Modulation Strategy for the Boost Matrix Converter

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Abstract – The present thesis offers a novel contribution to the study of three-phase matrix converters, ensuring that the matrix converter presents voltage step-up characteristics. Simultaneously, the matrix converter allows an input/output frequency adaptation, adjustable power factor in the point of common coupling and bidirectional power flow. This is the Boost Matrix Converter (Boost MC). A full detailed model is developed, including an innovative approach to the modulation strategy, which uses Space Vector Modulation and Pulse-Width Modulation combined with classical techniques of controller design. The validation of the modulation process is successfully performed, with a generic RL load connected to the matrix converter terminals. The obtained results in Matlab/Simulink®, which can be later complemented with tests in laboratory environment, anticipate the Boost MC potential in several engineering applications, like High-Voltage Direct Current, Dynamic Voltage Restorer, Unified Power Flow Controller and electrical drives.

Index Terms – Three-phase Matrix Converter, Boost Matrix Converter, Space Vector Modulation, Pulse-Width Modulation, Controller Design.

I. INTRODUCTION

In 1980, Venturini and Alesina (Venturini & Alesina, 1980) proposed the first algorithm capable of synthesizing output sinusoidal voltages from a three-phase voltage source connected to the matrix converter input terminals. Since then, this field has been subject to intense research and development.

In power electronics, an AC/AC power converter is an electronic device, normally fed by a sinusoidal voltage system (input) and composed by power semiconductors (GTO, TJB, IGBT, MCT or RB-IGBT), which displays output sinusoidal quantities with different characteristics of the input (RMS value, frequency and/or power factor).

A three-phase matrix converter has the generic topology as depicted in Fig. 1.

Up to now, the conventional configuration of the matrix converter is a device known as Buck Matrix Converter (Buck MC), because the output RMS voltage is lower than the input RMS voltage.

The main advantages of the Buck MC are as follows: high efficiency; capability to control the fundamental frequency and the RMS value of the output voltages and also the input power factor as seen from the generator; lower volume, with the correspondent power density increase; bidirectional power flow; input current waveforms nearly sinusoidal.

On the opposite, there are also several disadvantages: large number of semiconductors; complexity of the control system; output RMS voltage limited to, at most, $\sqrt{3}/2$ of the input; higher probability of disturbances due to the high frequency operation of semiconductors.

In recent years, matrix converters are being increasingly used in several applications: Dynamic Voltage Restorer (DVR), Unified Power Flow Controller (UPFC), traction substations in railway network, electrical drives with $v/f$ command, renewable energy applications (control of Doubly Fed Induction Generator (DFIG) and Permanent Magnet Synchronous Generator (PMSG)).

A DVR is a power electronic topology that aims at protecting sensitive loads (mainly in Low Voltage (LV) distribution grids) from disturbances in the power supply. Usually, DVR ensures a low time response, therefore allowing the distribution grid to become nearly immune to voltage sags and voltage swells. This goal is achieved by inserting a voltage in series with the LV distribution grid, being that compensation voltage granted by a matrix converter (Alcaria, 2012) (Wang & Venkataramanan, 2009) (Pandey & Rajlakshmi, 2013) (Gamboa, Silva, Pinto, & Margato, 2009).

An UPFC is a power electronic device capable of regulating the power flow in transmission grids. Selecting an appropriate matrix converter switching state, it is possible to control the active and reactive power that flows through some branches of the network. Recent approaches, based on sliding mode control techniques, also guarantee a decoupled control of active and reactive power (Monteiro, Silva, Pinto, & Palma, 2014) (Monteiro, Silva, Pinto, & Palma, 2011).

Traction substations are located along a railway network and its function is to receive the electrical power from the transmission grid and convert it to an adequate voltage to supply the locomotive’s traction systems. However, there are numerous locomotives crossing several countries, supplied by different traction substations, so locomotives’ traction systems are equipped with some electronic and mechanical devices that adjust the type of supply. To avoid the use of these devices, it is proposed that the traction substation on its own is able to adapt the supply to the
characteristics of the locomotive crossing its zone. This can be accomplished using matrix converters and a high frequency transformer (Mendes, 2013) (Drabek, Peroutka, Pittermann, & Cédil, 2011).

$v/f$ command is widely used in electrical drives, namely in applications that involve asynchronous motors. The torque developed by the motor is nearly proportional to the ratio of voltage amplitude and frequency of the supply, so it is possible, by acting in the $v/f$ ratio, to keep the torque constant throughout the speed range (Dente, 2011). A matrix converter, due to its capability to change output voltage amplitude and frequency, is being gradually adopted in this type of applications.

Matrix converters are replacing indirect converters in some electrical generators used in renewable energy applications, like DFIG (Castro, 2012) or PMSG. When a DFIG is used, the matrix converter is controlled with the aim of extracting the maximum available power from the wind and to control the power factor in the point of common coupling (Afonso, 2011) (Djeriri, Meroufel, Massoum, & Boudjema, 2014); when a PMSG is used, the matrix converter is controlled with the double objective of extracting the maximum available power from the wind and adapting the variable frequency of the stator quantities to the constant frequency of the grid (Fernandes, 2013).

In the applications described above, the matrix converter is operated as a Buck MC. This means that the voltage displayed by the conventional matrix converter is reduced, at least, by a factor of $\sqrt{3}/2$ in relation to the input voltage. In some applications, this can be a serious drawback. It could be interesting to have a device that could increase the voltage, instead of reducing it, because this type of feature is required by some applications.

In order to achieve the purpose of increasing the output voltage with respect to the input voltage, a different configuration of the matrix converter is studied in this paper – the Boost Matrix Converter (Boost MC).

We will see now a few exemplificative situations wherein a larger range of output voltage variation is required, therefore justifying the use of a Boost MC.

- **DVR** – In distribution networks, but also in transmission networks, the use of DVR helps in keeping the voltage profile under control, namely when voltage swells or voltage sags occur. When voltage sags are to be addressed, an increase in the output voltage with respect to the input voltage would be welcome.

- **UPFC** – To enhance active and reactive power control in transmission grids, a wider range of voltage variation would be a plus, since those quantities depend upon the voltage.

- **Electrical drives with $v/f$ command** – Sometimes, in electrical drives with $v/f$ command, it is necessary to increase the frequency of the supply $f$ to achieve a desired machine speed. To maintain the magnetization level and, at the same time, to keep the torque nearly constant, the voltage must be increased. As so, a matrix converter capable of increasing the voltage amplitude can be useful.

- **High-Voltage Direct Current (HVDC)** - is a long distance transmission system. It is composed by an AC/DC converter station at the emission, a DC transmission line and a DC/AC converter station at the receiving end. In order to guarantee an adequate DC transmission voltage, the input AC voltage must be step up using a transformer. To perform this function, a Boost MC maybe used instead.

This paper’s main goal is to give a novel contribution to the study of the Boost MC, as this type of matrix converter is poorly assessed in the available literature. In order to achieve such goal, the following twofold objective is to be accomplished:

1. Development of a full model, including modulation strategy, regulators design and filters sizing, to enable the study of the Boost matrix converter;
2. Validation of the modulation process, with the capability to control, over a wide range, the input/output quantities in terms of RMS value, frequency and power factor.

These are quite innovative aspects, portraying original contributions of this paper, because a review of the available literature showed that Boost MC have been insufficiently addressed, up to now.

This paper is organized as follows. In this chapter, a summary of the most important limitations of the classic matrix converter (Buck MC) utilization in some engineering applications is made and a different configuration of the matrix converter (Boost MC) is presented, in order to overcome those limitations. Chapter II offers an overview on matrix converter basics. The next chapter provides a full description of the innovative approach adopted to control the Boost MC. The changes performed in the conventional modulation process, as well as the details about the regulators design, are assessed in this chapter. Chapter IV presents the results that validate the modulation process, showing that the targets were attained; furthermore, the respective results discussion is offered. The last chapter finalizes the paper by presenting a set of conclusions that can be drawn.

II. MATRIX CONVERTER BASICS

The three-phase matrix converter is a particular case of the generic matrix converter and is composed by nine bidirectional switches that allow a total of $3^3=27$ possible combinations. Three-phase matrix converters allow the connection of each one of the three output phases to any one of the three input phases.

Referring to Figure 1 and assuming that the semiconductors that compose the bidirectional switches are ideal, each switch can be represented by a variable $S_{ij}$, described as follows:

$$S_{ij} = \begin{cases} \ 1, & \text{switch turned on} \\ \ 0, & \text{switch turned off} \end{cases} \quad i, j \in \{1, 2, 3\}$$

(1)

The switch states can be compacted in a $3x3$ matrix $[S]$:

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$

(2)
It is worth to point out that matrix \([S]\) relates line-to-neutral output voltages \(v_{ABC}\) with line-to-neutral input voltages \(v_{abc}\). Output currents \(i_{ABC}\) are converted in input currents \(i_{abc}\) through matrix \([S^T]\):

\[
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix} = S
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix}
= S^T
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]

(3)

III. MODULATION STRATEGY

A. Space Vector Representation

Two modulation strategies can be adopted to control the matrix converter: the Venturini approach and the Space Vector Modulation (SVM) approach. In the scope of this work, SVM approach was chosen over Venturini approach, because it ensures better input-output transfer relationships and also minimum harmonic distortion (Pinto S. F., 2003).

The main principle of the SVM approach is to consider that, at each time instant, the output voltages and the input currents can be represented as vectors in the \(\alpha\beta\) plan. This polar representation can be achieved by applying the Concordia’s transformation to each switch state combination.

When this operation is performed, it is possible to divide the resulting vectors in three groups: (i) rotating vectors (group I): constant amplitude, but variable angle; pulsating vectors (group II): constant angle, but variable amplitude and signal along the time; null vectors (group III): null amplitude and angle.

Rotating vectors were not considered in the modulation process, because the rotation in \(\alpha\beta\) plan increases the process complexity (Pinto S. F., 2003), but both pulsating and null vectors will be used.

Since the variable amplitude of pulsating vectors is dependent of the instantaneous values of input voltages \(v_{abc}\) or output currents \(i_{ABC}\), spatial location of output voltage vectors depends on time location of input voltages and spatial location of input current vectors depends on time location of output currents. The time location of input voltages is performed, dividing the waveform in twelve zones.

The criterion to perform the waveform division is to choose some notable points where a significant change in the relative position of the variables can occur.

Also, the same technique is applied in what concerns the time location of output currents.

B. Indirect Modulation

SVM approach requires a Pulse-Width Modulation (PWM) modulator, whose main function is to synthetize output voltages from input voltages and input currents from output currents. To allow the application of the well-known PWM modulation techniques, the matrix converter is represented by a rectifier-inverter association without DC link, in a process known as indirect modulation.

Under these conditions, the goal is to control input currents \(i_{abc}\) based on the intermediate stage current \(I_{DC}\) and to control output voltages \(v_{ABC}\) based on the intermediate stage voltage \(V_{DC}\). However, as there is no DC link, \(V_{DC}\) and \(I_{DC}\) are not real constant quantities, as so they suffer a time variation.

This rectifier-inverter association leads to several switch state combinations. Each switch is represented by a different variable, for the rectifier and inverter, respectively, that assumes the value ‘1’ when the switch is turned on and ‘0’ when the switch is turned off. One must keep in mind that input currents \(i_{abc}\) are directly related to \(I_{DC}\) through the rectifier’s modulation function \([S_R]\) and output voltages \(v_{ABC}\) are directly related to \(V_{DC}\) through the inverter’s modulation function \([S_I]\).

Intermediate stage voltage \(V_{DC}\) is imposed by the rectifier and is directly dependent on input voltages \(v_{abc}\). On the other hand, intermediate stage current \(I_{DC}\) is imposed by the inverter and is directly dependent on output currents \(i_{ABC}\).

For each pair of rectifier-inverter possible combinations, there is a correspondent configuration of switches of the matrix converter and thus an associated vector, excluding rotating vectors.

As discussed previously, the output voltage displayed by the conventional matrix converter is limited to, at most, \(\sqrt{2}\) of the input voltage. This means that this converter reduces the voltage displayed in the output, as compared to the input voltage, so it is called Buck Matrix Converter (Buck MC).

In this case, the quantities to be controlled are the output (load) voltage and the input (feeder) currents, so the PWM modulator receives the reference values \((V_{out-ref} \text{ and } I_{in-ref})\) and also the information about the quantities \((V_{DC} \text{ and } I_{DC})\) used to generate the controlled quantities.

In the matrix converter developed in the scope of this paper, it is intended that the voltage displayed by the converter is higher than the input voltage, so it is named Boost Matrix Converter (Boost MC). The quantities to be generated by the PWM modulator are the input voltage and the output current, but now these quantities are treated as command quantities, being the control process of the load voltages and the feeder currents performed by two independent regulators. The design of these regulators will be detailed further in this paper.

C. Space Vector Modulation – Application to the Boost Converter

Rectifier

The rectifier has two functions: (i) to guarantee that the output current (a command current) follows its reference; (ii) to generate the intermediate stage voltage \(V_{DC}\).

When applying Concordia’s transformation, the nine possible switch state combinations of the rectifier result in nine spatial vectors.

Knowing the desired location for the output current in the \(\alpha\beta\) plan, it is possible to synthetize it using the vectors adjacent to the respective sector. This process is illustrated in Fig. 2.

In Fig. 2 \(I_{\delta\theta}\) are generic adjacent vectors, \(d_{\delta\theta}\) are the appropriate duty cycles and \(\theta\) is the angle of the current reference vector in the respective sector.
Considering that the converter operates with a switching frequency much higher than the output frequency ($f_s \gg f_{out}$), it can be ensured that, in each switching period, the reference vector $I_{out_refa\beta}$ is given nearly by:

$$I_{out_refa\beta} \approx I_0 d_0 + I_\alpha d_\alpha + I_\beta d_\beta$$

(4)

Based on a trigonometric analysis of the diagram depicted in Fig. 2, the duty-cycles $d_\alpha$, $d_\beta$, and $d_0$ are given by the following expressions:

$$\begin{align*}
    d_\alpha &= m_s \sin(\frac{\pi}{3} - \theta_i) \\
    d_\beta &= m_s \sin(\theta_i) \\
    d_0 &= 1 - d_\alpha - d_\beta
\end{align*}$$

(5)

wherein $m_s$ is the current modulation index.

The intermediate stage current

$$I_{out_refa\beta}$$

relates to the amplitude of the reference vector $V_{in_refa\beta}$ with the intermediate stage voltage $V_{DC}$ as follows:

$$m_s = \frac{V_{in_refa\beta}}{V_{DC}}$$

(6)

wherein $V_{in_{max}}$ is the amplitude of the reference vector $V_{in_refa\beta}$:

It should be noted that the intermediate stage current $I_{DC}$ imposed by the rectifier.

The intermediate stage voltage $V_{DC}$ is the rectifier output and can be calculated considering that the active power is invariant along the system: $P_{DC} = P_{out}$, wherein $P_{DC}$ is the power in the DC intermediate stage and $P_{out}$ is the output power.

Developing the power equality, we get:

$$V_{DC}I_{DC} = \frac{3}{2} I_{out_{max}}V_{out_{max}} \cos(\phi_{out})$$

(7)

wherein $V_{out_{max}}$ is the amplitude of the output voltage and $\phi_{out}$ is the angle between the output voltage and the output current.

From (7), it results:

$$V_{DC} = \frac{3}{2} \frac{I_{out_{max}}V_{out_{max}} \cos(\phi_{out})}{I_{DC}} = \frac{3}{2} m_s V_{out_{max}} \cos(\phi_{out})$$

(8)

**Inverter**

The inverter has two functions: (i) to guarantee that the input voltage (a command voltage) follows its reference; to generate the intermediate stage current $I_{DC}$.

Once again, when applying Concordia’s transformation, the eight possible switch state combinations of the inverter result in eight spatial vectors.

The technique is similar to the one presented for the rectifier’s output currents, but in this case the methodology is applied to the inverter’s input voltages.

Now, the constant $m_v$ creates the relationship between the amplitude of the reference vector $V_{in_refa\beta}$ with the intermediate stage voltage $V_{DC}$ as follows:

$$m_v = \frac{V_{in_{max}}}{V_{DC}}$$

(9)

wherein $V_{in_{max}}$ is the amplitude of the reference vector $V_{in_refa\beta}$.

In this situation, the intermediate stage voltage $V_{DC}$ is imposed by the rectifier.

The intermediate stage current $I_{DC}$ is the inverter output and, once again, can be estimated considering that the active power is invariant along the system, leading to:

$$I_{DC} = \frac{3}{2} \frac{V_{in_{max}}}{V_{DC}} V_{in_{max}} \cos(\phi_{in}) = \frac{3}{2} m_v V_{in_{max}} \cos(\phi_{in})$$

(10)

wherein $V_{in_{max}}$ is the amplitude of the input current and $\phi_{in}$ is the angle between the input voltage and the input current.

**D. Indirect Modulation – Application to the Boost Converter**

Considering switching frequencies high enough when compared to the input and output frequencies ($f_s \gg f_{in}$ and $f_s \gg f_{out}$), it can be assumed that, during a switching period, the average values of $V_{DC}$ and $I_{DC}$ are constant.

Based on this assumption, the input voltage modulation and the output current modulation can be applied to the rectifier–inverter association, considering that the modulation function requires five state vectors: two nonzero vectors, which are used to perform the input voltage modulation, another two nonzero vectors, with the aim of performing the output current modulation, and a null vector.

The operating times of each one of the chosen vectors is obtained by multiplying the rectifier and inverter related duty-cycles. The result of these operations is given in (11).
\[
\begin{align*}
    d_y d_a &= m_c m_a \sin(\frac{\pi}{3} - \theta_1) \sin(\frac{\pi}{3} - \theta_2) \\
    d_y d_b &= m_c m_a \sin(\frac{\pi}{3} - \theta_1) \sin(\theta_2) \\
    d_y d_c &= m_c m_a \sin(\theta_1) \sin(\frac{\pi}{3} - \theta_2) \\
    d_y d_c &= m_c m_a \sin(\theta_1) \sin(\theta_2) \\
    d_0 &= 1 - d_y d_a - d_y d_b - d_y d_c - d_5 d_6
\end{align*}
\] (11)

For a matter of simplicity, \( m_c \) is defined as 1.

Once the duty-cycles are defined, it is mandatory to determine the vectors that participate in the modulation process, as well as the order in which they are selected. This degree of freedom could be used to minimize the harmonic distortion of the currents and/or to minimize the number of switching commutations. The selection of the vector in each instant depends not only on the sector location of the input reference voltage \( V_{in_a} \), but also on the sector location of the output reference current \( I_{out_a} \). A look-up table was built to help in the selection process.

To know the time interval during which the corresponding vectors are applied to the converter, a sawtooth high frequency carrier waveform is compared to the duty cycles stated in (11). This process can be seen in Fig. 4.

![Figure 4](image1.png)

**Fig. 4.** PWM modulation process used to select the time interval during the appropriate vectors are applied.

Fig. 5 illustrates the whole selection scheme, with an exemplificative situation.

### E. Regulators Design

This section presents the detailed project of the two regulators in the system.

One of the regulators controls the voltage at the load’s terminals and the other one controls the current injected in the grid. These regulators will generate the references to the command quantities used by the modulation process described in the previous section, therefore controlling the load’s voltages and the current injected in the grid.

![Figure 5](image2.png)

**Fig. 5.** Selection scheme for the SVM vectors.

### Voltage Regulator

The voltage regulator is designed to ensure that the voltage at the load terminals effectively follows a certain reference. So, the controlled voltage is the capacitor voltage \( V_c \), which is almost equal to the load voltage \( V_{load} \), as can be seen in the single-line diagram of Fig. 6.

![Figure 6](image3.png)

**Fig. 6.** Boost matrix converter feeding a RL load.

In the design of this regulator, the load current \( I_{load} \) is treated as a disturbance of the system. The current \( I_{matrix} \) represents the current that flows through the matrix converter and that is controlled by the current regulator, whose design will be further discussed next.

Applying the KCL (Kirchhoff’s Current Law) to the node and considering an alpha-beta representation, we have the following system of equations:

\[
\begin{align*}
    C \frac{dV_{ca}}{dt} &= i_{load_a} - i_{matrix_a} \\
    C \frac{dV_{cb}}{dt} &= i_{load_b} - i_{matrix_b}
\end{align*}
\] (12)

where \( V_{ca,cb} \) are the capacitor voltages, \( i_{matrix_a,cb} \) are the currents that flow through the matrix converter and \( i_{load_a,b} \) are the load currents, all in alpha-beta coordinates. \( C \) is the capacitance value of the capacitor.

Now, using Park’s transformation we set the dq representation of the system, in the canonical form:

\[
\begin{align*}
    \frac{dV_{cd}}{dt} &= i_{load_d} - i_{matrix_d} + \omega V_{cq} \\
    \frac{dV_{cq}}{dt} &= i_{load_q} - i_{matrix_q} - \omega V_{cd}
\end{align*}
\] (13)

where the additional terms \( \omega V_{cq,d} \) are the cross terms that result from the application of Park transformation; these terms represent the interaction between the two components of the transformation.

Rewriting the equations above as functions of \( l_{cd,eq} \), the command currents that allow the voltage control, we get the following system:

\[
\begin{align*}
    \frac{dV_{cd}}{dt} &= \frac{i_{load_d}}{C} + \frac{1}{C} l_{cd} \\
    \frac{dV_{cq}}{dt} &= \frac{i_{load_q}}{C} + \frac{1}{C} l_{eq}
\end{align*}
\] (14)

Thus,
\[
\begin{align*}
I_{eq} &= -l_{matrix_{eq}}' + C_o V_{eq} \\
I_{cd} &= -l_{matrix_{cd}}' + C_o V_{cd}
\end{align*}
\] (15)

where \(l_{matrix_{eq}}'\) is an image of the current \(l_{matrix_{eq}}\) that flows through the converter. \(l_{matrix_{cd}}\) differs from \(l_{matrix_{cd}}'\) by a delay introduced by the converter operation.

These equations can be used to build the voltage regulator block diagram, which is presented in Fig. 7, in which the cross terms have been neglected.

The reference current \(I_{ref_{eq}}\) and the measured capacitor voltage \(V_{meas_{eq}}\), the voltage error, is applied to a Proportional-Integral (PI) Controller, which generates the reference current \(I_{dq_{eq}}\) used by the modulation process. The block \(1/sT_{eq}\), a first order transfer function with a delay \(T_{eq}\), represents the matrix converter current by the converter and the modulation process; the constants \(a_c\) and \(a_i\) are the sensor voltage gain and sensor current gain, respectively. This is a consequence of \(K\) being an incremental gain that aims at representing the gain of the converter, relating the matrix converter output voltage to the disturbance introduced by the load current.

With respect to the PI controller, it normally ensures a null static error and a reasonable rise time. Parameters \(K_{pv}\) and \(K_{ip}\) can be calculated by deriving the transfer function that represents the capacitor voltage response to the disturbance introduced by the load current.

### Current Regulator

The current regulator aims at imposing the grid injected \(I_{grid}\) current within some pre-determined values. The process employed to model the current regulator is similar to the one used in the voltage regulator. Hereafter, we present only the main stages of the methodology.

First, we apply the KVL (Kirchhoff’s Voltage Law) to the grid mesh, and then we apply Park’s to the resulting set of equations. After some algebraic manipulation, we obtain:

\[
\begin{align*}
\frac{di_{grid_{d}}}{dt} &= -\frac{R_{filt}}{L_{filt}}i_{grid_{d}} - \frac{V_{grid_{d}}}{L_{filt}} + 1/L_{filt}U_{cd} \\
\frac{di_{grid_{q}}}{dt} &= -\frac{R_{filt}}{L_{filt}}i_{grid_{q}} - \frac{V_{grid_{q}}}{L_{filt}} + 1/L_{filt}U_{cq}
\end{align*}
\] (16)

wherein \(i_{grid_{d}}\) are the RMS grid injected currents, \(V_{grid_{d}}\) are the RMS grid voltages, \(U_{cd}\) are the command voltages used by the modulation process that ensure grid currents follow their references, \(R_{filt}\) is the resistance of the grid filter and \(L_{filt}\) is the inductance of the grid filter.

The current regulator block diagram obtained is represented in Fig. 8:

Fig. 8. Simplified current regulator block diagram.

The reference current \(I_{grid_{ref_{eq}}}\) and the measured current \(I_{meas_{eq}}\) are subtracted and the difference is applied to a Proportional-Integral (PI) Controller, which returns the command voltage \(U_{eq}\) used by the SVM. Moreover, the block \(K/sT_{eq}\), a first order transfer function with a delay \(T_{eq}\), models the matrix converter and the modulation process. The constant \(a_c\), that affects the reference current and the measured current, is a sensor current gain, as was referred previously. \(K\) is an incremental gain that aims at representing the gain of the converter, relating the matrix converter output voltage with the command voltage.

For simplicity in the controller design, the contribution of the disturbance, the grid voltage \(V_{grid}\), is accounted with a fictitious resistance \(R_{grid}\), which is added to the filter resistance \(R_{filt}\), leading to a total resistance \(R_{eq}\). In what concerns the PI controller, its parameters can be estimated by deriving the transfer function that relates the measured grid current with the reference grid current. However, it should be pointed out that the incremental gain \(K\) and the parameter \(R_{eq}\) change with the operating conditions, therefore \(T_{eq}\) and \(T_{eq}\) (which depend on \(K\)) are not constant, also depending on the operating conditions.

### IV. VALIDATION RESULTS AND DISCUSSION

The simulation and the respective results record are performed in Matlab/Simulink® and are aimed at validating the adopted modulation process, with a few tests performed with a generic RL load connected to the Boost matrix converter terminals.

Bearing in mind the approach followed in this paper in terms of modulation strategy, regulators design and also filter sizing, the Boost matrix converter must be able:

1. To increase the RMS value of the voltage displayed at its own terminals;
2. To adapt the frequency of the quantities associated to the load to the grid frequency;
3. To control the power factor as seen from the grid (variable \(\Phi_{grid}\)).

The tests are conducted with the aim of showing the above mentioned Boost matrix converter features.

#### A. Case-Study 1

In this case-study, the Boost MC capability of displaying a voltage with an amplitude value \(V_{load}\) higher than the grid voltage amplitude value \(V_{grid}\), for the same frequency conditions, will be demonstrated. In this case, the objective is to set a load voltage equal to 2000 V (maximum value) from a feeder voltage equal to \(\sqrt{2} 690\) V (maximum value).

Fig. 9 shows both the time evolutions of the load voltage displayed by the Boost MC and the grid voltage.
From Fig. 9, it can be observed the increase of the voltage amplitude between the grid side and the load side of the converter, which was the purpose of this test.

B. Case-Study 2

In this case, a frequency test is made in order to proof that the Boost MC is able to adapt the load frequency to the grid frequency. For this purpose, a step in the load frequency is imposed, wherein the frequency associated to the load quantities jumps from an initial value ($f_{in} = 50\text{Hz}$) to a final value ($f_{fin} = 100\text{Hz}$) at 0.8 seconds.

In order to demonstrate that a successful frequency adaptation is performed by the Boost MC, a simulation was carried on and the corresponding results referring to the time evolution of both the load current and the grid current are depicted in Fig. 10.

As can be seen from Fig. 10, when a frequency fluctuation occurs in the load side of the Boost MC, the frequency of the grid current remains unchanged, as required. It should be noted that to the boost effect in the load voltage corresponds a decrease of the load current so that the active power remains constant.

C. Case-Study 3

In this test, the Boost MC’s capability to control the power factor at the interconnection point with the grid is to be verified. Now, we set the simulation conditions to achieve a capacitive power factor in the grid ($\phi_{grid} = -20^\circ$). The grid voltage and the grid current are depicted in Fig. 11.

Analysing the results presented in Fig. 11, one come to the conclusion that, although the load inductive characteristics, the current injected into the grid can be controlled so that it presents a capacitive power factor. It should be noticed that this procedure is required, in many cases, by the Transmission System Operator (TSO), to help voltage control.

D. Case-Study 4

As far as case-study 4 is concerned, a double change in the simulation conditions will be performed: at 0.6 seconds, the frequency of the load voltage jumps from 50Hz to 100Hz and, at the same time, the amplitude of the load voltage jumps from 1500V to 2000V.

Regarding this case-study, the most interesting results are shown in Fig. 12 and Fig. 13.

Concerning Fig. 12, until 0.6 seconds, the Boost MC successful elevates the voltage to 1500V, with the desired frequency of 50Hz. After this critical point, when the simulation conditions are modified, a short transient can be observed. However, the converter’s response is very fast and the desired values of voltage amplitude ($V_{load} = 2000V$) and frequency ($f_{load} = 100Hz$) are quickly reached.

With respect to Fig. 13, the main conclusion is that, despite the existence of a current peak at the critical point, the current injected in the grid is not affected by the change in the load conditions ($V_{load} = 2000V$ and $f_{load} = 100Hz$): the frequency remains invariant and equal to 50Hz and the inevitable increase in the current amplitude in order to accommodate the boost in load voltage amplitude can be observed.
Matrix converters are advanced power electronics devices that have been subject to intense research and development over the past years. As a consequence, there are already some applications where they are used. Up to now, matrix converters have been used as Buck matrix converters, meaning that they operate as AC/AC electronic transformers, in which the output voltage is lower than the input voltage. However, its operation as Boost matrix converters, i.e. electronic AC/AC transformers that increase the output voltage with respect to the input voltage, can be envisaged. This was the main objective of this paper: to propose a novel operation of the matrix converter with voltage boost characteristics.

The work performed in the scope of this paper allowed the development of a full detailed model able to describe the behaviour of the Boost matrix converter. The used methodology combined Space Vector Modulation, Pulse-Width Modulation and classic control techniques in an innovative approach to the conventional modulation strategies.

After the completion of the paper, it was theoretically established and demonstrated via simulation that this converter is able to:

- Increase the RMS value of the voltage displayed at its own terminals.
- Perform a frequency adaptation between the input and output quantities.
- Control the power factor in the point of common couple.

From the developed project tasks, the most significant one is undoubtedly the innovative Boost matrix converter modulation strategy and its validation through simulation results. This fills a gap in the matrix converter area, since the conventional matrix converter - the Buck matrix converter - presents some relevant limitations that restrain its application field. In engineering applications that require a larger range of output voltage, like High-Voltage Direct Current, Dynamic Voltage Restorer, Unified Power Flow Controller or electrical drives with v/f control, an increase in the output voltage with respect to the input voltage will be most welcome, hence the interest of the Boost matrix converter.

V. CONCLUSIONS

VI. REFERENCES


