phase isolating transformer 300 VA, synchronous servo motor 0.3 kW, and incremental position encoder with 1024 pulses analog/digital multimeter, wattmeter and power factor meter, servo test stand for 0.3 kW machines.

![Figure 7. Experimental set-up of SSMD for NMPC](image)

4.3 Results
Figures 8 and 9 show the simulation and experimental results for three-phase currents for SSMD employing NMPC before the fault.

![Figure 8. Simulation result of Three-Phase Currents](image)

![Figure 9. Experimental result of Three-Phase Currents](image)

Figure 10. Phase A current under SOCF fault (Speed=500 rpm)

Figure 11. Phase A current under SOCF fault (Speed=1000 rpm)
Figures 10 – Figure 15 shows that employing novel model predictive control, the fault clearance time for all the three different types of faults that occurred in servo drive is short, which is less than 5 ms compared to the other fault-tolerant algorithms.

5. CONCLUSION

In this paper, a fault-tolerant synchronous servo motor drive (SSMD) considering a real-time fault diagnostic method employing novel model predictive control has been presented. Here the three different types of faults; single-phase open-circuit fault (SOCF), short circuit fault (SCF), and permanent magnet demagnetization fault (DF) under parameter mismatch of a PMSM drive are considered. Implementation of the proposed algorithm for SSMD, employing novel model predictive control considering circuit faults performed using Lucas Nulle Servo Drive system with MATLAB Simulink. The experimental results show the effectiveness of the proposed algorithm.

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