Predictive Control Strategies in a Two-Level Voltage Source Inverter

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Abstract—In recent years, predictive control has emerged as an alternative for the control of power electronic converters. In this paper, a comparison is presented between the implementation of a predictive current control strategy operating at variable switching frequency and another working at fixed switching frequency. Both strategies use a mathematical model of the converter and load in discrete time in order to predict the behaviour of the load currents and thus choose the switching state that minimizes a given cost function, state which is applied in the next sampling time. The comparison is done based on the percentage of total harmonic distortion (THD) and the error of the output current compared to its reference. The results demonstrate that both techniques work well, but the one operating a fixed switching frequency generates lower ripple and harmonic distortion.

Index Terms—Closed loop systems, DC-AC power converters, Digital control, Predictive control, Prediction methods, Renewable energy sources

I. INTRODUCTION

O VER the past few years, current control in voltage source inverters (VSI) has been an important and researched areas in power electronics. The voltage source inverter is immersed in applications in all types of industries and contexts where this kind of power converter is used [1]. Several methods have been proposed for the control of the VSI, the most common are linear and hysteresis control due to their low implementation complexity [2].

Thanks to new technological advances, the processing speed of microprocessors is improving, allowing the implementation of advanced and more complex control algorithms such as Model Predictive Control (MPC), which has been used in current control for inverters as well as for rectifiers and active filters [3]–[5].

MPC uses a mathematical model of the load and the converter in an intuitive manner to predict the output current and selecting the best state to meet the reference for the following sampling instant. MPC has the advantage and possibility to include nonlinearities in the system and can also be extended to many applications [6], [7].

However, there are some disadvantages associated with the implementation of MPC, such as high computational cost and those related to the finite number of valid switching states. In the absence of a modulator, MPC can produce noise and some oscillations in the voltage and current.

Section II describes the implementation of two predictive control strategies with a fixed switching frequency. The first strategy is a standard implementation of a fixed switching frequency in classical predictive control [10], [11]. The second strategy is a conventional predictive control strategy presented in this paper, a comparison is presented between the implementation of a fixed frequency switching strategy, with the modulation of spatial vectors in discrete time within the control algorithm [12] or a conventional modulation within a PI controller [13]. However, these solutions have the problem of complex calculation expressions that are difficult to include into the cost function.

In this paper a predictive control strategy operating at fixed switching frequency which emulates the implementation of space vector modulation (SVM) with a PI linear controller is presented. This technique uses a modulation scheme within the minimization of the cost function which considers a finite number of valid switching states. Conventional predictive control techniques generate a spread frequency spectrum, which can decrease the performance of the power converter. Moreover, it requires the use of a filter for a wider frequency range [8], [9]. The literature offers some solutions to the problem of variable frequency in classical predictive control [10], [11]. The include the implementation of a fixed frequency switching strategy, with the modulation of spatial vectors in discrete time within the control algorithm [12] or a conventional modulation within a PI controller [13]. However, these solutions have the problem of complex calculation expressions that are difficult to include into the cost function.

In this paper a predictive control strategy operating at fixed switching frequency which emulates the implementation of space vector modulation (SVM) with a PI linear controller is presented. This technique uses a modulation scheme within the minimization of the cost function which considers a finite number of valid switching states. Working cycles are generated for each vector within a certain sector of the $\alpha - \beta$ plane, which, together with the zero voltage vectors, are applied to the converter using a given pattern sequence. In addition, the conventional predictive current control strategy is presented in order to establish a comparison between both techniques, demonstrating that both strategies allow a good tracking of the load current reference, but the technique operating at fixed switching frequency has a lower ripple and harmonic distortion.

II. TOPOLOGY AND MATHEMATICAL MODEL OF THE VSI

The Voltage Source Inverter (Fig. 1), consists of two fundamental elements, which are the six insulated-gate bipolar transistors (IGBTs) distributed into three legs and a dc-link at the input.

For the current regulation of the load using a model based predictive control (MPC) technique, it is necessary to know the mathematical model that defines the dynamic behavior.

Fig. 1: Topology of the voltage source inverter.
of the system. For this, Kirchhoff’s laws is applied to the three-phase load. Fig. 2 shows a simplified model of the system, considering a R-L load and the IGBT switches.

Using Kirchhoff’s law, it is possible to obtain the following model of the load:

\[ v_{xN} = v_L + v_R + v_{nN} \]  \hspace{1cm} (1)

Equation (1) shows a generic model, applicable to the three outputs of the converter. If the following relations for the voltage across the inductance and the resistance are now added,

\[ v_L = L \frac{di_x}{dt} \]  \hspace{1cm} (2)

\[ v_R = Ri_x \]  \hspace{1cm} (3)

Equation (1) can now be defined as:

\[ v_{xN} = L \frac{di_x}{dt} + Ri_x + v_{nN} \]  \hspace{1cm} (4)

Applying equation (4) to the three outputs, an expression for the load voltages can be obtained as:

\[ v_{aN} = L \frac{di_a}{dt} + Ri_a + v_{nN} \]  \hspace{1cm} (5)

\[ v_{bN} = L \frac{di_b}{dt} + Ri_b + v_{nN} \]  \hspace{1cm} (6)

\[ v_{cN} = L \frac{di_c}{dt} + Ri_c + v_{nN} \]  \hspace{1cm} (7)

For the smooth operation of the converter, it is necessary to consider Table I, which contains the eight valid switching states of the VSI. This table also details the line-to-line voltages lines \( v_{ab}, v_{bc}, \) and \( v_{ac} \) and the dc-link current \( i_{dc} \) for each valid switching state.

The eight available switching states are defined based on the operating restrictions of the converter. The dc-link cannot be short circuited and the current in the load cannot be interrupted.

The control scheme is shown in Fig. 4. The technique predicts the behavior of the current in the instant of time \( k+1 \) for each valid switching state, using the dynamic equation that describes the operation of the converter in conjunction with the \( R-L \) load. This value is obtained by using the measurements of load currents \( i_a, i_b, i_c \) and the dc-link voltage \( v_{dc} \).

Predictive control works with a prediction model implemented in discrete time. Equation (4) defines the system model discretized using the Euler’s method, based on a tangential approximation of the derivative:

\[ S_a = \begin{cases} 1 & \text{if } S_1 \text{ on and } S_4 \text{ off} \\ 0 & \text{if } S_1 \text{ off and } S_4 \text{ on} \end{cases} \]  \hspace{1cm} (8)

\[ S_b = \begin{cases} 1 & \text{if } S_3 \text{ on and } S_6 \text{ off} \\ 0 & \text{if } S_3 \text{ off and } S_6 \text{ on} \end{cases} \]  \hspace{1cm} (9)

\[ S_c = \begin{cases} 1 & \text{if } S_5 \text{ on and } S_2 \text{ off} \\ 0 & \text{if } S_5 \text{ off and } S_2 \text{ on} \end{cases} \]  \hspace{1cm} (10)

In order to meet these restrictions and to ensure the safe operation of the converter, a dead time based switching strategy can be implemented. It consists of opening both switches of each leg of the converter at the time of making a change in the value of \( S_a, S_b \) or \( S_c \). The opening of the switches is generated for a moment of time “\( T_m \)” and is shown in Fig. 3, where the change in \( S_a \) occurs.

III. PREDICTIVE CONTROL APPLIED TO THE VSI

Current control in two-level voltage source inverters is an area that is well studied in the field of power electronics. A predictive control strategy applied to the VSI is based on the fact that there is a finite number of possible switching states that can be generated by the power converter. In addition, a system model can be used to predict the behavior of the variables for each switching state. For the choice of the appropriate switching state to be applied at the next sampling time, a cost function \( g \) is evaluated, which acts as a state selection criterion. The cost function considers each possible switching state, and then chooses the option that produces the least possible error between the reference and prediction.

A. Predictive current control for the VSI operating at variable switching frequency

The control scheme is shown in Fig. 4. The technique predicts the behavior of the current in the instant of time \( k+1 \) for each valid switching state, using the dynamic equation that describes the operation of the converter in conjunction with the \( R-L \) load. This value is obtained by using the measurements of load currents \( i_a, i_b, i_c \) and the dc-link voltage \( v_{dc} \).

Predictive control works with a prediction model implemented in discrete time. Equation (4) defines the system model discretized using the Euler’s method, based on a tangential approximation of the derivative.
The prediction model used in the classical model predictive control control strategy operating at fixed switching frequency evaluates each sector of the \( \alpha - \beta \) plane at every sampling instant, which is composed of two adjacent voltage vectors in addition to a zero vector. The load current predictions are evaluated based on these adjacent vectors, obtaining two cost functions \( g_1 \) related to the first vector of the load current prediction and \( g_2 \) related to the second vector of the load current prediction.

\[
i_\beta = \left[ \frac{i_b - i_c}{\sqrt{3}} \right]
\]  

(16)

The cost function \( g \) is as follows:

\[
g = [i^*_{\alpha} - i^p_{\alpha}]^2 + [i^*_{\beta} - i^p_{\beta}]^2
\]  

(17)

\( i^*_{\alpha} \) and \( i^*_{\beta} \) are the reference currents in the \( \alpha - \beta \) coordinates and \( i^p_{\alpha}, i^p_{\beta} \) correspond to the predicted currents of the converter. This function is inserted within a cycle, which evaluates the currents generated by the eight valid switching states and chooses the option that generates the minimum error (minimum value of \( g \)).

B. Predictive control of the VSI operating at fixed switching frequency

Classical model predictive control has the particularity of evaluating all the valid switching states of the VSI to predict the current that the converter should have in the following instant to minimize the error and meet the current reference. This process occurs at a variable switching frequency, because the same available switching state could be selected as the optimal during several times. However it is possible also that at every sampling time a different switching state is selected and thus varying the switching frequency, generating ripple and high harmonic distortion in both the load voltage and current. A solution to solve this problem is to use predictive control to emulate the operation of a space vector modulation together with a PI linear controller.

The prediction model used in the classical model predictive control is the same as the one used in the strategy operating at fixed switching frequency. On the other hand, the eight valid switching states of the VSI can be represented in the \( \alpha - \beta \) coordinates, considering six available sectors such as shown in Fig. 6.

A model predictive control strategy operating at fixed switching frequency evaluates each sector of the \( \alpha - \beta \) plane at every sampling instant, which is composed of two adjacent voltage vectors in addition to a zero vector. The load current predictions are evaluated based on these adjacent vectors, obtaining two cost functions \( g_1 \) related to the first vector of the load current prediction and \( g_2 \) related to the second vector of the load current prediction.

\[
i_\alpha = \left[ \frac{2i_a - i_b - i_c}{3} \right]
\]  

(15)
the sector and \( g_2 \) related to the second vector of the sector. This is done at each iteration, evaluating all the sectors in the \( \alpha - \beta \) plane, and obtaining different cost functions \( g_1 \) and \( g_2 \) for each of the six sectors for the VSI. A third cost function \( g_0 \) is calculated only once and corresponds to the prediction when switching states producing zero load voltage are applied.

In addition, the different \( g_1 \) and \( g_2 \) cost functions are used to determine the working cycles that are associated with each vector and can be determined using the following relationships:

\[
d_0 = \frac{K}{g_0} \quad (18)
\]
\[
d_1 = \frac{K}{g_1} \quad (19)
\]
\[
d_2 = \frac{K}{g_2} \quad (20)
\]
\[
d_0 + d_1 + d_2 = 1 \quad (21)
\]

It is important to highlight that a high value in a cost function, indicates a low duty cycle, which means that the associated vector is applied for less time. By replacing equations (18), (19) and (20) in (21) can be obtained:

\[
\frac{K}{g_0} + \frac{K}{g_1} + \frac{K}{g_2} = 1 \quad (22)
\]
\[
\frac{Kg_1g_2}{g_0g_1g_2} + \frac{Kg_0g_2}{g_0g_1g_2} + \frac{Kg_0g_1}{g_0g_1g_2} = 1 \quad (23)
\]

Obtaining the expression for the constant \( K \):

\[
K = \frac{g_0g_1g_2}{g_1g_2 + g_0g_2 + g_0g_1} \quad (24)
\]

and substituting equation (24) into equations (18), (19) and (20):

\[
d_0 = \frac{g_1g_2}{g_1g_2 + g_0g_2 + g_0g_1} \quad (25)
\]
\[
d_1 = \frac{g_0g_2}{g_1g_2 + g_0g_2 + g_0g_1} \quad (26)
\]
\[
d_2 = \frac{g_1g_0}{g_1g_2 + g_0g_2 + g_0g_1} \quad (27)
\]

the new cost function that is optimized (minimized) is determined using the following relationship:

\[
g_{(k+1)} = d_1g_1 + d_2g_2 \quad (28)
\]

The optimal vectors chosen to be applied in the next sampling time to the converter will be those that minimize this new cost function. After the selection of the optimal vectors and, considering the duty cycles, the time \( T_0, T_1 \) and \( T_2 \) that each optimal vector is applied can be obtained by:

\[
T_0 = T_s d_0 \quad (29)
\]
\[
T_1 = T_s d_1 \quad (30)
\]
\[
T_2 = T_s d_2 \quad (31)
\]
\[
T_s = T_0 + T_1 + T_2 \quad (32)
\]

Once the optimal vectors and their times of application have been stated, the switching strategy that will be applied at the next sampling time is established. This commutation strategy can be summarized in seven steps:

1) The switching pattern is initiated applying the zero vector, a quarter of its time \( T_0 \left( \frac{T_s}{4} \right) \).
2) Then it is applied the first optimal vector \( v_1^{opt} \) half of its time \( T_1 \left( \frac{T_s}{2} \right) \).
3) Continue applying the second vector \( v_2^{opt} \) half of its time \( T_2 \left( \frac{T_s}{2} \right) \).
4) Next, the zero vector is applied for a period equivalent to half of its time \( T_0 \left( \frac{T_s}{2} \right) \).
5) The second optimal vector \( v_2^{opt} \) is applied half of its time \( T_2 \left( \frac{T_s}{2} \right) \).
6) The first optimal vector \( v_1^{opt} \) is applied half of its half of its time \( T_1 \left( \frac{T_s}{4} \right) \).
7) Finally the zero vector is applied, a quarter of its time \( T_0 \left( \frac{T_s}{4} \right) \).

It is important to define which selected vector will be considered as optimum vector one and which one as optimum vector two, in order to ensure that only a change on a single leg of the converter occur. This way the application of the method is optimized and better results are provided. Specifically, for odd sectors (one, three and five) the optimum vector will correspond to the first vector of the sector, considering that the optimal vector will be the one that follows counterclockwise. In the opposite case, for the even sectors (two, four and six), the optimal vector will correspond to the first vector of the sector and the optimal vector will be the one that follows in a clockwise direction. The zero voltage vector can be obtained by two different combinations, the first is when \( S_1, S_3 \) and \( S_5 \) are worth zero and the second when \( S_1, S_3 \) and \( S_5 \) are worth one. For the correct application of the sequence, the first combination must be applied at the beginning and the end of the sequence, while the application of the zero voltage vector at the middle of the sequence is achieved by applying the second combination. The steps for the implementation of this method are summarized in Fig. 7, where the symmetrical and cyclic performance of the technique can be seen.
order to implement the dead time commutation strategy as well as the synchronization with the digital signal processor (DSP). A Delfino F28335 DSP has been used for the implementation of the predictive control techniques.

The experimental results are shown in Fig. 10 and Fig. 11 for steady and transient states, respectively. The experimental results validate the results obtained in the simulations, ensuring sinusoidal load currents with a fast dynamic response. This is also seen in the load voltage $v_{an}$ where is evident that the technique operating at fixed switching frequency has lower harmonic distortion than the load voltage $v_{an}$ obtained with the predictive control technique operating a variable switching frequency.

This result is obtained because the predictive control strategy operating at fixed switching frequency presents an homogeneous commutation sequence, observing load currents with less ripple and a more sinusoidal waveform. In addition, Table VI, VII and VIII detail the comparison of the results obtained experimentally in terms of harmonic distortion percentage for the voltage $v_{an}$ and for the current $i_a$, in addition to the steady state error for the current $i_a$.

VI. CONCLUSION

In this paper two predictive control strategies have been implemented in simulation and practically for a two-level voltage source inverter. One predictive control technique operates at variable switching frequency, choosing a single optimal vector at every sampling instant to be applied to the power converter. The second predictive control strategy operates at fixed switching frequency by implementing a commutation sequence with two active vectors and one zero vector. Both techniques work well, obtaining sinusoidal load currents and voltage with fast dynamic response, but the technique operating at fixed switching frequency shows better results with currents and voltage with less ripple and lower harmonic distortion in comparison to the predictive control technique operating at variable switching frequency.
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Table VI: Percentage of harmonic distortion of the voltage \( v_{an} \) in the experimental results.

| Frequency | Amplitude | %THD \( v_{an} \) Variable Frequency | %THD \( v_{an} \) Fixed Frequency |
|-----------|-----------|--------------------------------------|---------------------------------|
| 50[Hz]    | 0.5[A]    | 208.44%                              | 184.99%                         |
| 25[Hz]    | 1[A]      | 121.94%                              | 104.86%                         |
| 25[Hz]    | 0.5[A]    | 210.42%                              | 191.99%                         |

Table VII: Percentage of harmonic distortion of the current \( i_a \) in the experimental results.

| Frequency | Amplitude | %THD \( i_a \) Variable Frequency | %THD \( i_a \) Fixed Frequency |
|-----------|-----------|--------------------------------------|--------------------------------|
| 50[Hz]    | 1[A]      | 115.62%                              | 98.40%                         |
| 25[Hz]    | 1[A]      | 115.62%                              | 98.40%                         |
| 25[Hz]    | 0.5[A]    | 22.39%                               | 13.78%                         |

However, for both cases, there are notable differences between the simulated and experimental results, especially when working with small reference currents. Some of the causes of the differences were the absence of filters at the converter output and mainly the arrangement of the elements within the setup structure. Despite of these differences, has been possible to demonstrate the good performance of the predictive control techniques showing by simulations and experiments that they are a good alternative for the control of power converters.

Table VIII: Percentage of average absolute error of the current \( i_a \) in the experimental results.

| Frequency | Amplitude | %Error \( i_a \) Variable Frequency | %Error \( i_a \) Fixed Frequency |
|-----------|-----------|--------------------------------------|--------------------------------|
| 50[Hz]    | 0.5[A]    | 7.62%                                | 7.25%                          |
| 25[Hz]    | 1[A]      | 6.74%                                | 6.02%                          |
| 25[Hz]    | 0.5[A]    | 8.02%                                | 7.47%                          |

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ChVSI with an amplitude of 1[A] and a reference change from 50[Hertz] to 25[Hertz].

Fig. 11: Experimental results of the predictive control at variable frequency (on the left) and at fixed frequency (on the right) applied to the VSI with a reference of 25[Hertz] and 1[A] at steady state. $Ch_1 \rightarrow$ dc voltage ($v_{dc}$) - $Ch_2 \rightarrow$ phase voltage a ($v_{an}$) - $Ch_3 \rightarrow$ current in the load ($i_a$) - $Ch_4 \rightarrow$ current in the load ($i_b$).

Fig. 11: Experimental results of the predictive control at variable frequency (left) and fixed frequency (right) applied to the VSI with an amplitude of 1[A] and a reference change from 50[Hertz] to 25[Hertz]. $Ch_1 \rightarrow$ dc voltage ($v_{dc}$) - $Ch_2 \rightarrow$ phase voltage a ($v_{an}$) - $Ch_3 \rightarrow$ current in the load ($i_a$) - $Ch_4 \rightarrow$ current in the load ($i_b$).

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