Power Electronics Active Voltage Regulators for Unbalanced LV grids

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Abstract – This paper presents the analysis, design and implementation of a matrix converter for voltage regulation in low voltage (LV) grids for unbalanced loads. The proposed regulator contains a direct AC/AC converter with four arms, and uses sliding mode direct control associated to the space vector representation technique. Together with the Matrix converter, a series transformer is used to allow the voltage regulation in the LV distribution line. The proposed system is able to regulate the voltage in a low grid even when the load is different in all phases in addition the system is also able to regulate the voltage in low grid if it occurs a perturbation in medium voltage.

Keywords – Low Voltage Grid Regulation, Unbalanced System, Four Arms Matrix Converter, Sliding mode control, Voltage Sag, Voltage Swells.

I. Introduction

In the past the electrical system was considered a unidirectional grid, but nowadays the paradigm has changed. Decentralized electric energy production has been assuming an increasing weight, creating new problems to the control and stability of the power grid. The connection of micro generators directly on LV grid creates a few problems like swells and sags in the voltage to the terminals of load especially in no load scenarios. Due to this situation the regulation of voltage on grids presents new problems and requires a more complex and frequently regulator.

With this new paradigm is necessary to rethink the strategies to make the regulation of voltage in LV grids and make new approaches which are capable to guarantee the quality of energy.

The quality of energy established for the EN 50160 is the main purpose of these regulators.

The main aim of the proposed system is to ensure that the rms value of the grid voltage is always within the range defined by the standard EN 50160 [1].

The proposed voltage regulator (Fig.1) is based on a Conventional Matrix Converter with Four Arms (CMC4A) which allows the control of unbalanced loads and the direct AC/AC power conversion, without a DC energy storage link which allows the reduction of the power converter volume, weight and cost when compared to the AC/DC/AC converter.

Figure 1 - Distribution transformer with active voltage regulator

The entire system consisting of a CMC4A and additional series transformer, that should be installed in the substation in the low voltage side.

II. Matrix Converter

A. Four Arms Matrix Converter

The Conventional Matrix Converter with Four Arms is made by bi-directional semiconductor switches that connected the input three phase system to the three phase and neutral output system (Fig. 2). The bi-directional switches result from the association of a pair of power semiconductors with turn-off capability with a pair of diodes. This association allows bidirectional power flow and direct AC/AC conversion without any intermediate stage, guaranteeing higher efficiencies.
The converter for three-phase systems could be considered as an array of twelve bidirectional ideal switches. Representing each switch $S_{ij}(k \in \{1,2,3,4\} \ j \in \{1,2,3\})$ as a binary variable with two possible states: “$S_{ij}=1$” if the switch is ON and “$S_{ij}=0$” if it OFF. The twelve switches could be represented by a matrix $3 \times 4 \ S$ (1).

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \\ S_{41} & S_{42} & S_{43} \end{bmatrix}$$

(1)

In this three-phase four leg converter some topological constraints should be guaranteed. It is not possible to short-circuit the input phases of the converter connected to the grid and it is not allowed to leave the converter output inductive phases open. As a result of these constraints, there are only 81 possible switching combinations.

With $S$ matrix it is possible to relate the output phase voltage of the converter with the input phase voltages (2). It is also possible to relate the input currents to the output currents of the converter (2).

$$\begin{bmatrix} V_A \\ V_B \\ V_C \\ V_N \end{bmatrix} = S \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \hspace{1cm} \begin{bmatrix} I_A \\ I_B \\ I_C \\ I_N \end{bmatrix} = S^T \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

(2)

**B. Filter Sizing**

Due to the high frequency of the commutation that semiconductors operate the AC/AC energy conversion needs filter elements to ensure the energy quality.

The input filter is a second order filter with damping resistance that monophasic model is representing in figure 3 [2].

**Figure 3 - Monophasic Model of Input Filter**

This is the filter topology that presents lower losses and minimizes the oscillations. The values of filter parameters are resumed in table 1.

<table>
<thead>
<tr>
<th>$C_f (\mu F)$</th>
<th>$L_f (\mu H)$</th>
<th>$r_b (\Omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>245</td>
<td>542</td>
<td>0.5148</td>
</tr>
</tbody>
</table>

Table 1 – Input Filter Parameters

The output filter is necessary to filter the high frequency harmonics present in matrix converter output voltages. To guarantee this filtering it is used a lowpass filter that monophasic model is representing in figure 4.

**Figure 4 - Monophasic model of Output Filter**

The values of filter parameters are presented in table 3.

<table>
<thead>
<tr>
<th>$L (\mu H)$</th>
<th>$C (\mu F)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>79</td>
<td>888</td>
</tr>
</tbody>
</table>

Table 2 - Output Filter Parameters
III. Control of the System

To control the matrix converter it is used the space vector representation. The space vectors are obtained representing the output voltages and currents as vectors in a plane αβ0 using the transpose of Concordia transformation (3).

\[
\begin{bmatrix}
V_a \\
V_β \\
V_0
\end{bmatrix} =
C^T
\begin{bmatrix}
V_{AN} \\
V_{BN} \\
V_{CN}
\end{bmatrix}
(3)
\]

A. Control of Matrix Converter Output Currents

To control the matrix converter output currents it is necessary to implement a sliding mode controller [3]. In this closed loop controller the currents measured at the converter output are compared to their reference values (4). The difference between the measured value and the reference value would be indicating what the value of the vector that will have a better effect on a value of an output converter current.

\[
\begin{align*}
e_{ia} &= i_{a,ref} - i_a \\
e_{ib} &= i_{b,ref} - i_b \\
e_{io} &= i_{0,ref} - i_0
\end{align*}
(4)
\]

The control errors at αβ0 are quantified using two hysteresis comparators using two comparators, it’s possible to obtain three levels of error (-1,0,1). Crossing this information with the voltage zone where system was in each instant and analyse the components of all vector, it’s made the choice in which vector would be chosen to make a better control of the system.

The criterions to choose the space vector are:

- If \( e_a > 0 \) then \( i_{a,ref} > i_a \) so should be chosen a vector to increase the current \( i_a \) it should be a vector with \( V_a > 0 \).

- If \( e_a < 0 \) then \( i_{a,ref} < i_a \) so should be chosen a vector to decrease the current \( i_a \) it should be a vector with \( V_a < 0 \).

- If \( e_q = 0 \) then \( i_{q,ref} = i_q \) so should be chosen a vector to increase the current \( i_q \) it should be a vector with \( V_q = 0 \).

The same criterions are used to the component \( β0 \).

After analysing all the 81 vectors, we conclude that exist always two possibilities for control the matrix converter output current. It’s that degree of liberty that will permit to control the matrix converter input current.

B. Control of Matrix Converter Input Power Factor

To control the input power factor of the matrix converter is also implement a sliding mode control. In this case the close loop is over the component \( q \) of the input current. In this case the main aim is to have the input power factor unitary then the reactive power should be zero. In coordinates \( dq \) the reactive power could be written by (5) [4].

\[ Q_{dq} = V_d i_q \]

(5)

It’s possible to conclude that the reference of \( i_q \) should be zero. The control is made measuring the difference between the reference value and the measured value (6).

\[ e_{iq} = i_{q,ref} - i_q \]

(6)

The control errors \( e_{iq} \) are quantized using one hysteresis comparators obtained two level of error (-1,1). Based on this information and considering the two available vectors to control the matrix converter output current that will be chosen the vector that has the best component of \( i_q \) to approximate the measure value to the reference.

The criterions to choose vector are:

- If \( e_{iq} > 0 \) then \( i_{q,ref} > i_q \) so should be chosen a vector to increase the current \( i_q \).

- If \( e_{iq} < 0 \) then \( i_{q,ref} < i_q \) so should be chosen a vector to decrease the current \( i_q \).
In case of the error in matrix converter output current be zero and considering that in this situation the a non-ideal chosen for an output current doesn’t have a very harmful effect, in this situation is harmless to use the vector that better control the input current.

To know which is the vector that have the better component of $i_q$ is calculated in each instant the value of $i_q$ of all vectors.

C. Control of the Low Voltage Grid

The main aim of the propose system is guarantee that low voltage in LV grid within the limits establish by the EN 50160 [1]. To obtain this main the system should be able to measure the voltage in a capacitor that was in parallel with LV grid and generate a reference current for the matrix converter output current control [5].

As the output currents of matrix converter are controlled, it is possible to represent the distribution line as a current source (Fig 3).

### Table 3 - Parameters of PI Controller

<table>
<thead>
<tr>
<th>$T_d(\mu s)$</th>
<th>$K_p$</th>
<th>$K_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.6530</td>
<td>3316</td>
</tr>
</tbody>
</table>

IV. Simulation Results

In order to analyse the performance and robustness of the system, several simulations were performed in MatLab/ Simulink. These simulations are made considering a resistive load at 80% of the transformer rated power (630kVA) and duration of 0.4 [s].

A. Balanced Load in the LV grid

These simulations are made considering a balance decreasing of load in LV grid of 20% at nominal value.

![Figure 5 - Scaled Model of Low Voltage Control](image1)

![Figure 6 - Diagram blocs of the system](image2)

Calculating the transfer function in closed loop (7) and equalizing the denominator to a three order polynomial (8) it’s possible obtain the values of the parameters of the PI controller $T_d$, $K_p$, $K_i$.

$$\frac{V_{carga}}{I_{carga}} = \frac{s^3 T_d + s^2}{s^3 T_d C + s^2 + s k_p \frac{G_i}{\alpha_i} + k_i \frac{G_i}{\alpha_i}}$$  \hspace{1cm} (7)

$$f(s) = s^3 + 1.75\omega_n s^2 + 2.15\omega_n^2 + \omega_n^3$$ \hspace{1cm} (8)

Analysing the figures 7 and 8 it’s possible to confirm the positive reply of propose system because even the current in LV grid increases due to the decreasing of load the value of voltage doesn’t change, its value keeps according to the established by EN 50160 [1].

![Figure 7 - Current in LV grid](image3)

![Figure 8 - Voltage in LV grid](image4)
For the same situations it is possible to see that current in medium voltage (MV) grid isn’t very affected by the change of load voltage.

**B. Unbalanced Load in LV Grid**

These simulations are made considering a balance decreasing of load in phase A of LV grid of 20% of nominal value.

The good reply of system is also confirmed when the unbalanced occurs in more than one phase as shown by the figures 12 and 13.

For these both situations the current in the medium voltage grid keep without effects of these changes in the load.

The figures 10 and 11 show the good reply of system with this disturbance on the load value.
The current increases its value and distorts its form, this is a consequence of the system has operated near its limits.

Even considering this fact, the current and voltage in LV grid maintain their form and aren’t affected by this perturbation as can be seen in figures 18 and 19.

It’s also important to show the voltage in series transformer because in this situation de AC/AC converter is injecting power in the LV grid, so the voltage in series transformer increases and keeps the same phase (Fig 20).

C. Voltage Sag at MV Grid

These simulations are made considering 10% balance sag at MV grid. This is the most onerous situation for the system because the feed voltage of converter suffers a important decreasing and this fact places the converter works near his physic capacity.

Figure 16 and 17 shows the sag in MV grid.
D. Voltage Swell at MV Grid

These simulations are made considering 10% balance swell at MV grid. In this situation, the system has a good reply even in the current in MV grid. The Figures 21 and 22 show the effect of a swell in voltage and current in MV grid.

Even the effect of the swell in LV grid is controlled by the system proving the efficiency of the proposed system (Fig 23 and Fig 24).

It's also important to show the voltage in serie transformer because in this situation the AC/AC converter is receiving power of the grid, so voltage in serie transformer increases its value and changes the phase to compensate this perturbation (Fig 25).

CONCLUSIONS

The solution proposed in this work showed to be robust in the LV grid voltage regulation. Its permitted the right control of voltage in LV grid for different issues on the load. Its main advantage is the low time response, allowing the LV grid to be nearly immune to issues as voltage sags (10%) or voltage swells (20%) in Medium Voltage.

The sliding mode control method of the Matrix Converter input currents associated to the space vector representation, proved to be adequate, guaranteeing that the converter can be seen as an almost resistive load due to the nearly unitary PF at the input of the converter.

The voltage controller used (based on PI compensators) performed well, allowing a quick response while ensuring system stability for multiple operation scenarios.
REFERENCES


