Evolution of Model Predictive Control in Multiphase Electric Drives

1. Introduction

Multiphase electric machines (i.e., those with more than three phases) have been completely remained in the shadow of their three-phase counterparts for a long time. The choice to build three-phase power systems made multiphase machines unable for a direct connection to the network, and the development of high-performance multiphase electric drives was still not feasible in those early days. It was not until 1969 when the first proposal of a multiphase drive was recorded [1], but little attention was paid to this field in the subsequent three decades. Although some basic foundations of multiphase electric drives were established in the 90s [2], the number of studies during the 20th century were very scarce [3].

On another side, model predictive control (MPC) also journeyed through the wilderness to be applied in the field of electric drives. MPC was already popular in the chemical industry during the 1980s, but the application to drives was hindered by the lack of appropriate technology for the real-time implementation of predictive algorithms [4]. The high computational cost of MPC was unreachable for power electronics with high switching frequency requirements [5].

Curiously enough, the hibernation of the multiphase technology and the impossibility to apply MPC in electrical systems came simultaneously to an end by the beginning of the 21st century. With the development of power electronics and the advent of much more powerful digital signal processors (DSPs), multiphase electric drives flourished [3] and MPC became feasible for three-phase systems [5]. Since then, the growth of both fields has been exponential [3]. With multiphase machines and predictive strategies in full development, those parallel paths were destined to converge, and it was in 2009 when the first attempt to insert a predictive current controller into a multiphase system was performed [6]. This milestone gave a proof of concept and opened a new field of research that rapidly arose the interest of researchers. Nevertheless, the newborn area was still far from achieving the attractive standards of MPC in three-phase drives.

Quite unfortunately, standard finite-control set MPC (FCS-MPC) was unable to provide sufficient accuracy in these highly complex multi-dimensional systems. Predictive current controllers provided a rather poor steady-state power quality, and for this reason FCS-MPC was perceived as the Cinderella of multiphase regulation strategies from the current quality point of view. Classical linear control methods from the 1970s, such as the field-oriented control (FOC) with proportional-integer (PI) current controllers, were still highly superior in terms of current distortion and torque ripple [5,7].

Many different efforts were devoted from 2009 onwards to enhance the current quality of predictive techniques, to compete with FOC at the same level [7-9]. In this context, a key finding was brought in 2011 with the concept of virtual/synthetic voltage vectors (VVs). Initially suggested for direct torque control (DTC) [10, 11], VVs were subsequently used for MPC to enhance the regulation of the new degrees of freedom in multiphase systems [9, 12-20]. Although MPC kept on skipping the use of an independent pulse width modulation (PWM) stage, VVs allowed the use of several switching states per sampling period from the voltage source converter (VSC), which can be regarded as an implicit modulation included within the control. The concept of VVs simply seemed to be the glass slipper that perfectly fit into MPC's foot [9, 12-20].

The creation of VV-based MPC strategies was then continuously improved to finally reach the level of linear PI regulators in FOC using a carrier-based PWM stage. The empowerment of MPC led to a current tracking capability in the range of FOC and allowed retaining, at the same time, some of the inherent advantages of the predictive approach: fast dynamic response, control flexibility and simple utilization of the dc-bus voltage, to name a few. Even though the area of multiphase electric drives with predictive current controllers is rather young, the tour from 2009 to 2021 is a story of success [4-9, 12-55] (Fig. 1). This manuscript walks briefly along this teenager field of research and provides experimental evidence of its capability to compete and even outperform linear current controllers.

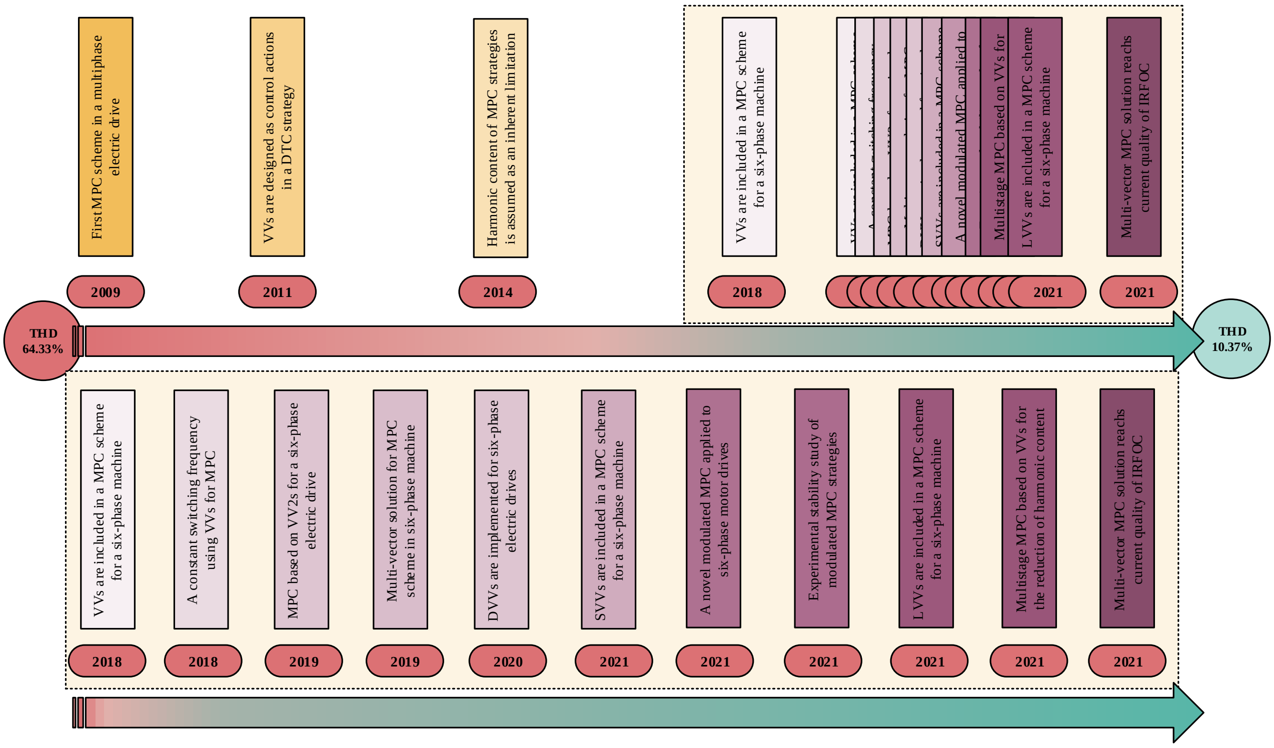


Fig. 1: Evolution of FCS-MPC in multiphase electric drives.

2. Multiphase electric drives in a nutshell

Multiphase electric drives show several advantages over three-phase systems, providing hardware-free fault tolerance, better efficiency, higher flexibility, and some exclusive modes of operation thanks to the extra phases [2-3]. Some of these beneficial features have convinced industry to develop some emblematic products [3], but the higher number of phases also implies a higher complexity for the control strategies.

The principle of operation of multiphase electric machines is essentially the same as in three-phase ones: the creation of a rotating (Tesla's) field. A first main difference is however that multiphase machines create the rotating field with the contribution of more phases. The additional degrees of freedom, other than α-β components, are typically referred in literature as x-y components.

A couple of questions might arise now: *i)* What are these mysterious x-y currents? In distributed-winding machines with sinusoidal magneto-motive force (MMF) they are just circulating currents that flow through the stator of the machine, but do not link the rotor side because they cancel out in the airgap, and *ii)* Are x-y currents beneficial or harmful? Although they can be used for some innovative modes of operation [3], in general they are simply a source of stator copper losses and consequently they should be minimized for the sake of efficiency, especially when the x-y impedance is low [13, 56].

It is fair noting here that the role of x-y currents is very different in the presence of spatial harmonics. When the distribution of the MMF in the airgap is not sinusoidal, these currents become flux/torque-producing components and, consequently, they can be deliberately injected to enhance the torque [2]. Nevertheless, this scenario has been scarcely studied in combination with MPC [28-31], hence this paper will assume hereafter that the spatial harmonics of the electric machine are negligible.

A second distinctive difference of multiphase systems is the amount of switching possibilities, which is equal to m^n in m-level VSCs. This extended availability implies a higher number of sectors, sizes and subspaces. For the sake of example, six-phase VSCs allow 64 switching states that provide voltage vectors with five different sizes (null, small, medium, medium-large and large), mapped onto two orthogonal planes, as it is depicted in Fig. 2. As the number of phases (n) and levels (m) is augmented the number of voltages vectors dramatically increases, e.g., 243 with $m = 3$ and $n = 5$ [51].

Is it beneficial or harmful to have all these new possibilities? In spite of the higher complexity to select the optimal switching states and duties, the extended availability can be regarded as advantageous for two main reasons: *i)* phase voltages can take more discrete values, and this helps improving the current quality and *ii)* there is further room for improvement by considering VSC states that reduce the switching frequency. However, the higher amount of control actions also implies a computational burden for FCS-MPC, hence the optimal design of predictive strategies is consequently a major challenge.

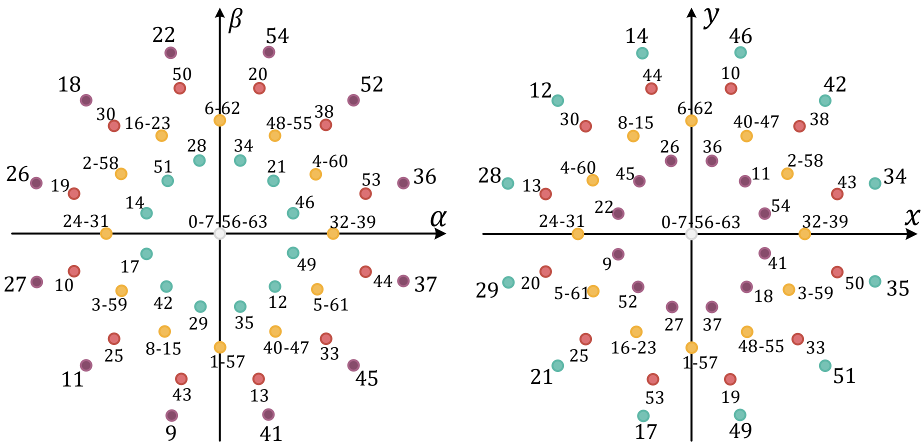


Fig. 2. Voltage vectors from a six-phase VSC: α-β plane (left) and x-y plane (right).

3. Model predictive control in a nutshell

Although predictive control refers to a wide family of control techniques, FCS-MPC is the branch with a higher popularity in the field of multiphase systems thanks to its ease of implementation, flexibility in the definition of control objectives and fast dynamic response [4-5]. It has been applied to various number of phases (e.g., five [17, 40, 43, 44], six [15, 19, 38, 48], nine [47] and eighteen [54]), winding arrangements (e.g., symmetrical, asymmetrical and dual [52, 53]), converter levels (e.g., two [20, 46] and three [50, 51]) and types of machines (e.g., induction [23, 25, 26, 39], permanent magnet [33, 45, 49, 55]).

In essence, FCS-MPC is based on the prediction of the future states of the drive and the selection of the control action that better approaches the desired future state. Although MPC can be directly applied to torque control [8,18,23,37,39,40,51,54], the most popular option in the field of multiphase drives is to restrict MPC to the inner current control loops [6-9,12-17,19,20,22-26,24-26,29-36,41-49,52,55,57], as in FOC-type control schemes. In such case the states are typically the VSD currents ($i_{\alpha\beta xy}$), as shown in Fig. 3. The control actions are, in turn, the switching states of the VSC.

The prediction ($\hat{\imath}_{\alpha\beta xy}$) is typically performed using a discretized multiphase machine model with standard assumptions [6], although advanced observers and auto-regressive estimators can be used to enhance the accuracy and robustness [46, 48, 51] and reduce the parameter dependence [32,46]. The latter issue is relevant since MPC is known to be sensitive to parameter mismatch [57] caused by different operating conditions (e.g., due to saturation or thermal effects) [58]. The control actions are then designed to follow a reference trajectory ($i^*_{\alpha\beta xy}$) by minimizing a certain cost function J:

$$J = (i_\alpha^* - \hat{\imath}_\alpha)^2 + \left(i_\beta^* - \hat{\imath}_\beta\right)^2 + K_{xy} \cdot \left[(i_x^* - \hat{\imath}_x)^2 + \left(i_y^* - \hat{\imath}_y\right)^2\right] \tag{1}$$

where the weighting factor K_{xy} promotes the tracking of the x-y currents at the expense of the α-β currents. The control action is then typically selected to track the α-β currents (flux/torque production) and the x-y currents (typically driven to zero in distributed-winding machines), although some works also focus on the common mode voltage minimization [32, 33, 51].

Two new challenges are found in the implementation of MPC for multiphase drives:

i) The implementation of the control algorithm in real-time.
ii) The regulation of x-y currents to preserve efficiency and current quality.

While issue *i)* is just a matter of computational resources and software optimization, issue *ii)* becomes critical, as it is explained next.

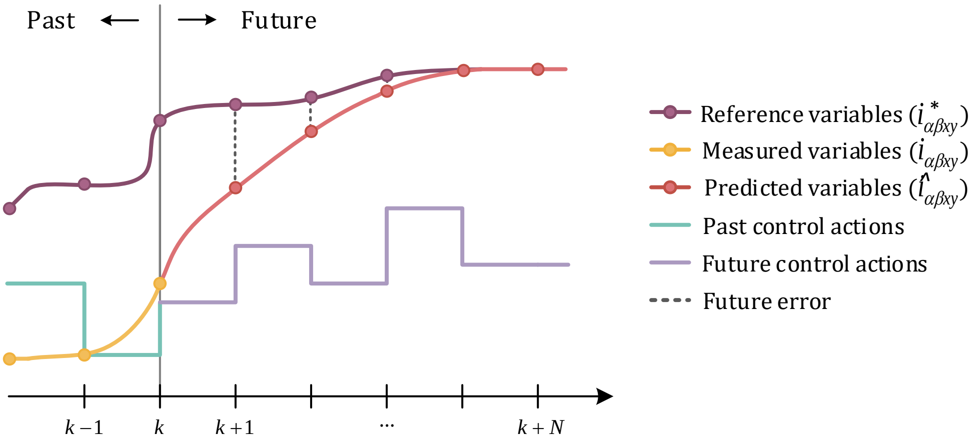


Fig. 3. Simplified scheme of the MPC principle of operation.

4. The elephant in the room

After the first predictive controller was applied to a six-phase drive, many different approaches were suggested to improve MPC. Selecting the switching states of the VSC to minimize the switching frequency [21], enhancing the machine model [8, 23], estimating non-measurable variables [24], using a variable sampling period [25], reconfiguring the control scheme for fault-tolerant operation [26, 55] or including different restrictions in the cost function [21, 27] are just some examples of these efforts. Even though each proposal had its own interest, none of these attempts could narrow the gap from MPC to FOC in terms of current quality.

In the light of this low performance, researchers started to feel that there was an elephant in the room that nobody was looking at. The non-addressed issue was the incapability of MPC to properly regulate x-y currents if only one switching state per sampling period is applied. Regardless of how precise the model is, the control action cannot generate flux/torque with null x-y currents for the simple reason that one switching state simultaneously maps onto α-β and x-y planes.

After the elephant in the room was pointed at, it became clear that a single control action could not satisfy the requirements of such a multidimensional system. At this moment, it was time to move on and include some further accuracy in the control actions.

5. The glass slipper

While MPC could not achieve the FOC performance in terms of current quality, the situation with DTC was even more worrisome. DTC completely disregarded the x-y components because the look-up tables were only designed to track flux and torque, and the result was dramatic when the impedance on the x-y plane was low, leading to an unacceptable current distortion [12]. For this reason, it is not strange that the first solution for this issue was suggested in the context of a DTC technique [10].

The performance was improved by changing the control action: instead of applying a single switching state per sampling period, a combination of two switching states was suggested and implemented in a DTC-based five-phase drive [10]. The key idea was to use switching states and dwell times in such manner that the x-y voltages could be null on average during a sampling period. Ideally, these zero x-y voltages should lead to zero x-y currents if asymmetries are neglected. Consequently, DTC could concentrate on the flux and torque tracking. The result of combining switching states with this purpose was termed virtual or synthetic voltage vectors. The same concept was then exported to MPC, either for predictive current or torque control [12, 51], including these newborn VVs as control actions.

Fig. 4 shows the creation of VVs for a six-phase drive, where switching states 36 and 53 are applied during 73% and 27% of the sampling period [12]. With the inclusion of VVs in six-phase drives, iterations were reduced from 64 to 13. Furthermore, the model and cost function could fully omit the x-y terms, therefore the scheme was also simpler than standard MPC. It can be said that the VV concept was the glass slipper to start competing with FOC in terms of current quality.

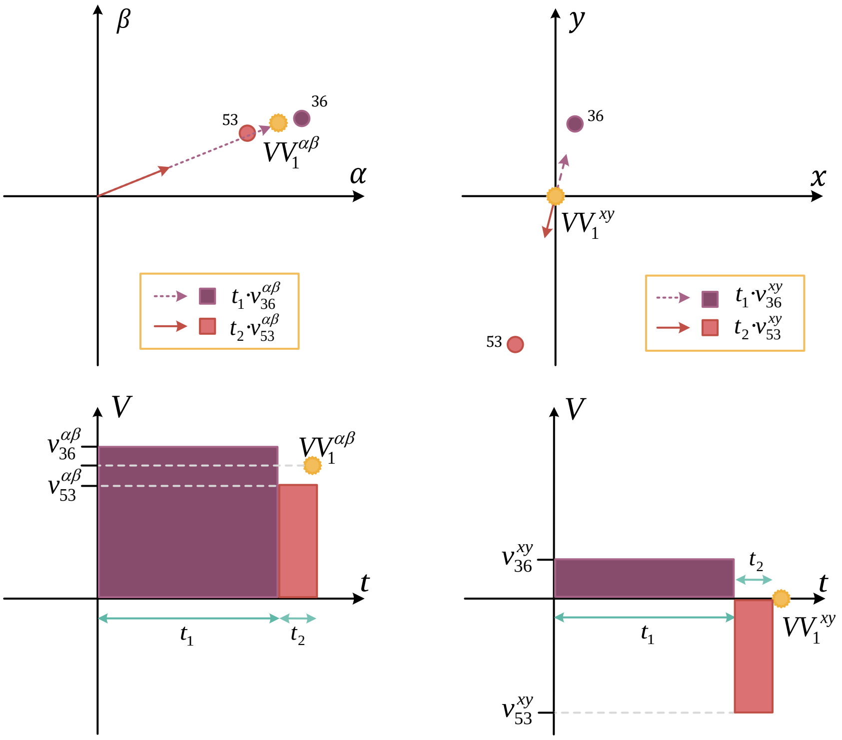


Fig. 4. Creation of VVs in a six-phase drive: vector combination in the α-β and x-y planes (upper plots) and time scheme and average value (yellow circle) for α-β and x-y voltage components (lower plots).

6. The average deception

Since the semiconductors of power converters only operate in cutoff and saturation states, the electric machine is supplied with switched voltages. However, the predictive models in MPC only consider the averaged values over a sampling period. It follows that the estimations are identical when the average voltages remain constant, regardless of the voltage waveform. Unfortunately, this simplification can be deceiving in some specific cases.

Let us take an example from our daily life. It is well-known that it is not the same to run seven kilometers six days a week than to run a full-marathon on Saturday morning. Even though the average amount of kilometers is the same, we will likely suffer a muscular soreness on Sunday morning if the exercise was not well distributed along the time. Resorting back to the case of a multiphase drive, it is not the same if the x-y voltage average is null because the voltages are constantly zero or because high instantaneous voltages cancel out. In the latter case, even with zero-average voltages, some switching harmonics will appear.

Taking the VV from Fig. 4 as an example, voltage vector 53 is mapped onto the secondary subspace as a medium-large voltage vector, this being less favorable than using large voltage vectors with a small contribution in the x-y subspace [13]. The best choice depends on each specific setting, but it is worth having in mind that it is not only the average value what determines the optimum performance in the current regulation of the x-y plane.

7. The boules game

The main aim of the control is to track the reference currents $i_{\alpha\beta}^{*}$, which in turn implies approaching the reference voltage $v_{\alpha\beta}^{*}$. Taking a sport simile, the selection of the α-β voltages resembles the popular boules game. In this comparison, the *jack* would be the desired voltage $v_{\alpha\beta}^{*}$ (small yellow balls in Fig. 5) and the balls would be the available voltages (i.e., the control actions). The aim of the game is then to approach the jack ($v_{\alpha\beta}^{*}$) to get the currents $i_{\alpha\beta}^{*}$ that will generate the proper flux/torque. The player (MPC) will evaluate the best position of the ball (cost function) and will then throw the ball (control action) to one of the allowed positions.

In the case of VV-MPC for a six-phase system [12-13], the VSC can only deliver 13 discrete voltage outputs (i.e., VV_i with $i\epsilon[1,13]$). Therefore, it is like playing boules with the restriction that you can only place the ball in certain specific points (valleys in Fig. 5a). Despite the interest of VVs, as far as the α-β plane is concerned the control action is still quite coarse [12]. The discrete nature of VV-MPC highly compromises the capability of the player to win the game. Conversely, the voltage output in FOC strategies with explicit PWM stages is a continuous control action [7], and this implies that you can locate the ball wherever you want (Fig. 5b).

In the light of these limitations, it was the time to improve the precision of MPC in the α-β plane. Some works suggested the combination of VVs with a zero vector [14, 44], whereas other proposals used two virtual vectors [16] and VVs formed by more than two switching states [18]. The control actions in those multi-vector MPC strategies were still discrete, but the ball could then be placed in many more different places (Fig. 5c). This higher degree of refinement in the voltage output possibilities allowed a better approach to the jack.

A next move to improve the precision of MPC in this boules game was to make VVs more dynamic [15], hence the duties started to be variable and online calculated. While the dynamic approach allowed a better adaptation to the operating point, the estimation of the duty cycle was simplified and improved using VVs formed by sets of adjacent large voltage vectors with a null voltage vector [9, 32, 33].

The price to be paid in all different multi-vector MPC strategies (Fig. 5c) is the reduction of the dc-bus utilization (although some works have improved this aspect [33]) and the increase of the effective switching frequency. Nevertheless, the new family of MPC strategies achieved, for the first time, the current quality of conventional vector control strategies, as it is shown next.

8. The maturity of MPC

Retaining a discrete nature and inherent advantages, FCS-MPC has shown a significant progress in the last decade. Apart from the improvement in the predictive model [8, 23], the modifications in the cost function [21, 27], and the reduction of the computational efforts [45, 49], the most relevant improvements have gone hand in hand with the refinement of the control actions [9, 32, 33]. The evolution can be summarized in the following stages:

1) Application of one switching state during the whole sampling period (e.g., standard MPC [6]).
2) Application of two switching states with fixed times of applications (e.g., VV-MPC [12], using one large and one medium large vector).
3) Use of a multi-vector approach with variable times of application (e.g., MV5-MPC, using four adjacent large vectors plus a null vector). This control strategy has been designed extending the regulation technique presented in [9].

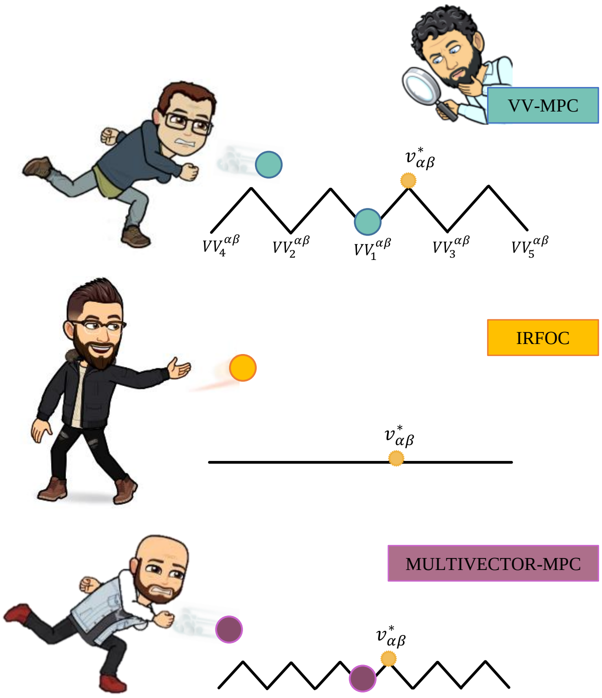
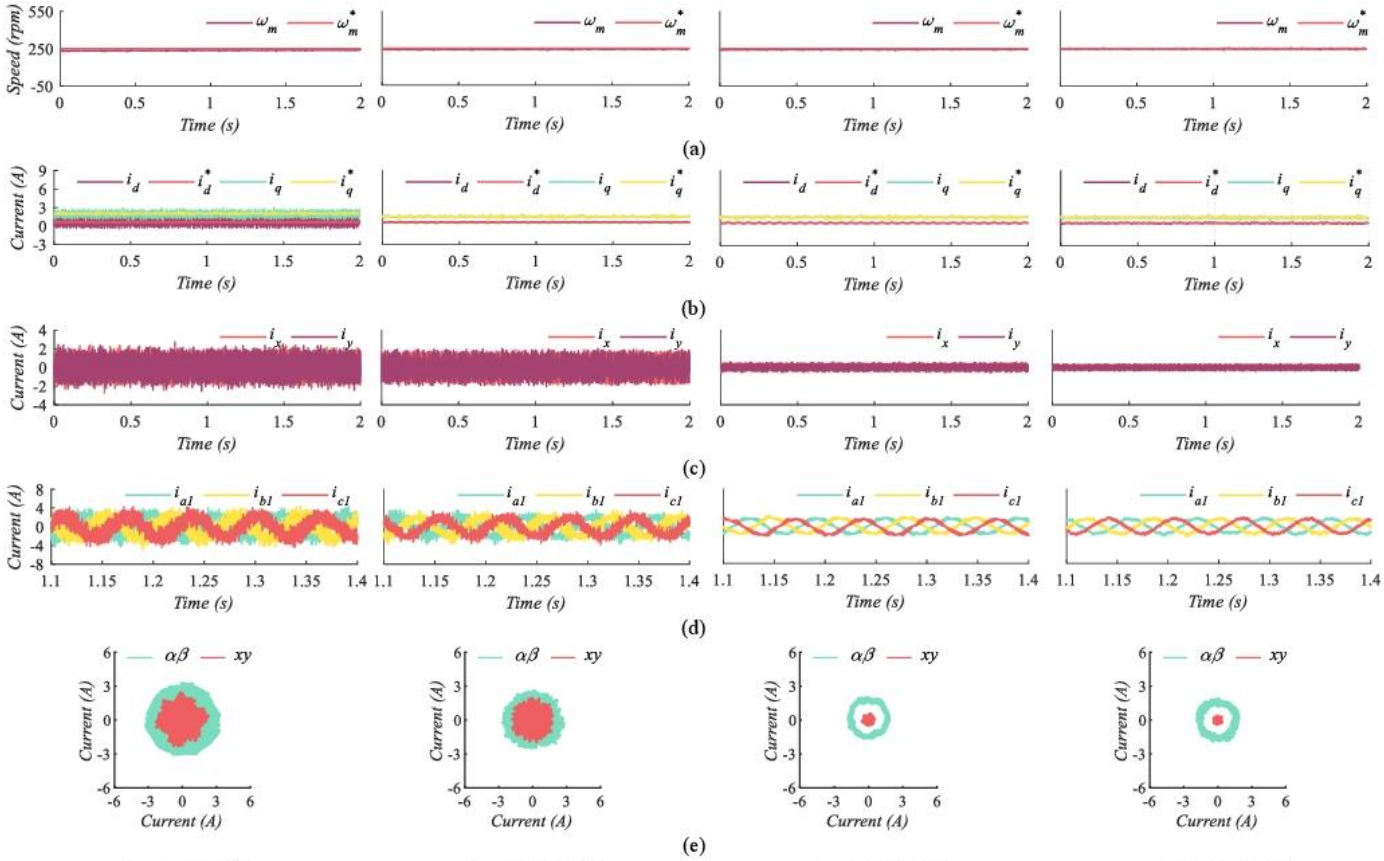


Fig. 5. Simile of the boules game with the voltage vector selection in the α-β plane.

The maturity of FCS-MPC is exemplified and highlighted in this section providing experimental results that compare its performance from the current quality point of view. In addition, a conventional IRFOC scheme using a CB-PWM stage (likely the most implemented control approach in industrial applications) is employed as a comparative basis for the discussion. From left to right, Figs. 6 and 7 show the performance of MPC, VV-MPC, FOC with carrier-based PWM and MV5-MPC in low-speed and high-speed scenarios, respectively. Although the speed tracking is similar in all methods, the current tracking is significantly different.

In the low-speed scenario, currents in the main plane (Fig. 6b) show a high current ripple in standard MPC due to the use of a single control action. Fortunately, this limitation is overcome when the number of applied switching states increases, as shown in VV-MPC and MV5-MPC results. In fact, the α-β current quality in MV5-MPC is in the same range of IRFOC with CB-PWM (see Fig. 6e). Concerning x-y current mitigation, the better performance is obtained in MV5-MPC (Fig. 6c), slightly outperforming the current tracking with FOC. The main reason for this improvement is the exclusive use of switching states with a low contribution in the x-y plane. In addition, the use of the null voltage vector diminishes the x-y injection providing an overall reduction of the harmonic content.



$f_{sw} = 2.4\ kHz$
$RMS_{ph} = 1.75\ A$
$i_{xy,pp} = 5.18\ A$
$\sigma_x = 0.68\ A$
$THD_{ph} = 64.33\ \%$

$f_{sw} = 1.86\ kHz$
$RMS_{ph} = 1.50\ A$
$i_{xy,pp} = 3.93\ A$
$\sigma_x = 0.56\ A$
$THD_{ph} = 41.64\ \%$

$f_{sw} = 2.50\ kHz$
$RMS_{ph} = 1.16\ A$
$i_{xy,pp} = 1.12\ A$
$\sigma_x = 0.11\ A$
$THD_{ph} = 10.95\ \%$

$f_{sw} = 2.70\ kHz$
$RMS_{ph} = 1.14\ A$
$i_{xy,pp} = 0.81\ A$
$\sigma_x = 0.08\ A$
$THD_{ph} = 10.37\ \%$

(f)

Figure 6. Steady-state performance at 250 rpm. From left to right: FCS-MPC, VV-MPC, IRFOC with CB-PWM and MV5-MPC. From top to bottom: (a)motor speed, (b)d-q currents, (c)x-y currents, (d)set 1 of phase currents, (e)α-β and x-y currents, (f)switching frequency and quality indices.

In the high-speed scenario, the application of switching states with a low production in the x-y subspace is especially necessary (Fig. 7e and 7f). For this reason, MV5-MPC achieves considerable better current quality indices than IRFOC using CB-PWM (see Fig. 7f). As shown in Fig. 7d, phase currents show a lower harmonic content in the case of MV5-MPC, confirming the maturity of MPC. In addition, the use of VV approaches has allowed the reduction of the computational time of the FCS-MPC, mitigating in this manner one of the main MPC limitations (Table I).

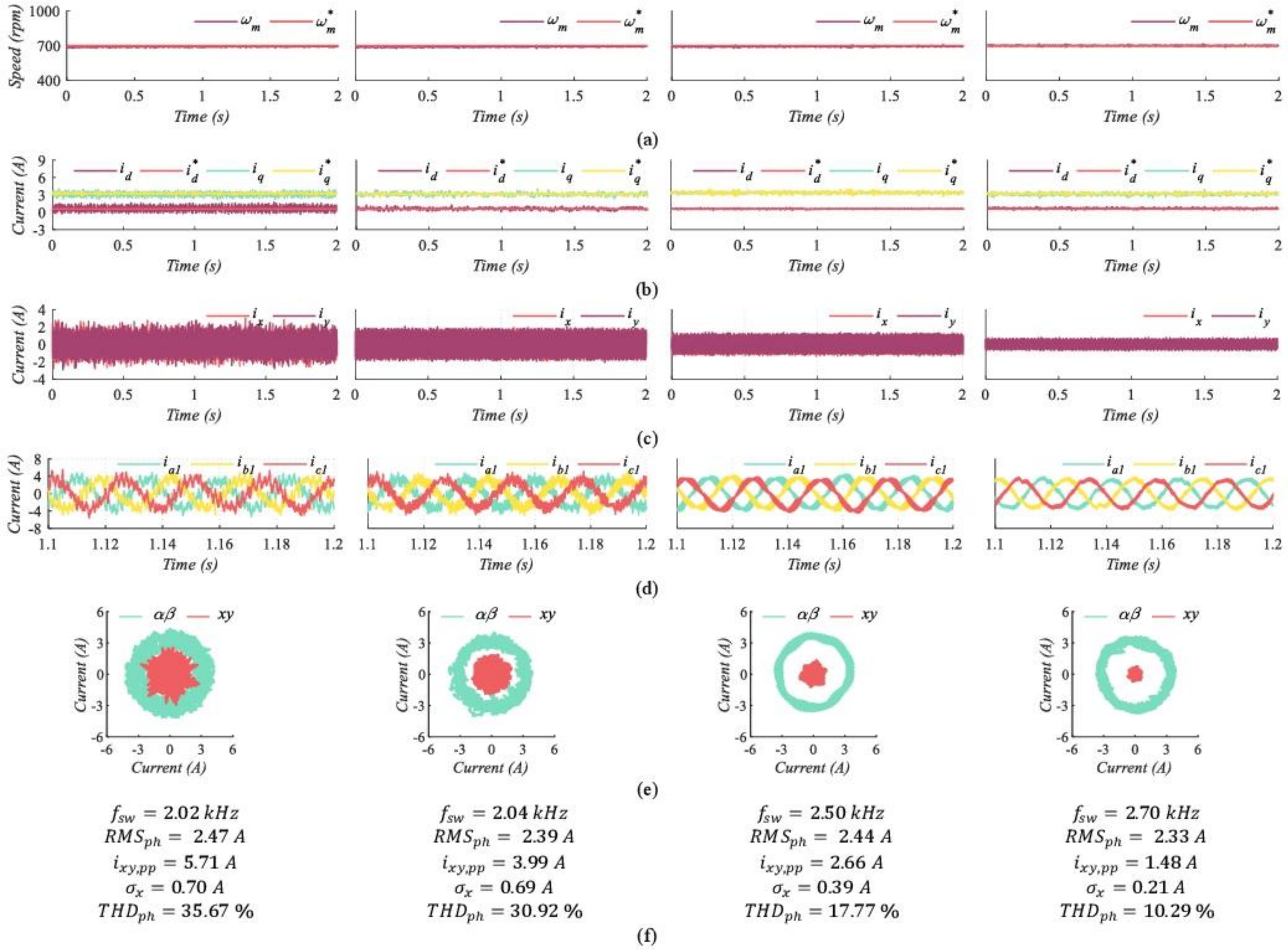


Figure 7. Steady-state performance at 700 rpm. From left to right: FCS-MPC, VV-MPC, IRFOC with CB-PWM and MV5-MPC. From top to bottom: (a)motor speed, (b)d-q currents, (c)x-y currents, (d)set 1 of phase currents, (e)α-β and x-y currents and (f)switching frequency and quality indices.

Table I. Computational time.

Control method	Computational Time (μs)
FCS-MPC	67.2
VV-MPC	19.6
IRFOC	17.0
MV5-MPC	21.0

9. Conclusions

In a field where linear controllers have been the preferred choice for the regulation of multiphase electric drives, a new player is now sitting at the same table. In fact, the use of multi-vector control actions has been the ace up the sleeve of FCS-MPC strategies to significantly improve their current tracking capability. The evolution of those multi-vector predictive strategies during the last decade has come to a tipping point where the current quality of FOC with conventional CB-PWM has been reached and even surpassed. In this manner, the control designer can benefit from the inherent advantages of MPC schemes and simultaneously obtain an excellent current tracking with low distortion.

References

[1] G.K. Singh, “Multi-phase induction machine drive research-a survey,” *Electr. Power Syst. Res.*, 61(2) 139-147, 2002.

[2] E. Levi *et al.*, “Multiphase induction motor drives - a technology status review,” *IET EPA*, 1(4), 489-516, 2007.

[3] M.J. Duran *et al.*, “Multiphase electric drives: Introduction,” *in Proc. Wiley Encyclopedia Electr. Electron. Engineer.*, 1–26, 2017.

[4] S. Kouro *et al*, “Model predictive control: MPC's role in the evolution of power electronics,” *IEEE Ind. Electron. Mag.*, 9(4), 8-21, 2015.

[5] H.A. Young *et al.*, “Assessing finite-control-set model predictive control: A comparison with a linear current controller in two-level voltage source inverters,” *IEEE Ind. Electron. Mag.*, 8(1), 44-52, 2014.

[6] F. Barrero *et al.*, “A proof of concept study of predictive current control for VSI-driven asymmetrical dual three-phase AC machines,” *IEEE TIE*, 56(6), 1937-1954, 2009.

[7] C. Lim *et al.*, “A comparative study of synchronous current control schemes based on FCS-MPC and PI-PWM for a two-motor three-phase drive,” *IEEE TIE*, 61(8), 3867-3878, 2014.

[8] H. Miranda *et al.*, “Predictive torque control of induction machines based on state-space models,” *IEEE TIE*, 56(6), 1916-1924, 2009.

[9] A. González-Prieto *et al.*, “Current harmonic mitigation using a multi-vector solution for MPC in six-phase electric drives,” *IEEE Access*, 9, 117761-117771, 2021, doi: 10.1109/ACCESS.2021. 3104999.

[10] L. Zheng *et al.*, “A novel direct torque control scheme for a sensorless five-phase induction motor drive,” *IEEE TIE*, 58(2), 503-513, 2011.

[11] J.K. Pandit *et al.*, “Simplified implementation of synthetic vectors for DTC of asymmetric six-phase induction motor drives,” *IEEE TIA*, 54(3), 2306-2318, 2018.

[12] I. González-Prieto *et al.*, “Model predictive control of six-phase induction motor drives using virtual voltage vectors,” *IEEE TIE*, 65(1), 27–37, 2018.

[13] M.J. Duran *et al.*, “Large virtual voltage vectors for direct controllers in six-phase electric drives,” *Int.J. Electr.Power Energy Syst.*, 125, 2021.

[14] A. Gonzalez-Prieto *et al.*, “Smart voltage vectors for model predictive control of six-phase electric drives,” *IEEE TIE*, 68(10), 9024-9035, 2021.

[15] J.J. Aciego *et al.*, “Model predictive control based on dynamic voltage vectors for six-phase induction machines,” *IEEE JESTPE*, 9(3), 2710-2722, 2021.

[16] J.J. Aciego *et al.*, “Model predictive control of six-phase induction motor drives using two virtual voltage vectors,” *IEEE JESTPE*, 7(1), 321-330, 2019.

[17] C. Xue *et al.*, “A constant switching frequency finite-control-set predictive current control scheme of a five-phase inverter with duty-ratio optimization,” *IEEE TPE*, 33(4), 3583–3594, 2018.

[18] Y. Luo *et al.*, “Multi-vectors based model predictive torque control for a six-phase PMSM motor with fixed switching frequency,” *IEEE TEC*, 34(3), 1369-1379, 2019.

[19] M. Ayala *et al.*, “A novel modulated model predictive control applied to six-phase induction motor drives,” *IEEE TIE*, 68(5), 3672-3682, 2021.

[20] P. Gonçalves *et al.*, “Multistage predictive current control based on virtual vectors for the reduction of current harmonics in six-phase PMSMs,” *IEEE TEC*, 36(2), 1368-1377, 2021.

[21] I. González-Prieto et al, “Constrained model predictive control in nine-phase induction motor drives,” *IEEE TEC*, 34,(4), 1881-1889, 2019.

[22] R. Vargas *et al.*, “Predictive control of a three-phase neutral-point-clamped inverter,” *IEEE TIE*, 54(5), 2697-2705, 2007.

[23] C. A. Rojas *et al.*, “Comments on “Predictive torque control of induction machines based on state-space models,” *IEEE TIE*, 61(3), 1635-1638, 2014.

[24] J. Rodas *et al.*, “Influence of covariance-based ALS methods in the performance of predictive controllers with rotor current estimation,” *IEEE TIE*, 64(4), 2602-2607, 2017.

[25] M. R. Arahal *et al.*, “Assessing variable sampling time controllers for five-phase induction motor drives,” *IEEE TIE*, 67(4), 2523-2531, 2020.

[26] H. Guzman *et al.*, “Comparative study of predictive and resonant controllers in fault-tolerant five-phase induction motor drives,” *IEEE TIE*, 63(1), 606-617, 2016.

[27] D. Zhou *et al.*, “Multiple-vector model-predictive power control of three-phase four-switch rectifiers with capacitor voltage balancing,” *IEEE TPE*, 33(7), 5824-5835, 2018.

[28] A. Alireza *et al.*, “Predictive control of permanent magnet synchronous motor with non-sinusoidal flux distribution for torque ripple minimisation using the recursive least square identification method,” *IET Electric Power Applications*, 11(5), 847-856, 2017.

[29] C. Xiong *et al.*, “A constant switching frequency multiple-vector-based model predictive current control of five-phase PMSM with nonsinusoidal back EMF,” *IEEE TIE*, 67(3), 1695-1707, 2020.

[30] J. L. Romeral-Martinez *et al.*, “Predictive current control of outer-rotor five-phase BLDC generators applicable for off-shore wind power plants”, *Electric Power Systems Research*, 121, 260-269, 2015.

[31] M. Salehifar *et al.*, “Fault diagnosis and fault-tolerant finite control set-model predictive control of a multiphase voltage-source inverter supplying BLDC motor”, *ISA Transactions*, 60, 143-155, 2015.

[32] B. Yu *et al.*, “Improved finite control set model predictive current control for five-phase VSIs,” *IEEE TPE*, 36(6), 7038-7048, 2021.

[33] B. Yu *et al.*, “A finite control set model predictive control for five-phase PMSMs with improved DC-link utilization”, *IEEE TPE*, 37(3), 3297-3307, 2022.

[34] Y. Luo and C. Liu, “Pre- and post-fault tolerant operation of a six-phase PMSM motor using FCS-MPC without controller reconfiguration,” *IEEE Trans. Veh. Technol.*, 68(1), 254–263, 2019.

[35] T. Tao *et al.*, “Enhanced fault-tolerant model predictive current control for a five-phase PM motor with continued modulation,” *IEEE TPE*, 36(3), 3236–3246, 2021.

[36] S. Liu and C. Liu, “Virtual-vector-based robust predictive current control for dual three-phase PMSM,” *IEEE TIE* 68(3), 2048–2058, Mar. 2021.

[37] W. Huang *et al.*, “Model predictive torque control with SVM for five-phase PMSM under open-circuit fault condition,” *IEEE TPE*, 35(5), 5531–5540, 2020.

[38] W. Hua *et al.*, “Multi-vector-based model predictive control with geometric solution of a five-phase flux-switching permanent magnet motor,” *IEEE TIE*, 67(12), 10035–10045, 2020.

[39] A. Bhowate *et al.*, “Predictive torque control of five-phase induction motor drive using successive cost-functions for CMV elimination,” *IEEE TPE*, 36(12), 14133–14141, 2021.

[40] A. Bhowate *et al.*, “Predictive torque control algorithm for a five-phase induction motor drive for reduced torque ripple with switching frequency control,” *IEEE TPE*, 35(7), 7282–7294, 2020.

[41] W. Zhao *et al.*, “A novel finite-control-set model predictive current control for five-phase PM motor with continued modulation,” *IEEE TPE*, 35(7), 7261–7270, 2020.

[42] Y. Luo and C. Liu, “Model predictive control for a six-phase PMSM motor with a reduced-dimension cost function,” *IEEE TIE*, 67(2), 969–979, 2020.

[43] B. Yu *et al.*, “Virtual voltage vector-based model predictive current control for five-phase VSIs with common-mode voltage reduction,” *IEEE Trans. Transp. Electrific.*, 7(2), 706–717, 2021.

[44] W. Song *et al.*, “Finite-control-set model predictive current control for five-phase voltage-source inverter,” *IEEE Trans. Transp. Electrific.*, 7(2), 718-729, 2021.

[45] Y. Luo and C. Liu, “A flux constrained predictive control for a six-phase PMSM motor with lower complexity,” *IEEE TIE*, 66(7), 5081-5093, 2019.

[46] M. Bermudez *et al.*, “Model predictive control of six-phase electric drives including ARX disturbance estimator,” *IEEE TIE*, 68(1), 81-91, 2021.

[47] P. Garcia-Entrambasaguas *et al.*, “Direct torque and predictive control strategies in nine-phase electric drives using virtual voltage vectors,” *IEEE TPE*, 34(12), 12106-12119, 2019.

[48] P. Gonçalves *et al.*, “Disturbance observer based predictive current control of six-phase permanent magnet synchronous machines for the mitigation of steady-state errors and current harmonics,” *IEEE TIE*, vol. 69(1), 130-140, 2022.

[49] B. Yu *et al.*, “A computationally efficient finite control set model predictive control for multiphase PMSM drives,” *IEEE TIE*, doi: 10.1109/TIE.2021.3131858.

[50] M. Gu *et al.*, “Interleaved model predictive control for three-level neutral-point-clamped dual three-phase PMSM drives with low switching frequencies,” *IEEE TIE*, 36(10), 11618-11630, 2021.

[51] A. Bhowate *et al.*, “Speed sensor-less predictive torque control for five-phase induction motor drive using synthetic voltage vectors,” *IEEE JESTPE*, 9(3), 2698-2709, 2021.

[52] A. Gonzalez-Prieto *et al*., “On the advantages of symmetrical over asymmetrical multiphase AC drives with even phase number using direct controllers,” *IEEE TIE,* 69(8), 7639-7650, 2022.
[53] A. Shawier *et al.*, “Assessment of predictive current control of six-phase induction motor with different winding configurations,” *IEEE Access*, 9, 81125-81138, 2021.
[54] G. Wu *et al.*, “Robust predictive torque control of n*3-phase PMSM for high-power traction application,” *IEEE TPE*, 35(10), 10799-10809, 2020.
[55] D. Ye *et al.*, “Study on steady-state errors for asymmetrical six-phase permanent magnet synchronous machine fault-tolerant predictive current control,” *IEEE TPE*, 35(1), 640-651, 2020.
[56] A.S.Abdel-Khalik et al, “Effect of winding configuration on six-phase induction machine parameters and performance,” *IEEE Access*, 8, 223009-223020, 2020.
[57] C. Martin et al, “Sensitivity of predictive controllers to parameter variation in five-phase induction motor drives,” *Control Engineering Practice,* 68, 23-31, 2017.
[58] M.J. Duran et al, “Lumped-parameter thermal model for induction machines,” *IEEE TEC*, 19(4), 791-792, 2004.