

Multivector Model Predictive Control for Multiphase Induction Machines with Dead-Time Knowledge

Manuel Cordoba-Ramos¹, Rafael Lara-Lopez¹, Juan Carrillo-Rios¹, Ignacio Gonzalez-Prieto^{1,*}, Mario J. Duran¹, Juan Jose Aciego¹, Pablo Mora-Moreno¹, and Angel Gonzalez-Prieto²

¹University of Malaga, Department of Electrical Engineering, Malaga, 29010, Spain.

²Polytechnic University of Madrid, Department of Electrical Engineering, Madrid, 28040, Spain.

*Correspondence should be addressed to Ignacio Gonzalez-Prieto at igp@uma.es.

ABSTRACT

As requirements in the field of energy efficiency and transport have become more demanding, multiphase technology has begun to emerge in commercial applications in order to meet these demands. In terms of multiphase electric drive regulation, model predictive control has gained traction thanks to its fast dynamic response, flexibility and easy control design. Furthermore, the development of implicit modulators such as multivector solutions has provided these schemes with competitive current quality results. However, the use of higher sampling frequencies in the pursuit of an improved performance presents a blind spot for these control solutions. More concretely, the dead time of voltage source converters (VSCs) has an increasing impact on multiphase electric drives as the sampling frequency becomes higher. The present work first analyses how this phenomenon affects the uniquely available subspaces which characterize multiphase systems. Following these results, dead-time information is added in a multivector predictive scheme and the cost function is reformulated to mitigate its impact. Different operating metrics have been employed to illustrate the effectiveness of the proposed algorithm to increase current quality in a six-phase drive when dead-time effect appears.

Introduction

Multiphase machines have become an interesting solution for industry applications where high power and reliability are required¹⁻³. By presenting more than three phases, these devices bring forth numerous advantages such as inherent fault tolerance, better power density and higher efficiency⁴. However, the exploitation of these desirable traits was limited by the control complexity of these machines, which needed to account for the extra degrees of freedom that emerged from the increased number of phases⁵. Fortunately, the advances in the field of digital signal processing have procured a renaissance of multiphase systems both in academia and industry, with companies implementing multiphase motors in different electric vehicle systems⁶⁻⁸.

Focusing on control algorithms for multiphase electric drives, finite control set model predictive control (FCS-MPC) has appeared as an appealing option in the last decade⁹. Its main benefits include high flexibility thanks to the existence of a cost function¹⁰⁻¹³ and fast dynamic response due to a notable use of the dc-link voltage¹⁴. Nevertheless, the higher number of phases produces the appearance of secondary subspaces whose currents must be carefully controlled due to their impact on harmonic injection⁵. In order to tackle this problem, one suitable approach is the use of multivector solutions, which are based on applying more than one voltage vector per control cycle¹⁵⁻¹⁷. When these vectors are selected with the intention of ideally producing null average voltages in the secondary subspaces, the current harmonic injection can be greatly reduced, leading to an improved performance. Through this method, FCS-MPC has achieved a lower harmonic distortion than field-oriented control (FOC), without the need for an explicit modulator⁵.

Even though multivector FCS-MPC based on virtual voltage vectors (VVs) has successfully regulated multiphase machines¹¹, it also presents limitations. Some well-known disadvantages are the worse utilization of the dc-bus voltage, which leads to lower achievable modulation indices, and less flexibility when VVs are calculated offline¹¹. However, an often overlooked limitation in multiphase FCS-MPC with VVs is the higher sensitivity to dead-time effects¹⁸. Since the multivector approach applies more than one control action per cycle, the time of application of each switching state is lower for the same sampling period¹⁹. Consequently, the proportion of the dead time in the voltage source converter (VSC) with respect to the application time is higher. In this situation, transitional voltage vectors caused by VSC switches can become a critical issue²⁰. The mitigation of this phenomenon in multiphase drives can be essential, since their secondary subspaces typically present low impedance values, resulting in high current disturbances that can jeopardize control quality^{5,11}.

Unfortunately, there is another factor that negatively contributes to the dead-time problem, the decrease in sampling period. Short control times are desirable to obtain fast regulation responses and overall improved performance. Nevertheless, despite these implementation conditions being ideal for improving the system behavior, the impact of dead time notably increases since the specific duty cycle of each switching state of the applied VVs decreases. This undesirable effect was observed in¹⁸, where the increase of the sampling frequency caused a higher injection of low-order harmonic currents. Therefore, in order to exploit the desirable traits of multivector FCS-MPC strategies and higher control frequencies, it becomes mandatory to consider the dead-time influence.

Due to the importance of the dead-time phenomenon, many studies have been performed, each proposing a suitable answer according to their control scheme and machine configuration. For regulation methods with an explicit modulator, one popular solution is to modify the reference voltage values to compensate for the mismatch between the ideal voltage output and the real one caused by the dead time^{21,22}. However, this approach is not suitable for discrete FCS-MPC, since it does not select the control action based on a voltage reference. Focusing on previous solutions applicable to multiphase direct schemes, a dead-time compensation method is suggested in²³ for an open-end winding (OeW) nine-phase machine where VVs based on three switching states are used as control actions. This proposal injects a fourth voltage vector that is aligned with the VV in the α - β plane and in quasi-opposite direction of the dead-time voltage vectors in the remaining four x - y subspaces. A follow-up proposal is presented in²⁴ where, instead of applying a fourth vector to achieve dead-time compensation, a second set of VVs are defined and applied alongside the original VVs every control cycle with this objective. These methods successfully compensate the dead-time effect at the expense of a higher complexity and switching losses, but the solution is specific for OeW configuration where a huge amount of switching states ($> 10^4$) are available for the cancellation procedure.

As an alternative, the dead-time impact on the current quality can be reduced by informing the control scheme of its existence, as it has been observed in three-phase systems²⁰. By accounting for the voltage modification, the FCS-MPC algorithm can improve its decisions and performance. Extending this approach to multiphase electric drives for the first time, this work firstly studies how the VSC dead time affects both the primary and secondary subspaces. This initial contribution provides further insight into the problem of using VV-based FCS-MPC at increasingly higher switching frequencies. After this analysis, a second contribution includes the implementation of an improved multivector FCS-MPC equipped with knowledge of dead-time effect and backed by experimental results. This proposal for multivector FCS-MPC strategies opens the possibility to keep on employing VVs with a satisfactory performance in a higher range of switching frequencies.

The manuscript is structured as follows. First the topology of a six-phase system based on an induction machine (IM) is reviewed. The next section details how to estimate the influence of the dead time in the subspaces that model the machine's performance. Later FCS-MPC for both single and multivector schemes is detailed, further illustrating the importance of the dead-time phenomenon when a higher switching frequency is reached. Next, the proposed multivector method and experimental comparative results are presented. Finally, the conclusions of the work are detailed.

Six-phase induction motor drive

The selected electrical drive presents two main components: a six-phase IM and a dual three-phase two-level VSC (see Fig. 1). The stator of the electrical IM is formed by two three-phase windings shifted 30° , and configured with two isolated neutral points. The VSC is connected to a single dc link, providing $2^6 = 64$ switching states. The VSC behavior can be expressed using a vector $[S]$ where its S_{ij} components illustrate the state of each VSC leg. Subscripts $i \in \{a, b, c\}$ and $j \in \{1, 2\}$ indicate phase and stator winding, respectively. S_{ij} equals 1 if the upper switch of the leg is ON and the lower switch is OFF, whereas S_{ij} would equal 0 if the opposite scenario occurs. The values of the stator phase voltages (v_{ij}) can be estimated using $[S]$ and the dc-link voltage (V_{dc}) :

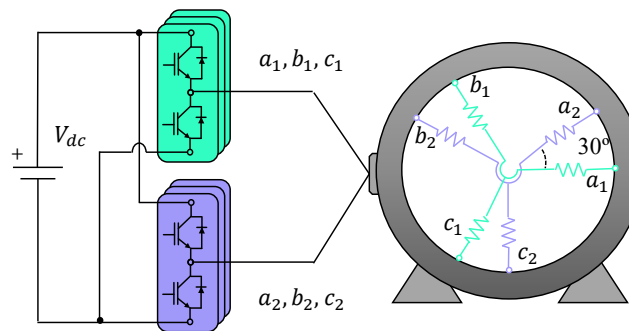


Figure 1. Topology of the asymmetrical six-phase IM with a double three-phase two-level VSC.

$$\begin{bmatrix} v_{a1} \\ v_{b1} \\ v_{c1} \\ v_{a2} \\ v_{b2} \\ v_{c2} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 & 0 \\ -1 & -1 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & -1 & -1 \\ 0 & 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_{a1} \\ S_{b1} \\ S_{c1} \\ S_{a2} \\ S_{b2} \\ S_{c2} \end{bmatrix}. \quad (1)$$

Phase variables can be used to describe the behavior of the drive. However, some reference frames have been widely employed to simplify understanding and control. In this regard, vector space decomposition (VSD) is the most popular solution²⁵. Applying VSD approach, phase variables can be transformed onto three orthonormal subspaces with specific physical meaning. The first subspace is α - β , which is related to flux and torque production, whereas the second plane (x - y) only represents stator copper losses when the machine has distributed windings and spatial harmonics can be neglected. Finally, it is relevant to highlight that zero-sequence has no influence on control strategies since the isolated neutral configuration does not allow these currents to flow.

The Clarke transformation matrix (2) based on the stator winding configuration²⁶ permits expressing phase variables onto VSD components:

$$[C] = \frac{1}{3} \begin{bmatrix} 1 & -1/2 & -1/2 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 1/2 & 1/2 & -1 \\ 1 & -1/2 & -1/2 & -\sqrt{3}/2 & \sqrt{3}/2 & 0 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 & 1/2 & 1/2 & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}, \quad (2)$$

$$[v_{\alpha s}, v_{\beta s}, v_{xs}, v_{ys}, v_{z1}, v_{z2}]^T = [C] \cdot [v_{a1}, v_{b1}, v_{c1}, v_{a2}, v_{b2}, v_{c2}]^T. \quad (3)$$

After applying (2), all possible switching states are mapped onto the α - β and x - y planes, as shown in Fig. 2. The available voltage vectors can be classified according to their magnitude in the main subspace: large (V_l), medium-large (V_{ml}), medium (V_m), small (V_s), and null (V_0)²⁷. V_l is extensively used in control schemes^{28,29} due to its high α - β and low x - y voltage production compared to other options, which enables high achievable torque and flux with low stator copper losses caused by secondary components.

Furthermore, it is useful in terms of control to decouple flux and torque regulation. This can be achieved thanks to the Park transformation, which project the α - β components onto a rotational reference frame, d - q :

$$[D] = \begin{bmatrix} \cos \theta_s & \sin \theta_s \\ -\sin \theta_s & \cos \theta_s \end{bmatrix}, \quad (4)$$

$$[v_{ds}, v_{qs}]^T = [D] \cdot [v_{\alpha s}, v_{\beta s}]^T. \quad (5)$$

where θ_s is the angle of the reference frame.

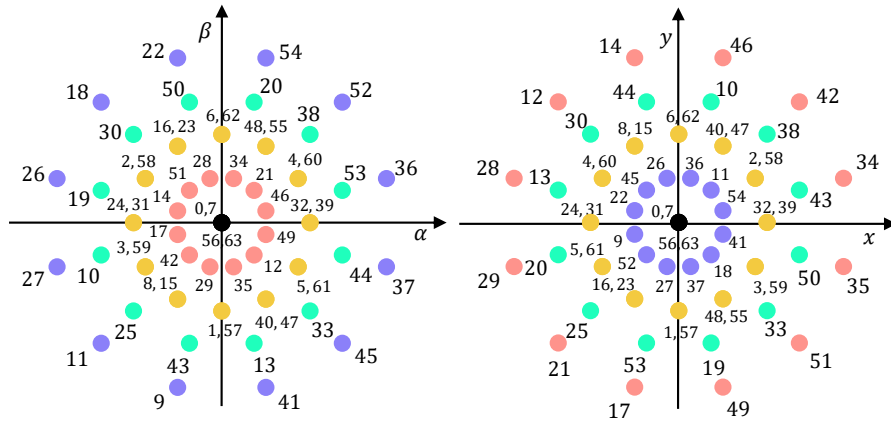


Figure 2. Voltage vector distribution in the α - β and x - y subspaces for a dual three-phase two-level VSC supplying an asymmetrical six-phase IM.

Dead-time influence estimation

The performance of an electric drive can be influenced by many factors that are commonly considered. Some examples are the voltage drop on the power devices, the time delay in gate drive circuits or the effect that the parasitic capacitance has on the turn-on and turn-off times that switches require³⁰. However, the most impactful factor in drive performance is the delay required between the switching of the two semiconductors in the same leg, in order to avoid leg short circuits, also known as dead time³¹. This phenomenon deserves a thorough explanation to better comprehend its negative side effects.

Ideally, the gate control signals of the upper and lower semiconductors on the same phase leg are strictly complementary. Nevertheless, when the switch state changes, the mentioned dead time must be deployed to avoid dc-link short circuit. During this interval, both power switches are open, and the load current flows through one of the freewheeling diodes. Depending on current polarity, two different scenarios appear:

- Positive current polarity (Fig. 3a): Current flows through lower freewheeling diode and pole voltage is clamped to zero volts during dead time.
- Negative current polarity (Fig. 3b): Current flows through upper freewheeling diode and pole voltage is held at V_{dc} volts during dead time.

That is, the appearance of a transitional switching state ($[S^{dt}]$) can generate undesirable voltages in the different subspaces. In fact, to consider the dead-time effect in FCS-MPC, some works have proposed modeling it as a voltage vector that is involuntarily applied^{20,31} (henceforward, dead-time voltage vector V_{dt}), resulting from the transition between two VSC switching states. In order to determine $[S^{dt}]$, it is essential to know three key factors: the previously applied switching state $[S]_k$, the control action to be applied next $[S]_{k+1}$, and the polarity of the current in the phases whose state changes. The vector $[S^{dt}]$ is defined based on the status of each phase during the dead time, as determined by the procedure described in the flowchart (see Fig. 3c). Table 1 presents an example of the calculation of $[S^{dt}]$ that arises during the switching process between active vectors 9 and 22 (see Fig. 2) for a given current state.

It is demonstrated in²⁰ that the effect of V_{dt} degrades the performance of three-phase machines by worsening the α - β current tracking. The reason behind this fact is that the control scheme is unknowingly applying an undesired voltage vector between the chosen control actions. In multiphase drives, this issue becomes more critical due to the existence of the secondary x - y plane, usually characterized by a low impedance³². This low impedance amplifies the effect of small voltage levels, inducing high current magnitudes that contribute to spoil current quality, increasing power losses in the machine. For that reason, V_l are commonly employed as active control actions because they generate minimal voltage in the x - y plane^{28,29}. However, the example in Table 1 illustrates that switching between two V_l (e.g., vectors 9 and 22) can result in a V_{dt} classified as small in α - β but large in x - y (e.g., vector 12), introducing a detrimental effect on the drive efficiency.

MPC for multiphase machines

Standard MPC

FCS-MPC is based on predicting future drive states using a discretized mathematical model of the machine (hereafter, predictive model), in order to select the control action that minimizes the deviation from the desired future state. In electric drives, these states are generally the VSD stator currents ($i_{\alpha\beta\gamma}$), and the control actions correspond to the switching states of the VSC⁵. The standard structure of FCS-MPC typically consists of two different control loops. The outer one uses a proportional-integral (PI) controller to regulate the speed, whereas the inner loop uses the predictive model to regulate the currents. For the electrical

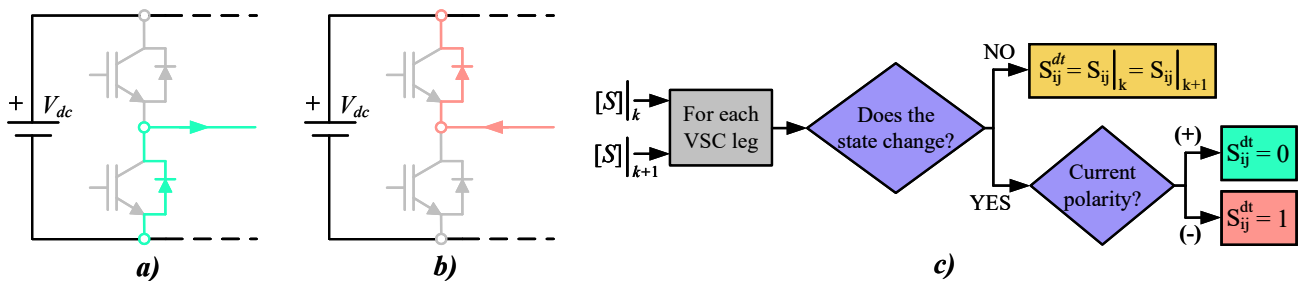


Figure 3. Dead-time effect with different current polarity: a) Positive and b) Negative. c) Flowchart for determining $[S^{dt}]$.

Phase	$[S_1] = 9$	$[S_2] = 22$	Polarity	$[S^{dr}] = 12$
a_1	0	0	Ignored	0
b_1	0	1	+	0
c_1	1	0	−	1
a_2	0	1	−	1
b_2	0	1	+	0
c_2	1	0	+	0

Table 1. An example of dead-time vector determination

drive under consideration, the machine model in space state variables can be represented as follows:

$$\begin{aligned}
 \frac{d}{dt} [X_{\alpha\beta xy}] &= [A] [X_{\alpha\beta xy}] + [B] [U_{\alpha\beta xy}], \\
 [U_{\alpha\beta xy}] &= [v_{\alpha s}, v_{\beta s}, v_{xs}, v_{ys}, 0, 0], \\
 [X_{\alpha\beta xy}] &= [i_{\alpha s}, i_{\beta s}, i_{xs}, i_{ys}, \lambda_{\alpha r}, \lambda_{\beta r}]^T,
 \end{aligned} \tag{6}$$

where matrices $[A]$ and $[B]$ describe the dynamic behavior of a six-phase IM and are parameter-dependent. To effectively employ the predictive model, the expression (6) has been discretized through the application of the Euler forward method.

With the objective of meeting real-time requirements, it is necessary to implement the one-step delay (OSD) compensation³³. This control solution involves evaluating the predictive model twice consecutively to calculate the predicted currents two steps ahead in time $(k+2)$. The total error associated to each switching state current response is quantified by means of a predefined cost function (7), and the control action that minimizes its value is selected.

$$J = e_{\alpha s}^2 + e_{\beta s}^2 + K_{xy}(e_{xs}^2 + e_{ys}^2), \tag{7}$$

where:

$$e_{ms} = i_{ms}^*|_{k+2} - \hat{i}_{ms}|_{k+2}, \forall m \in \{\alpha, \beta, x, y\}, \tag{8}$$

being K_{xy} a weighting factor related to the x - y currents, and the superscripts “ $\wedge$ ” and “ $*$ ” meaning predicted and reference values, respectively. The q current reference is determined by the external speed controller, while the d current reference is usually set constant to provide the rated stator flux in the base speed region. These reference values are rotated into the stationary α - β reference frame using the inverse Park transformation. Regarding the x - y reference currents, they are commonly set to zero, as they are purely related to copper losses in machines with distributed-winding stator configurations.

The switching state selected through the cost function (7) seeks to achieve the control objectives. Unfortunately, applying a single switching state per control period inherently limits the ability to simultaneously satisfy the output voltage requirements in both planes. This limitation can result in undesired harmonic injection in the secondary subspace when the control prioritizes the requirements of the primary plane. To address this problem, various multivector approaches have been proposed in the literature¹¹.

Multivector MPC

FCS-MPC based on multivector control actions has become a hotspot of research in recent years^{34,35}. These techniques apply multiple switching states per control period to compose control actions that simultaneously meet the requirements in all subspaces.

In the considered six-phase IM, if the dead-time effect is neglected, control actions with a zero average in the x - y plane can be achieved through the application of a set of three adjacent large vectors (V_l^1 , V_l^2 and V_l^3)³⁶. The per-unit duty cycles of each vector is $t_1 = 0.2679$, $t_2 = 0.4642$ and $t_3 = 0.2679$ respectively, being V_l^2 located between the two other vectors³⁶. Throughout this work, the method utilizing these control actions will be referred to as triple vector model predictive control (TV-MPC). This control strategy employs a modified cost function which only considers α - β errors since the regulation in the x - y subspace is performed in open-loop mode. It evaluates thirteen control actions in each sampling period (see Fig. 4) :

- Twelve multivector actions composed of adjacent V_l trios. Henceforth denoted as TV_i , $i \in \{1, 2, \dots, 12\}$.
- One single-vector action that is entirely null in both subspaces, designated as V_{null} .

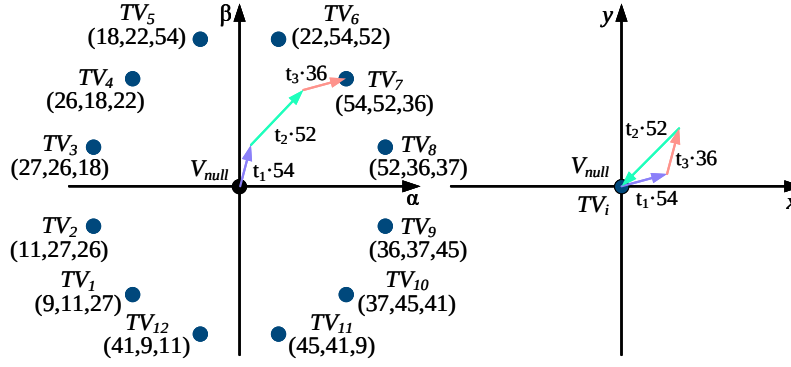


Figure 4. Control action set of TV-MPC neglecting dead-time effect.

The TV-MPC method will be employed as a benchmark, as it constitutes the simplest multivector control approach that ideally achieves a null average voltage in the secondary subspace by applying only V_l . Furthermore, this method will highlight the challenges encountered by multivector control strategies at high frequencies and will provide the foundational basis for the development of the control method proposed in this work.

Multivector MPC at high frequencies

Although dead time is always present in the VSC, its impact is negligible at low frequencies and can therefore be disregarded. Nonetheless, as the frequency grows, the application time (duty) of each voltage vector decreases while the dead time remains constant, becoming a significant factor. Fig. 5 compares the mean voltages obtained in both subspaces applying the virtual vector TV_7 at various control frequencies, taking into consideration the impact of the dead-time effect. The comparison includes the ideal case as a reference. Theoretically, the proposed control action averages zero voltage in the secondary subspace. However, the dead-time effect results in a non-zero value, which increases the x - y currents due to the low impedance of the secondary plane. The voltages, included in Fig. 5, have been calculated for a dead-time duration equal to that of the VSC used on the experimental testing in this work (see *Experimental results* section). As can be observed, the higher the frequency, the greater the deviation of the resulting voltage from the ideally expected value, thereby exacerbating the issue caused by the dead time.

A theoretical study has been carried out to analyze the effect of dead time on the currents in the secondary plane when applying the considered multivector control actions. The RL circuit corresponding to the x - y subspace has been modeled to obtain the behavior of the nonlinear currents:

$$\begin{aligned} i_{xs} &= \frac{v_{xs}}{R_s} + \left(i_{xs0} - \frac{v_{xs}}{R_s} \right) \cdot e^{-t/\tau_s}, \\ i_{ys} &= \frac{v_{ys}}{R_s} + \left(i_{ys0} - \frac{v_{ys}}{R_s} \right) \cdot e^{-t/\tau_s}, \end{aligned} \quad (9)$$

where τ_s is the stator time constant and R_s is the stator resistance. The computation is performed using the parameters of the selected IM, shown in Table 2. The initial currents, denoted as i_{xs0} and i_{ys0} , are initialized to zero.

Fig. 6 shows the evolution of currents in the secondary subspace at a frequency of 20 kHz, under the application of a control action TV_7 . It compares the ideal case with two scenarios, C1 and C2, each with distinct conditions, where the polarity of the currents and the initial vector differ. Despite applying the same control action, the effect of dead time on the currents depends on the aforementioned conditions. While the x - y currents should ideally return to zero at the end of the control period, the presence of dead time introduces an offset in this value (see Fig. 6). Moreover, the instantaneous peak value is also higher when this effect is considered. Taking into consideration this phenomenon, it extends to reason that an algorithm that accounts for the high variability in secondary currents due to dead time will better exploit the advantages of multivector solutions.

Proposed dead-time influence estimation MPC

The objective of the dead-time influence estimation model predictive control (DIE-MPC) is to characterize the effect of dead time on multiphase electric drive behavior, allowing the control method to consider its impact. In this vein, the designed predictive algorithm uses the same control actions as TV-MPC but provides the control method with a better understanding of the effects of their application. This additional knowledge enables the selection of optimal actuation, even at high control frequencies.

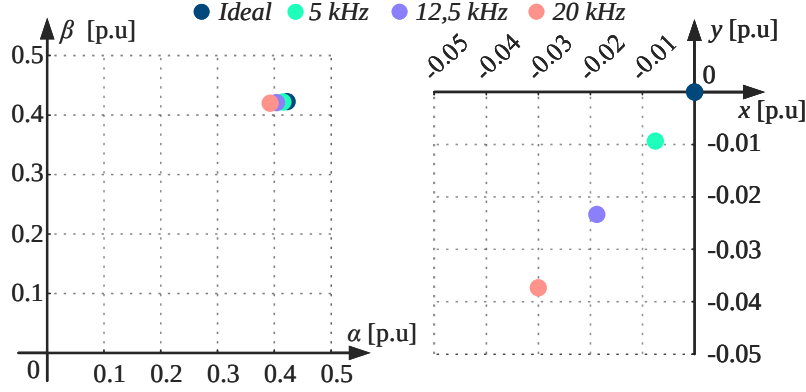


Figure 5. Resulting average voltage of the same TV-MPC control action at different frequencies, considering the dead-time effect.

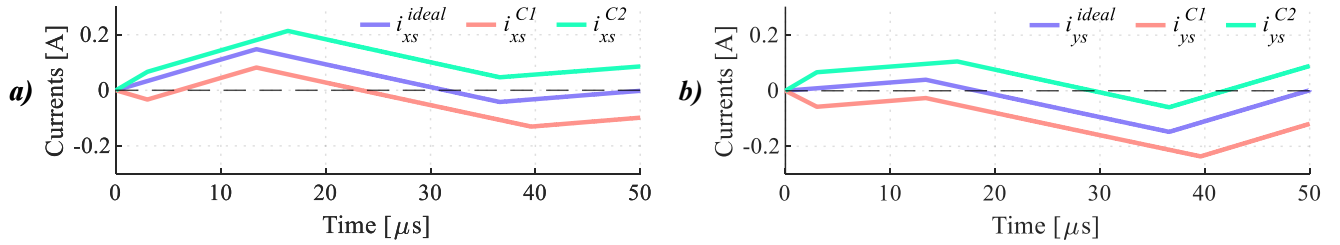


Figure 6. Theoretical evolution of the x-y currents for the application of the same TV-MPC control action and different conditions. a) x-current. b) y-current.

Neglecting dead time results in a detrimental effect on drive control, which manifests in two distinct aspects:

- In the assessment of the available control actions. As illustrated in Fig. 5, the resulting average voltage in each subspace deviates from the ideal one, thereby leading to an inaccurate evaluation of the control action.
- In the OSD compensation to calculate the future currents in the drive, caused by the control action selected in the previous period. The effect of the action previously chosen as optimal does not align with expectations, resulting in an error in the initial state considered for evaluating future control actions.

DIE-MPC addresses the two previously identified issues. To this end, it calculates the resulting average voltage of the control action, taking into account the dead time. Fig. 7a) depicts the ideal case, where three adjacent V_l are applied, alongside the real case 7b), in which three additional V_{dt} are present. In this way, the average voltage in each subspace (henceforward, denoted as $\bar{V}$) can be obtained as follows:

$$\bar{V} = K_{dt} \cdot \sum_{i=1}^3 V_{dt}^i + \sum_{i=1}^3 K_i \cdot V_l^i, \quad (10)$$

where:

$$\begin{aligned} K_{dt} &= t_d / T_s, \\ K_i &= (T_s \cdot t_i - t_d) / T_s, \end{aligned} \quad (11)$$

with T_s representing the sampling time, t_d the dead time and t_i the ideal per-unit duty cycle of each V_l . Moreover, the three V_{dt} are calculated using the procedure described in *Dead-time influence estimation* section.

The flowchart of the proposed control scheme is shown in Fig. 8. Focusing on the proposed strategy, the predictive model is first employed with the previously calculated average voltage $\bar{V}(k)$, accounting for dead time, to determine the phase currents at $(k+1)$. Next, the 13 available control actions are evaluated using the DIE method, which provides the average voltage $\bar{V}(k+1)$ based on:

- Polarity of the phase currents at $(k+1)$.

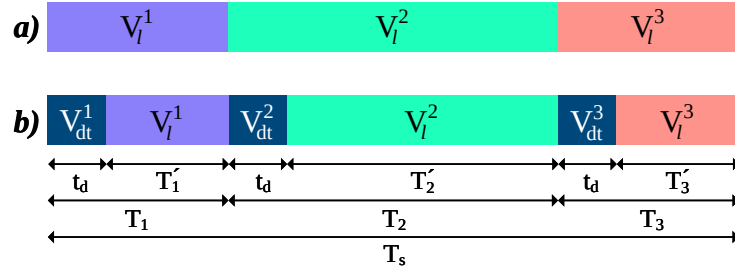


Figure 7. Vectors applied during a TV-MPC control action. a) Ideal case and b) considering dead-time effect.

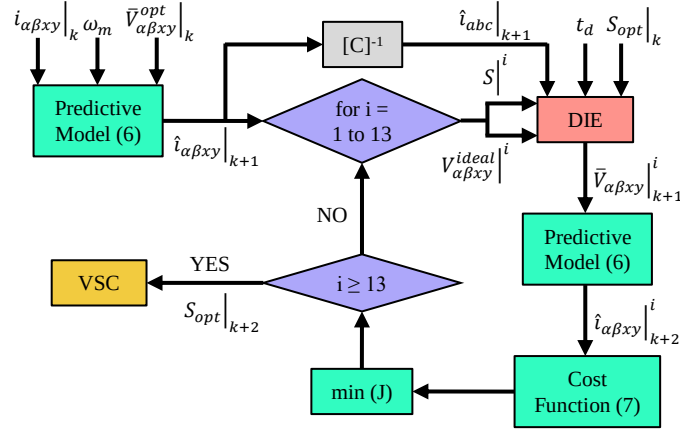


Figure 8. DIE-MPC flowchart.

- Switching state (k) and the one being evaluated.
- Ideal voltage provided by the evaluated action.

Subsequently, VSD currents at instant $(k + 2)$ are estimated for each action, and the optimal switching state is selected as the one that minimizes the predefined cost function (7). Despite using multivector actions designed to theoretically average zero in the x - y plane, the employed cost function considers now the error generated by dead time in both subspaces. This marks a key difference between the proposed method and the ideal virtual vector solutions previously developed.

To sum up, the proposed DIE-MPC achieves a better selection of the optimal action compared to TV-MPC, due to its additional knowledge about dead time. The experimental results presented in the following section confirm the impact of this enhanced multivector FCS-MPC on current quality and other relevant metrics.

Experimental results

Test bench

The test bench employed to evaluate the performance of the control schemes is shown in Fig. 9. The six-phase drive consists of an asymmetrical IM supplied from a pair of conventional two-level three-phase VSCs (Semikron SKS22F modules). Additionally, a single dc source is responsible for powering the VSCs. The parameters of the custom-built multiphase IM can be observed in Table 2.

Control methods are implemented in a digital signal processor from Texas Instruments (TMS320F28335) programmed using a JTAG and TI proprietary software called Code Composer Studio. The sensors that acquire current and speed signals are four hall-effect sensors (LEMLAH25-NP) and a digital encoder (GHM510296R/2500), respectively. The IM is loaded by coupling it to a dc machine by the shaft, thus working as a generator. The armature of the dc machine is connected to a resistive circuit that dissipates power. The load torque is consequently dependent on speed.

Experimental validation

This section shows experimental results with the purpose of confirming the advantages of the designed DIE-MPC over the previously exposed TV-MPC, which does not consider the effect of dead time. To achieve this objective, total harmonic

Figure 9. Scheme of the test bench employed to acquire experimental results.

Focusing on high control frequencies, multiple tests have been performed at 20 kHz. The results of these tests are summarized in Table 4. Regardless of the considered case, THD levels are improved without increasing the switching frequency, resulting in a lower product of these two indices for the proposed method. Furthermore, Figs. 10 and 11 show that, for two different operating points, DIE-MPC reduces currents in the x - y subspace without compromising the tracking of speed and current references in the d - q plane, leading to phase currents with lower harmonic distortion. Expanding this analysis, through the application of the fast Fourier transform at $\omega = 800$ rpm, DIE-MPC achieves a reduction of 53.83% and 31.55% of the 5th and 7th harmonic, reflecting x - y currents reduction³⁷.

In multiphase drives, mitigating dead-time impact on x - y currents is essential to ensure high current quality. This requirement becomes even more critical than the influence on the main components, as it occurs in three-phase drives. In order to illustrate this issue, Fig. 12 shows a comparative test between TV-MPC and the proposed method. For the designed DIE-MPC two different configuration solutions have been considered. In the first case Fig. 12b, DIE-MPC has been implemented without considering the control of the secondary currents in the cost function, i.e. using $K_{xy} = 0$. In the second case Fig. 12b, DIE-MPC has been implemented with $K_{xy} = 1.5$. As shown in Fig. 12, taking into account dead-time effect is not sufficient to achieve a significant improvement in terms of THD in the phase currents if secondary currents are not considered. Fortunately, when x - y currents are incorporated into the control loop, a proper balance can be established between satisfying magnetic flux and torque

Speed (rpm)	Method	THD (%)	$f_{sw}(kHz)$	THD $\cdot f_{sw}$
500	TV-MPC	12.05	8.19	98.69
500	DIE-MPC	9.17	7.71	70.70
650	TV-MPC	11.53	7.91	91.20
650	DIE-MPC	7.85	7.63	59.89
800	TV-MPC	11.20	7.51	84.13
800	DIE-MPC	7.65	7.44	56.92

Table 4. Quality indices in a range of speed, $f_c = 20kHz$

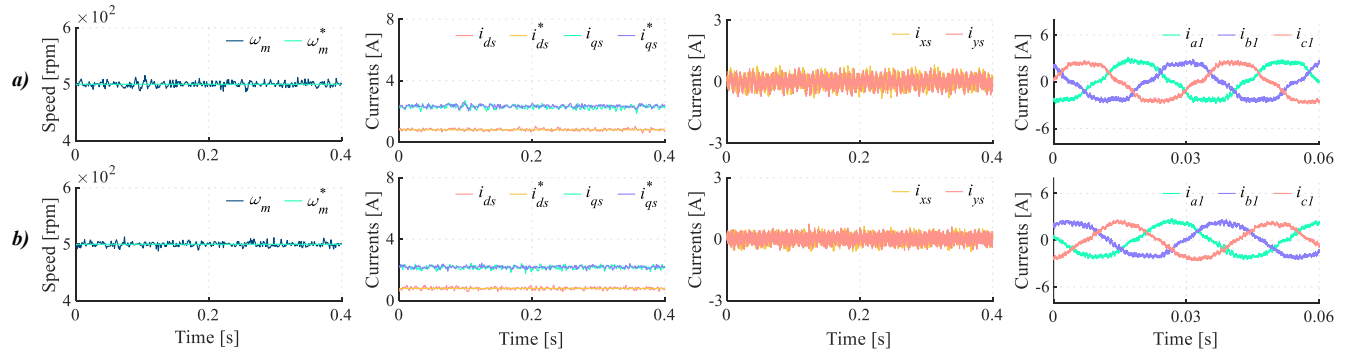


Figure 10. Medium-speed test for a) TV-MPC and b) DIE-MPC. From left to right: Speed, d - q currents, x - y currents, and phase currents when $f_c=20$ kHz.

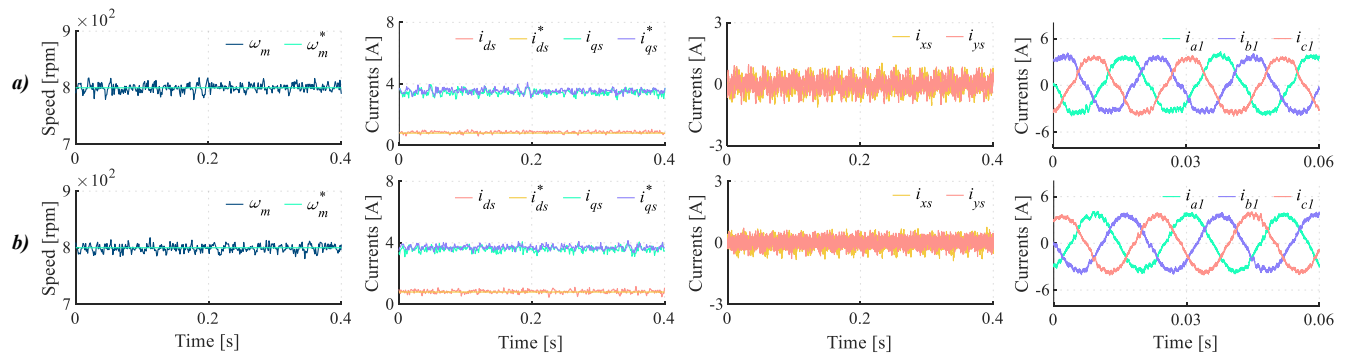


Figure 11. High-speed test for a) TV-MPC and b) DIE-MPC. From left to right: Speed, d - q currents, x - y currents, and phase currents when $f_c=20$ kHz.

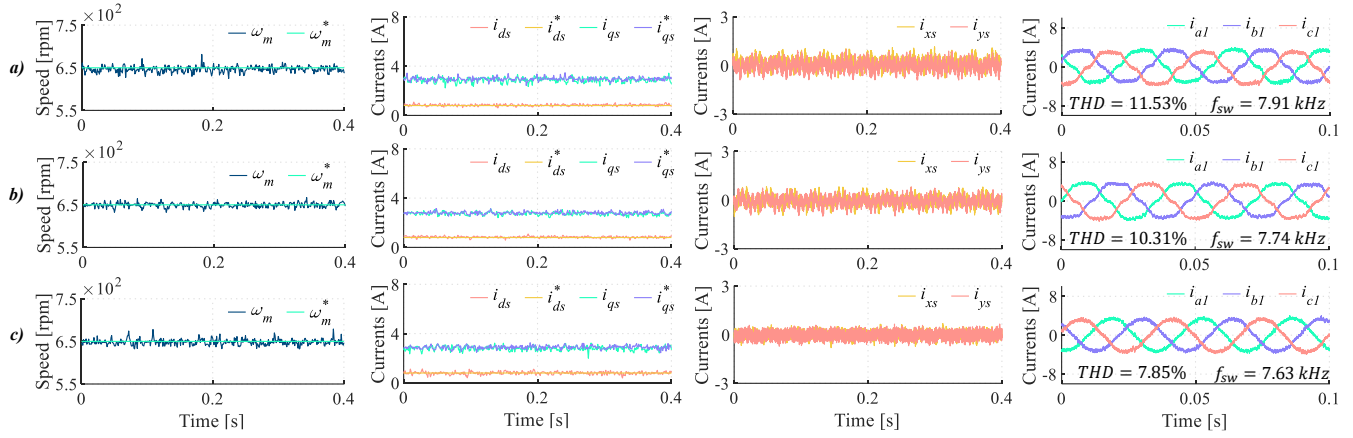


Figure 12. Test at 650 rpm for a) TV-MPC, b) DIE-MPC ($K_{xy} = 0$) and c) DIE-MPC ($K_{xy} = 1.5$). From left to right: Speed, d - q currents, x - y currents, and phase currents when $f_c = 20$ kHz.

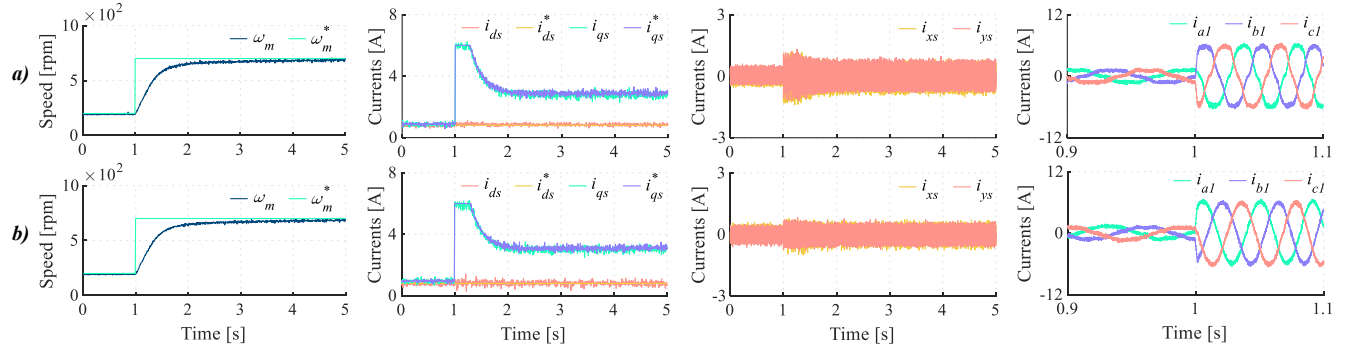


Figure 13. Dynamic test for a) TV-MPC and b) DIE-MPC. From left to right: Speed, d - q currents, x - y currents, and phase currents when $f_c = 20$ kHz.

requirements and reducing secondary subspace loss currents. This is evidenced by a reduction in the ripple of the x - y currents and an overall improvement in the quality of phase currents. In conclusion, for multiphase drives the mitigation of dead-time impact on secondary currents is a must.

Finally, Fig. 13 presents a dynamic test evaluating both regulation schemes. This test aims to confirm the effectiveness of the proposed method in mitigating harmonic distortion under varying conditions, preserving the control of the main components. As it can be seen in Figs. 13a and 13b, speed and d - q currents regulation have an appropriate tracking in both cases. However, x - y currents are notably lower in DIE-MPC than in TV-MPC (see Fig. 13c), specially when transition state is occurring. This improvement is achieved thanks to the better control actions selection of the considered DIE-MPC. As a consequence of considering dead-time effect on cost function, phase currents show a lower harmonic distortion in this transient scenario, as shown in Fig. 13d.

Conclusion

The usage of VVs at high control frequencies presents itself as an interesting option to fully exploit the advantages of multiphase systems and FCS-MPC. Nevertheless, this scenario provides new complications, such as the undesirable and now notable effect of the VSC dead time. This phenomenon is translated into an error between the voltage vector modeled in the control algorithm and the real output, which leads to poorer control action selection and worse overall performance. This work tackles this issue, providing a theoretical analysis of the problem in order to bring further insight into the consequences of using multivector MPC strategies at increasing values of the control frequency. Moreover, the model of an FCS-MPC scheme based on multivector actions is improved by including knowledge of the dead-time effect. The experimental results of the proposed DIE-MPC back the importance of considering this phenomenon, providing a reduction of both the switching frequency and the current harmonic content at different operating points and control frequencies. In fact, this improvement in current quality is also achieved under dynamic conditions without affecting the transient response of the electric drive.

References

1. Levi, E., Bojoi, R., Profumo, F., Toliyat, H. & Williamson, S. Multiphase induction motor drives - a technology status review. *Electr. Power App., IET* **1**, 489 – 516 (2007).
2. Levi, E. Multiphase electric machines for variable-speed applications. *IEEE Trans. on Ind. Electron.* **55**, 1893–1909 (2008).
3. Salem, A. & Narimani, M. A review on multiphase drives for automotive traction applications. *IEEE Trans. on Trans. Electrification* **5**, 1329–1348 (2019).
4. Levi, E. Advances in converter control and innovative exploitation of additional degrees of freedom for multiphase machines. *IEEE Trans. on Ind. Electron.* **63**, 433–448 (2016).
5. Duran, M. J., Gonzalez-Prieto, I., Gonzalez-Prieto, A. & Aciego, J. J. The evolution of model predictive control in multiphase electric drives: A growing field of research. *IEEE Ind. Electron. Mag.* **16**, 29–39 (2022).
6. *H3X HPDM-1500*. Available at: <https://www.h3x.tech/products/hpdm-1500>.
7. *Audi QE-tron*. Available at: <https://www.audi-mediacentre.com/en/audi-at-the-dakar-rally-2023-15116/technical-data-audi-rs-q-e-tron-dakar-2023-15119>.
8. *Zeroavia EPS*. Available at: <https://zeroavia.com/electric-propulsion/>.
9. Tenconi, A., Rubino, S. & Bojoi, R. Model predictive control for multiphase motor drives – a technology status review. In *2018 International Power Electron. Conference (IPEC-Niigata 2018 -ECCE Asia)*, 732–739 (2018).
10. Arahall, M. R., Martín, C., Kowal, A., Castilla, M. & Barrero, F. Cost function optimization for predictive control of a five-phase im drive. *Optim. Control. App. Methods* **41**, 84–93 (2020).
11. Aciego, J. J., Gonzalez-Prieto, I., Duran, M. J., Gonzalez-Prieto, A. & Carrillo-Rios, J. Guiding the selection of multi-vector model predictive control techniques for multiphase drives. *Machines* **12** (2024).
12. Ayala, M., Doval-Gandoy, J., Rodas, J., Gonzalez, O. & Gregor, R. Current control designed with model based predictive control for six-phase motor drives. *ISA Trans.* **98**, 496–504 (2020).
13. Abbaszadeh, A., Khaburi, D. A., Mahmoudi, H. & Rodríguez, J. Simplified model predictive control with variable weighting factor for current ripple reduction. *IET Power Electron.* **10**, 1165–1174 (2017).
14. Aciego, J. J., González Prieto, I., Duran, M. J., Bermudez, M. & Salas-Biedma, P. Model predictive control based on dynamic voltage vectors for six-phase induction machines. *IEEE J. Emerg. Sel. Top. Power Electron.* **9**, 2710–2722 (2021).
15. Luo, Y. & Liu, C. Multi-vector-based model predictive torque control for a six-phase pmsm motor with fixed switching frequency. *IEEE Trans. on Energy Convers.* **34**, 1369–1379, DOI: [10.1109/TEC.2019.2917616](https://doi.org/10.1109/TEC.2019.2917616) (2019).
16. Sun, J. *et al.* An efficient multi-vector-based model predictive current control for pmsm drive. *CPSS Trans. on Power Electron. Appl.* **9**, 79–89, DOI: [10.24295/CPSS TPEA.2023.00044](https://doi.org/10.24295/CPSS TPEA.2023.00044) (2024).
17. Parvathy, M. L. & Kumar, T. V. A multivector-based model predictive current control of pmsm drive with enhanced torque and flux response. *IEEE J. Emerg. Sel. Top. Power Electron.* **10**, 7527–7538, DOI: [10.1109/JESTPE.2022.3180027](https://doi.org/10.1109/JESTPE.2022.3180027) (2022).
18. Carrillo-Ríos, J. *et al.* Reevaluating the role of single-vector fcs-mpc for multiphase electric drives. *IEEE Trans. on Power Electron.* **40**, 3419–3429, DOI: [10.1109/TPEL.2024.3490179](https://doi.org/10.1109/TPEL.2024.3490179) (2025).
19. Morya, A. K., Yepes, A. G., Doval-Gandoy, J. & Toliyat, H. A. Evaluation of current distortion improvement in an asymmetrical six-phase induction motor drive by using sic mosfets with reduced dead time. In *2020 IEEE Energy Conv. Congress and Exposition (ECCE)*, 723–727 (2020).
20. Imura, A., Takahashi, T., Fujitsuna, M., Zanma, T. & Doki, S. Dead-time compensation in model predictive instantaneous-current control. In *IECON 2012 - 38th Annual Conference on IEEE Ind. Electron. Society*, 5037–5042 (2012).
21. Jeong, S.-G. & Park, M.-H. The analysis and compensation of dead-time effects in pwm inverters. *IEEE Trans. on Ind. Electron.* **38**, 108–114 (1991).
22. Sakauchi, R., Doki, S., Imai, K., Kondo, K. & Aoki, Y. Capacitor current reduction in dual three-phase pmsm drive system by model predictive control considering dead time. In *2023 25th European Conference on Power Electron. and App. (EPE'23 ECCE Europe)*, 1–8 (2023).
23. Wang, H., Zheng, X., Yuan, X. & Wu, X. Low-complexity model-predictive control for a nine-phase open-end winding pmsm with dead-time compensation. *IEEE Trans. on Power Electron.* **37**, 8895–8908 (2022).

24. Zhang, Z. & Wang, H. Comparison of dead-time compensation based on model predictive current control schemes for nine-phase open-end winding motors. In *2024 IEEE 7th International Electrical and Energy Conference (CIEEC)*, 4462–4469 (2024).
25. Zhao, Y. & Lipo, T. Space vector pwm control of dual three phase induction machine using vector space decomposition. In *Proceedings of 1994 IEEE Industry Applications Society Annual Meeting*, vol. 1, 742–749 vol.1 (1994).
26. Carrillo-Rios, J., Gonzalez-Prieto, I., Gonzalez-Prieto, A., Duran, M. J. & Aciego, J. J. Long-prediction horizon fcs-mpc for multiphase electric drives with a selective control action promotion. *IEEE Trans. on Ind. Electron.* **71**, 9982–9993 (2024).
27. Serra, J., Jlassi, I. & Cardoso, A. J. M. A computationally efficient model predictive control of six-phase induction machines based on deadbeat control. *Machines* **9** (2021).
28. Yan, L., Zhang, X., Yang, J., Yang, G. & Deng, R. Synthetic vectors-based predictive control of dual three-phase pmsms for current harmonics mitigation considering average deception effect. *IEEE J. Emerg. Sel. Top. Power Electron.* **12**, 3103–3114, DOI: [10.1109/JESTPE.2024.3385022](https://doi.org/10.1109/JESTPE.2024.3385022) (2024).
29. Saeed, M. S. R., Song, W., Huang, L. & Yu, B. Double-vector-based finite control set model predictive control for five-phase pmsms with high tracking accuracy and dc-link voltage utilization. *IEEE Trans. on Power Electron.* **37**, 15234–15244, DOI: [10.1109/TPEL.2022.3188578](https://doi.org/10.1109/TPEL.2022.3188578) (2022).
30. Chen, W., Li, B., Xu, D. & Cai, L. A dead-time compensation method for voltage source inverters. In *2019 22nd International Conference on Electrical Machines and Systems (ICEMS)*, 1–6, DOI: [10.1109/ICEMS.2019.8921871](https://doi.org/10.1109/ICEMS.2019.8921871) (2019).
31. Li, Y., Zhang, Z., Li, K., Zhang, P. & Gao, F. Predictive current control for voltage source inverters considering dead-time effect. *CES Trans. on Electr. Mach. Syst.* **4**, 35–42, DOI: [10.30941/CESTEMS.2020.00006](https://doi.org/10.30941/CESTEMS.2020.00006) (2020).
32. Duran, M. J., Gonzalez-Prieto, I., Gonzalez-Prieto, A. & Aciego, J. J. The evolution of model predictive control in multiphase electric drives: A growing field of research. *IEEE Ind. Electron. Mag.* **16**, 29–39 (2022).
33. Karamanakos, P., Liegmann, E., Geyer, T. & Kennel, R. Model predictive control of power electronic systems: Methods, results, and challenges. *IEEE Open J. Ind. App.* **1**, 95–114 (2020).
34. Hua, W. *et al.* Multivector-based model predictive control with geometric solution of a five-phase flux-switching permanent magnet motor. *IEEE Trans. on Ind. Electron.* **67**, 10035–10045 (2020).
35. Gonçalves, P. F. C., Cruz, S. M. A. & Mendes, A. M. S. Multistage predictive current control based on virtual vectors for the reduction of current harmonics in six-phase pmsms. *IEEE Trans. on Energy Convers.* **36**, 1368–1377, DOI: [10.1109/TEC.2021.3055340](https://doi.org/10.1109/TEC.2021.3055340) (2021).
36. González-Prieto, A., González-Prieto, I., Duran, M. J., Aciego, J. J. & Salas-Biedma, P. Current harmonic mitigation using a multi-vector solution for mpc in six-phase electric drives. *IEEE Access* **9**, 117761–117771, DOI: [10.1109/ACCESS.2021.3104999](https://doi.org/10.1109/ACCESS.2021.3104999) (2021).
37. Zoric, I., Jones, M. & Levi, E. Arbitrary power sharing among three-phase winding sets of multiphase machines. *IEEE Transactions on Ind. Electron.* **65**, 1128–1139, DOI: [10.1109/TIE.2017.2733468](https://doi.org/10.1109/TIE.2017.2733468) (2018).

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Author contributions statement

M.C.-R. and I.G.-P. conceived the study. M.C.-R. and R.L.-L. designed and implemented the experiments. M.C.-R., R.L.-L., J.C.-R., I.G.-P., M.J.D., J.J.A., P.M.-M. and A.G.-P. contributed to the analysis and interpretation of the results. M.C.-R., R.L.-L., J.C.-R., I.G.-P., M.J.D., J.J.A., P.M.-M. and A.G.-P. wrote and reviewed the manuscript. I.G.-P. and M.J.D. supervised the work and secured the funding that supported this research.

Additional information

Competing interests The corresponding author, I.G.-P., declares on behalf of all authors that there are no competing interests.