Linear multi-vector model-based predictive control for grid side converters of renewable power plants under severe grid disturbances

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Abstract
Grid side converters of renewable power plants have to be capable of dealing with severe grid disturbances, such as, grid faults and voltage sags. Model-based predictive control provides outstanding performance to grid side converters: fast dynamic response, good tracking error and high-quality currents. However, choosing the best set of vectors for the modulation requires assessing all the possible combinations of vectors using a cost function, which is very time consuming. Thus, the modulation is normally carried out with only 1 or 2 vectors per PWM period to save computing time, but this turns the modulation non-linear. This lack of linearity makes it impossible to use symmetrical components in unbalanced grids. A linear multi-vector model-based predictive control that controls the power of both sequences using a sole cost function and analyses the effect of the transient response of several sequence decomposition systems on the model-based predictive control predictions and dynamic response is proposed. Moreover, the proposed multi-vector provides low THD currents while keeping the computing time low. In addition, the paper addresses the extrapolation of the proposed multi-vector model-based predictive control to N-level converters. The good performance obtained is supported by the results obtained in simulations and the laboratory.

1 INTRODUCTION

Coastal connection points of offshore wind farms are often relatively weak. Likewise, small onshore wind farms, photovoltaic farms or isolated wave power plants, Figure 1, are often located in remote areas and connected to weak grids. Since weak grids are more prone to unbalances, disturbances, short circuits due to the falling of trees etc. the grid side converter (GSC) control in power plants must be robust to grid disturbances.

Model-based predictive controls (MPCs) provide many advantages to GSCs [1–3] such as fast dynamic response, superb reference tracking and low ripple in the currents. Nevertheless, they are sensitive to variations in the parameters of the model on which they are based, such as the filter inductance, grid voltage etc. If the grid becomes unbalanced, the predictions of active and reactive power carried out by the MPC contain errors because the grid is different from that of the model on which it is based.

The state of the art regarding MPC for GSCs is continuously growing; however, the MPCs developed until now are not specifically designed to deal with unbalanced grids. A recently developed MPC for STATCOM addresses the connection of unbalanced loads [4] but no decomposition into sequences is performed, and just one vector per PWM period is used, which leads to a high THD. Conversely, the MPC proposed in ref. [5] uses 19 voltage vectors for the prediction. Low grid current THD and low switching losses are obtained, but it features high computation time that is partially solved using a sliding mode-based preselection step. However, the system cannot operate in unbalanced grids. In the approach presented in ref. [6], the proposed multi-objective cost function optimization considers tracking control of balanced grid currents,
filter capacitance voltage, converter-side current and switching frequency to allocate weights in its calculations. However, as the horizon length increases, the solution search enlarges exponentially which is time consuming. Two new implementations of MPC methods applied to ac-dc converters with an inductive-capacitive-inductive filter are presented in ref. [7]. Both MPCs are improved with an active damping algorithm that eliminates low-order grid current harmonics, which decreases sensitivity to grid voltage distortion, although no unbalanced grids are considered. The modified FCS-MPC with virtual vectors presented in ref. [8] improves the quality of the input current of the grid-connected rectifier. To reduce the computational burden, a pre-selective scheme combined with the two-step optimisation is proposed. However, no operation under unbalanced grids is reported. The MPC presented in ref. [9] exploits the convex and elliptical paraboloid properties of the cost error to adopt a systematic iterative algorithm within each control cycle to progressively synthesise finite sets of virtual voltage vectors for the control optimisation stage. Fast transient, easy tuning and maximum utilisation of the dc bus are achieved, but no operation under unbalanced grids is contemplated. This work presented in ref. [10] presents a control strategy with seamless transfer characteristics for GSCs using model predictive control MPC. The main objectives are a decoupled power control in balanced grid-connected mode, load voltage control in islanded mode and seamless transition between modes of operation. The main novelty is an auto-tuning strategy for weight factors in the cost function proposed to simplify the weight factor tuning strategy. In ref. [11], several state feedback approaches of MPC for GSCs with an LCL filter and balanced grids are presented. High dynamic performance, reduced switching losses and low harmonic current distortion are achieved.

As shown above, the literature about MPC for GSCs is extensive, but the connection to unbalanced grids has hardly been addressed. A straightforward solution to deal with unbalanced grids has traditionally been obtaining the symmetrical components of the grid voltage and current by applying the Fortescue's theorem and controlling the positive and negative sequences separately [12]. However, the superposition principle implies that all transfer functions of the GSC control system must be linear.

This paper presents a linear multi-vector MPC for N-level GSCs. It is based on carefully choosing each of the parts that make it up so that they meet the superposition principle. The positive and the negative sequences are controlled in a common cost function that provides two reference voltages that are combined linearly and sent to a common SVM stage. The proposed MPC provides to GSCs controlled with MPC, the needed ability to deal with grid disturbances. Moreover, during the disturbance, the low tracking error featured by traditional MPCs is kept for each sequence, whereas, the multi-vector strategy combines excellent grid current quality and constant switching frequency with a low computing time. In addition, this system allows GSCs controlled by MPC to meet the grid code of the country where the power plant is installed.

This paper also presents the generalisation, based on ref. [13], of the proposed linear multi-vector MPC to N-level converters, making them capable to deal with unbalanced grids. Some examples of GSCs based on multi-level converters (specifically MMC) used for grid connections of offshore wind farms or wind generator controls are: Siemens HVDC Plus, ABB (HVDC Light (3–400 MW), Alstom HVDC MaxSine and EPRI (HVDC Flexible).

Summarising, the proposed control system comprises 3 stages:

1. A linear decomposition stage that splits the unbalanced voltages and currents into their positive and negative sequences
2. A linear MPC strategy that obtains the optimal unbalanced reference voltage using a multi-vector strategy
3. A linear modulation stage that averages the reference vector using a multi-vector strategy.

The linearity of these stages has to be analysed to guarantee that they meet the superposition principle, so the paper is organised as follows.

The first part of the paper is a preliminary study where each stage is presented, and its linearity is analysed to discard some options commonly used in other MPC approaches. Thus, after the Introduction, Section 2 presents three decomposition systems, and their transient response is analysed. Then, Section 3 presents an MPC strategy for just one sequence and a cost function with three vectors. To finish this first part, Section 4 analyses three commonly used modulation strategies and justifies why only one is suitable for the proposed MPC from the linearity point of view.

Once the three stages have been chosen, and their linearity is justified, the second part is devoted to developing the proposed MPC for unbalanced grids, Section 5. Then, the corresponding block diagram is presented in Section 6. Section 7 shows the results of some preliminary simulations aimed to verify the performance of the proposed control system. Finally, the proposed multi-vector MPC is tested in the laboratory, where it is subjected to several grid disturbances. The section Conclusions summarises the features of the proposed multi-vector MPC and its performances.

2 | DECOMPOSITION STAGE LINEARITY

The first stage of the proposed control system is the decomposition of the unbalanced voltages and currents into their
positive and negative sequences. This section presents three decomposition systems that work in the discrete-time to analyse their effects on the dynamic response of the proposed MPC.

When a grid imbalance is detected by the GSC control system, it decomposes of the grid voltage into a positive sequence and a negative sequence by applying Fortescue’s theorem [12]. The independence of the symmetrical components and their additivity meet the superposition principle, which is the basis of the work presented in this paper. In steady state, the decomposition algorithms behave linearly, but not during the transients. Indeed, all of them take some control cycles until the samples of each sequence are correct [7, 14–16]. That affects the predictions carried out by the MPC, making it to lose one of its biggest advantages: the fast and precise dynamic response.

### 2.1 Positive-/negative-sequence calculation based on the dual second order generalised integrator

The dual second order generalised integrator (DSOGI-FLL), Figure 2, is a relatively simple algorithm that is frequency-adaptive since uses an FLL and not a PLL, and is highly robust against transient events [17, 18]. In steady-state and regarding positive-sequence detection, the DSOGI-FLL acts as both a low-pass filter for positive sequence and a notch filter for the negative-sequence so it attenuates high-order harmonics of the grid voltage. However, its high selectivity entails higher oscillations in the response and longer stabilisation time (around one grid period), which causes transient non-linear behaviour.

### 2.2 Digital signal cancellation

The traditional digital signal cancellation (DSC) [14, 16, 19], Figure 3, is relatively slow when compared to the fast MPC response but not as slow as other more sophisticated algorithms [17]. This method was developed for online detection of positive and negative sequence components of three-phase undistorted quantities, in the discrete domain. Unfortunately, it implies delaying the signal by one-quarter of the period at the fundamental frequency [14, 19], which then constitutes its inherent time delay and implies a transient non-linear behaviour.

### 2.3 Fast convergence digital signal cancellation

The third decomposition system is a fast version of the previous DSC, Figure 4, [15], and features the shortest transient of the three systems. This fast convergence digital signal cancellation (fast DSC) is capable to estimate the positive/negative-sequence signals within a small fraction of a cycle (shorter non-linear transient) at the cost of overshoot. Thus, a compromise between noise, overshoot, and minimum delay angle has to be reached for a particular application.

The time delay of $N \times T_s$ seconds corresponds to a delay angle of $\theta_d$ rads. Using $\theta_d = \pi/2$, the conventional DSC is obtained.

Finally, Table 1 summarises the main characteristics of the decomposition systems considered in this work.

| System         | Transient time          | Others         |
|----------------|-------------------------|----------------|
| DSOGI-FLL      | Long                    | Damped response|
| DSC            | Medium                  | Fixed response |
| Fast DSC       | Very short (adjustable) | Can overshoot  |
3 | MODEL-BASED PREDICTIVE CONTROL FOR GRID SIDE CONVERTERS LINEARITY

The second stage of the proposed control system is the MPC for each sequence.

All model predictive controls for GSCs are based (independently of the sequence) on the electrical model of the grid connection and the MPC of Figure 5.

In the stationary reference frame, the linear electrical model is

\[ \vec{r}_{\text{GSC}} = \vec{i}_g + L_\text{f} \frac{d\vec{v}_g}{dt} + R_\text{f} \vec{v}_g. \]  

(1)

where, \( r_{\text{GSC}}, v_{\text{GSC}}, i_{\text{GSC}}, L_\text{f} \) and \( R_\text{f} \) are the GSC voltage, grid voltage, grid current, filter inductance and resistance, respectively.

The active power, \( P_{\text{GSC}} \), and the reactive power, \( Q_{\text{GSC}} \), exchanged by the GSC and the electrical grid can be calculated as

\[ P_{\text{GSC}} = 1.5 \times (v_{\text{GSC}} i_{\text{GSC}} + v_{\text{GSC}}^* i_{\text{GSC}}^*). \]  

(2)

\[ Q_{\text{GSC}} = 1.5 \times (v_{\text{GSC}} i_{\text{GSC}} - v_{\text{GSC}}^* i_{\text{GSC}}^*). \]  

(3)

and the derivatives of these powers are

\[ \frac{dP_{\text{GSC}}}{dt} = 1.5 \times \left( \frac{dv_{\text{GSC}}}{dt} i_{\text{GSC}} + \frac{di_{\text{GSC}}}{dt} v_{\text{GSC}} + \frac{dv_{\text{GSC}}^*}{dt} i_{\text{GSC}}^* + \frac{di_{\text{GSC}}^*}{dt} v_{\text{GSC}}^* \right). \]  

(4)

\[ \frac{dQ_{\text{GSC}}}{dt} = 1.5 \times \left( \frac{dv_{\text{GSC}}}{dt} i_{\text{GSC}} - \frac{di_{\text{GSC}}}{dt} v_{\text{GSC}} - \frac{dv_{\text{GSC}}^*}{dt} i_{\text{GSC}}^* - \frac{di_{\text{GSC}}^*}{dt} v_{\text{GSC}}^* \right). \]  

(5)

The grid voltage can be represented by its \( \alpha - \beta \) components

\[ v_{\text{GSC}} = v_g \cos \omega_s t. \]  

(6)

\[ i_{\text{GSC}} = v_g \sin \omega_s t. \]  

(7)

and the derivatives of this voltage in the stationary frame are

\[ \frac{d v_{\text{GSC}}}{dt} = -\omega_s v_g \sin \omega_s t = -\omega_s v_{\text{GSC}}. \]  

(8)

\[ \frac{d i_{\text{GSC}}}{dt} = \omega_s v_g \cos \omega_s t = \omega_s i_{\text{GSC}}. \]  

(9)

According to Equation (1), the derivative of the grid current can be calculated as

\[ \frac{d i_{\text{GSC}}}{dt} = \frac{v_{\text{GSC}} - v_{\text{GSC}} - R_i i_{\text{GSC}}}{L_i}. \]  

(10)

\[ \frac{d i_{\text{GSC}}}{dt} = \frac{v_{\text{GSC}} - v_{\text{GSC}} - R_i i_{\text{GSC}}}{L_i}. \]  

(11)

Now, by substituting Equations (8)–(11) into Equations (4) and (5), it is possible to obtain the corresponding power variations that each voltage vector generated by the GSC causes in the grid connection

\[ S_{\text{P}} = \frac{dP_{\text{GSC}}}{dt} = \frac{1.5}{L_\text{f}} \left[ (v_{\text{GSC}} v_{\text{GSC}} - v_{\text{GSC}} v_{\text{GSC}}^*) - \left( v_{\text{GSC}}^2 + v_{\text{GSC}}^* \right) \right] \]  

(12)

\[ S_{\text{Q}} = \frac{dQ_{\text{GSC}}}{dt} = \frac{1.5}{L_\text{f}} \left( v_{\text{GSC}} v_{\text{GSC}} - v_{\text{GSC}} v_{\text{GSC}}^* \right) - \frac{R_i}{L_\text{f}} Q_{\text{GSC}} + \omega_s P_{\text{GSC}}. \]  

(13)

By adding the effect of all the GSC voltage vectors successively to the power value at the beginning of the cycle (instant \( k \)), it is possible to obtain the power value at the end of the switching cycle (instant \( k+1 \)) [20, 21]. If \( n \) vectors per PWM period are used

\[ P_{\text{GSC}}(k+1) = P_{\text{GSC}}(k) + S_{\text{P}}(k) \]  

(14)

\[ Q_{\text{GSC}}(k+1) = Q_{\text{GSC}}(k) + S_{\text{Q}}(k) \]  

(15)

where, \( S_{\text{P}} \) and \( S_{\text{Q}} \) are the power variations generated by each voltage vector \( \vec{V}_n \) \( \ldots \) \( \vec{V}_1 \), calculated using Equations (12) and (13).

The control system of the GSC minimises the error between the actual power and the references using a cost function that, expressed in terms of power at the end of each period, is typically [20–22]

\[ F(k+1) = (Q_{\text{GSC}}(k+1) - Q_{\text{GSC}}^*(k))^2 + (P_{\text{GSC}}(k+1) - P_{\text{GSC}}^*(k))^2. \]  

(16)

where the superscript \* denotes the reference values. After minimising the cost function, the optimised duration times (\( t_1 \) \( \ldots \) \( t_n \)) of the \( n \) vectors used in the modulation are obtained [20, 21].

Finally, the modulation applies several vectors \( \vec{V}_1 \ldots \vec{V}_n \) throughout the time interval (PWM period) between the instants \( k \) and \( k+1 \), to average the reference voltage, \( \vec{v}_{\text{ref}} \)

\[ \vec{v}_{\text{ref}} = \vec{V}_1 \times \frac{t_1}{T} + \ldots + \vec{V}_n \times \frac{t_n}{T}. \]  

(17)

Regarding the linearity of the MPC, notice that it is based on the electrical model of the grid connection, Equation (1), which is a linear equation. By expressing the model in the stationary
reference frame and applying the Laplace transformation, the
GSC current can be presented as:

\[ I_\alpha(s) = \left(V_{\text{GSC}}^\alpha(s) - V_{\text{ref}}^\alpha(s)\right) \times \left(\frac{1}{L_{d}\omega_f + R_f}\right). \]  \hspace{1cm} (18)

\[ I_\beta(s) = \left(V_{\text{GSC}}^\beta(s) - V_{\text{ref}}^\beta(s)\right) \times \left(\frac{1}{L_{d}\omega_f + R_f}\right). \]  \hspace{1cm} (19)

Therefore, for a given grid connection \((V_e, R_f, L_d)\), the current components, \(I_\alpha(s)\) and \(I_\beta(s)\), depend linearly and exclusively on \(V_{\text{GSC}}^\alpha(s)\) and \(V_{\text{GSC}}^\beta(s)\) (GSC reference voltage), respectively. In addition, according to Equations (2) and (3), once the current components are imposed by the electronic converter, \(P\) and \(Q\) are also imposed.

Consequently, MPC is, on average, a linear control system that fulfills the superposition principle so that it would be possible to combine several \(\tilde{V}_{\text{GSC}}\) to obtain a certain power. This fact is a key to control the symmetrical components of an unbalanced system and allows the MPC to regulate positive and negative sequences.

The optimisation of the cost function provides the voltage reference \(v_{\text{GSC}}^\alpha\) and \(v_{\text{GSC}}^\beta\) for the desired \(P_f\) and \(Q_f\) and to obtain a reduced tracking error. However, the achieved results for the currents or powers are not checked out by the MPC and no corrective actions are taken. In addition, the controls of \(P_f\) and \(Q_f\) are not independent.

Let us think of a cost function that provides the reference for a continuous (not modulated) voltage source. The change from \(P_g(k)\) and \(Q_g(k)\) to \(P_{g}(k + 1)\) and \(Q_{g}(k + 1)\) in a straight line can be represented by the slopes \(s_P\) and \(s_Q\). Therefore, solving for \(r_{GSC}\), \(v_{\text{GSC}}^\alpha\) and \(v_{\text{GSC}}^\beta\) in the system of equations made up by Equations (12) and (13) at the instant \(k\) \((P_g, Q_g, v_{\text{GSC}}^\alpha, v_{\text{GSC}}^\beta, s_P, s_Q\) are constant), the voltage needed for that change \((v_{\text{GSC}}^\alpha, v_{\text{GSC}}^\beta)\) in the time domain results in

\[ v_{\text{GSC}}^\alpha = \frac{2}{3L_{d}\omega_f} \left[ r_{\text{GSC}}^\alpha s_P - r_{\text{GSC}}^\beta s_Q + \left( r_{\text{GSC}}^\alpha \omega_f - \frac{R_f}{L_d}\right) P_g\right] - \left( r_{\text{GSC}}^\beta \omega_f - \frac{R_f}{L_d}\right) Q_g + v_{\text{GSC}}^\alpha. \]  \hspace{1cm} (20)

\[ v_{\text{GSC}}^\beta = \frac{2}{3L_{d}\omega_f} \left[ r_{\text{GSC}}^\alpha s_P + r_{\text{GSC}}^\beta s_Q + \left( r_{\text{GSC}}^\beta \omega_f - \frac{R_f}{L_d}\right) P_g\right] + \left( r_{\text{GSC}}^\beta \omega_f + \frac{R_f}{L_d}\right) Q_g. \]  \hspace{1cm} (21)

This function is clearly linear, supposing the converter is connected to a stiff grid. However, it should be noted that there is a cross coupling between \(P\) and \(Q\), as in traditional vector controls.

Think now of when, instead of a continuous voltage, a modulated voltage is used. In this case, the modulation averages the needed voltage, \(\tilde{V}_{\text{GSC}}\), using several voltage vectors per PWM period. Indeed, the cost function optimisation provides the vectors and their duration times to carry out that modulation.

## 4 Modulation Linearity

The final stage of any MPC is the modulation. A non-linear behaviour would make it impossible to combine two modulations linearly.

For a GSC to be linear its output must be capable of reproducing, on average, any \(\tilde{V}_{\text{ref}}\). Since \(\tilde{V}_{\text{ref}}\) describes circumferences in the \(\alpha\beta\) plane, \(\tilde{V}_{\text{GSC}}\) should be able to describe any circumference inside a circle whose radius is limited by its DC bus voltage. However, the modulations most commonly used in MPC uses 1 or 2 voltage vectors per period. The reason is that, otherwise, the number of combinations of vectors to be assessed using the cost function is very high, which implies a very long computing time. However, since MPCs directly obtain the duration times for each vector, so these values can be loaded in the PWM hardware of the microcontroller and no SVM stage is needed. In the following subsections, three possible modulations are analysed from the linearity point of view. In addition, since the computing time is critical to choose the best option in each case, they have been programmed in C language in an F28M35x Concerto dual-core microcontroller.

### 4.1 Modulation with one vector per PWM period

Using only one vector per period [23–26] accelerates the assessment of vectors using the cost function and allows using a look-up table with pre-calculated values [25]. Each vector, either \(V_0\) or \(V_1\), in Figure 6, contributes to change the GSC active and reactive power so all the \(6+2\) possible vectors have to be assessed using the cost function. This type of modulation is very limited because it is not able to obtain intermediate values of \(\tilde{V}_{\text{ref}}\) (different to \(V_0\) or \(V_1\)) using the cost function. Furthermore, the GSC works like a bang-bang voltage control across the periods, the switching frequency is variable, and its behaviour is clearly non-linear so that it cannot be used in the system proposed in this paper. Since all the \(6+1\) vectors have to
be assessed, the computing time for the whole MPC is around $6 \times 20 \mu s = 120 \mu s$.

4.2 Modulation with two vectors per PWM period

Using two vectors per period is a common practice aimed to accelerate the assessment of all the possible combinations of adjacent vectors using the cost function. It facilitates using a pre-calculated look-up table [25] to save computing time. Although there are other options like using only one active vector and a zero vector [27], or methods where actually only one vector is assessed and the second one is the adjacent active vector [20], simplified methods [28] or the one presented in ref. [29], where the pair of vectors have to be chosen between two active vectors and one active vector plus the zero vector.

The pair of vectors are chosen in every program cycle, either combining two active vectors (6 possibilities) or one active vector and one zero vector (6 possibilities), Figure 7. Therefore, the number of possible combinations that must be assessed using the cost function is higher than in the previous case.

This modulation only allows reproducing the hexagonal perimeter, blue line in Figure 7, and, again, the GSC features non-linear behaviour so that it cannot be used in the system proposed in this paper. The computing time of the MPC (without using a look-up table) is around 6 assessments 30 $\mu s = 180 \mu s$ or $6 \times 20 \mu s + 6 \times 20 \mu s = 300 \mu s$ if the zero vector is also used.

4.3 Modulation with three vectors per PWM period

Modulation techniques such as PWM or SVM can be modelled as linear systems [23]. Specifically, when the zero vector is used in a modulation [20, 28, 30], it allows adjusting the vector magnitude, Figure 8. Thus, it is possible to reproduce $\vec{v}_{ref}$ across the entire blue area of the inscribed circle shown in Figure 9. Consequently, this modulation is suitable for the linear multi-vector MPC proposed in this paper.

The selected vectors, $\vec{V}_i$, $\vec{V}_{i+1}$ and $\vec{V}_0$, contribute to the active and reactive power exchanged by the GSC. At the end of the next modulation period, instant $k+1$, the resulting powers are

$$P_g (k + 1) = P_g (k) + S_{PI} t_i + S_{PI} t_{i+1} + S_{P0} t_0,$$

$$Q_g (k + 1) = Q_g (k) + S_{QI} t_i + S_{QI} t_{i+1} + S_{Q0} t_0,$$

where $t_i$, $t_{i+1}$, $t_0$ are the duration times and $S_{PI}$, $S_{QI}$, $S_{Q0}$ are the power slopes calculated according to Equations (12) and (13), which must be estimated for all the 35 possible combinations of three vectors. Once the values of $t_i$, $t_{i+1}$, $t_0$ are obtained, the modulation can be carried out using those duration times.

The behaviour is linear so that it can be used in the system proposed in this paper, but the computing time is too big. In effect, since the MPC assesses each pair of adjacent vectors plus the zero vector, $\vec{V}_0$, using the cost function, and since each assessment takes around 40 $\mu s$, the total computing time for this task is high, around 240 $\mu s$. The high computing time is due to the number of vector combinations to be assessed using the cost function and to the complexity of the equations used in
the assessment. Therefore, it is advisable to find a solution to keep the computing time within reasonable values. The solution to this problem has been largely pursued in the technical literature by a number of authors. An efficient solution can be found in ref. [21] wherein the duration times for the modulation of \( \vec{r}_{\text{ref}} \) are always obtained for the vectors, \( \vec{V}_1, \vec{V}_2, \vec{V}_0 \), despite \( \vec{r}_{\text{ref}} \) rotates throughout the six sectors defined by \( \vec{V}_1, \vec{V}_2, \vec{V}_3, \vec{V}_4, \vec{V}_5 \) and \( \vec{V}_6 \), as shown in Figure 10. That keeps the computing time constant and low although makes it necessary to use a last SVM stage.

Notice that, although the calculated duration times, using Equations (22) and (23) in the cost function Equation (16), are sometimes negative or greater than \( T_s \), the coordinates of \( \vec{r}_{\text{ref}} \) are always correct and can be used by the SVM stage. For example, in Sector I

\[
\begin{align*}
\vec{r}_{\text{ref}}^{\alpha} &= V_1 \times \frac{t_{V_1}}{T_s} + V_2 \times \frac{t_{V_2}}{T_s} + 0 \times \frac{t_{V_0}}{T_s}, \\
\vec{r}_{\text{ref}}^{\beta} &= V_1 \beta \times \frac{t_{V_1}}{T_s} + V_2 \beta \times \frac{t_{V_2}}{T_s} + 0 \times \frac{t_{V_0}}{T_s}.
\end{align*}
\]

and, in Sector II

\[
\begin{align*}
\vec{r}_{\text{ref}}^{\alpha} &= V_3 \alpha \times \frac{t_{V_3}}{T_s} + V_4 \times \frac{t_{V_4}}{T_s} = V_0 \times \frac{t_{V_0}}{T_s} < 0 \times \frac{t_{V_0}}{T_s} + V_2 \times \frac{t_{V_2}}{T_s}, \\
\vec{r}_{\text{ref}}^{\beta} &= V_3 \beta \times \frac{t_{V_3}}{T_s} + V_4 \beta \times \frac{t_{V_4}}{T_s} = 0 \times \frac{t_{V_3}}{T_s} + V_2 \beta \times \frac{t_{V_2}}{T_s}.
\end{align*}
\]

and so on. Using this method, the computing time for the MPC plus the SVM keeps low, at around 70 \( \mu s \).

### 4.4 Modulation with three vectors per PWM period: Generalisation to N-level converters

When the number of levels in the converter is not just two but \( N \), the converter is known as multi-level. In this case, as in Section 4.3, it is possible to obtain any \( \vec{r}_{\text{ref}} \) inside the inscribed circumference by using three vectors, Figure 11, so that the voltage source behaves linearly and can be used with the superposition principle, which is needed for the control system proposed in this work. However, the problem is, again, how to assess the huge number of possible combinations of 3 vectors using the cost function in a reasonable computing time. The literature about this issue for the case of N-levels is not extensive but ref. [13] presents a fast method that is briefly explained below.

Like in Section 4.3, the hexagon is divided into six sectors using the six basic vectors shown in Figure 11, regardless of how many multi-level vectors are inside the hexagon. Notice that \( \vec{V}_3, \vec{V}_4, \vec{V}_5, \vec{V}_6 \) are expressed as a function of \( \vec{V}_1 \) and \( \vec{V}_2 \) in Figure 11. Once \( \vec{r}_{\text{ref}} \) has been calculated using \( \vec{V}_1, \vec{V}_2 \) and \( \vec{V}_0 \), and despite some duration times could result negative or greater than \( T_s \), a search algorithm is capable to find the three multi-level vectors, \( \vec{n}_{01}, \vec{n}_{02}, \vec{n}_{03} \), Figure 12, that define the triangle containing the endpoint of that \( \vec{r}_{\text{ref}} \) and to calculate their duration times \( (t_1, t_2, t_3) \), needed for the following multi-level SVM stage.

\[
\begin{align*}
\vec{n}_{01} &= t_{01} \alpha + j t_{01} \beta, \\
\vec{n}_{02} &= t_{02} \alpha + j t_{02} \beta, \\
\vec{n}_{03} &= t_{03} \alpha + j t_{03} \beta.
\end{align*}
\]

The search algorithm used in this paper is described in ref. [22]. However, other algorithms may also be used, such as that described in ref. [23]. It is based on finding the space vectors whose distances to \( \vec{r}_{\text{ref}} (t_1, t_2, t_3) \) are minimum, Figure 12. The inputs to the search algorithm are the coordinates of \( \vec{r}_{\text{ref}} \), expressed in the stationary reference frame.

The proposed cost function, Equations (32) and (35), combined with the multi-level modulation, provide a linear behaviour and a reasonable computing time (around 105 \( \mu s \)) to the MPC and, therefore, meet the requirements of this work.
The voltage vector,\( \mathbf{v} \), the current control period and performs the predictions. Next, multi-vector MPC calculates the active and reactive powers in measured, and the sequences are calculated, the proposed linear is shown in Figure 13. After the grid voltages and currents are to deal with unbalanced grids can be developed.

Once the linearity of all the stages that comprise the proposed control system has been assessed, the MPC specifically designed to deal with unbalanced grids can be developed.

The block diagram of the proposed linear multi-vector MPC is shown in Figure 13. After the grid voltages and currents are measured, and the sequences are calculated, the proposed linear multi-vector MPC calculates the active and reactive powers in the current control period and performs the predictions. Next, the voltage vector,\( \mathbf{v}_{\text{GSC}} \), that minimises the power tracking error for both sequences is obtained using the proposed cost function. Finally,\( \mathbf{v}_{\text{GSC}} \) is averaged using an SVM stage.

5 | LINEAR MULTI-VECTOR MODEL-BASED PREDICTIVE CONTROL FOR UNBALANCED GRIDS

Regarding the cost function, the active and reactive powers injected into the unbalanced grid can be controlled as a whole by using the cost function shown in Equation (16).

However, in this paper, the power in each sequence is controlled individually due to the advantages for the grid support provided by the GSC, as will be shown later in the experimental tests. Thus, the proposed cost function that provides separated power tracking for each sequence (denoted as p and n) is

\[
F(k + 1) = F_p(k + 1) + F_n(k + 1). \tag{31}
\]

\[
F(k + 1) = \left( Q_{\text{gp}}(k + 1) - Q_p^*(k) \right)^2 + \left( P_{\text{sp}}(k + 1) - P_p^*(k) \right)^2 + \left( Q_{\text{gn}}(k + 1) - Q_n^*(k) \right)^2 + \left( P_{\text{sn}}(k + 1) - P_n^*(k) \right)^2. \tag{32}
\]

The minimisation is achieved by finding the derivatives for each duration time,\( t_i \)

\[
\frac{\partial F_p}{t_i} = \frac{\partial F_p}{t_i} + \frac{\partial F_n}{t_i} = 0. \tag{33}
\]

There are two possible solutions. The first one is choosing

\[
\frac{\partial F_p}{t_i} = - \frac{\partial F_n}{t_i}. \tag{34}
\]

which should be chosen if a global power error minimisation is desired.

However, if the objective is to obtain good power tracking for each sequence, the solution is

\[
\frac{\partial F_p}{t_i} = \frac{\partial F_n}{t_i} = 0. \tag{35}
\]

By deriving \( F_p \) and \( F_n \) separately and finding the values of \( t_i \) that make those functions null, the duration times for each sequence result in

\[
t_{i+1} = \frac{(P_p(k) - P_p^*)(\mathbf{v}_p^{22} - \mathbf{v}_p^{24}) + (Q_p(k) - Q_p^*)(\mathbf{v}_p^{22})}{\mathbf{v}_p^{22} - \mathbf{v}_p^{24}} + \frac{(P_p(k) - P_p^*)(\mathbf{v}_p^{22} - \mathbf{v}_p^{24})}{\mathbf{v}_p^{22} - \mathbf{v}_p^{24}} + \frac{(Q_p(k) - Q_p^*)(\mathbf{v}_p^{22})}{\mathbf{v}_p^{22} - \mathbf{v}_p^{24}} + \frac{(Q_p(k) - Q_p^*)(\mathbf{v}_p^{22})}{\mathbf{v}_p^{22} - \mathbf{v}_p^{24}} + \frac{(Q_p(k) - Q_p^*)(\mathbf{v}_p^{22})}{\mathbf{v}_p^{22} - \mathbf{v}_p^{24}} + \frac{(Q_p(k) - Q_p^*)(\mathbf{v}_p^{22})}{\mathbf{v}_p^{22} - \mathbf{v}_p^{24}} + \frac{(Q_p(k) - Q_p^*)(\mathbf{v}_p^{22})}{\mathbf{v}_p^{22} - \mathbf{v}_p^{24}} + \frac{(Q_p(k) - Q_p^*)(\mathbf{v}_p^{22})}{\mathbf{v}_p^{22} - \mathbf{v}_p^{24}}. \tag{36}
\]
where \( \omega_g \) is the grid frequency, \( P \) is the power, \( Q \) is the reactive power, \( g \) is the grid, and \( i \) is the current.

The superposition principle allows calculating the effective values by using Equations (32) and (35), and sum them up before sending them to the SVM.

Finally, the corresponding block diagram is shown in Figure 13, where the positive and negative sequences are controlled separately using a sole cost function.

In the case of a multi-level converter, the only difference is that the standard SVM is substituted by a search algorithm and a multi-level SVM, Figure 14.

The block diagram of the proposed linear multi-vector MPC is shown in Figure 15. Notice that the SVM in Figure 13 changes to a search algorithm plus a multi-level SVM in the multi-level converter case.

**6 | BLOCK DIAGRAM**

The block diagram of the proposed linear multi-vector MPC is shown in Figure 15. Notice that the SVM in Figure 13 changes to a search algorithm plus a multi-level SVM in the multi-level converter case.

**7 | PRELIMINARY SIMULATIONS**

Before starting the tests of severe grid disturbances, the first step is to determine the performance of the different parts that make up the proposed linear multi-vector MPC.

**7.1 | Effect of the decomposition on the model-based predictive control dynamic response**

In this case, the simulations are carried out with two-level GSC connected to a positive sequence grid. The results obtained for the grid voltage and the line current using the decomposition systems in the control loop are compared with the ideal response obtained when Clarke transformations are used.

Firstly, the results for the slowest and filtered system (DSOGI-FLL) are shown in Figure 16. The errors for the voltage and line current last almost one cycle with respect to those obtained using the Clarke transformation. However, the dynamic response is in every moment under control, and the undesirable effects disappear after some cycles.

Next, the step response of a faster decomposition method (DSC) is simulated. The results, Figure 17, show that, despite the predictions provided by the DSC are incorrect during the transient of incorrect decomposition, the effects on the current generated by the GSC are limited to \( \frac{1}{4} \) of a period. After which the response is the same as when the Clarke transformation is used.

Finally, the fastest decomposition system (fast DSC) is simulated. In this case, the results represented in Figure 18 show that while the voltage transient is short, the dynamic response for the current is clearly affected at the beginning of the transient. As shown in Figure 18, the fast DSC requires approximately...
FIGURE 16  Effect of the dual second order generalised integrator on the model-based predictive control dynamic response. Components of the line current generated by the grid side converter (top). Components of the grid voltage (bottom)

FIGURE 17  Effect of the digital signal cancellation on the model-based predictive control dynamic response. Components of the line current generated by the grid side converter (top). Components of the grid voltage (bottom)

FIGURE 18  Effect of the fast digital signal cancellation on the model-based predictive control dynamic response. Components of the line current generated by the grid side converter (top). Components of the grid voltage (bottom)

FIGURE 19  Step response of the proposed model-based predictive control for several decomposition systems

the same time as the DSC to provide the same response as the Clarke transformation.

The above simulations show that smoother decomposition systems (DSOGI-FLL) produce more controlled transient line currents than faster systems (fast DSC). The DSC is an intermediate case, wherein the transient of currents is worse but the settling time shorter than in the DSOGI-FLL case.

The following results, depicted in Figure 19, shows the step response from the GSC output power point of view. The best dynamic response (closest to the ideal obtained using Clarke transformation) is attained using the DSC decomposition system. The DSOGI-FLL features a slightly slower dynamic and the Fast DSC leads to an unacceptable step response.

7.2 Multi-vector model-based predictive control versus other model-based predictive controls

In the following simulation, the GSC is connected to a balanced positive sequence grid and the switching frequency is set to 5 kHz. The GSC is successively controlled by three different MPCs: MPC with one vector per PWM period, MPC with two vectors per PWM period and the proposed multi-vector MPC (three vectors per PWM period).

As can be seen in Figure 20 (top), the MPC that uses just one vector per PWM period presents the highest THD (THD = 14.66%) and ripple. In the Figure 20 (middle), the MPC with two vectors per PWM period features a significantly lower THD (THD = 8.5%) and ripple than the previous one. Finally, the proposed multi-vector MPC features the lowest THD (THD = 1.3%) and ripple, Figure 20 (bottom).

8 EXPERIMENTAL TESTS OF SEVERE GRID DISTURBANCES

In this section, the response of the proposed linear multi-vector MPC against several types of common grid faults is analysed. These faults are normally caused by random load changes or by faults due to equipment, operator failures, and natural causes and result in single-phase to ground, phase to phase to ground or phase to phase faults. Later on, the low voltage ride through (LVRT) capability of the proposed linear multi-vector MPC is experimentally analysed. Finally, a wave energy converter
Figure 20 Simulation results obtained for the phase currents and their corresponding harmonic spectrum and THD: Model-based predictive control with one vector per PWM period (top); model-based predictive control with one vector per PWM period (middle); multi-vector model-based predictive control (bottom).

Table 3 Grid connection used in the laboratory

| Component | Value          |
|-----------|----------------|
| $R_c$     | 0.5 Ω          |
| $L_f$     | 20 mH          |
| $V_{dc}$  | 500 V          |
| $V_{grid}$| 200 V (LVRT: 240V) |
| Switching frequency | 4.0 kHz |

The WEC emulator is used to reproduce the power profile generated by a floating OWC-based WEC. That power is delivered to the grid by the GSC during several grid faults.

The proposed control system was programmed in a dual-core floating point F28M35x microcontroller, Figure 21. The values of the components used in the laboratory are shown in Table 3.

The computing time of implementation used in the laboratory for the entire code resulted in around 121 μs. It is split into 32 μs for measurements and digital filtering, 50 μs for the MPC, and 21 μs for the SVM, and 17 μs for auxiliary tasks such as communications with the other core, protections etc., Figure 22.

8.1 Transient response to unbalances

In the first test, an unbalance is generated by suddenly connecting a resistor in series with phase c. Once the DSC detects the negative sequence, the control increases the reactive power in a step. Figure 23 shows the correct operation of the DSC and the short transient of power generated by the incorrect predictions.

Next, Figure 24 shows a basic FFT analysis performed using a Rohde & Schwarz RTA4000 oscilloscope corresponding to phase b current, before the fault. As expected, the harmonics gather around the SVM carrier frequency (5 kHz) and its
8.2 Phase-to-phase to ground fault

In this test, the GSC is connected to an unbalanced grid where the phase-to-ground voltages of phases b and c are 1/3 their rated value. The power references for each sequence are: \( P_{b\text{ref}} = 1.5 \text{ kW} \), \( Q_{b\text{ref}} = 0.35 \text{ kvar} \) and \( P_{c\text{ref}} = 0.5 \text{ kW} \), \( Q_{c\text{ref}} = 0.2 \text{ kvar} \). The decomposition is carried out using the multiples. The reason is that, unlike other MPC strategies, the proposed multi-vector MPC features constant switching frequency. Notice that the firmware of the oscilloscope provides a relative value (dBV) with respect to an internal reference of 1Veff (dBA and 1Aeff when current clamps are used)

DSC system. Notice that the voltage amplitude of the negative sequence is much smaller than that of the positive sequence, Figure 25 (top), which greatly limits the injection of power in that sequence.

Figure 25 (middle) shows the corresponding components of the sequences expressed in the \( \alpha-\beta \) reference frame. The resulting unbalanced line currents in Figure 25 (bottom) are shown.

Figure 26 shows the active and reactive powers obtained in each sequence. As can be seen, the reference tracking is good in both sequences. However, it is better for higher power values, whereas there is a small tracking error for lower values due to the sensitivity of the predictive control to parameter errors in the model on which it is based.

Figure 27 shows the FFT analysis corresponding to phase b during the fault. Notice that the modulation of both sequences simultaneously has little impact on the harmonic spectrum.
8.3 | Single-phase to ground fault

In this test, the GSC is connected to an unbalanced grid where the phase-to-ground voltage of phase c has been reduced to 1/3 its original value, Figure 28 (top). The power references for each sequence are: \( P_{\text{pref}} = 1.5 \text{ kW}, Q_{\text{pref}} = 500 \text{ var} \) and \( P_{\text{nref}} = 0.2 \text{ kW}, Q_{\text{nref}} = 0.1 \text{ kvar} \). Figure 28 (middle) shows the components of both sequences expressed in the \( \alpha-\beta \) reference frame, and Figure 28 (bottom) shows the unbalanced line current generated by the GSC.

The power reference tracking, Figure 29, is again good for both sequences.

Figure 30 shows the FFT analysis corresponding to phase b during the fault. Notice that, again, the simultaneous modulation has little impact on the harmonic spectrum.

8.4 | Low voltage ride through capability

The first test of this section shows the behaviour of the GSC when the voltage of the three phases drops from 230 Vrms to 160 Vrms, Figure 31. The converter keeps sending the same power, 1.5 kW, and 0.5 kvar to the grid at the cost of increasing the line current.

However, in a practical application, during three phase voltage sags, the power plant must fulfil the grid code of the country in which it is operating. Although there are differences in each country, all the grid codes establish that, during the voltage sag created by the fault, the active power injected by the power plant into the grid must be reduced, and the majority of the power exchanged must be reactive. Figure 32 shows the case of the Spanish grid code.

In the following test, the grid voltage drops from 240 Vrms to 150 Vrms, Figure 33. Once the MPC detects the voltage has dropped below a preset threshold, it reduces the active power from 1.5 kW to 0.5 kW and, after some cycles to reduce the transient, increases the reactive power injected into the grid from 0 var to 750 var, Figure 34. In this situation, the grid code is fulfilled, and the GSC keeps these powers until
the grid voltage rises above a preset limit again. After the fault is cleared, the active and reactive power references are again set to 1.5 kW and zero respectively. The results demonstrate the excellent LVRT capability of the proposed linear multi-vector MPC.

8.5 Wave energy power plant

The section is devoted to testing the proposed linear multi-vector MPC in the GSC of a renewable power plant. More specifically, the power profile of a floating OWC-based WEC [31] was reproduced using a small-scale emulator. The details about this emulator, Figure 35, can be found in ref. [32].

In normal conditions, a floating OWC-based WEC provides low-frequency oscillating power like that shown in Figure 36 (top) and a ripple-free current in Figure 36 (bottom). Both characteristics are reproduced by the emulator in the laboratory. Two grid faults tests were reproduced in the point of common coupling of the power plant. The first one reproduces a two-phases to ground fault where the voltage of phase b and phase c is reduced to 1/3 their pre-fault value. The second one reproduces a one-phase to ground fault, and the voltage of phase c is 1/3 its pre-fault value. In both cases, the results for the power, Figure 37 (top) show that the GSC sends as much...
active power to the positive sequence as in no-fault condition. That proves the capability of the proposed linear multi-vector MPC to deal with unbalanced grids when facing irregular power profiles. Figure 37 (bottom), shows the line current corresponding to phases, a and b, during the faults.

9 | GENERALISATION TO MULTILEVEL CONVERTERS

Finally, this section shows the results of a simulation carried out in simulink, using a 6-level multi-level converter model (MMC). An MMC with 10 kV DC bus voltage and an inductive filter of 15 mH is connected to an unbalanced grid. The grid voltage positive and negative sequences have the same magnitude of 2.75 kV and a phase shift of 30°, Figure 38 (top). The active power references for the positive sequence is changed from $P_p = 40$ kW to $P_p = 80$ kW and for the negative sequence from $P_n = 25$ kW to $P_n = 50$ kW, whereas the reactive power is kept to zero. The results are shown in Figure 38, where the MMC combined output voltage generated from Equations (39) and (40) is shown in Figure 38 (middle). Figure 38 (bottom) shows the high-quality current achieved by the MMC controlled with the proposed linear multi-vector MPC. Finally, Figure 39 shows the resulting powers, proving the good reference tracking achieved.

10 | CONCLUSION

GSCs controlled by MPC feature outstanding performance such as fast dynamic response, good tracking error, and low ripple in the currents. However, if the grid becomes unbalanced, either due to a transient disturbance or a permanent unbalance, pre-fault MPCs are no longer suitable for the GSC control. A straightforward solution consists in decomposing the unbalanced voltage into symmetrical components and building two independent MPCs to control both sequences separately. However, that is only possible if the superposition principle is applicable, which implies that all the transfer functions involved in the control system must be linear. The MPCs developed for GSC normally use only one or two vectors per PWM period in order to keep the computing time within reasonable values, but in return, its behaviour is not linear. This paper presents a linear multi-vector MPC valid for N-level converters that makes it possible to control both sequences simultaneously in a sole cost function.

The decomposition of the unbalanced grids into sequences takes some control cycles before providing correct values for the sequences, which leads to incorrect predictions. The simulation results have shown that to keep the MPC output under control during that transients; smoother decomposition systems provide a more controlled dynamic response that those that feature a shorter transient. In addition, the results have shown that once the steady-state is reached, the behaviour of the linear multi-vector MPC for each sequence is as good as in the pre-fault state.

The simulations have proven that the multi-vector strategy provides far lower THD currents than other modulation strategies and constant switching frequency while keeps the computing time low.

The experimental results have shown that the proposed multi-vector MPC is capable to deal with single-phase, phase-phase faults, and voltage sags. Despite the disturbances, the pre-fault harmonic spectrum is kept, meaning that the simultaneous modulation of both sequences does not lead to worse performance.

The proposed multi-vector MPC presents the same shortcomings as standards MPCs, mainly the sensitivity to parameter variations (particularly the inductance) but, in addition, the loss of accurate predictions during the decomposition system transient, which degrades the dynamic response.

The system presented in this paper is a necessary complement to GSCs controlled by MPCs that need to be capable to deal with grid disturbances (unbalanced grids, voltage sags in one or two phases etc.), something that weak grids are more prone to suffer.
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