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MODEL PREDICTIVE CONTROL OF FIVE-PHASE PERMANENT MAGNET
ASSISTED SYNCHRONOUS RELUCTANCE MOTOR

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MODEL PREDICTIVE CONTROL OF FIVE-PHASE PERMANENT MAGNET
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ABSTRACT

The thesis presents a control system developed based on model predictive control (MPC) technique for a five-phase permanent magnet assisted synchronous reluctance motor (PMaSynRM). The control system is designed in cascaded structure with a proportional-integral (PI) controller and the developed MPC. MPC is designed with the objective of minimizing torque error. The maximum torque per ampere (MTPA) condition is derived for a five-phase PMaSynRM and has been used to generate the reference currents. To take advantage of the fault-tolerant capability of five-phase PMaSynRM, the applicability of the developed controller for fault tolerant operation (FTO) has been investigated.

A comprehensive analysis has been carried out along with Matlab simulations to verify the performance of the proposed MPC over a benchmark controller (modeled completely with PI controllers) for both healthy and faulty conditions. MPC performs better in fault scenario than the benchmark controller. The model used in MPC depends on motor parameters and they are susceptible to change due to environmental conditions. Therefore, a sensitivity analysis has been carried out and proved the resiliency of the controller for dynamic parameter variations. Initial experimental results are provided to validate the controller operation.

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CHAPTER I

INTRODUCTION TO MULTI-PHASE MOTOR DRIVES AND MODEL PREDICTIVE CONTROL

The electric motor has become a vital tool in the modern world with its wide applications ranging from everyday household appliances to transportation and in many more industries. With the increased demand, research has been carried out extensively over the years on motor drive systems to improve the efficiency, reliability and other performance related aspects required in applications.

A typical electric motor drive system is illustrated in Fig. 1.1. Basically, the system consists of a motor and a controller connected through an inverter. The controller penalizes the input to the motor to reach the required operation. The control system can be closed loop or open loop depending on the criticality of the application. In a closed loop control system, there is a feedback mechanism to update the controller on plant behavior to take necessary actions in the next control cycle.

In general, motors have a three-phase configuration as implied in Fig.1.1. Motors that have more than three phases are recognized as multi-phase motors. Although multi-phase motors are equipped with complex hardware and control structure, they still find primacy in certain applications [2]. This is mainly due to the advantages listed below.

Figure 1.1: A basic motor drive architecture.

- More degrees of freedom.
- Reduced torque ripple percentage.
- Better power distribution among a higher number of phases.
- Being able to operate at high speeds.
- High energy density.
- Less current stress per phase.

Further, there are various motor types developed addressing different requirements. Among them, the induction motor (IM) has been deployed in many situations from early days due to its lower cost and ease of handling [3, 4]. However, the permanent magnet synchronous motor (PMSM) has been gaining attention for its high performance in terms of efficiency, controllability and torque density even though it is relatively costly [5, 6]. With the definite advantages, PMSM has become a prospect

in many emerging performance critical applications such as electrified transportation and military [7, 8]. The basic PMSM is evolved in different directions to facilitate different objectives. One such variant of PMSM is permanent magnet assisted synchronous reluctance motor (PMSynRM). This research has been carried out focusing a five-phase PMSynRM and a detailed review of the particular motor has been done in section 2.1.

The controller in Fig. 1.1 adopts a control technique as per the requirements of application. There are various control techniques developed addressing different objectives and a few are listed in Fig. 1.1. Field oriented control (FOC) is a widely used control mechanism in which the torque and flux components are separately controlled [9–12]. In FOC, the system performance is maintained by controlling the current. The inherent bandwidth of the inner current loop of FOC has limited its dynamic performance. The applications that demand high dynamic performance have applied direct torque control (DTC) in the recent past [13–15]. DTC can outperform FOC with improved dynamic performance since it can directly control the output voltage vector. However, DTC has disadvantages such as large current and torque ripples since the control is based on a finite switch table. But improved DTC techniques are developing addressing its weaknesses [16].

Model predictive control (MPC) is a highly developing control area for motor drives with its optimized and improved control performance and numerous other benefits [17–21]. One major advantage of MPC is being able to control, considering several conditions and constraints at the same time and being able to prioritize each

condition depending on its importance to the system [22]. However, the execution time of the predictive controller is comparatively high due to its computational complexity. Nevertheless, application of MPC in motor drives has become realistic with the technological advancement in powerful micro-controllers/processors. A rigorous analysis of MPC has been done in section 2.2.

Different motor configurations and control algorithms are developed to meet the demands of various applications. In multi-phase motor configurations, the most highlighted feature is the inherent redundancy that arises from the increased number of degrees of freedom. This enables multi-phase motors to operate continuously, even under open-phase faults. However, even multi-phase motors display reduced performance [23] at fault. The high torque ripple limits the broad application of fault tolerant schemes. Increased torque ripples in a motor cause destructive vibrations and increase the heat generation. Thus, motor controlling techniques are developed targeting improved performance for fault tolerant operation (FTO). An overview of FTO is done further in section 2.3.

This thesis unfolds as two main sections; developing a MPC based controller for five-phase PMaSynRM with proved resiliency for dynamic parameter variations and investigating the controller's applicability for FTO. Additionally the use of MPC on speed control for a very high speed motor application has been explored.

1.1 Contributions of the Thesis

The main contribution of this thesis can be broadly viewed as developing a control system based on MPC strategy for five-phase PMSynRM. The work done can be summarized as follows;

1. A control system has been developed based on MPC technique for five-phase PMSynRM. In this purpose, a mathematical model for the five-phase PMSynRM has been derived. The main focus of the proposed control system is to improve torque performance; therefore, the optimization problem of MPC is designed to minimize the torque error. The maximum torque per ampere (MTPA) condition for five-phase PMSynRM has been derived and is incorporated to generate reference currents to the controller. A rigorous performance analysis for the proposed controller has been carried out with MATLAB simulations comparing with a benchmark system. The proposal is further validated through experimental results. The model parameters of a motor vary with changes in environment, so can deviate from the name plate data of the motor. Therefore, a controller design that depends on model parameters should be investigated for its resiliency to the variations. A thorough analysis has been carried out to check the controller's sensitivity to dynamic parameter variations. Different practical and analytical techniques are adopted to identify the practical ranges of variations for winding resistance and dq-axis inductance.

From the analysis it is observed that the controller has very low susceptibility to dynamic parameter variations.

2. MPC performance for FTO has not been extensively studied for multi-phase permanent magnet machines. This work is an attempt to address that need, by exploring the applicability of the developed controller for FTO under single-phase open-fault. The proposed controller provides a convincing approach in fault tolerant control with less torque ripples and better performance. Abrupt changes to model parameters are inevitable with extreme environment conditions due to fault. Therefore, a modified MPC changing the winding resistance is analyzed. Initial findings in this direction imply that the resistance variations during a fault does not have a considerable impact on system performance.

The research contributions have been reported in four conference publications upto now.

1.2 Thesis Outline

The contents of the thesis unfold as follows.

Chapter 2 presents basic principles and background research on five-phase PMaSynRM, MPC and FTO. The chapter starts by introducing PMaSynRM and explains related machine theories. Next, the discussion is developed towards MPC techniques, followed by a detailed description on basic concepts and theories on MPC. The discussion extends to finite control set model predictive control (FCS-MPC), the

specific MPC strategy used. Then a brief introduction is given on FTO and the use of multi-phase machines in FTO. Finally a comprehensive review is presented on previous research in the same direction.

Chapter 3 presents the derivation of a MPC based control system for five-phase PMaSynRM. The controller design is discussed giving a high focus for current reference generation and optimization technique. A benchmark control system is used in which MPC is replaced by a proportional-integral (PI) controller to provide a comparative analysis on performance. Simulation and experimental results are presented to prove the viability of the proposed controller. Further a sensitivity analysis for the controller has been carried out to check the resiliency to dynamic parameter variations of the proposed controller and the results have been illustrated and quantified.

Chapter 4 explores the applicability of the proposed controller for FTO. A single-phase open-fault is considered here and simulations with MATLAB are carried out to check the viability. Further, a new direction in modeling the faulty motor is explored and compared with the performance of the previous model.

Chapter 5 provides an extension of MPC in the direction of speed control. Here, the objective is to develop a high performance controller for high speed operation for an application of a mechanically based ULF/VLF transmitter. The MPC strategy is integrated in this regard with the focus to minimize speed error. A machine model has been developed for bench-marked five-phase PMaSynRM which can

operate at very high speed and a controller was designed for that model. Simulation results produced with MATLAB are presented.

Chapter 6 provides the summary of the work carried out in this thesis along with the conclusions, and potential future work.

CHAPTER II

LITERATURE REVIEW

This chapter reviews the literature on five-phase PMSynRM, MPC, FTO and related. The exploration of basic theories and their evolution from different machine typologies to control techniques for fault tolerant operation has been presented. Initially the fault types of motor drives and different fault tolerant operation approaches that has been proposed earlier, were discussed. Then the use of multi-phase machines and theories related particularly to the five-phase PMSynRM are presented. After that the discussion extends to the control techniques in use, to improve the system performance during a fault. Finally, various fault tolerant operation techniques using model predictive control has been discussed rigorously.

2.1 Five-phase Permanent Magnet assisted Synchronous Reluctance Motor

In a typical PMSM structure, permanent magnets are rigidly fixed to the rotary part to create a constant rotor flux. The energized stator windings create a rotating electromagnetic field and stator currents are controlled to control the electromagnetic field. Five-phase winding system is the minimum multi-phase motor configuration. It provides all the advantages listed in Chapter 1 for multi-phase motors. Using the smallest multi-phase configuration is advantageous in a way, since the increment in

number of hardware components increase the complexity in potential failures and in fault detection and control techniques. A five-phase motor can operate even with up to two-phase loss without connecting additional hardware.

2.1.1 Fundamental Principles of Five-Phase Electric Motor

Normally, the five-phase motor is supplied through a five-leg inverter which uses ten switches (MOSFET/IGBT). A five-phase motor has five stator winding connected to five separate excitation which are electrically 72° apart from each other. The balanced distribution of five-phase electrical quantities with angular position is given in Fig. 2.1. Those quantities can be mathematically represent as (2.1).

Figure 2.1: Five-phase balanced distribution.

$$\begin{aligned}
X_a &= X_{am} \sin(\omega t) \\
X_b &= X_{bm} \sin(\omega t + 2\pi/5) \\
X_c &= X_{cm} \sin(\omega t + 4\pi/5) \\
X_d &= X_{dm} \sin(\omega t + 6\pi/5) \\
X_e &= X_{em} \sin(\omega t + 8\pi/5)
\end{aligned} \tag{2.1}$$

Here X_{abcde} can be voltage or current and $X_{am} - X_{em}$ are the peak value of each phase. The electrical speed ω is in radians per second and t is the time in seconds.

2.1.2 Permanent Magnet Synchronous Reluctance Motor

A broad classification can be given to electric motors depending on whether torque is produced electromagnetically or by variable reluctance. Majority of motors in industry uses only the first technique, in which the two magnetic fields of rotor and stator interact with each other to produce motion. Different machine types has this same operating principle; in some, field is generated with energized winding and in some, it's permanent magnets. Second technique is based on the variable reluctance of the airgap between rotor and stator. With the electromagnetic field produced by the energized stator winding, the rotor tends to move to its minimum reluctance position. This is called the reluctance torque. Switched reluctance motor (SRM) has this operating principle. Reluctance motors have the advantage of passive rotor (no magnet or winding) which makes the motor more suitable for high speed operation.

Further absence of magnets reduce the cost of motor. But on the other hand they are disadvantaged with low power factor and high torque ripple [24, 25].

While some motors operate solely with magnet torque (surface mounted PMSM) or reluctance torque (SRM), there are other motors that use both these torque components to generate the motion. IPM motor is one such type in which permanent magnets positioned inside the rotor structure to create different reluctance paths in the airgap [26]. It has a high power density and capable of operating over wide speed range in higher efficiency.

The motor model considered in this research is PMaSynRM. It is a variation of PMSM and has the advantage of using lesser magnet quantity compared to other types of permanent magnet motors which lowers the manufacturing cost [27–29]. Further, PMaSynRM has both reluctance and magnetic torques contributing to the electromagnetic torque.

The rotor configurations of IPM motor and synchronous reluctance motor (SynRM) is combined to design the rotor structure of PMaSynRM as shown in Fig. 2.2. PMaSynRM inherits the advantages of both machine types; IPM and SynRM [30–32]. Nevertheless, it has inherited a higher torque ripple percentage and cross saturation effect from SynRM. The flux distribution pattern defines the d and q axis directions for a certain motor. For a IPM motor the d axis is aligned along the permanent magnet axis and the q axis is quadratic to it. In SynRM, the q axis aligned along the flux barrier (air) and the d axis is quadratic to q axis. In

Figure 2.2: Rotor structures of IPMSM, SynRM and PMaSynRM.

PMa-SynRM the d axis is in between two flux barrier-magnet sets and q axis is along the flux barrier.

2.1.3 Electrical Circuit of Five-Phase PMaSynRM

Equivalent circuit of five-phase PMaSynRM is shown in 2.3. Here, R_a, R_b, R_c, R_d, R_e are winding resistances and L_a, L_b, L_c, L_d, L_e are the phase inductances. The stator voltage equation for the motor is shown below.

$$V_{abcde} = R_{abcde} I_{abcde} + \frac{d\lambda_{abcde}}{dt} \quad (2.2)$$

Here, V_{abcde} and I_{abcde} gives phase voltages and currents. R_{abcde} is the winding resistance and λ_{abcde} is the flux linkage. Usually for the simplification of control (see section 2.2), the system is transformed from synchronous reference frame to dq

Figure 2.3: Five-phase equivalent circuit for PMaSynRM.

rotating reference frame. There are two individual steps followed in the transformation. First one is "Clarke transformation", in which the abcde phase quantities are transformed to $\alpha - \beta$ stationary reference frame. Then the "Park transformation" is used to transform from $\alpha - \beta$ to d-q rotating reference frame. The transformations are explained in Fig. 2.4.

The angular position of the rotor is, θ . As the machine rotates, the d-q reference frame too rotates at a speed of $\omega = \frac{d\theta}{dt}$, while the stator a,b,c,d,e axes are fixed in space. Here δ is the load angle. The mathematical relationship for overall transformation from abcde to dq is shown in (2.3).

Figure 2.4: (a)Phase to $\alpha - \beta$ transformation (b) $\alpha - \beta$ to d-q transformation.

$$\begin{bmatrix} X_d \\ X_q \\ X_{3d} \\ X_{3q} \\ X_0 \end{bmatrix} = \frac{2}{5} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{5}) & \cos(\theta - \frac{4\pi}{5}) & \cos(\theta - \frac{6\pi}{5}) & \cos(\theta - \frac{8\pi}{5}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{5}) & \sin(\theta - \frac{4\pi}{5}) & \sin(\theta - \frac{6\pi}{5}) & \sin(\theta - \frac{8\pi}{5}) \\ \cos(3\theta) & \cos(3\theta - \frac{2\pi}{5}) & \cos(3\theta - \frac{4\pi}{5}) & \cos(3\theta - \frac{6\pi}{5}) & \cos(3\theta - \frac{8\pi}{5}) \\ \sin(3\theta) & \sin(3\theta - \frac{2\pi}{5}) & \sin(3\theta - \frac{4\pi}{5}) & \sin(3\theta - \frac{6\pi}{5}) & \sin(3\theta - \frac{8\pi}{5}) \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \\ X_d \\ X_e \end{bmatrix} \quad (2.3)$$

Here first two rows calculate the d and q axis components and the next two rows are for the third harmonic component. The fifth row calculates the zero sequence component. But in this research the third harmonic and zero sequence components

didn't take into consideration. The equivalent circuit for dq reference frame is shown in Fig.2.5.

Figure 2.5: Equivalent circuit for PMaSynRM in dq reference frame.

The stator voltage equations in dq reference is derived in (2.4) from the equivalent circuit.

$$\begin{aligned} V_d &= R_d I_d + L_d \frac{dI_d}{dt} - w_r L_q I_q + w_r \lambda_{PM} \\ V_q &= R_q I_q + L_q \frac{dI_q}{dt} + w_r L_d I_d \end{aligned} \quad (2.4)$$

The electromagnetic torque equation for the five-phase PMaSynRM in dq reference frame is given in (2.1.3). The first component of the torque equation is the magnetic torque and the second one is the reluctance torque component.

$$T_e = \frac{5P}{2} (\lambda_{PM} I_d + (L_d - L_q) I_d I_q) \quad (2.5)$$

2.2 Model Predictive Control

MPC is an advanced control technique which is mainly used in process industry since 1970s [33]. This strategy can handle multi-input, multi-output (MIMO) systems and able to predict and optimize operations in time horizon. Due to its control complexity only slow processes such as chemical industry, oil refineries used MPC. But with the fast-paced evolution in micro-controller and processor technology, the applications of MPC has spread into different areas in recent years. Large scale operation- control problems (control of supply chain), vehicle path planning and control, under water vehicle guidance, missile guidance are few MPC used emerging applications [34]. Now MPC is being used in power systems and power electronics areas too.

2.2.1 Model Predictive Control for Motor Drives

In recent past MPC has attracted more attention in motor drives field. Two main reasons can point out for MPC being much suitable and beneficial for motor drives.

1. Motor drive systems can accurately represent in analytical models.
2. MPC can deal with system constraints that is essential with the dynamics of the drive system [35].
3. MPC is good at handling higher order complexity, non-linearity, multiple control variables and disturbances which is very advantageous in motor operation [36, 37].

Further, with MPC, it is possible to abandon the cascaded structure and control all the variables by a single controller.

Applications of MPC in motor drives area is arising and still largely unexplored. A huge amount of research can found for induction motor systems that used MPC [38–41]. An important research related to PMSM with MPC is given in [21, 42–45]. Research can be found that utilized MPC for torque control [21, 43] while [44] and [45] are focused in improving speed performance.

2.2.2 Fundamental Principles of Model Predictive Control

The basic idea behind MPC is to select an optimum upcoming input sequence to the plant, based on the predictions made for future state behavior. Predictions are made using the plant model which takes past states as the inputs and generate the prediction for the future state. The plant model is in discrete-time state-space form given in (2.6).

$$\begin{aligned}x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k)\end{aligned}\tag{2.6}$$

Here, x and u are state variable vector and control input vector respectively. A more specific state-space model for MPC is given in (2.7).

$$x(k+j+1) = Ax(k+j) + Bu(k+j), j = 0, \dots, N_p - 1 \tag{2.7}$$

Here, the state variable x is predicted for $x(k+1)$ state to $x(k+N_p)$. N_p is the prediction horizon and k is the sampling instant. At each sampling instant, the optimizer

takes in the predicted states and the reference trajectory to solve the optimization problem for the prediction horizon and provide the optimum input sequence for future operation. Optimization is done based on a cost function which can consist of several conditions that are weighted differently. System constraints can also be added as conditions in the cost function. Cost function has the general form of (2.8).

$$J_{N_p} = x(k + N_p)^T M x(k + N_p) + \sum_{j=1}^{N_p} ft[x(k + j - 1)^T Q x(k + j - 1) + u(k + j - 1)^T R u(k + j - 1)] \quad (2.8)$$

M, N, Q are the weights for each component of cost function. The L_2 (quadratic) norm of the state or L_1 or L_∞ norms can be used to derive the cost function. L_2 norm is used to derive the cost function given in (2.8).

At each sampling instant k , the optimization problem is solved to obtain the associated optimum input sequence for the prediction horizon. Optimization problem can be described as (2.9).

$$\begin{aligned} \text{Minimize} \quad & J = \sum_{n=0}^{N_p} f(x(n), u(n)) \\ \text{Subject to} \quad & u(k) \in U, \quad x(k) \in X \dots \end{aligned} \quad (2.9)$$

Once the optimum input sequence has been calculated, the first value of the computed sequence is applied. Same procedure repeats.

MPC can be categorized in to two as continuous control set model predictive control (CCS-MPC) and finite Control Set Model Predictive Control (FCS-MPC). FCS-MPC considers discrete switching states of the inverter into account for the

optimization technique. CCS-MPC has continuous nature which uses pulse width modulation (PWM) (such as space vector modulation) schemes and each voltage vector considered depends on the extracted voltage of previous state [46–48].

2.2.3 Finite Control Set Model Predictive Control

FCS-MPC is the most popular form of MPC in motor drives area. Features such as simplified control structure, elimination of a modulation technique and fast dynamic responses may be contributed towards its popularity. As the name implies FCS-MPC considers a finite number of control actions in solving the optimization problem to chose the next step. This method is much suitable for converter control applications in which the control actions can be constrained.

For motor drive applications FCS-MPC considers the voltage vector set relevant to the inverter as the finite set. The voltage vector set for the five-phase inverter used in this research is shown in Fig. 2.6. In a two-level five-phase inverter there are 32 different switching states. Each of this state corresponds to a voltage vector and so 31 different voltage vectors including the voltage vector by zero state (00000, 11111). The voltage vector set for all switching states of the five-phase inverter can calculate using the equation (2.2.3) [49]. S_a, S_b, S_c, S_d, S_e are switching states of each inverter leg.

$$V_k = \frac{2}{5}V_{DC}(S_a + S_b e^{j\frac{2\pi}{5}} + S_c e^{j\frac{4\pi}{5}} + S_d e^{j\frac{6\pi}{5}} + S_e e^{j\frac{8\pi}{5}}) \quad (2.10)$$

All possible switching states and corresponding voltage vectors used in this research are shown in Table. 2.1. The voltage vectors are in three different amplitude sets and

in 10 different vector directions which are 36° apart from each other. The output of the inverter becomes a finite set since no modulation technique is in use. The discrete-time system predicts the future behavior for every possible switch vector of the inverter to choose the minimum cost option.

Figure 2.6: Layout of voltage space vectors.

2.3 Fault Tolerant Operation of Electric Motor Drives

As any mechanical system, both voltage source inverter and the electric motor itself is susceptible to fault. Faults that can occur in a machine can classify mainly into

Table 2.1: Voltage vectors of a five-phase inverter

S_k	S_e	S_d	S_c	S_b	S_a	V_k	
S_1	0/1	0/1	0/1	0/1	0/1	V_1	0
S_2	0	0	0	0	1	V_2	$0.4V_{DC}e^{0^\circ}$
S_3	0	0	0	1	0	V_3	$0.4V_{DC}e^{72^\circ}$
S_4	0	0	0	1	1	V_4	$0.647V_{DC}e^{36^\circ}$
S_5	0	0	1	0	0	V_5	$0.4V_{DC}e^{144^\circ}$
S_6	0	0	1	0	1	V_6	$0.247V_{DC}e^{72^\circ}$
S_7	0	0	1	1	0	V_7	$0.647V_{DC}e^{108^\circ}$
S_8	0	0	1	1	1	V_8	$0.647V_{DC}e^{72^\circ}$
S_9	0	1	0	0	0	V_9	$0.4V_{DC}e^{-144^\circ}$
S_{10}	0	1	0	0	1	V_{10}	$0.247V_{DC}e^{-72^\circ}$
S_{11}	0	1	0	1	0	V_{11}	$0.247V_{DC}e^{144^\circ}$
S_{12}	0	1	0	1	1	V_{12}	$0.247V_{DC}e^{36^\circ}$
S_{13}	0	1	1	0	0	V_{13}	$0.647V_{DC}e^{180^\circ}$
S_{14}	0	1	1	0	1	V_{14}	$0.247V_{DC}e^{180^\circ}$
S_{15}	0	1	1	1	0	V_{15}	$0.647V_{DC}e^{144^\circ}$
S_{16}	0	1	1	1	1	V_{16}	$0.4V_{DC}e^{108^\circ}$
S_k	S_e	S_d	S_c	S_b	S_a	V_k	
S_{17}	1	0	0	0	0	V_{17}	$0.4V_{DC}e^{-72^\circ}$
S_{18}	1	0	0	0	1	V_{18}	$0.647V_{DC}e^{-36^\circ}$
S_{19}	1	0	0	1	0	V_{19}	$0.247V_{DC}e^{0^\circ}$
S_{20}	1	0	0	1	1	V_{20}	$0.647V_{DC}e^{0^\circ}$
S_{21}	1	0	1	0	0	V_{21}	$0.247V_{DC}e^{-144^\circ}$
S_{22}	1	0	1	0	1	V_{22}	$0.247V_{DC}e^{-36^\circ}$
S_{23}	1	0	1	1	0	V_{23}	$0.247V_{DC}e^{108^\circ}$
S_{24}	1	0	1	1	1	V_{24}	$0.4V_{DC}e^{36^\circ}$
S_{25}	1	1	0	0	0	V_{25}	$0.647V_{DC}e^{-108^\circ}$
S_{26}	1	1	0	0	1	V_{26}	$0.647V_{DC}e^{-72^\circ}$
S_{27}	1	1	0	1	0	V_{27}	$0.247V_{DC}e^{-108^\circ}$
S_{28}	1	1	0	1	1	V_{28}	$0.4V_{DC}e^{-36^\circ}$
S_{29}	1	1	1	0	0	V_{29}	$0.647V_{DC}e^{-144^\circ}$
S_{30}	1	1	1	0	1	V_{30}	$0.4V_{DC}e^{-108^\circ}$
S_{31}	1	1	1	1	0	V_{31}	$0.4V_{DC}e^{180^\circ}$

mechanical, electrical and magnetic. A detailed classification of fault types is shown in Fig. 2.7 [50,51]. Among them one of the most common type of fault for PMSM

is the open-phase fault. This can occur in a stator winding or due to power switch failure in the inverter. The open-phase fault can happen for a single-phase or for two or more phases that can be adjacent or non-adjacent. Even with technological advances in power electronics and machine design, the possibility of an open-phase fault is inevitable. And on the other hand there are applications that demands the fault free operation, such as aerospace, subways, electric ship propulsion, military and electric vehicles [20, 52–57]. Sudden interrupts in safety critical applications can endanger both human lives and properties and also can cause huge financial losses. Since faults are inevitable, at least the uninterrupted operation of the motor is a must for such applications in the occurrence of a fault. Hence the continuous development in the field of fault tolerant operation of motor drives is demanded. Several different approaches can be found in literature for FTO. One is change the hardware design by keeping alternative paths. In a standard three-phase motor drive fed by a three-leg voltage source inverter (VSI), a loss of a phase, interrupts the drive system operation. For this case, different techniques have been proposed to enable FTO, such as keeping the extra hardware. Keeping additional components or supplementary legs in the standard inverter structure has proposed in [58, 59].

Multi-phase motor is a good candidate for safety critical applications as stated in chapter 1. Therefore a lot of research work on FTO is focused on multi-phase machines. A technological status review of multi-phase induction motor drives, their control strategies and possible approaches to design fault tolerant strategies is presented in [60]. A recently published journal [61], investigates the behavior of six-phase

Figure 2.7: Classification of fault types of permanent magnet synchronous machine.

synchronous motor based on the mathematical model of the machine under open and short circuit fault conditions. Further [10] and [62] proposes techniques to improve the performance of faulty machine and both are focused on permanent magnet machines with open-phase fault.

2.4 Model Predictive Control for Fault Tolerant Operation of Motor Drives

There are few publications can be found on MPC used in FTO for PMSM. One of the initiating work on fault tolerant control (FTC) with MPC is published in [63]. It is proposed for a three-phase magnetically isotropic PMSM for open-phase fault and the predictive model is established for remaining two stator phase currents. It uses

a flux estimator to calculate the stator flux and its corresponding torque. The cost function is designed to minimize the torque and flux error.

A common MPC for both normal and post-fault operations of three-phase PMSM drive is proposed in [64] considering single phase open-fault. An extra-leg/switch structure has implemented for the faulty situation here. But to build this generalized model they have simplified the comparison analysis assuming two operations have same d-q currents and the stator resistance is ignored. The cost function is designed to minimize the current error. The major contribution of this paper is to find the fact that the same controller model can be utilized for both normal and post-fault operations without any modifications. And this finding has been validated with theoretical analysis and experimental results. In [65] presents a FTC proposal for a single open-phase fault in a three-phase PMSM based on FCS-MPC and then a comparison has been carried out with a fault tolerant DTC method. All the researches discussed on MPC based FTC techniques up to now are applied for three-phase machines.

MPC performance has not been extensively studied for multi-phase PMSMs and only few literature can found in this direction. One of the first papers that MPC applied in a multi-phase motors for FTO is [66]. A predictive model is designed here from the mathematical model of a six-phase PMSM to perform current control. MPC for fault-tolerant function of six-phase and three-phase PMSM series-connected drive systems are realized in [67]. The optimal voltage vector predictions are made to minimize errors of torque and stator flux amplitude and zero-sequence current. In

almost all of the above mentioned research, MPC is applied for PMSM variants that doesn't have the saliency; so the torque control is not complicated as in salient rotor motors like PMaSynRM.

CHAPTER III

DEVELOPING A MODEL PREDICTIVE CONTROLLER FOR FIVE-PHASE PERMANENT MAGNET ASSISTED SYNCHRONOUS RELUCTANCE MOTOR

3.1 Introduction

The work presented in this chapter is focused on developing a control system based on MPC for a five-phase PMaSynRM. The related theories for this chapter are explained in section 2.2. A mathematical model in discrete-time state-space form is derived for a five-phase PMaSynRM. The optimization problem for the controller is designed with the objective of minimizing torque error. The MTPA condition is derived for the five-phase PMaSynRM and used to generate the current reference from the torque reference. Extensive theoretical analysis has been conducted along with MATLAB simulations to verify the proposed method. Further, the controller is tested for its resiliency for motor parameter variations. Initial experimental results are presented to support the proposed MPC.

3.2 Modeling Five-phase Permanent Magnet assisted Synchronous Reluctance Motor (PMSynRM) Drive System

As explained in section 2.2, MPC has two main components, plant model and the optimizer. In order to model the motor, stator voltage equations of five-phase PMSynRM in d-q reference frame (2.4) are used. Modeling the motor in d-q reference frame simplifies the control [20, 68]. For a current controlled motor drive system, d-q axes currents of the stator are used as the state variable vector and d-q axes stator voltages as the input vector for state-space system. Therefore, the equation (2.4) is converted to equation (3.2).

$$\begin{aligned}\frac{di_d}{dt} &= \frac{1}{L_d}(V_d - R_d i_d - p\omega_m(L_q i_q - \lambda_{pm})), \\ \frac{di_q}{dt} &= \frac{1}{L_q}(V_q - R_q i_q + p\omega_m(L_d i_d))\end{aligned}\tag{3.1}$$

In order to implement MPC, the motor model should be in discrete form. So the equation (3.1) is discretized using Forward Euler approximation. The derived mathematical model of five-PMSynRM is given in (3.2) and it is in the general form given in (2.7). The prediction horizon (N_p) is considered as one for the controller.

$$\begin{aligned}i_d(k+1) &= i_d(k)\left(1 - \frac{R_d T_s}{L_d}\right) + V_d(k)\frac{T_s}{L_d} - \frac{p\omega_m T_s}{L_d}(L_q i_q(k) - \lambda_{pm}) \\ i_q(k+1) &= i_q(k)\left(1 - \frac{R_q T_s}{L_q}\right) + V_q(k)\frac{T_s}{L_q} + \frac{p\omega_m T_s}{L_q}L_d i_d(k)\end{aligned}\tag{3.2}$$

Motor parameters, R_d, R_q, L_d, L_q in the model are d axis, q axis stator resistances and inductances and λ_{pm} is the permanent magnet flux linkage. ω_m and p are mechanical rotor speed and number of pole pairs respectively. And T_s is the sampling time of

the discrete system. Ideal conditions are assumed for the model, considering motor parameters are fixed throughout the operation.

3.3 Proposed Model Predictive Controller

The proposed control strategy is based on FCS-MPC explained in 2.2.3 which eliminates the use of a modulation technique and therefore results a faster control performance. The derived motor model (3.2) is used to predict currents in next state considering the finite set of voltage vectors as the input. The voltage vector set is related to the possible switching states of a two-level five-phase inverter and is given in Table. 2.1.

The control system is illustrated in a block diagram in Fig. 3.1. The controller is designed in a cascaded structure in which a PI controller is used for the outer control loop. Torque reference is produced by this PI controller taking current error as the input. The produced torque reference is fed to the MTPA block which gives current reference to the MPC system. Functionality of MTPA block is explained in section 3.3.2. The controller takes the current measurements of five-phases and fed to the predictive model block. The machine model implemented in the controller is used to predict next d-q current states $(i_d(k+1), i_q(k+1))$. Inputs to the predictive model are current at this state $(i_d(k), i_q(k))$ and the voltage vector set. Next, costs are calculated for all predicted current sets based on the designed cost function. The voltage relate to the minimum cost is chosen for next state operation. Selected d-q

Figure 3.1: Block diagram of the proposed control system for 5-phase PMaSynRM.

voltages are transformed to the synchronous reference frame and supplied to motor through the inverter.

3.3.1 Optimization Problem

Later in this research, the developed controller has utilized for FTO for an open-phase fault. With the occurrence of the open-phase fault, the load currents in remaining phases get significantly distorted resulting a high pulsating torque. And due to loss of a phase the average current to the motor goes down, so decreases the average torque. Considering the ultimate research goal as applying for FTO, the controller proposed in this research is targeted in minimizing the torque error. The equation of electromagnetic torque for five-phase PMaSynRM is given in (2.1.3). Both d-q axes currents are contributing to the torque; hence the currents in both axes needed to be

controlled to reduce the torque error. This simplifies to calculate the current error as the cost.

The cost function is derived from the general form given in (2.8). For this case it gets simplified since the prediction horizon is one. The first condition of the cost function is the current error. The MTPA condition is used to calculate the reference current in this proposal and a detailed explanation on MTPA is presented in section 3.3.2. Then the stator current is further constrained by the rated current of the machine, (J_c). The designed cost function J , is shown in 3.4 and the conditional constraint is 3.3.1. Each condition of the cost function is weighted differently by the weighting factors, K_1, K_2 .

$$J(k+1) = K_1(T_e(k+1) - T_e^*)^2 + K_2J_m + K_3J_c \quad (3.3)$$

$$J_c = \begin{cases} (I_r - \sqrt{i_d(k+1)^2 + i_q(k+1)^2})^2 & |I_r - \sqrt{i_d^2 + i_q^2} \leq 0 \\ 0 & \text{Otherwise} \end{cases} \quad (3.4)$$

The optimization problem here is to minimize the cost of (3.3.1) in each step. In this case it's possible to select the minimum cost index without using any complex numerical method since a finite control set is considered and the prediction horizon is one.

3.3.2 Current Reference Generation

In PMaSynRM, there is a reluctance torque component in the torque equation. So the electromagnetic torque has both d-q axes currents in the equation. The angle between the rotor magnetic field and the stator field is called the load angle (δ)

and can depict the relation with d-q currents as (3.5). Refer Fig. 2.4 for graphical representation of angle placement.

$$\begin{aligned} i_d &= i_s \cos(\delta), \\ i_q &= i_s \sin(\delta) \end{aligned} \tag{3.5}$$

Here i_s is the phase current to the motor. δ must be carefully controlled to produce the maximum torque and achieve high electro-mechanical conversion efficiency. For this purpose, the MTPA condition is utilized to tune δ in order to draw a minimum amount of current under the same torque values. This condition enables the maximum torque generation with minimum d-q axes currents increasing the efficiency of operation. Further, it minimizes the ohmic losses. In this research the motor operation is focused only upto the base speed. Hence, the operation at flux-weakening region is not considered.

MTPA condition for five-phase PMaSynRM is derived to use in reference current generator. To obtain the optimal current angle δ_{opt} , first the torque equation (2.1.3) is rewritten in terms of i_s and δ . The resulting torque expression is then differentiated with respect to the angle. By letting $\frac{\partial T_e}{\partial \delta}$ equals to zero, the quadratic equation (3.6) is obtained and it is solved to get δ_{opt} which is expressed in (3.7).

$$2(L_d - L_q)i_s \sin^2(\delta_{opt}) + \lambda_{pm} \sin(\delta_{opt}) - (L_d - L_q)i_s = 0 \tag{3.6}$$

$$\delta_{opt} = \sin^{-1} \frac{-\lambda_{pm} \sqrt{\lambda_{pm}^2 + 8(L_d - L_q)^2 i_s^2}}{4(L_d - L_q)i_s} \tag{3.7}$$

Then by substituting the relationship in (3.5) to (3.7), a quadratic function is obtained which provides a connection between i_d and i_q (3.8).

$$i_q = \frac{-\lambda_{pm} + \sqrt{\lambda_{pm}^2 + 8(L_d - L_q)^2(i_d^2 + i_q^2)}}{4(L_d - L_q)} \quad (3.8)$$

Solving the quadratic equation (3.8), the MTPA condition is derived as (3.9). Then combining (2.1.3) and (3.9), (3.10) is derived for the five-phase PMSynRM.

$$i_q = \frac{-\lambda_{pm} + \sqrt{\lambda_{pm}^2 + 4(L_d - L_q)^2 i_d^2}}{2(L_d - L_q)} \quad (3.9)$$

$$4T_e^2 - 10p\lambda_{PM}T_e i_d - 25p^2(L_d - L_q)^2 i_d^4 = 0 \quad (3.10)$$

The real positive solution of (3.10) is used as the d axis current reference. Then by substituting the just calculated i_d on (3.9), reference of i_q is calculated.

3.4 Performance Analysis using MATLAB Simulations

Prior to implement in hardware, the developed controller was tested analytically in MATLAB-Simulink environment. In order to study the performance of the proposed MPC controller rigorously, a comparative analysis has been carried out relative to a benchmark control system. The benchmark system is designed with three PI controllers one for speed control and the others for torque control. All PIs are tuned empirically for the plant. The block diagrams of benchmark controller is shown in Fig. 3.2. In the proposed controller MPC replaces the PI of inner control loop. MTPA condition is incorporated in both control systems to move from torque to current references. It is quite complex to solve the fourth order equation (3.10) in each cycle, to

Table 3.1: System Parameters

Parameters	Values
Rated speed	1800 rpm
Rated torque	15 Nm
No. of pole pairs (p)	2
Stator resistance (RS)	0.3 Ω
d-axis inductance	10 mH
q-axis inductance	2.8 mH
Flux linkage	0.06 Wb
Sampling time (Ts)	0.00005 s
K1, K2	1, 0.2

calculate the reference current. Hence using 3.10 and 3.9, i_d and i_q were calculated for different torque values. Then, the torque was plotted against i_d, i_q and a relationship for currents in terms of torque is derived using curve-fitting. This relationship is used to implement the MTPA algorithm in Simulink.

Five-phase PMaSynRM is implemented in Simulink with the model parameters given in Table 3.1. The controller performance is measured by torque, current and speed behaviors. The simulation results of both controllers are given in Fig. 3.3 to Fig. 3.6 comparatively. Simulations are carried out considering a load torque of

Figure 3.2: Block diagram of the benchmark control system.

2 Nm and a reference speed of 400 rpm. Fig. 3.3 shows simulation results obtained

Figure 3.3: Simulation results: electromagnetic torque of the system with (a) benchmark controller and (b) MPC controller.

for electromagnetic torque for both benchmark and MPC based systems. In healthy system, torque ripple is almost zero for the benchmark model in which the PI controllers are tuned for the plant. But with the proposed controller, there is a torque

Figure 3.4: Simulation results: phase currents of the system with (a) benchmark controller and (b) MPC controller.

ripple around 1%. The applied controller is based on FCS-MPC which considers a finite set of voltages in controlling the input to the system. This discrete nature of the controller, generates the small torque ripple in the output.

Fig. 3.4 and Fig. 3.5 analyze the phase currents and d-q axis currents respectively for the healthy system. Due to the same phenomenon explained for torque, the current contains a small percentage of ripples for the proposed controller.

Fig. 3.6 shows the comparison of speed performance with the benchmark controller and MPC. Both has initial transients and reaches to the steady state almost at similar time (within 0.5 s).

3.5 Sensitivity Analysis for Dynamic Parameter Variations

The accuracy of the system model is very important in MPC since it is the core of the controller. A deviation of designed model in controller, from the actual system can

Figure 3.5: Simulation results: currents in dq axis in the system with (a) MPC controller (b) Benchmark controller.

Figure 3.6: Simulation results: speed of the system with (a) benchmark controller and (b) MPC controller.

have a considerable effect on predictions which directly affects the control decision. The mathematical model of the motor (3.2), is dependent on electrical parameters of the system such as resistances, inductance and permanent magnet flux linkage.

But these motor parameters are susceptible to internal and external environmental changes which can cause deviations from the original. For an example the

temperature changes in the motor due to external or internal environmental conditions can impact on resistance. Further it is hardly possible to imitate the exact motor parameters in the model of the controller even during normal healthy operation. Because of this, the controller being resilient to the dynamic model parameter variations is very critical for improved control performance. Hence it is very important to carry out an extensive analysis on sensitivity of the proposed model predictive controller to parameter variations. This section addresses that need.

3.5.1 Sensitivity to dynamic resistance variations

Phase resistances of a motor can change due to various reasons. Over the time the winding insulation can deteriorate which result imbalances in the winding resistance between phases. Further, resistance is a temperature dependent property and dynamically vary over temperature fluctuations.

The temperature at the stator is directly get affected by the magnet temperature. Fig.3.7 shows the continuous temperature variation in permanent magnets of the five-phase PMSynRM machine over the time. These temperature data were wirelessly measured through temperature dependent resistor (RTD) sensors connected to the rotor magnets when the machine operates at 58.5 Hz. Starting from the room temperature it reaches to the steady state at around 3000 s of operation. Using (3.7) the resistance variation over the period was derived considering $\alpha = 0.00393\Omega^0C^{-1}$, the temperature coefficient of copper. The resistance variation corresponding to the given temperature behavior is given in Fig. 3.8. It can be seen that the change of

Figure 3.7: Continuous temperature variations of permanent magnets in the motor.

Figure 3.8: Resistance variation corresponding to the temperature behaviour in 3.7.

resistance is quite small due to the temperature increment during normal operation of a motor. With these observations, 0.30Ω to 0.31Ω is identified as the practical increment range to carry out sensitivity analysis.

In order to analyze the sensitivity, winding resistance of the motor is changed from 0.3Ω to 0.31Ω and measured the system performance with and without making changes in the model. Fig. 3.9 shows the measured system performance in both sit-

Figure 3.9: Torque, Phase current and Speed behaviours for the proposed controller when winding resistance of the motor changed to 0.31Ω (a) without updating the model, (b) with modified controller.

uations in terms of torque, current and speed. The waveform doesn't indicate any quantifiable variation for the 3.3% increment in resistance. Therefore, can conclude the proposed controller doesn't get affected for resistance variations due to temperature during normal operation.

3.5.2 Sensitivity to dynamic inductance variations

Due to the magnetic saturation in the air gap, L_d and L_q vary with the d-q axes currents [69,70]. The variation of L_d and L_q with current for PMSynRM is presented in [71]. To obtain this variation, a finite element analysis (FEA) technique has been performed for different phase currents for the five-phase PMSynRM and the values

for L_d and L_q were obtained as given in Fig. 3.10. With the data from FEA, the

Figure 3.10: Inductance variation for different loading conditions.

possible range of dynamical variations of the inductance due to magnetic saturation is identified. From Fig. 3.10, 0.02 H and 0.005 H are selected as the value to change into for L_d and L_q to perform sensitivity analysis.

Same procedure as in 3.5.1 carried out. The performance is measured in-terms of torque, current and speed behavior in the system before and after updating the model. According to Fig. 3.11, both current and speed behavior doesn't get impacted by the change happen to L_d in the motor. But in electromagnetic torque, there is a higher ripple density before the update compared to the updated one. But still its not quantifiable. Similar to Fig. 3.11, in Fig. 3.12 there is almost no difference in current and speed wise. But the electromagnetic torque has reduced ripple percentage from 2.4% to 1.4% after updating the model with modified parameters.

Figure 3.11: Torque, Phase current and Speed behaviours for the proposed controller when d-axis inductance of the motor changed to 0.02 H (a) without updating the model, (b) with modified controller.

3.6 Experimental Validation of the Proposed Control Algorithm

The preliminary results obtained from the actual hardware experimental setup are presented in this section as a proof of operation of the proposed MPC based controller for five-phase PMaSynRM machines. The overview block diagram of the five-phase PMaSynRM motor based experimental setup is shown in Fig. 3.13. As shown in the figure, the setup mainly consists of a digital signal processor (DSP) for executing the control algorithm, a gate driver circuit, the five-phase inverter, five-phase PMaSynRM, the DC generator and an electronic load connected to it. A Texas Instruments TI F28335 [72] DSP based processing platform which has been custom

Figure 3.12: Torque, Phase current and Speed behaviours for the proposed controller when q-axis inductance of the motor changed to 0.005 H (a) without updating the model, (b) with modified controller.

Figure 3.13: Overall block diagram of the experimental setup.

Figure 3.14: The DSP and the platform.

designed for five-phase motor controlling is used to create the PWM signals for the gate drivers. A Semikron-SKHI61R model is used as the gate driver and each driver board can drive upto three-phases and therefore two driver boards are used in the setup to drive the five-phases. The gate driver boards provide gate signals to the ten insulated gate bipolar transistor (IGBT) switches in five-phase voltage source inverter. The controlled voltage from the inverter is then supplied to the five-phase PMaSynRM. A 3.75 kW DC generator system was used as the load to the system. The DC generator is connected to an electronic load to provide the required load torque.

The DSP platform is accepting 6 analog inputs from which 5 are for current sensor inputs and the other is for the position sensor (incremental encoder) input.

Figure 3.15: Hardware setup for the control of the five-phase PMaSynRM motor.

These inputs are sampled via the analog to digital converters available in the DSP and are used as inputs for the control algorithm program developed in section. 3.3. A torque sensor was used with the DC load setup as indicated to measure the torque exerted on the load and the output of the sensor was connected to a host computer to record the data. Fig. 3.15 shows a picture of the actual experimental setup.

The proposed MPC algorithm is developed in code composer studio version-5.3, to implement in TI DSP F28335. The benchmark controller explained in sec-

tion 3.4 is also implemented to perform a comparative analysis. Initial experiments are conducted with both controllers for a reference speed of 450 rpm. To provide the same load condition, the DC generator connected to the same electronic load and field supply in both situations.

Figure 3.16: Experimental results: electromagnetic torque of the system with (a) benchmark controller and (b) MPC controller.

The observed torque behavior is given in Fig.3.16. There is around 1% ripple in the torque of MPC controller, so the pattern is very close to the simulation result. The benchmark controller displays almost zero ripples in simulations and in actual system it is around 0.4%. Compared to the benchmark controller performance, the increase of ripple percentage for MPC is just 0.6% in experimental results.

The speed waveform in Fig. 3.17 shows the steady state speed patterns in where 0.3% fluctuation of speed is observed for benchmark controller and for MPC it's around 0.6%. Both ripple percentages are negligible and the controllers stays at the reference speed.

Figure 3.17: Experimental results: speed of the system with (a) benchmark controller and (b) MPC controller.

Figure 3.18: Experimental results: phase currents of the system with (a) benchmark controller and (b) MPC controller.

Fig. 3.18 shows phase current patterns of phase A and B for benchmark and MPC controllers. The current waveforms from experimental setup contains a big harmonics component compared with simulations results. The experiment is carried out at a low load condition (around $2.3/15 \text{ Nm} = 15\%$). Therefore, the efficiency

at this situation is very low and contributes in harmonic generation. Other than harmonics, the MPC system displays current ripples due to its discrete nature.

3.7 Conclusion

A control system has been developed based on MPC for a five-phase PMSynRM. MTPA condition is derived for this motor and used to generate the reference current which provides the benefit of increased efficiency and minimized ohmic loss. A sensitivity analysis has been performed to check the controller's vulnerability for dynamic model parameter variations. The controller displays almost zero impact for resistance variations due to the temperature change during normal operation. It seems to have a very small effect with inductance variation; but only for L_q it is quantifiable. The L_q is increased in 78% in the motor and there is around 1 % torque ripple reduction when the model updated accordingly. Therefore the obtained results proves the resiliency of the controller.

The performance of the controller is analyzed compared to a conventional PI based benchmark controller through simulation and experimental setups. Both systems display a good performance in terms of torque and speed. But around 1% torque ripple can be seen in MPC based controller since it considers a discrete set of voltages for control.

CHAPTER IV

IMPLEMENTATION OF THE DESIGNED MODEL PREDICTIVE CONTROLLER FOR FAULT TOLERANT OPERATION

The main idea behind the use of multi-phase machines is being able to operate continuously even in an occurrence of a fault (see chapter 2). Having a resilient and robust controlling strategy is vital to leverage the advantages of the multi-phase systems. Having given a general review on FTO of motor drives in chapter 2, this chapter investigates the felicitousness of using MPC for FTO, targeting five-phase permanent magnet machines. The specific target machine considered here is the five-phase PMaSynRM. The chapter evaluates the MPC controller proposed in chapter 3 for its FTO for the five-phase PMaSynRM and further explores possible enhancements to the proposed controller for improved performance under FTO.

For this analysis the focus of FTO is constrained to an occurrence of a single-phase open fault. The torque waveform get highly distorted during a fault. The ripples in torque can increase the motor vibrations which leads to energy losses in the form of heat and sound. To address this issue different techniques are proposed in literature. The MPC based controller developed in chapter 3 is targeted to minimize the torque error. Therefore, that controller can be mostly suitable for FTO.

Figure 4.1: Simulation results for fault: electromagnetic torque of the system with (a) benchmark controller and (b) MPC controller.

Figure 4.2: Simulation results for fault: phase currents of the system with (a) benchmark controller and (b) MPC controller.

The work in [64] has proved the viability of utilizing a common controller for both healthy and faulty situations analytically and experimentally for a three-phase PMSM. Therefore, the possibility of implementing the same controller developed in Chapter 3 for FTO is investigated in section 4.1.

Figure 4.3: Simulation results for fault: currents in dq axis of the system with (a) benchmark controller and (b) MPC controller.

4.1 Performance Analysis of the Developed Predictive Controller under Single Phase Open Fault

The developed MPC based controller is tested for a single-phase open fault analytically in Matlab Simulink environment. In this analysis the open-phase fault was created in phase A. The same comparison has been carried out as in section 3.4 with the benchmark model given in 3.2. The results were taken for a load torque of 2 Nm and at a reference speed of 400 rpm.

The torque waveform during the fault is given in Fig. 4.1. Very high ripples observed for the benchmark controller which is approximately 67.5% from the average torque and the average torque which has reduced to 1.95 Nm, a reduction of 2.5%. The introduction of proposed MPC based controller to the system has reduced the ripple percentage to 30% and the average torque is almost same at the fault.

Figure 4.4: Simulation results for fault: speed of the system with (a) benchmark controller and (b) MPC controller.

The phase and d-q axis current behaviors are shown in Fig. 4.2 and Fig. 4.3. Since phase A is out now, Fig. 4.2 show the imbalance among phases with both PI and MPC based controllers. At the occurrence of fault, phase currents have increased to maintain the same performance with the remaining phases. In healthy system (Fig. 3.4), the peak current was around 5.5 A to bear the same load and here the highest peak is around to 8.2 A with benchmark controller and 6.5 A with the MPC based controller during the fault. Further, the harmonic content in the current of benchmark controller seems to be higher than the model based controller. During the fault, d-q axes currents shows very high ripples in the benchmark controller. The proposed controller shows a considerable ripple percentage but still the machine is in operable state. The harmonic content of phase current of phase C is analyzed in Fig. 4.5. It points out that with MPC the third harmonic component reduces from 45% to 7.7% compared to PI controller. The other higher order harmonics are almost

negligible here. Given in Fig. 4.4, the speed of the benchmark controller has almost

Figure 4.5: Harmonic content of C-phase current under fault for (a) benchmark controller, (b) MPC controller.

around 18.75% ripple while the proposed controller has a 10% ripple percentage. Hence, can conclude that the MPC controller performs well in FTO.

4.2 Modified Model Predictive Controller for the Open Circuit Fault

Under open-phase condition, the characteristics of the motor is primarily degraded due to unwanted flux harmonics, localized saturation, and temperature increments. These adverse effects can immensely alter the machine model because of the non-linear, non-symmetrical variations in the electrical parameters. And again the phases become unbalanced at this time and previous d-q transformations are not valid anymore.

One of the main features of MPC is being able to recreate the motor inside the controller. Therefore with MPC, the extreme environmental conditions explained

Figure 4.6: Proposed fault tolerant control algorithm with logic flow.

earlier can be taken in to consideration. In order to experiment more in this direction, a new model (MPC-2) was derived by modifying model parameters. Here, the proposal is to switch the predictive model to MPC-2 (faulty mode) with the indication of phase lost fault. The fault detection technique proposed in [23] is suggested in this research. The process flow diagram of this concept is shown in 4.6.

4.2.1 Adopting model parameter variations

The winding resistances of the five-phase motor can represent as equation (4.1).

$$R_{abcde} = \begin{bmatrix} R_a & 0 & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 & 0 \\ 0 & 0 & R_a & 0 & 0 \\ 0 & 0 & 0 & R_a & 0 \\ 0 & 0 & 0 & 0 & R_a \end{bmatrix} \quad (4.1)$$

The system is modeled in d-q reference frame for MPC, so the phase resistance matrix also need to convert in to the same reference frame. The transformation matrix (2.3) is used for the transformation. Since resistance doesn't depend on the angular position, angle θ is considered zero.

To derive resistance in d-q direction, the equation (4.2) is utilized.

$$R_{dq} = T.R_{abcde}.T^{-1} \quad (4.2)$$

Table 4.1: dq axis resistances in different fault situations

Faulty phase	R_d	R_q
Phase A	0.18	0.3
Phase B	0.2885	0.1915
Phase C	0.2215	0.2585
Phase D	0.2215	0.2585
Phase E	0.2885	0.1915

Then the d and q axis resistance can be shown as a function of phase resistances (equation (4.3)).

$$\begin{aligned}
 R_d &= 0.4(R_a + R_b \cos^2(\frac{2\pi}{5})) + R_c \cos^2(\frac{4\pi}{5}) + R_d \cos^2(\frac{6\pi}{5}) + R_e \cos^2(\frac{8\pi}{5}), \\
 R_q &= 0.4(R_b \sin^2(\frac{2\pi}{5})) + R_c \sin^2(\frac{4\pi}{5}) + R_d \sin^2(\frac{6\pi}{5}) + R_e \sin^2(\frac{8\pi}{5}) \quad (4.3)
 \end{aligned}$$

Here R_d and R_q are equal to the phase resistance ($R_d = R_q = R_a = R_b = R_c = R_d = R_e = R_s$) when the phases are balanced. But under open-phase fault $R_d \neq R_q \neq R_s$. The machine considered in this research has a phase resistance of 0.3Ω and the open-phase fault in each phase results different R_d, R_q values. The d-q axis resistances for open-phase fault in different phases are given in Table 4.1.

Resistance is a temperature dependent parameter. The relation of resistance to the temperature is given in (4.4). Here α is the temperature coefficient of the

Table 4.2: Temperature Sensor Data (in $^{\circ}\text{C}$) of Rotor Magnet referred from [1].

Sensor number	1	2	3	4	5	6	7	8
Normal	30.7	31	31.3	31.4	30.7	30.7	30.6	30.5
Single phase open fault	30.6	30.9	31.3	31.2	30.5	30.6	30.4	30.4
Adjacent two phase open fault	29	29.3	29.7	29.7	28.9	29.1	28.9	28.9
Non-adjacent two phase open fault	29.1	29.4	29.8	29.8	29.1	29.1	29	28.9

particular material.

$$R_T = R_0(1 + \alpha(T - T_0)) \quad (4.4)$$

During FTO, the currents in the remaining healthy phases get increase and this can cause temperature increments. And, there is a possibility that the temperature inrushes effectively impact on winding resistances. Table 4.2, cited from [1] presents temperature data collected for the same motor under different faults. Referring to the data in Table 4.2, the difference in magnet temperature from healthy to single phase fault is not that significant. It is evident that under adjacent and non-adjacent two-phase open faults, there are considerable variations in the temperature. Since this research is focused on single-phase fault, the effect of temperature difference is neglected. Therefore, the resistance is defined as a function of fault type for this research.

Figure 4.7: (a),(b) Torque, (c),(d) Current, (e),(f) Speed waveforms for the original and modified model predictive controllers respectively.

During an open-circuit fault, to maintain the same torque, more currents are drawn by the remaining phases of the motor. And this can create localized saturation which affect the inductance and the flux linkage. This creates a complex flux environment and for this research the change of inductance and flux linkage is not taken in to consideration.

4.2.2 Performance analysis of modified model predictive controller

Adhering to the changes in model parameters discussed in 4.2.1, simulations are carried out for the modified model predictive controller. All simulation results are for the open-phase fault occurred at phase A.

A comparison in system performance for MPC-2 with MPC-1 (original controller) is given in Fig. 4.7. From the results it can observe that there is no significant improvement in the system by using the modified controller adopting resistance variations.

4.3 Conclusion

The system performance is evaluated under open-phase fault at phase-A with the MPC based controller developed in chapter 3. A benchmark control system is utilized for comparative analysis. The PI controller based benchmark system provides around 67.5% torque ripple and 2.5% reduction in average torque while, the replacement of PI with MPC reduces ripples to approximately to 30% and almost no deviation in average torque. The phase currents in both controllers have increased by 49% and

18% respectively compared to the healthy system. This is to facilitate the same operational conditions with the remaining phases. In benchmark system the speed has around 18.75% fluctuations and MPC has reduced it to 10%.

Further a novel technique to design the model was explored by introducing the winding resistance changes during the fault to the controller. But with simulation results, it can conclude that there is no significant improvement by modifying the resistances in the controller model.

CHAPTER V

SPEED CONTROL OF HIGH-SPEED MOTORS BASED ON MODEL PREDICTIVE CONTROL

The work described in this chapter is conducted to investigate another application of model predictive controlling discussed in chapter 2 for speed control of high-speed driven motors. The underline motivation is to design a reliable controlling algorithm for high-speed mechanically rotating antennas which will be used to establish wireless communication to areas that are not feasible with today's wireless technologies [73,74].

At present, initiating a wireless link to deep-water submarines, deep mines or other underground facilities is considered as in-feasible or extremely hard. This is due to short skin depths for radio-frequency (specially microwave range) electromagnetic waves within the medium. As skin-depth is inversely proportional to the frequency, the situation can be alleviated by using extremely low frequencies such as ultra-low frequency (ULF) and very-low frequency (VLF). But this will result in larger antenna sizes and typical ground to submarine ULF/VLF transmitters are constrained by practical limitations the antenna size and power consumption requirements [75,76]. A recent Defense Advanced Research Projects Agency (DARPA) programs has declared a separate program to investigate the feasibility of "A Mechanically Based Antenna (AMEBA)" systems as solution for the aforementioned problem [74].

The paper [77] proposes a methodology of achieving a such AMEBA by using permanently polarized materials based (such as ferroelectrics—electrets and ferromagnets) mechanically rotors to generate the desired oscillating ULF/VLF electric or magnetic field [73]. Although this idea is still this in its conceptual stage, possible practical implementations has been analyzed in collaboration with Dr. S. Mandal, J. Glickstein, and A. Sehirlioglu from Case Western Reserve University and A. Madanayake, S. Choi, M. Tarek and myself from University of Akron.

In the proposed system, several dipoles are mechanically connected to electric motor shafts which then needed to be rotated at very high speed. For such application, the motor drives should be accurately controlled to maintain synchronous rotation of the dipoles with minimum phase errors between them. Further it requires to reduce transients during high speed operation with less overshoot and settling time. Therefore, a new advanced motor controlling technique is required. As described in section 2.2.1 model predictive control strategy tend to perform better than the classical controllers for highly dynamic applications with improved accuracy [78, 79]. Due to this reason MPC based controlled algorithm becomes suitable candidate for this task. The contribution from the thesis author to the project comes in this aspect to design the motor controller based on MPC.

5.1 Proposed model predictive control algorithm for speed control

A bench-marked five-phase PMSynRM, specially designed for high speed operation [80] is used for the initial simulations. The machine model takes the same form as

Figure 5.1: Proposed fault tolerant control algorithm with logic flow.

(3.2) given in chapter 3 since this motor is also a five-phase PMaSynRM. The motor parameters of the bench-marked design are given in Table. 5.1.

The goal of the proposed real-time algorithm is to reach to the reference speed, fast and with minimum error in order to implement the proposed data modulation technique. A block diagram of the control system is shown in Figure 5.1. The reference speed from the data modulation is the input to the control system. The future value of the d-q currents $I_d(k+1)$ and $I_q(k+1)$ are estimated at the predictive model block using the numerical model of the motor (3.2). Here k is the current state of the discrete system. Using the model, the algorithm first computes the electromagnetic torque $T_e(k+1)$, then the rotor speed $\omega_r(k+2)$. Equations (5.1) and (5.2) are used to calculate torque and speed of future states using $I_d(k+1)$ and

Table 5.1: Machine parameters of IPMSM

Parameter	Value
Rated speed	25,000 rpm
No. of poles	4
Winding resistance	0.082 Ω
d-axis Inductance	0.00271 H
q-axis Inductance	0.00459 H
Flux linkage	0.05 Wb
Inertia	0.0008853 kgm ²

$$I_q(k+1).$$

$$T_e(k+1) = 2.5p(\lambda_{PM}I_d(k+1) + (L_d - L_q)I_d(k+1)I_q(k+1)) \quad (5.1)$$

$$\omega_r(k+2) = \omega_r(k+1)(1 - \frac{BT_{sm}}{J}) + \frac{T_s}{J}T_e(k+1) - \frac{T_s}{J}T_l(k+1) \quad (5.2)$$

The cost function is designed accordance with general form (2.8) and speed error considered as the cost (5.1).

$$C(k+3) = \lambda_P C_P(k+3) + \lambda_{L1} C_{L1}(k+3) + \lambda_{L2} C_{L2}(k+3) \quad (5.3)$$

In (5.1), λ_P and $\lambda_{Ln}, n = 1, 2$ are weighting constants for each condition. Here C_p is the condition for speed error and C_{L1} and C_{L2} are constraints on the rated current and voltage at high speed. $C_P(k+3) = (\theta(k+3) - \theta^*(k+3))^2$ and $C_{L1}(k+3) = u^2$ where $u = I_{rated} - \sqrt{I_d^2(k+3) + I_q^2(k+3)}$ when $u < 0$ and zero otherwise. $C_{L2}(k+3)$ is the

Figure 5.2: Reference and actual speed waveforms.

voltage constraint and the rated voltage of the machine considered as the limit. In this case, the speed is predicted for a prediction horizon(N_p) of two and the costs are calculated considering 31 voltage states of the five-phase inverter given in Table. 2.1. The optimization problem was to select the suitable voltage vector to minimize the cost in next cycle of operation.

5.2 Simulation results

For initial simulations of the proposed controller, a 3 kW PMaSynRM Table. (5.1) is used which has a rated speed of 25000 rpm. To test the applicability of the controller for the given application, the angular speed of motor was sinusoidally varied around 9,550 rpm (159.17 Hz) with a modulation amplitude of 955 rpm (15.92 Hz) and a frequency of 3.18 Hz Fig. 5.2. The proposed controller drives the speed to the

Figure 5.3: Angular position versus time.

desired value approximately within 0.1 s and then tracks the target function with small difference.

Fig. 5.3 shows the angular position variation in time horizon after applying the proposed controller to the machine.

5.3 Conclusion

MPC based controller is developed to accurately control the speed, targeting a very high speed motor application. MPC is applied for a bench-marked five-phase PMaSynRM designed for high speed operation. The controller is tested analytically in Matlab-Simulink environment. From the simulation results, it can be observed that the controller performs smoothly for the dynamic command.

The motor reaches to the high speed (9550 rpm) less than 0.1 s. Then keep up with the sinusoidally varying speed with a rate of 3.18 Hz with all most zero steady state error.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this thesis, a controller has been developed based on MPC for a five-phase PMaSynRM. The proposed system is in cascaded structure which includes a PI controller and the developed model predictive controller. MTPA condition has been derived for five-phase PMaSynRM and utilized for current reference generation which provides the benefit of increased efficiency. The performance of the controller has been analyzed and compared to a totally PI based benchmark system. Further, a sensitivity analysis has been performed to check the controller's susceptibility to dynamic model parameter variations. According to simulated results, the controller is highly resilient for the changes in resistance and inductance. For normal operation, both the proposed system and the benchmark system exhibit similar performance with MPC based system bearing around 1% torque ripple.

Then performance of the proposed controller is evaluated under single phase open-fault at phase A. The same scenario is also applied to the benchmark control system for comparison purpose. The MPC based system shows significant improvements relative to all-PI based benchmark controller. The torque ripples are approximately

30% for MPC and 67.5% for the benchmark. Further, a new approach has been explored by modifying the controller model according to resistance variations that occur during the fault. But with simulation results, it can be understood that there is no significant improvement by modifying the controller model.

After completely analyzing through Matlab simulations, the controller was physically implemented using TI DSP 28335 based five-phase motor controlling platform to obtain preliminary results as a proof of concept. Initial test results have been reported that verify the functionality of the proposed MPC in experimental hardware setup.

6.2 Future Work

There are many streams along which the work that has been carried out can be moved forward. This section will provide potential extensions on the work carried out in a broader sense, with respect to the work presented in Chapters 3, 4 and 5.

1. Exploration of ‘continuous control set model predictive control’ to investigate the possibilities of improving torque performance further in both healthy and faulty systems.
2. Checking the viability to design a controller that is totally MPC based without introducing PIs for torque control.
3. Exploration for mathematical derivations to predict inductance and flux linkage variations during a fault to utilize for MPC.

4. Improving the speed control technique with MPC for higher speed operations, particularly by introducing the possible system constraints that can occur during hardware implementation.

BIBLIOGRAPHY

- [1] A. K. M. Arafat, J. Herbert, M. T. B. Tarek, and S. Choi. Study of the thermal effects of a five-phase permanent magnet assisted synchronous reluctance motor under fault tolerant control. In *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, pages 1–6, May 2017.
- [2] L. Parsa. On advantages of multi-phase machines. In *31st Annual Conference of IEEE Industrial Electronics Society, 2005. IECON 2005.*, pages 6 pp.–, Nov 2005.
- [3] I. Takahashi and T. Noguchi. A new quick-response and high-efficiency control strategy of an induction motor. *IEEE Transactions on Industry Applications*, IA-22(5):820–827, Sept 1986.
- [4] A. Boglietti, A. Cavagnino, M. Lazzari, A. Miotto, and S. Vaschetto. Induction motor design methodology based on rotor diameter progressive growth. In *2011 IEEE Energy Conversion Congress and Exposition*, pages 3104–3111, Sept 2011.
- [5] P. Pillay and R. Krishnan. Modeling, simulation, and analysis of permanent-magnet motor drives. i. the permanent-magnet synchronous motor drive. *IEEE Transactions on Industry Applications*, 25(2):265–273, Mar 1989.
- [6] P. Pillay and R. Krishnan. Application characteristics of permanent magnet synchronous and brushless dc motors for servo drives. *IEEE Transactions on Industry Applications*, 27(5):986–996, Sep 1991.
- [7] Q. Chen, D. Liang, Y. Liu, and Q. Wang. Design and multi-object optimisation of axial flux interior pmsm for ev and hev applications. *The Journal of Engineering*, 2017(13):2215–2220, 2017.
- [8] W. L. Mao and Suprpto. Indirect fuzzy contour tracking for x-y pmsm actuated motion system applications. *IET Electric Power Applications*, 12(1):12–24, 2018.

- [9] A. Gaeta, G. Scelba, and A. Consoli. Modeling and control of three-phase pmsms under open-phase fault. *IEEE Transactions on Industry Applications*, 49(1):74–83, Jan 2013.
- [10] A. Arafat and S. Choi. Active current harmonic suppression for torque ripple minimization at open phase faults in a five-phase pma-synrm. *IEEE Transactions on Industrial Electronics*, pages 1–1, 2018.
- [11] Jen-Ren Fu and T. A. Lipo. Disturbance-free operation of a multiphase current-regulated motor drive with an opened phase. *IEEE Transactions on Industry Applications*, 30(5):1267–1274, Sep 1994.
- [12] Tian-Hua Liu, Jen-Ren Fu, and T. A. Lipo. A strategy for improving reliability of field-oriented controlled induction motor drives. *IEEE Transactions on Industry Applications*, 29(5):910–918, Sep 1993.
- [13] G. Scarcella, G. Scelba, M. Pulvirenti, and R. D. Lorenz. Fault-tolerant capability of deadbeat-direct torque and flux control for three-phase pmsm drives. *IEEE Transactions on Industry Applications*, 53(6):5496–5508, Nov 2017.
- [14] M. Bermudez, I. Gonzalez-Prieto, F. Barrero, H. Guzman, M. J. Duran, and X. Kestelyn. Open-phase fault-tolerant direct torque control technique for five-phase induction motor drives. *IEEE Transactions on Industrial Electronics*, 64(2):902–911, Feb 2017.
- [15] L. Zhang, Y. Fan, R. Cui, R. D. Lorenz, and M. Cheng. Fault-tolerant direct torque control of five-phase ftfscw-ipm motor based on analogous three-phase svpwm for electric vehicle applications. *IEEE Transactions on Vehicular Technology*, 67(2):910–919, Feb 2018.
- [16] Q. Tang, X. Ge, Y. C. Liu, and M. Hou. Improved switching-table-based dtc strategy for the post-fault three-level npc inverter-fed induction motor drives. *IET Electric Power Applications*, 12(1):71–80, 2018.
- [17] H. Guzman, M. J. Duran, F. Barrero, B. Bogado, and S. Toral. Speed control of five-phase induction motors with integrated open-phase fault operation using model-based predictive current control techniques. *IEEE Transactions on Industrial Electronics*, 61(9):4474–4484, Sept 2014.
- [18] W. Wang, J. Zhang, and M. Cheng. Common model predictive control for permanent-magnet synchronous machine drives considering single-phase open-circuit fault. *IEEE Transactions on Power Electronics*, 32(7):5862–5872, July 2017.

- [19] H. T. Pham, J. M. Bourgeot, and M. Benbouzid. Fault-tolerant model predictive control of 5-phase pmsg under an open-circuit phase fault condition for marine current applications. In *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, pages 5760–5765, Oct 2016.
- [20] Q. Liu and K. Hameyer. Torque ripple minimization for direct torque control of pmsm with modified fcsmpc. *IEEE Transactions on Industry Applications*, 52(6):4855–4864, Nov 2016.
- [21] M. Preindl and S. Bolognani. Model predictive direct torque control with finite control set for pmsm drive systems, part 1: Maximum torque per ampere operation. *IEEE Transactions on Industrial Informatics*, 9(4):1912–1921, Nov 2013.
- [22] P. Cortes, S. Kouro, B. La Rocca, R. Vargas, J. Rodriguez, J. I. Leon, S. Vazquez, and L. G. Franquelo. Guidelines for weighting factors design in model predictive control of power converters and drives. In *2009 IEEE International Conference on Industrial Technology*, pages 1–7, Feb 2009.
- [23] A. Arafat, S. Choi, and J. Baek. Open-phase fault detection of a five-phase permanent magnet assisted synchronous reluctance motor based on symmetrical components theory. *IEEE Transactions on Industrial Electronics*, 64(8):6465–6474, Aug 2017.
- [24] T. J. E. Miller, A. Hutton, C. Cossar, and D. A. Staton. Design of a synchronous reluctance motor drive. *IEEE Transactions on Industry Applications*, 27(4):741–749, Jul 1991.
- [25] L. Xu, X. Xu, T. A. Lipo, and D. W. Novotny. Vector control of a synchronous reluctance motor including saturation and iron loss. *IEEE Transactions on Industry Applications*, 27(5):977–985, Sep 1991.
- [26] T. M. Jahns, G. B. Kliman, and T. W. Neumann. Interior permanent-magnet synchronous motors for adjustable-speed drives. *IEEE Transactions on Industry Applications*, IA-22(4):738–747, July 1986.
- [27] S. S. R. Bonthu, S. Choi, and J. Baek. Comparisons of three-phase and five-phase permanent magnet assisted synchronous reluctance motors. *IET Electric Power Applications*, 10(5):347–355, 2016.
- [28] S. Morimoto, S. Ooi, Y. Inoue, and M. Sanada. Experimental evaluation of a rare-earth-free pmasynrm with ferrite magnets for automotive applications. *IEEE Transactions on Industrial Electronics*, 61(10):5749–5756, Oct 2014.

- [29] E. E. Montalvo-Ortiz, S. N. Foster, J. G. Cintron-Rivera, and E. G. Strangas. Comparison between a spoke-type pmsm and a pmasynrm using ferrite magnets. In *2013 International Electric Machines Drives Conference*, pages 1080–1087, May 2013.
- [30] S. Ooi, S. Morimoto, M. Sanada, and Y. Inoue. Performance evaluation of a high-power-density pmasynrm with ferrite magnets. *IEEE Transactions on Industry Applications*, 49(3):1308–1315, May 2013.
- [31] N. Bianchi, S. Bolognani, D. Bon, and M. Dai Pre. Rotor flux-barrier design for torque ripple reduction in synchronous reluctance and pm-assisted synchronous reluctance motors. *IEEE Transactions on Industry Applications*, 45(3):921–928, May 2009.
- [32] P. Guglielmi, B. Boazzo, E. Armando, G. Pellegrino, and A. Vagati. Permanent-magnet minimization in pm-assisted synchronous reluctance motors for wide speed range. *IEEE Transactions on Industry Applications*, 49(1):31–41, Jan 2013.
- [33] S. Joe Qin and Thomas A. Badgwell. A survey of industrial model predictive control technology. *Control Engineering Practice*, 11(7):733 – 764, 2003.
- [34] Dmitry Gorinevsky. Lecture 14 - Model Predictive Control Part 1: The Concept. Dr. Dmitry Gorinevsky, 2005.
- [35] S. Bolognani, S. Bolognani, L. Peretti, and M. Zigliotto. Design and implementation of model predictive control for electrical motor drives. *IEEE Transactions on Industrial Electronics*, 56(6):1925–1936, June 2009.
- [36] S. A. Raziei and Z. Jiang. Model predictive control for complex dynamic systems. In *2016 IEEE National Aerospace and Electronics Conference (NAECON) and Ohio Innovation Summit (OIS)*, pages 193–200, July 2016.
- [37] Q. Feng, H. Lian, and J. Zhu. Model predictive control of nonlinear dynamical systems based on genetic programming. In *2017 36th Chinese Control Conference (CCC)*, pages 4540–4545, July 2017.
- [38] K. Kiran, S. Das, and D. Singh. Model predictive field oriented speed control of brushless doubly-fed reluctance motor drive. In *2018 International Conference on Power, Instrumentation, Control and Computing (PICC)*, pages 1–6, Jan 2018.

- [39] V. P. K. Kuniseti, R. E. Kodumur Meesala, and V. K. Thippiripati. Improved predictive torque control strategy for an open end winding induction motor drive fed with four-level inversion using normalised weighted sum model. *IET Power Electronics*, 11(5):808–816, 2018.
- [40] J. Su, R. Gao, and I. Husain. Model predictive control based field-weakening strategy for traction ev used induction motor. *IEEE Transactions on Industry Applications*, 54(3):2295–2305, May 2018.
- [41] L. Yan, M. Dou, Z. Hua, H. Zhang, and J. Yang. Optimal duty cycle model predictive current control of high-altitude ventilator induction motor with extended minimum stator current operation. *IEEE Transactions on Power Electronics*, 33(8):7240–7251, Aug 2018.
- [42] C. Zhang, G. Wu, F. Rong, J. Feng, L. Jia, J. He, and S. Huang. Robust fault-tolerant predictive current control for permanent magnet synchronous motors considering demagnetization fault. *IEEE Transactions on Industrial Electronics*, 65(7):5324–5334, July 2018.
- [43] H. Zhu, X. Xiao, and Y. Li. Torque ripple reduction of the torque predictive control scheme for permanent-magnet synchronous motors. *IEEE Transactions on Industrial Electronics*, 59(2):871–877, Feb 2012.
- [44] P. Kakosimos and H. Abu-Rub. Predictive speed control with short prediction horizon for permanent magnet synchronous motor drives. *IEEE Transactions on Power Electronics*, 33(3):2740–2750, March 2018.
- [45] M. Preindl and S. Bolognani. Model predictive direct speed control with finite control set of pmsm drive systems. *IEEE Transactions on Power Electronics*, 28(2):1007–1015, Feb 2013.
- [46] A. A. Ahmed, B. K. Koh, and Y. I. Lee. A comparison of finite control set and continuous control set model predictive control schemes for speed control of induction motors. *IEEE Transactions on Industrial Informatics*, 14(4):1334–1346, April 2018.
- [47] M. Preindl and S. Bolognani. Comparison of direct and pwm model predictive control for power electronic and drive systems. In *2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, pages 2526–2533, March 2013.

- [48] Z. Ma and S. S. R. Kennel. Continuous set nonlinear model predictive control for pmsm drives. In *2013 15th European Conference on Power Electronics and Applications (EPE)*, pages 1–10, Sept 2013.
- [49] T. Kamel, D. Abdelkader, and B. Said. Vector control of five-phase permanent magnet synchronous motor drive. In *2015 4th International Conference on Electrical Engineering (ICEE)*, pages 1–4, Dec 2015.
- [50] Prashant W.Thamke, Nishant M. Yewale, Uttam B. Vaidya, and Prashant G. Asutkar. Faults associated with permanent magnet synchronous motor. *International Journal Of Core Engineering & Management (IJCEM)*, 2015.
- [51] Cao Chuang, Zhang Wei, Wang Zhifu, and Li Zhi. The diagnosis method of stator winding faults in pmsms based on som neural networks. *Energy Procedia*, 105:2295 – 2301, 2017. 8th International Conference on Applied Energy, ICAE2016, 8-11 October 2016, Beijing, China.
- [52] L. Zhang, Y. Fan, R. Cui, R. D. Lorenz, and M. Cheng. Fault-tolerant direct torque control of five-phase ftfscw-ipm motor based on analogous three-phase svpwm for electric vehicle applications. *IEEE Transactions on Vehicular Technology*, 67(2):910–919, Feb 2018.
- [53] L. Zhang, Y. Fan, R. D. Lorenz, R. Cui, C. Li, and M. Cheng. Design and analysis of a new five-phase brushless hybrid-excitation fault-tolerant motor for electric vehicles. *IEEE Transactions on Industry Applications*, 53(4):3428–3437, July 2017.
- [54] W. Wang, M. Cheng, B. Zhang, Y. Zhu, and S. Ding. A fault-tolerant permanent-magnet traction module for subway applications. *IEEE Transactions on Power Electronics*, 29(4):1646–1658, April 2014.
- [55] E. Levi. Multiphase electric machines for variable-speed applications. *IEEE Transactions on Industrial Electronics*, 55(5):1893–1909, May 2008.
- [56] I. Subotic, N. Bodo, E. Levi, B. Dumnic, D. Milicevic, and V. Katic. Overview of fast on-board integrated battery chargers for electric vehicles based on multiphase machines and power electronics. *IET Electric Power Applications*, 10(3):217–229, 2016.
- [57] N. Bianchi, S. Bolognani, and M. Dai Pre. Strategies for the fault-tolerant current control of a five-phase permanent-magnet motor. *IEEE Transactions on Industry Applications*, 43(4):960–970, July 2007.

- [58] A. Gaeta, G. Scelba, and A. Consoli. Modeling and control of three-phase pmsms under open-phase fault. *IEEE Transactions on Industry Applications*, 49(1):74–83, Jan 2013.
- [59] G. Scarcella, G. Scelba, M. Pulvirenti, and R. D. Lorenz. Fault-tolerant capability of deadbeat-direct torque and flux control for three-phase pmsm drives. *IEEE Transactions on Industry Applications*, 53(6):5496–5508, Nov 2017.
- [60] E. Levi, R. Bojoi, F. Profumo, H. A. Toliyat, and S. Williamson. Multiphase induction motor drives - a technology status review. *IET Electric Power Applications*, 1(4):489–516, July 2007.
- [61] G. K. Singh and A. Iqbal. Modeling and analysis of six-phase synchronous motor under fault condition. *Chinese Journal of Electrical Engineering*, 3(2):62–75, September 2017.
- [62] A. A. A. Hafez, R. Todd, A. J. Forsyth, and A. M. Cross. Direct current ripple compensation for multi-phase fault-tolerant machines. *IET Electric Power Applications*, 5(1):28–36, January 2011.
- [63] Q Teng, J Bai, J Zhu, and Y Sun. Fault tolerant model predictive control of three-phase permanent magnet synchronous motors. 12:385–397, 08 2013.
- [64] W. Wang, J. Zhang, and M. Cheng. Common model predictive control for permanent-magnet synchronous machine drives considering single-phase open-circuit fault. *IEEE Transactions on Power Electronics*, 32(7):5862–5872, July 2017.
- [65] C. J. Meirinho, J. de Oliveira, M. S. M. Cavalca, and A. Nied. Fault tolerant control for permanent magnet synchronous motor. In *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, pages 1–8, May 2017.
- [66] J. Su, J. Liu, and G. Yang. Current control strategy for six-phase pmsm based on mpc under open-circuit fault condition. In *2014 17th International Conference on Electrical Machines and Systems (ICEMS)*, pages 1607–1611, Oct 2014.
- [67] Y. Zhou and G. Chen. Predictive dtc strategy with fault-tolerant function for six-phase and three-phase pmsm series-connected drive system. *IEEE Transactions on Industrial Electronics*, pages 1–1, 2017.
- [68] A. Linder and R. Kennel. Model predictive control for electrical drives. In *2005 IEEE 36th Power Electronics Specialists Conference*, pages 1793–1799, June 2005.

- [69] Musk Marek and Stulrajter Marek. Novel methods for parameters investigation of pm synchronous motors. *Acta Technica Corviniensis - Bulletin of Engineering*, 2013.
- [70] T. Sun, J. Wang, and X. Chen. Maximum torque per ampere (mtpa) control for interior permanent magnet synchronous machine drives based on virtual signal injection. *IEEE Transactions on Power Electronics*, 30(9):5036–5045, Sept 2015.
- [71] J. Baek, S. S. R. Bonthu, S. Kwak, and S. Choi. Optimal design of five-phase permanent magnet assisted synchronous reluctance motor for low output torque ripple. In *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, pages 2418–2424, Sept 2014.
- [72] Tms320f2833x, tms320f2823x digital signal controllers (dscs) datasheet. Technical report, Texas Instruments, 2016.
- [73] H. Rowe. Extremely low frequency communication to submarines. *IEEE Trans. Communications*, 22(4):371–385, Apr 1974.
- [74] Microsystems Technology Office (MTO) Broad Agency Announcement: A Mechanically Based Antenna (AMEBA) (Document HR001117S0007). Dr. Roy Olsson (Program Manager), Dec 2016.
- [75] E. C. Field, L. R. Kies, P. R. Bannister, R. F. Ingram, W. D. Hopkins, and M. A. Roberts. An aerostat-supported ELF/VLF transmitter. *Radio Science*, 24(02):235–246, March 1989.
- [76] R. Barr, W. Ireland, and M. J. Smith. ELF, VLF and LF radiation from a very large loop antenna with a mountain core. *IEE Proceedings H - Microwaves, Ant. and Prop.*, 140(2):129–134, Apr 1993.
- [77] A. Madanayake, S. Choi, M. Tarek, S. Dharmasena, S. Mandal, J. Glickstein, and A. Sehirlioglu. Energy-efficient ulf/vlf transmitters based on mechanically-rotating dipoles. In *2017 Moratuwa Engineering Research Conference (MER-Con)*, pages 230–235, May 2017.
- [78] S. C. Ferreira, R. B. Gonzatti, R. R. Pereira, C. H. da Silva, L. E. B. da Silva, and G. Lambert-Torres. Finite control set model predictive control for dynamic reactive power compensation with hybrid active power filters. *IEEE Transactions on Industrial Electronics*, 65(3):2608–2617, March 2018.

- [79] A. Veksler, T. A. Johansen, F. Borrelli, and B. Realfsen. Dynamic positioning with model predictive control. *IEEE Transactions on Control Systems Technology*, 24(4):1340–1353, July 2016.
- [80] M. T. B. Tarek and S. Choi. Design and rotor shape modification of a multiphase high speed permanent magnet assisted synchronous reluctance motor for stress reduction. In *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, pages 5389–5395, Oct 2017.