

# Predictive Control Strategy for Two Five-Phase Permanent Magnet Synchronous Motors Connected in Series Powered by A Single Inverter

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## ABSTRACT

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This paper presents the development and application of a Model Predictive Control (MPC) strategy for two five-phase permanent magnet synchronous machines (PMSMs) connected in series and supplied by a single five-leg inverter. The objective is to minimize circulating currents while ensuring accurate and independent control of each machine. A mathematical model of the system, consisting of two identical PMSMs with series-connected stator windings, is first established to demonstrate the feasibility of decoupled control despite the use of a common inverter. The MPC strategy is then applied, relying on the prediction of future inverter switching states using the discrete-time system model, with the optimal state selected according to a predefined cost function. The effectiveness of the proposed approach is validated through simulations conducted in MATLAB/Simulink, which confirm significant improvements in the system's dynamic performance, enhanced operational efficiency, and the successful realization of independent control of the two series-connected five-phase machines.

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## 1. Introduction

In recent years, advances in power electronics and control theory have significantly improved the efficiency, reliability, and flexibility of electrical drive systems [1], [2]. Among these systems, multi-phase machines-particularly five-phase permanent magnet synchronous motors (PMSMs)-have attracted considerable attention due to their superior performance compared to conventional three-phase machines [3], [4]. Their key advantages include higher fault tolerance, reduced torque ripple, increased torque density, improved acoustic characteristics, and lower inverter phase rating, making them suitable for high-performance applications such as electric vehicle traction, marine propulsion, wind turbines, high-power industrial applications, and aerospace systems [5]-[9].

Despite these advantages, controlling multi-phase systems in complex configurations remains challenging [10], [11]. One critical issue arises when two synchronous motors are connected in series and powered by a single multi-leg inverter [12]-[16]. Such configurations require independent speed

control for each motor, stable operation under varying loads, and balanced distribution of torque across phases [17]-[19]. The complex phase interactions make precise torque and speed tracking difficult, highlighting the need for advanced and flexible control strategies [20]-[23].

Previous research on multi-phase motor control has explored several classical and advanced approaches. Conventional proportional-integral (PI) control remains popular due to its simplicity, but it suffers from limited dynamic performance and poor handling of operational constraints [24], [25]. Field-oriented control (FOC) improves dynamic response and torque regulation but depends heavily on accurate system modeling and is sensitive to parameter variations [26]-[29]. Direct torque control (DTC) provides fast response, yet introduces high torque ripple and significant harmonic content [30].

Model predictive control (MPC) has emerged as a promising alternative. By leveraging a predictive model of the motor and inverter [31]-[36], MPC anticipates system behavior and optimally selects switching states in real time. Studies have demonstrated its advantages, including reduced torque ripple, improved current tracking, and flexible incorporation of constraints [37]-[42]. Recent work has also focused on reducing the computational burden of MPC for real-time implementation [43]-[47]. However, despite these advances, most studies focus on single motors or simpler configurations [48]-[50]. There remains a clear research gap in applying MPC to series-connected multi-phase motors under a single inverter, where independent control and dynamic performance optimization are simultaneously required [51]-[55]. This study addresses this gap by developing a model predictive control strategy for two five-phase synchronous motors connected in series and powered by a five-leg inverter. The research contributions include [56]-[58]:

- Precise modeling of the motors and inverter dynamics.
- Design and simulation of an MPC scheme integrated with inner PI loops for independent speed control.
- Analysis and validation of dynamic performance, including torque ripple reduction and overall system efficiency.

The proposed approach demonstrates the effectiveness of MPC for complex multi-phase configurations and provides a foundation for advanced high-performance electrical drive applications.

## 2. Analysis and Modeling of Series-Connected Multiphase Machines

In series-connected multiphase electrical machines, the stator windings of multiple machines are connected to the same supply line, enabling their operation from a single multiphase voltage source, typically implemented using a multi-leg inverter. This configuration makes it possible to supply several machines while preserving the ability to control each one independently [16], [17]. Fig. 1 illustrates the case of two five-phase machines connected in series. In this arrangement, the series connection allows a natural decoupling of their control dynamics, which facilitates the implementation of advanced and efficient control strategies.

From an analytical perspective, the behavior of series-connected machines can be described through voltage–current relations, forming the basis for mathematical models that capture the characteristics of each machine. To simplify the study of their dynamics, these models often employ d–q transformation techniques. Moreover, the introduction of phase transposition in the series connection enhances decoupling between flux- and torque-producing currents, thereby reinforcing the possibility of truly independent control [18]-[20]. The voltage and current expressions for both machines are defined as follows:

$$\begin{cases} v_A = v_{as1} + v_{as2} \\ v_B = v_{bs1} + v_{cs2} \\ v_C = v_{cs1} + v_{es2} \\ v_D = v_{ds1} + v_{bs2} \\ v_E = v_{es1} + v_{ds2} \end{cases} \text{ and } \begin{cases} i_A = i_{as1} = i_{as2} \\ i_B = i_{bs1} = i_{cs2} \\ i_C = i_{cs1} = i_{es2} \\ i_D = i_{ds1} = i_{bs2} \\ i_E = i_{es1} = i_{ds2} \end{cases} \quad (1)$$

The transformation from the natural reference frame to the fictitious ( $\alpha\beta xy$ ) reference frame is expressed as follows:

$$f(\alpha\beta) = [T]f(ABCDE) \quad (2)$$

$[T]$  is the clark transformation:

$$[T_5] = \sqrt{\frac{2}{5}} \begin{bmatrix} 1 & \cos(\alpha) & \cos(2\alpha) & \cos(3\alpha) & \cos(4\alpha) \\ 0 & \sin(\alpha) & \sin(2\alpha) & \sin(3\alpha) & \sin(4\alpha) \\ 1 & \cos(2\alpha) & \cos(4\alpha) & \cos(6\alpha) & \cos(8\alpha) \\ 0 & \sin(2\alpha) & \sin(4\alpha) & \sin(6\alpha) & \sin(8\alpha) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (3)$$

By applying Equation (1), the voltage and current equations of the five-phase inverter are derived as follows:

$$\begin{bmatrix} v_\alpha^{INV} \\ v_\beta^{INV} \\ v_x^{INV} \\ v_y^{INV} \\ v_o^{INV} \end{bmatrix} = [T] \begin{bmatrix} v_{as1} + v_{as2} \\ v_{bs1} + v_{cs2} \\ v_{cs1} + v_{es2} \\ v_{ds1} + v_{bs2} \\ v_{es1} + v_{ds2} \end{bmatrix} = \begin{bmatrix} v_{as1} + v_{xs2} \\ v_{\beta s1} - v_{ys2} \\ v_{xs1} + v_{\alpha s2} \\ v_{ys1} + v_{\beta s2} \\ 0 \end{bmatrix} \quad (4)$$

And

$$\begin{bmatrix} i_\alpha^{INV} \\ i_\beta^{INV} \\ i_x^{INV} \\ i_y^{INV} \\ i_o^{INV} \end{bmatrix} = [T] \begin{bmatrix} i_A \\ i_B \\ i_C \\ i_D \\ i_E \end{bmatrix} = \begin{bmatrix} i_{\alpha 1} = i_{x2} \\ i_{\beta 1} = -i_{y2} \\ i_{x1} = i_{\alpha 2} \\ i_{y1} = i_{\beta 2} \\ 0 \end{bmatrix} \quad (5)$$

The mathematical model of two five-phase synchronous machine system in the  $\alpha\beta$  reference frame is formulated as follows:

$$\begin{aligned} v_\alpha^{INV} &= (R_{s1} + R_{s2})i_\alpha^{INV} + \left(l_{s1} + \frac{5}{2}m_{s1}\right)\frac{d}{dt}i_\alpha^{INV} + l_{s2}\frac{d}{dt}i_\alpha^{INV} - \sqrt{\frac{5}{2}}\omega_1\phi_{f1}\sin(\theta_1) \\ v_\beta^{INV} &= (R_{s1} + R_{s2})i_\beta^{INV} + \left(l_{s1} + \frac{5}{2}m_{s1}\right)\frac{d}{dt}i_\beta^{INV} + l_{s2}\frac{d}{dt}i_\beta^{INV} + \sqrt{\frac{5}{2}}\omega_1\phi_{f1}\cos(\theta_1) \\ v_x^{INV} &= (R_{s1} + R_{s2})i_x^{INV} + l_{s1}\frac{d}{dt}i_x^{INV} + \left(l_{s2} + \frac{5}{2}m_{s2}\right)\frac{d}{dt}i_x^{INV} - \sqrt{\frac{5}{2}}\omega_2\phi_{f2}\sin(\theta_2) \\ v_y^{INV} &= (R_{s1} + R_{s2})i_y^{INV} + l_{s1}\frac{d}{dt}i_y^{INV} + \left(l_{s2} - \frac{5}{2}m_{s2}\right)\frac{d}{dt}i_y^{INV} + \sqrt{\frac{5}{2}}\omega_2\phi_{f2}\cos(\theta_2) \end{aligned} \quad (6)$$

$\phi_{f1}$  : The excitation flux of the permanent magnets in Stator 1

$\phi_{f2}$  : The excitation flux of the permanent magnets in Stator 2

The transformation from the ( $\alpha\beta$ ) components to the (d-q) and (x-y) components is defined by the following rotation matrix:

$$R = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & \cdot \\ \sin(\theta) & \cos(\theta) & \cdot \\ \cdot & \cdot & [I]^{3 \times 3} \end{bmatrix} \quad (7)$$

The application of Park's transformation reformulates the system into a set of (d-q) equations, where the currents, voltages, and electromotive force (EMF) remain constant. The angle  $\theta$  in Equation (7) represents the instantaneous rotor position, which differs between the two machines. Specifically, it is denoted as  $\theta_1$  for the first machine and  $\theta_2$  for the second machine. The voltage equations of the two machines are expressed by the following relation:

$$\begin{aligned} v_d^{INV} &= (R_{s1} + R_{s2})i_d^{INV} + \left(l_{s1} + \frac{5}{2}m_{s1}\right)\frac{d}{dt}i_d^{INV} + l_{s2}\frac{d}{dt}i_d^{INV} - \omega_1\left(l_{s1} + \frac{5}{2}m_{s1}\right)i_q^{INV} \\ v_q^{INV} &= (R_{s1} + R_{s2})i_q^{INV} + \left(l_{s1} + \frac{5}{2}m_{s1}\right)\frac{d}{dt}i_q^{INV} + l_{s2}\frac{d}{dt}i_q^{INV} + \omega_1\left(l_{s1} + \frac{5}{2}m_{s1}\right)i_d^{INV} + \sqrt{\frac{5}{2}}\omega_1\phi_{f1} \\ v_x^{INV} &= (R_{s1} + R_{s2})i_x^{INV} + l_{s1}\frac{d}{dt}i_x^{INV} + \left(l_{s2} + \frac{5}{2}m_{s2}\right)\frac{d}{dt}i_x^{INV} - \omega_2\left(l_{s2} + \frac{5}{2}m_{s2}\right)i_y^{INV} \\ v_y^{INV} &= (R_{s1} + R_{s2})i_y^{INV} + l_{s1}\frac{d}{dt}i_y^{INV} + \left(l_{s2} + \frac{5}{2}m_{s2}\right)\frac{d}{dt}i_y^{INV} + \omega_2\left(l_{s2} + \frac{5}{2}m_{s2}\right)i_x^{INV} + \sqrt{\frac{5}{2}}\omega_2\phi_{f2} \end{aligned} \quad (8)$$

The expressions for the electromagnetic torque of the two machines are formulated as follows:

$$\begin{cases} T_{e1} = p \left( (L_d - L_q)i_d^{INV}i_q^{INV} + \sqrt{\frac{5}{2}}\phi_{f1}i_q^{INV} \right) \\ T_{e2} = p \left( (L_x - L_y)i_x^{INV}i_y^{INV} + \sqrt{\frac{5}{2}}\phi_{f2}i_y^{INV} \right) \end{cases} \quad (9)$$

The mechanical equations of the two machines are expressed by the following relation:

$$\begin{cases} J_1 \frac{d\Omega_1}{dt} + f_1\Omega_1 = T_{e1} - T_{L1} \\ J_2 \frac{d\Omega_2}{dt} + f_2\Omega_2 = T_{e2} - T_{L2} \end{cases} \quad (10)$$

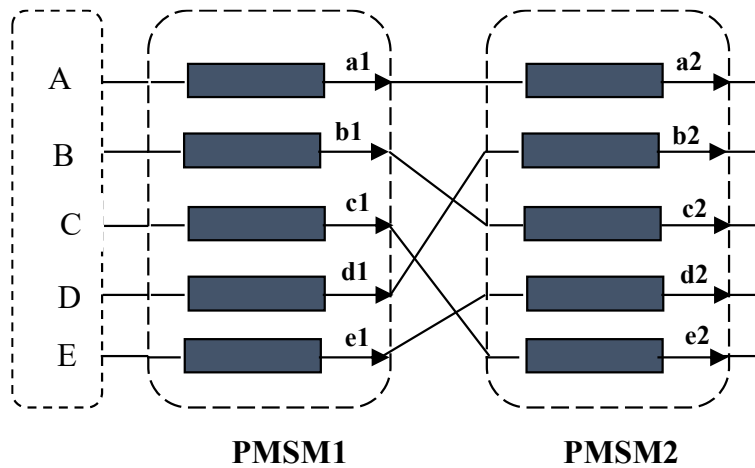


Fig. 1. Topology and representation of series-connected two five-phase PMSMs

### 3. Modeling and Analysis of a Five-Phase Voltage Source Inverter (VSI)

Fig. 2 illustrates the symmetrical configuration of a five-phase voltage source inverter supplying two series-connected five-phase permanent magnet synchronous machines (PMSMs). The inverter consists of ten switching devices, enabling precise control of the output voltages and currents [14], [15].

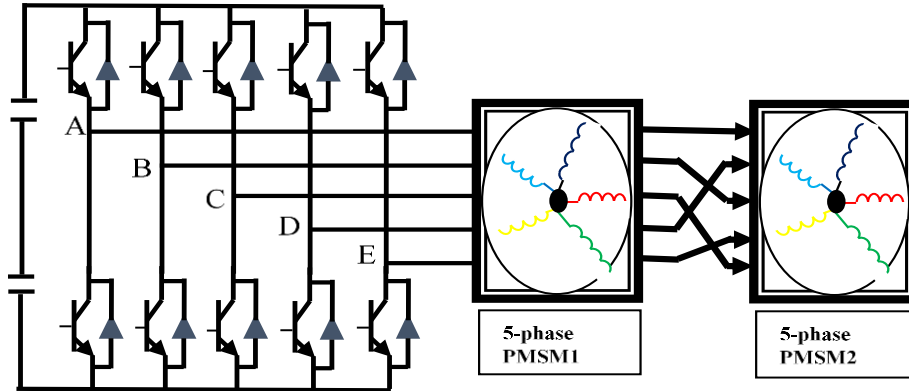


Fig. 2. Circuit configuration of a five-leg inverter for two five-phase synchronous machines

Each phase switching function, denoted as  $S_a S_b S_c S_d S_e$ , can assume one of two possible states: 1 or 0, depending on the status of the corresponding upper or lower switch. When the upper switch is turned ON, the switching function takes a value of 1; otherwise, it is set to 0. The corresponding phase voltages of the inverter can be represented as follows:

$$\begin{cases} V_{AN} = \frac{V_0}{5} (4S_a - S_b - S_c - S_d - S_e) \\ V_{BN} = \frac{V_0}{5} (-S_a + 4S_b - S_c - S_d - S_e) \\ V_{CN} = \frac{V_0}{5} (-S_a - S_b + 4S_c - S_d - S_e) \\ V_{DN} = \frac{V_0}{5} (-S_a - S_b - S_c + 4S_d - S_e) \\ V_{EN} = \frac{V_0}{5} (-S_a - S_b - S_c - S_d + 4S_e) \end{cases} \quad (11)$$

The five-phase inverter generates a total of 32 possible space vector combinations (25), comprising 30 active space vectors and 2 null space vectors (00000, 11111). These space vectors are defined within the d-q and x-y planes, as illustrated in Fig. 3.

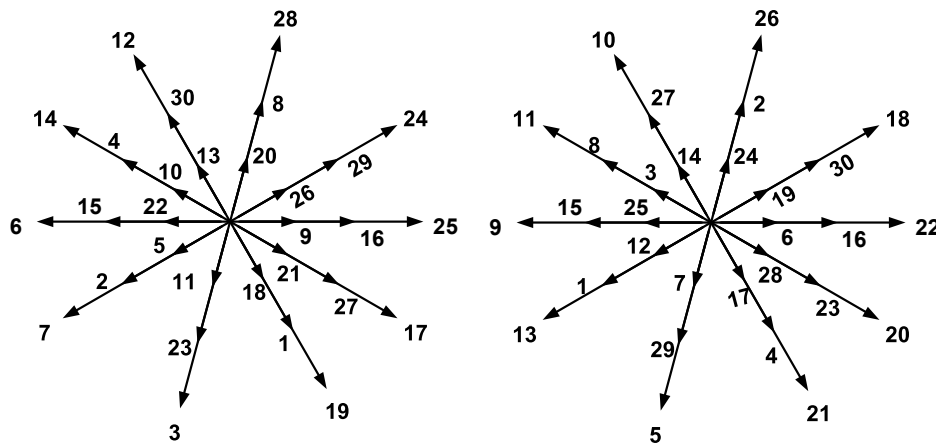


Fig. 3. Distribution of space voltage vectors in the  $(\alpha-\beta)$  and  $(x-y)$  planes

#### 4. Predictive Control Strategy

Model Predictive Control (MPC) relies on a mathematical model of the system to predict the evolution of the controlled variables over a specified period, known as the prediction horizon. Within a shorter interval, called the control horizon, the optimal control inputs are obtained by minimizing a cost function. The resulting control sequence is then applied following a receding horizon strategy.

The key strength of MPC lies in its capacity to anticipate future system behavior and compute control actions that optimally balance performance objectives and constraints. Fig. 4 illustrates the general principle of MPC operation: at time  $k$ , the available measurements are used to estimate future states up to  $k + N$ . After solving the optimization problem, only the first element of the optimal control sequence is implemented, and the procedure is repeated at each sampling instant with updated measurements [55]-[58]. The discrete model used for prediction can be formulated as a state-space model:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) \\ y(k) = Cx(k) + Du(k) \end{cases} \quad (12)$$

The cost function, representing the desired behavior of the controlled system, is defined by considering the reference trajectories, the future states of the controlled variables, and their anticipated optimal values. Generally, for a prediction horizon of length  $N$ , this cost function is written in the following form [46], [50]:

$$g = f(x(k); u(k); \dots; u(k+N)) \quad (13)$$

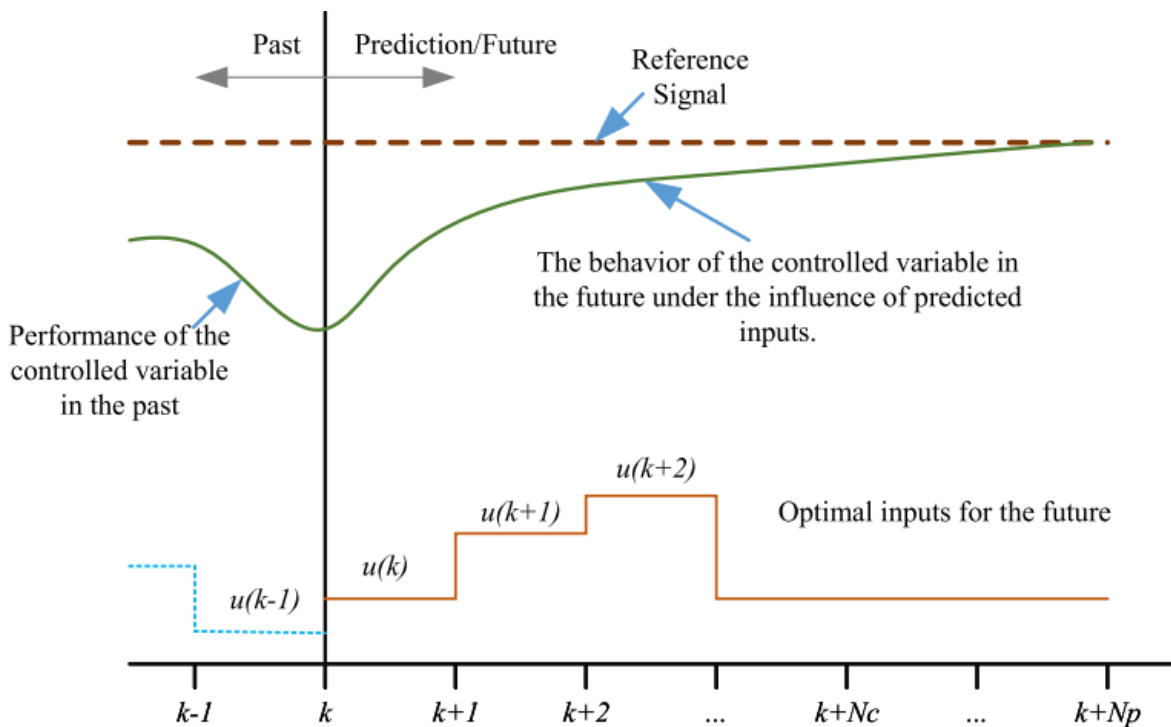


Fig. 4. Operating principle of a model predictive control (MPC) system

#### 5. MPC Control for Two Five-Phase Synchronous Machines

The model predictive control (MPC) framework for the coordinated operation of two five-phase permanent magnet synchronous machines (PMSMs) supplied by a single voltage source inverter (VSI) is illustrated in Fig. 5. Precise measurement of the stator phase currents and rotor mechanical speeds of both machines is essential to predict the system's future state over a one-step horizon. This

predictive step is a prerequisite for the subsequent optimization process, wherein a cost function is evaluated across all 32 possible switching states of the inverter. Based on this evaluation, the optimization module selects the optimal switching state that minimizes the cost function while satisfying control objectives. The resulting optimal switching sequence is then transmitted to the VSI, which enforces the corresponding voltage vector on the machine phases, thereby regulating their electromagnetic behavior. This systematic approach enables real-time, efficient control of two PMSMs through a shared inverter, ensuring optimal performance under dynamic operating conditions.

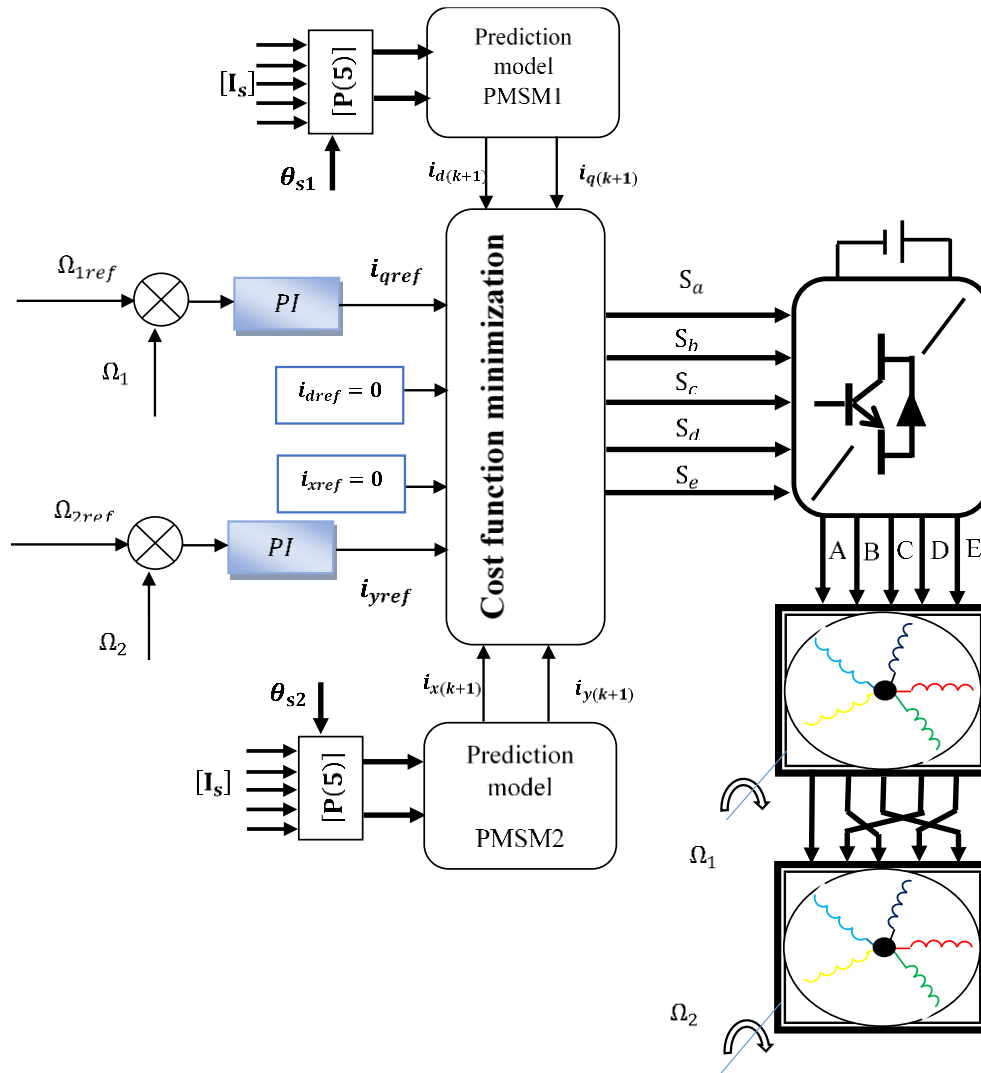


Fig. 5. General schematic diagram of the predictive control of two five-phase PMSMs supplied by a two-level inverter

### 5.1. Discrete-Time Predictive Modeling and Prediction of Two PMSMs

To derive a discrete-time model of the system, the Euler approximation is employed to discretize the time derivatives of the stator currents over a fixed sampling interval  $T$ . Specifically, the time derivative of the stator current is approximated as [54], [55]:

$$\frac{d}{dt} i \approx \frac{i^{k+1} - i^k}{T_s} \tag{14}$$

where  $i^k$  and  $i^{k+1}$  represent the stator current values at the current and next sampling instants, respectively. Based on this approximation, the discrete-time predictive model for two five-phase Permanent Magnet Synchronous Machines (PMSMs) can be formulated as follows:

$$\begin{cases} i_{d(k+1)}^{INV} = i_{d(k)}^{INV} + \frac{T_s}{\left(l_{s1} + \frac{5}{2}m_{s1} + l_{s2}\right)} (v_d^{INV} - (R_{s1} + R_{s2})i_{d(k)}^{INV} + \omega_1(l_{s1} + \frac{5}{2}m_{s1})i_{q(k)}^{INV}) \\ i_{q(k+1)}^{INV} = i_{q(k)}^{INV} + \frac{T_s}{\left(l_{s1} + \frac{5}{2}m_{s1} + l_{s2}\right)} (v_q^{INV} - (R_{s1} + R_{s2})i_{q(k)}^{INV} - \omega_1(l_{s1} + \frac{5}{2}m_{s1})i_{d(k)}^{INV} - \sqrt{\frac{5}{2}}\phi_f\omega_1) \end{cases} \quad (15)$$

$$\begin{cases} i_{x(k+1)}^{INV} = i_{x(k)}^{INV} + \frac{T_s}{\left(l_{s2} + \frac{5}{2}m_{s2} + l_{s1}\right)} (v_x^{INV} - (R_{s1} + R_{s2})i_{x(k)}^{INV} + \omega_2\left(l_{s2} + \frac{5}{2}m_{s2}\right)i_{y(k)}^{INV}) \\ i_{y(k+1)}^{INV} = i_{y(k)}^{INV} + \frac{T_s}{\left(l_{s2} + \frac{5}{2}m_{s2} + l_{s1}\right)} (v_y^{INV} - (R_{s1} + R_{s2})i_{y(k)}^{INV} - \omega_2\left(l_{s2} + \frac{5}{2}m_{s2}\right)i_{x(k)}^{INV} - \sqrt{\frac{5}{2}}\phi_f\omega_2) \end{cases} \quad (16)$$

## 5.2. Performance Optimization Via Cost Function Minimization

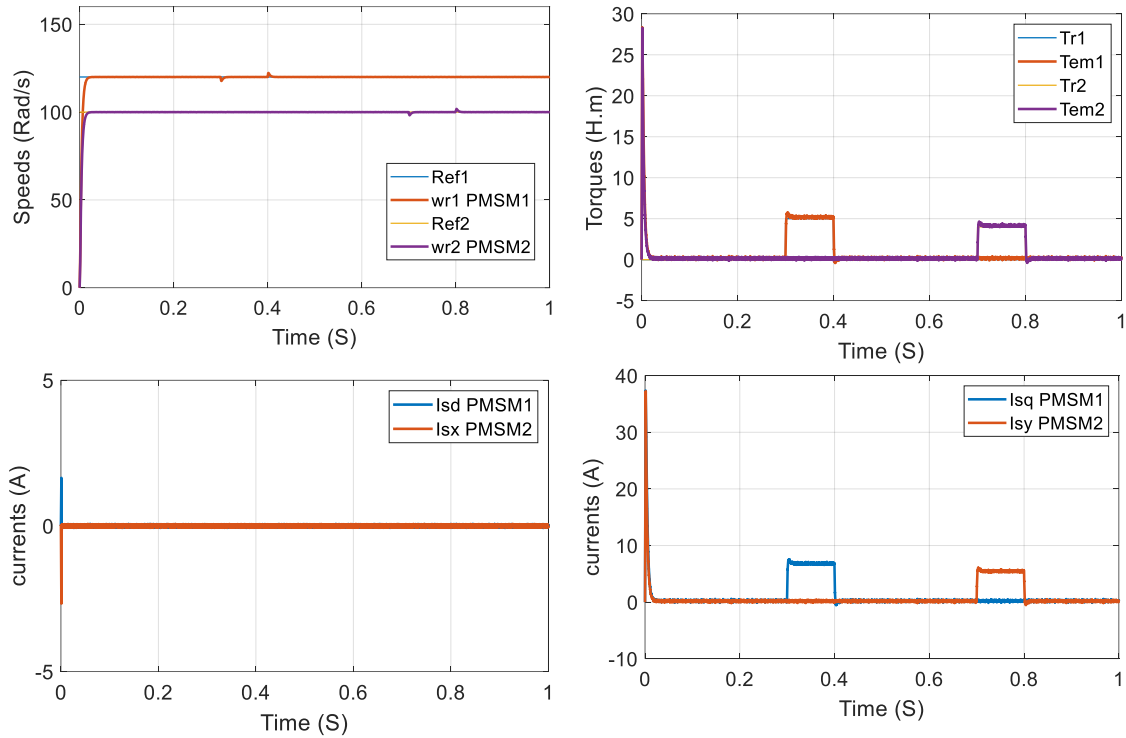
The selection of an appropriate cost function is a critical aspect of predictive control, particularly in systems where two five-phase Permanent Magnet Synchronous Machines (PMSMs) are simultaneously driven by a single voltage source inverter (VSI). In the proposed approach, the cost function is defined as the sum of the squared errors between the reference currents and the predicted stator currents of both machines. This formulation allows for the accurate tracking of reference signals while ensuring coordinated control of the two PMSMs. Mathematically, the cost function is expressed as follows [59], [60]:

$$g = (i_{d(k)ref}^{INV} - i_{d(k+1)}^{INV})^2 + (i_{q(k)ref}^{INV} - i_{q(k+1)}^{INV})^2 + (i_{x(k)ref}^{INV} - i_{x(k+1)}^{INV})^2 + (i_{y(k)ref}^{INV} - i_{y(k+1)}^{INV})^2 \quad (17)$$

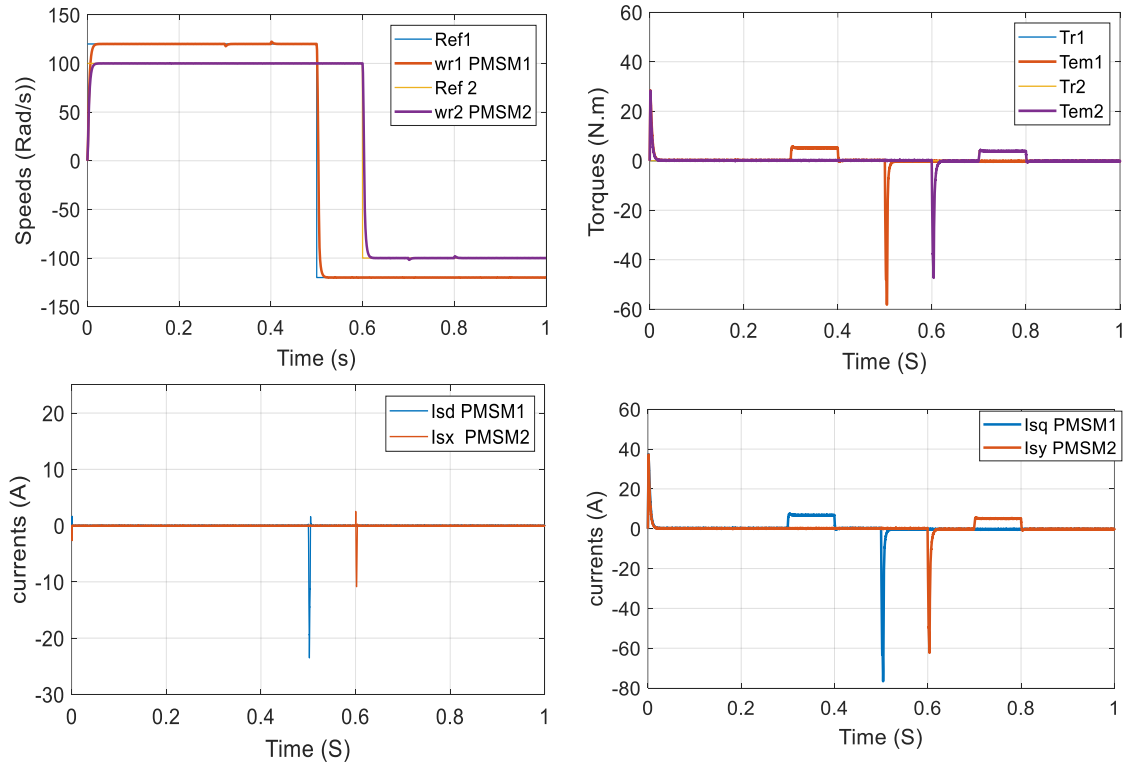
In the proposed control strategy, the optimal voltage vector is selected such that it minimizes the cost function  $g$ , ensuring that the most effective switching state is applied to the inverter. The reference currents  $I_d$  and  $I_q$  correspond to the d-q axis of the first Permanent Magnet Synchronous Machine (PMSM), while  $I_x$  and  $I_y$  are the reference currents along the x-y axis of the second machine. The components  $I_q$  and  $I_y$ , which are directly associated with torque production, are generated by the proportional-integral (PI) speed controller to meet the dynamic performance requirements. Additionally, control of the d-axis and x-axis current components is employed to regulate them to zero, thereby achieving effective decoupling and minimizing cross-coupling effects between flux and torque components.

## 6. Simulation Results

Comprehensive simulations were conducted using MATLAB/Simulink to assess the effectiveness of the proposed control strategy for the operation of two series-connected permanent magnet synchronous machines (PMSMs) supplied by a two-level inverter with five legs. These simulations were designed to examine the dynamic response and stability of the system under diverse operational conditions. Fig. 6 illustrates the speed response curves of both machines. The first machine accelerates from standstill (0 rad/s) to promptly reach its reference speed of 150 rad/s. Similarly, the second machine starts from rest and instantly reaches 100 rad/s. The same figure also depicts the torque and steady-state current responses. Moreover, a load torque of 5 N.m is applied to the first machine at time ( $t = 0.3s$  to  $t=0.4s$ ), while a torque of 4 N.m is applied to the second machine at ( $t = 0.7s$  to  $t=0.8s$ ). Subsequently, a reversal of rotational direction is performed: the speed of the first machine is switched from 120 rad/s to -120 rad/s at  $t = 0.5$  seconds, whereas the speed of the second machine is reversed from 100 rad/s to -100 rad/s at  $t = 0.6$  seconds. As shown in Fig. 7 an additional load torque of 5 N.m is imposed on the first machine at ( $t = 0.3s$  to  $t=0.4s$ ), and another torque of 4 N.m is applied to the second machine at ( $t = 0.7s$  to  $t=0.8s$ ). These tests are conducted to assess the system's dynamic performance under variable load conditions and during rapid speed reversal scenarios.



**Fig. 6.** The performance of model predictive control (MPC) for two series-connected five-phase permanent magnet synchronous motors (PMSMs) supplied by a voltage inverter



**Fig. 7.** The performance of model predictive control (MPC) for two series-connected five-phase permanent magnet synchronous motors (PMSMs) supplied by a voltage inverter. With speed reversal wr1 (120 rad/s to -120 rad/s) and wr2 (100 rad/s to -100 rad/s)

The currents along the d-axis and x-axis remained zero throughout the operation, indicating that the active current components are solely confined to the q-axis and y-axis. Consequently, the q-axis

current directly follows the torque behavior of the first machine, while the y-axis current reflects the torque response of the second machine.

The results obtained from the implementation of the predictive control strategy demonstrate a highly dynamic response and superior torque tracking performance. Furthermore, the findings reveal that altering or reversing the speed of the first machine has no impact on the speed or torque of the second machine, highlighting the effectiveness of the decoupling mechanism ensured by the proposed control system. These features confirm the system's ability to achieve precise and independent control of each machine, despite their series connection and shared supply via a multi-leg inverter.

## 7. Conclusion

This paper presents a Predictive Control strategy for two series-connected five-phase Permanent Magnet Synchronous Machines (PMSMs) fed by a single five-phase Voltage Source Inverter (VSI). By introducing a dedicated phase transposition technique, the proposed method ensures complete decoupling, allowing each machine to be controlled independently. MATLAB/Simulink results validate the effectiveness of the approach, showing that the torque and speed of one machine remain unaffected during the transient of the other. The method achieves fast dynamic response and significantly reduced current and torque ripples, highlighting its robustness and potential for multi-machine drive applications with a single inverter.

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