Matrix Converter Prototype with Four Arms Option

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Abstract—This paper describes the design, construction, and testing of a matrix converter prototype with a fourth arm option. This device makes a direct energy conversion (AC/AC) between source and load without the need of energy storage elements, this characteristic will allow the construction of a light and compact converter.

A short review will be made by decomposing the matrix converter global schematic in its several parts, namely: the power circuit and its protections; the command one, which with its galvanic insulation will allow the digital signs generated by the FPGA to be transmitted to the power modules; the voltage and current acquisition circuit that will provide to the DSP the images of the input voltages and both the input and output currents as well, and to the FPGA the signs of this last ones.

The experimental results were obtained over an RL load by setting the output frequency as 100 Hz and the voltage ratio as 60%. By comparing the obtained results with the MATLAB simulations it is seen that the prototype is operating as expected.

Keywords: Matrix Converter, Matrix Converter Prototype, Venturini PWM, Power Modules.

I. INTRODUCTION

In power electronics is named as AC/AC converter an electronic system, with switching power semiconductors, fed by electric alternating generators, transferring the energy from these generators into a load, with the shape of electrical alternating greatnesses with the characteristics of (voltage, current or frequency) different from the ones of the generator [1].

The energy conversion between load and generator can be achieved in two ways, directly or indirectly, this last one is performed in two stages, on the first one (AC/DC) the alternated greatnesses rectification is performed, the second one (DC/AC) performs the inversion, in this case there’s a need to use a middle storage stage with an electrolytic capacitor usually named as DC link (Fig. 1 a). The direct conversion (AC/AC) doesn’t need the middle storage stage (Fig. 1 b), the conversion is made based on power semiconductors by switching them on and off (IGBT, MOSFET and MCT).

The matrix converter is a direct converter because it barely uses storage elements. This characteristic will allow the construction of compact converters. The electronic bidirectional switches are the main elements operating on the conversion process (Fig. 2), here the output voltages will be obtained based on the input ones and the input currents based on the output ones, trying always to achieve sinusoidal wave forms with almost unity power factors by using dedicated control methods such as the Venturini PWM [2] and space the vector modulation (SVM) [3].

The matrix converter structure is based on power semiconductors and therefore there’s a need to integrate the biggest number as possible of this components into power modules. In this work each power module is composed by six IGBTs, forming tree bidirectional switches, such as $S_{11}$, $S_{12}$ and $S_{13}$ in (Fig. 2).

This converter provides output voltages with variable amplitude and frequency, these characteristics make it ideal for drives and by operating at high frequency will generate harmonic content that can be filtrated with a low pass filter.

The advantages of the matrix converter are: sinusoidal input current; low cost; high reliability; compactness; no need of storage capacitor (DC link), conversion of (AC/AC, AC/DC, DC/AC).

The disadvantages are: the amount of semiconductors; low output voltage; complex control techniques; new technology.

II. STATE OF THE ART

Nowadays the awareness of systems based on electrical energy has been increasing, either by demand of efficiency, by using renewable energy based systems or even by the demand of alternative mobility systems. Whatever the system may be it will certainly have an electronic power converter as its integrant part.

Due to the matrix converter versatility, reliability and compacticity they have been used in several areas, from renewable energy such as wind power generation applications [4], variable speed drives in which the company Yaskawa Electric as several matrix converters on the market, in power

Fig. 1. AC/AC generic power converter schematic: a) Indirect converter, b) Direct converter.

Fig. 2. Four arm matrix converter topology.
flow control [5] or even as utility power supply were by using the fourth arm allows the supply of unbalanced or single phase [6] loads.

III. GLOBAL OVERVIEW OF THE MATRIX CONVERTER

The global schematic of the matrix converter is shown on (Fig. 3). In this chapter it will be performed the description of all its parts, on the next two the sizing of the components will be performed, one chapter will be devoted to the matrix converter and another one to the voltages and currents acquisition circuit.

Fig. 3. Matrix converter global schematic.

The (Fig 3) is composed by tree main circuits, namely, the power circuit, the command and drive and the voltages and currents acquisition, these are divided in the following way:

- **Power circuit:**
  o Power modules (electronic bidirectional switches);
  o Input Filter;
  o Protection circuits;
  o Heat sink.

- **Command and drive circuit:**
  o Command circuit:
    - Four steps commutation strategy (in the FPGA);
    - FWM Venturini modulation (in the DSP);
  o Drive circuit (Optocouplers);
  o Switched power supply.

- **Voltages and currents acquisition circuit.**

A. Power Circuit

1) Power Modules

The power module of (Fig. 4) was extracted from the DANFOSS 1200V/25A datasheet.

Fig. 4. a) DANFOSS power module 1200V/25A, b) Connections schematic.

Each module is composed by six IGBTs in common collector, each of them can withstand 1200V of collector-emitter voltage and a 25A collector current, each of the matrix converter four arms is composed by one of the power modules.

Because there’s no bidirectional semiconductors, these are connected in anti-series, with diodes in anti-parallel, allowing the current to flow both ways, from source to load \((i_L > 0)\), e.g., throught \(S_{1p}\) and \(D_{1p}\), or from load to source \((i_L < 0)\) throught \(S_{1n}\) and \(D_{1n}\) (Fig. 5), and to block both positive and/or negative voltages, this electronic bidirectional switch could be \(T1\) and \(T2\) in (Fig. 4).

Fig. 5. ) Representation of the semiconductors who, depending on the load current sign with intervene in the commutation process.

The command signs applied to the IGBT gates will give rise to transients due to the LC characteristic of the circuit formed by the tracks parasitic inductance and the gate capacitance, in order to avoid this transients the sizing of a damping gate resistor will be necessary. Parallel to this other phenomena will arise, namely overvoltages between gate and
emitter, to avoid them a protection will have to be sized as well as a gate emitter discharge resistor.

2) Input filter

There are tight rules towards the power electronics harmonic injection, also these converters usually work by assuming that the input voltages have an ideal behavior, therefore a low pass input filter sizing is necessary for the filtering of high frequency harmonic content. It is expected due to these filter capacitors a low voltage ripple during the commutation process.

3) Input and output protection

In case of a commutations error and in order to avoid the damage of the matrix converter whether due to overvoltages or to over currents it should be provided with protections. The use of fuses will provide protection against over currents and short circuits. The protections against overvoltages is provided by the use of MOV varistors connected between the input and output phases, in case of a transient overvoltage this component will limit them to a safe value by short-circuiting the phases and releasing the excess of energy as heat.

4) Heat sink

A heat sink will be sized in order to provide the matrix converter released heat a safe dissipation path, this heat is originated on the power modules by the high commutation frequency and are a fraction of the power provided to the load.

B. Command and drive circuit

1) Four steps commutation strategy

Due to the absense of bidirecionality on the power semiconductors, dedicated commutation strategies should be adopted in order to avoid the cut of load inductive currents and the short circuit of the input voltages. (Fig. 6) represents one of the matrix converter arms and will be used to explain the four steps commutation process used on this work and programmed on a Xilinx FPGA by [5].

![Image](Fig. 6. Representation of tree bidirectional switches of one matrix converter arm.)

This commutation process warrants that when an electronic bidirectional switch is on, the two IGBT that are part of it are triggered to conduct, in this case when a current sign change occurs the diode that was initially on will turn off and the load current will be conducted by another IGBT of the electronic bidirectional switch [1].

For a current switch between the bidirectional switches $S_1$ and $S_2$ (Fig. 6 and 7) the four steps commutations strategy based on the load current sign will be performed in the following way, assuming $i_L > 0$:

1. Turn off the semiconductor of the electronic bidirectional switch $S$ that is not participating on the conduction process ($S_{op}$);
2. In order to keep the load current continuity semiconductor $S_{op}$ of the electronic bidirectional switch $S$ is turned on, allowing the flow of this current trough it;
3. Turn $S_{op}$ off;
4. Turn $S_{op}$ on.

In case the current flows on the opposite way ($i_L < 0$), the commutation process will be symmetric of the previous one.

In order to perform this commutation process it is important to know the load currents signs and above all to give the warranty that during the commutation process this sign doesn’t change abruptly (this will be achieved with a sign conditioning circuit).

2) PWM Venturini modulation

The two classic matrix converter control methods are the Venturini PWM modulation and the space vector modulation (SVM) [3], the PWM Venturini method introduced in 1981[7] works at high frequency and is based on the idea that input voltages and output currents have ideal behavior, on the beginning the output voltages could just reach half the input ones, on a latter work [2] the output voltages amplitude increased into $\sqrt{2}/2$ of the input ones by adding third harmonics on both input and output. A DSP implementation was proposed in 1996 by [8].

Though the matrix converter can be controlled by each of the two methods previously introduced, or other variants, the one used on this work is the Venturini PWM method.

3) Drive circuit (Optocouplers)

The drive circuit will be used to turn on and off the electronic bidirectional switches according to the signs provided by the FPGA/DSP. This circuit must be used in order
to provide a galvanic insulation between the command and the power circuit allowing the control signs to drive the IGBTs. For this drive one can use pulse transformers or optocouplers, the first choice provide by itself the IGBT drive energy but on the other side require a delicate sizing [9] and because is bulky requires precious room from a printed circuit board, the choice of optocouplers will require two extra power sources in order to provide the signs to turn on and off the IGBTs. In this work the component used was the optocoupler TLP250(INV) from Toshiba allowing a voltage insulation of 2500 V_RMS and operating in a frequency range up to 25 kHz.

4) Switched power supply

As seen on the previous chapter the use of optocouplers will require two extra power sources to provide the drive of the IGBTs, this is attained with the use of the DC/DC switched power sources with 2 W power, these are distributed along the four power modules with the output phases (U, V, W, N) and the input (R, S, T), for each two power modules a switched power source will provide for the common phases e.g. for the power modules I and II on (TABLE I) with the common input phase R the power sources will provide the drive of the IGBTs T_{1R} of the power module I and T_{1R} of the power module II (as T_{1R} and T_{1R} in TABLE I).

TABLE I. DISTRIBUTION OF THE SWITCHED POWER SOURCES ACCORDING TO THE POWER MODULES AND PHASES

<table>
<thead>
<tr>
<th>Switched Power Supply</th>
<th>Phase</th>
<th>Module</th>
<th>IGBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>U</td>
<td>I</td>
<td>T_{3U}, T_{4U}, T_{5U}</td>
</tr>
<tr>
<td>2</td>
<td>V</td>
<td>II</td>
<td>T_{3V}, T_{4V}, T_{5V}</td>
</tr>
<tr>
<td>3</td>
<td>W</td>
<td>II</td>
<td>T_{3W}, T_{4W}, T_{5W}</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>IV</td>
<td>T_{3N}, T_{4N}, T_{5N}</td>
</tr>
<tr>
<td>Input phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>R</td>
<td>I e II</td>
<td>T_{1R}, T_{1R}</td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td></td>
<td>T_{2R}, T_{3R}</td>
</tr>
<tr>
<td>7</td>
<td>T</td>
<td></td>
<td>T_{4R}, T_{5R}</td>
</tr>
<tr>
<td>8</td>
<td>R</td>
<td>III e IV</td>
<td>T_{1R}, T_{1R}</td>
</tr>
<tr>
<td>9</td>
<td>S</td>
<td></td>
<td>T_{3R}, T_{4R}, T_{5R}</td>
</tr>
<tr>
<td>10</td>
<td>T</td>
<td></td>
<td>T_{5R}, T_{5R}, T_{5R}</td>
</tr>
</tbody>
</table>

According to the power source datasheet two decoupling capacitors (1 and 10 μF) were used on its output terminals in order to minimize the voltage ripple.

The switched power sources have the reference NMK0515SC from Murata Power Solutions with 2 W power providing ±15V and allowing 3 kV_{DC} insulation.

C. Voltages and currents acquisition circuit

This circuit will provide the images of the line to line input voltages and currents as well the four output currents. These images will be provided to the DSP in order to be implemented the Venturini PWM method.

The four steps commutations process require at each instant to know the sign of the load current, if it is flowing from generator to load or in the opposite way, this sign will be provided by a conditioning circuit to the FPGA.

The current and voltage transducer with the reference LA 25-NP and LV 25-N respectively are from LEM, they provide an insulation voltage of 2500 V_{RMS} between the power and the control circuit.

IV. MATRIX CONVERTER COMPONENTS SIZING

After the description of the elements that compose the matrix converter and de voltages and currents acquisition circuit, in this chapter and the next the sizing of them will be performed.

It is important to start first by defining the operation regimes of the matrix converter regarding power and current.

With the matrix converter working with a maximum power of 6 kVA, the currents are obtained with (IV.1).

$$I = \sqrt{3} V$$ (IV.1)

With V as the line to line voltage the rated input current is given by:

$$I_{IN} = \frac{5}{\sqrt{3} V_{IN}} = \frac{6000}{400} = 0.7 A$$ (IV.2)

Due to the modulation process the matrix converter works as a buck converter with the output voltage as 87% of the input one, the output current is obtained with the more realistic value of 80%:

$$I_{OUT} = \frac{5}{\sqrt{3} V_{OUT}} = \frac{6000}{400} = 11 A$$ (IV.3)

The power will be used for the heat sink sizing. And both the input and output currents will be used to set the transducers transformation ratio as well to determine the printed circuit board tracks width.

1) Power Circuit

Due to the absence of information related to the DANFOSS power modules, it will be used as a guideline the datasheet information of a similar power module, this one as the reference 7MBR 25SA-120 of FUJI ELECTRIC, the major factor that allow the use of this module are the similar rating values, namely, 1200 V of collector emitter voltage and 25 A of collector current. The heat sink will be sized based on these datasheet thermal resistances parameters.

Gate-emitter overvoltage protection:

To turn the IGBTs on a +15 V must be applied between the gate and emitter terminals, and to turn it off a -15 V must be applied, in order to protect this semiconductor zener diodes must be mounted as depicted in the (Fig. 8).

![Zener diode location](image)

Fig. 8. Zener diode location.

These diodes must allow the ± 15 V to be applied between gate and emitter, but on the other hand they must provide a protection by ensuring that the rated V_{GE} = 20 V is not
reached/exceeded. The chosen zener have the following characteristics:

\[
V_z = 18 \text{ V} \quad (IV.4)
\]

\[
P_z = 1.3 \text{ W} \quad (IV.5)
\]

**Gate oscillations damping resistor:**

By applying the command signals to the IGBT gate they will give rise to oscillations due to the LC circuit formed by the gate capacitance and the tracks inductance, it will be necessary the use of a damping resistor \( R_G \) is needed in order to diminish these oscillations.

![Fig. 9. Equivalent RLC circuit for the damping resistor \( R_G \) computation.](image)

In order to obtain the damping resistor one has to compute the parasitic inductance of the track as well the gate capacitance [9].

The tracks parasitic inductance is given by (IV.6) were \( d \) stands for distance between adjacent tracks and \( w \) their width.

\[
L_5 = \frac{\mu_0 \pi d}{2w} = \frac{4\pi \times 10^{-7} \times 1 \times 10^{-2}}{2 \times 10^{-5}} = 6.28 \text{ nH/cm} \quad (IV.6)
\]

With the biggest track having 9 cm length (18 cm both ways), the total inductance is given by (IV.7).

\[
L_5 \approx 113 \text{ nH} \quad (IV.7)
\]

The IGBT input capacitance has a typical [9] value of:

\[
C_{iss} \approx 4 \text{ nF} \quad (IV.8)
\]

By relating the quality factor \( Q \) with the angular frequency \( \omega \) and damping factor \( \zeta \) the gate damping resistance will be determined.

\[
Q = \frac{\omega L_5}{R_\alpha \omega} = \frac{1}{\sqrt{L_5 C_{iss}}} \rightarrow Q = \frac{L_5}{R_\alpha} \quad (IV.9)
\]

Using a typical damping factor \( \zeta = 0.707 \)

\[
\zeta = \frac{R_\alpha}{2 \sqrt{L_5 C_{iss}}} = \frac{1}{2Q} \quad (IV.10)
\]

By changing the IGBT input capacitance and the tracks inductance the damping resistance is determined with (IV.11).

\[
R_\alpha = 1.44 \sqrt{\frac{L_5}{C_{iss}}} \quad (IV.11)
\]

By applying (IV.7) and (IV.8) in (IV.12), \( R_G \) is obtained.

\[
R_G \geq 1.44 \frac{113 \times 10^{-9}}{4 \times 10^{-6}} \approx 5.3 \text{ \Omega} \quad (IV.12)
\]

**Gate – emitter capacitance discharge resistor:**

In order to avoid a short circuit when the IGBT driver can’t turn it off due to a fault during the commutation process, a discharge resistor in the gate-emitter terminal \( R_{GE} \) will allow this capacitance to discharge and turn the IGBT off.

![Fig. 10. Gate-emitter capacitance discharge resistance \( R_{GE} \).](image)

To prevent that a short circuit current won’t reach a high value and admitting a time constant \( \tau = 40 \mu s \) (typical of an RC circuit such as this) and the gate emitter capacitance as a similar values as the input (IV.8),

\[
\tau = \frac{R_{GE} C_{iss}} \quad (IV.8)
\]

\[
\tau = \frac{R_{GE} C_{iss}}{\frac{R_{GE}}{C_{iss}}} = \frac{R_{GE}}{C_{iss}} \quad (IV.14)
\]

The discharge resistor \( R_{GE} \) as the value:

\[
R_{GE} \geq \frac{\tau}{C_{iss}} = \frac{40 \times 10^{-6}}{4 \times 10^{-6}} = 10 \text{ k\Omega} \quad (IV.15)
\]

2) **Input filter parameters**

The input filter parameters were obtained on some of the previous matrix converter works [1], [5] and [12].

**TABLE II. INPUT FILTER PARAMETERS**

<table>
<thead>
<tr>
<th>Capacitor</th>
<th>Inductor</th>
<th>Discharge resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 ( \mu \text{F} )</td>
<td>4.4 ( m\text{H} )</td>
<td>15 ( \Omega )</td>
</tr>
</tbody>
</table>

3) **Protexions**

To avoid an overvoltage on the matrix converter input and output varistors should be used. This component should be sized with a value two or three times greater that the nominal voltage in order to avoid it’s destruction over time due to overvoltages with a value near the nominal voltage. Being the varistor connect between phases, its nominal voltage is set as:

\[
V_v = 420 \text{ V} \quad (IV.16)
\]

The maximum clamping voltage \( V_c \) and the energy dissipation are:

\[
V_c = 1120 \text{ V} \quad (IV.17)
\]

\[
E_{\text{Energy}} = 90 \text{ J} \quad (IV.18)
\]

4) **Heat sink**

To determine the heat sink it’s important to know first the losses of the matrix converter, this is a hard task because these will depend on the used commutation processes, if it’s a two or four steps or even some other process, in each the conducting semiconductors will be different and therefore the losses.
On [13] was studied the losses of matrix converters and a particular case of a four steps commutation process was presented. From this study, by choosing on a graphic the commutation frequency of 10 kHz a 98% efficiency was obtained, in order to obtain another value to compare was used the efficiency obtained on a prototype [14], here was achieved a 96.4% efficiency. For the heat sink computation will be used a middle value 95%. By using this value on (IV. 19) the total power dissipation (conduction losses plus commutation) was obtained.

\[ P_d = 5 \times \frac{f}{f_p} \times (1 - \eta) \Rightarrow \]
\[ P_d = 5 \times f_p \times (1 - \eta) = 6000 \times 1 \times (1 - 0.95) = 300 \ W \]  
(IV.19)

The heat sink is characterized by a sink to ambient resistance \( R_{thS-A} \), by knowing the dissipated power on each power module \( (1/4 \text{ of the one determined on (IV. 19)}, \) the junction and ambient temperature (usually 125°C and 25°C), the junction to case and case to sink resistances \( R_{thJ-C}, R_{thC-S} \), the heat sink resistance is obtained with (IV. 20).

\[ R_{thS-A} = \frac{T_{j} - T_{a}}{P_d} - R_{thJ-C} - R_{thC-S} \]  
(IV.20)

By changing the values on (IV. 20) the thermal resistance per module is:

\[ R_{thS-C} = \frac{125 - 25}{75} - 0.69 - 0.05 \approx 0.59 \ ^\circ C/W \]  
(IV.21)

These four thermal resistances are connected in parallel, the total heat sink resistance should be less or equal to (IV. 22).

\[ R_{thS-A} \approx 0.15 \ ^\circ C/W \]  
(IV.22)

5) Schematics

(Fig. 11) show the location of all the components previously describes and sized namely: the power supply; optocouplers; zener; diode and the power modules. This figure represents just one of the four matrix converter arms, the rest of them have the same structure. In several of these components decoupling capacitor were used both between their supply terminals as well in their output terminals.

The input filter and its components (capacitor, varistor and discharge resistor) are shown in (Fig. 12).

V. VOLTAGE AND CURRENT ACQUISITION CIRCUIT SIZING

In order to provide to the DSP the images of the currents on the matrix converter and to the FPGA their signs, the turn ratio of the transducers must be set previously because they will be fixed on the printed circuit board.

The current transducer to be used is the LA 25-NP of LEM and for the input was defined the transformation ratio of 4/1000 allowing the measurement of the 6 A input current with a maximum range of 9 A, in (Fig. 13) as A. The output transducer transformation ration was set to 2/1000, allowing a 12 A current to be measured.

The signs of the load currents are provided by a conditioning circuit, in (Fig. 13) as B, obtained by [10], and will be applied to the FPGA where the four steps commutation process will be created.

The input voltages will be used on the DSP in order to the Venturini modulation be processed. The voltage transducers used are the LV 25-P from LEM as well, this ones will be connected to the line-to-line voltages, in (Fig. 13) as A. Both the current and voltage transducers provide an 2500 \( V_{RMS} \) insulation between the power and the control circuit, the measurement resistance \( R_M \) (in the datasheet) was defined as 180 \( \Omega \).

VI. PRINTED CIRCUIT BOARD DESIGN

The design of the PCB layouts was achieved by applying the standards compiled on the IPC, namely both the IPC-2221 [15] and IPC-9592, the first one has the rules of thumb for printed board design and the second is applied to power conversion devices. From this documents were obtained the
spacing between tracks according to the voltage, in this case was considered the phase-to-phase 400 V RMS, and the tracks width according to the maximum current. Table II shows the spacing and width according to the current as well the voltages between tracks.

<table>
<thead>
<tr>
<th>TABLE III. SPACING, WIDTH AND RATED CURRENTS ON THE PCB.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal tracks (5V, ±15V)</td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>Spacing [mm]</td>
</tr>
<tr>
<td>Width [mm]</td>
</tr>
<tr>
<td>MÁx. current @ 10°C [A]</td>
</tr>
</tbody>
</table>

For the PCB design were used [16] and [17] as well [18]. The printed circuit board program used was Altium Designer.

VII. LABORATORIAL EXPERIMENTS

The prototype is shown in (Fig. 14), on top of the structure there’s the voltage and currents acquisition circuit and on bottom the matrix converter.

![Matrix converter prototype](image)

In order to validate the prototype several tests were performed, beginning with the command and drive followed by the voltages and currents acquisition circuit. After the global test was performed over an RL load with R=10 Ω and L=12.5 mH. The output frequency was set to 100Hz and the voltage to 60% of the input one, the switched voltages have the shape as shown in (Fig. 15 a), they can be compared with the MATLAB simulation (Fig. 15 b).

![Switched phase to phase output voltages](image)

With this same test the output currents were obtained as shown in (Fig. 16 a) and the MATLAB simulation in (Fig. 16 b).

![Switched output currents](image)

VIII. CONCLUSIONS

By comparing the matrix converter laboratorial results with the MATLAB simulations it is seen that the prototype works correctly.

The built prototype has a fourth arm option, in the future further tests should be made in order to validate it.

REFERENCES


