INDIRECT MATRIX CONVERTER FOR AC INDUCTION MOTOR DRIVES

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***Abstract* – A matrix converter to directly connect a three-phase load to a three-phase power source using eighteen IGBTs and eighteen fast diodes is presented in this paper. The IGBTs are connected in a common-emitter (CE) configuration by versatile blocks, able to be used in other topologies such as sparse matrix converters and conventional matrix converters. The matrix converter allows many advantages compared to the conventional voltage or current source inverters. It does not require energy storage components as a bulky capacitor or an inductance in the DC-link and enables the bidirectional power flow between the power supply and load. The indirect modulation technique is adopted, since a dc-link without capacitive elements is established. The modulation technique adopted is able to provide practically sinusoidal waveforms of the input and output currents with negligible harmonics amplitude, with input displacement factor control. Some design and implementation details of a 1 kW three-phase to three-phase, as well, a complete theoretical description with simulation results of the design implementation are offered.**

***Keywords* – AC-AC power conversion, indirect matrix converter, induction motor, indirect space vector modulation.**

I. INTRODUCTION

Power converters having both adjustable output frequency and output amplitude are useful and employed in several industrial applications. These adjustable parameters, among others, may be used for directly controlling variables such as speed, power, temperature, torque, flow and others. Electronically controlled adjustable-speed drives (ASDs) are used for speed control in motors, being nowadays common since they usually offer higher energy efficiency and lower maintenance than traditional systems [1].

Some of the most desirable features in a ASD are:

- simple and compact power circuit;
- voltage generation with electronically adjustable amplitude and frequency;
- sinusoidal input and output currents;
- unitary power factor for any load;
- regeneration capability.

One of the converter topologies used for ASDs is the voltage source inverter (VSI) with diode front-end rectifier and dc-link capacitor for energy storage, as shown in Fig. 1. Although this converter topology is widely used in industry [2], it fails to fulfill some desirable features such as:

- Bulky size and volume, due the dc-link reactive components [3];
- Distortion in the input current, since the input of a diode bridge rectifier feeding a dc-link capacitor deviates significantly from a sinusoidal waveform [4];
- Low power factor, since there is no control in the input current;
- No regeneration capability, because of the diode rectifier in the front-end [2].

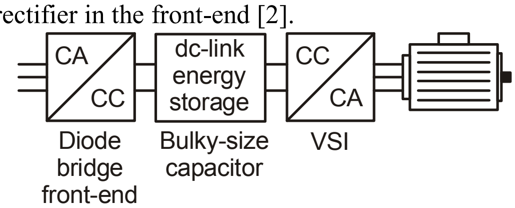

Fig. 1. Block-diagram of a VSI with a diode rectifier bridge and dc-link [5]

On the other hand, all of the previously presented desirable features can be achieved by using matrix converters. This is the reason for the growing interest in such topology class [6].

Motor speed is adjusted by a V-F open loop control. Since the main goal of this study is the topology and modulation, no torque or current closed-loop control strategies were adopted at this time and it will be focus of future works.

II. INDIRECT MATRIX CONVERTER

Matrix converters was firstly introduced in 1980 [7], being able to provide sinusoidal input currents, bidirectional power flow and not needing the bulky dc-link capacitor. Conventional matrix converters (CMC) consist of nine bidirectional switches that connect any of the input phases to any of output phases. Its main disadvantages are the voltage-transfer ratio lower than unity (~0.86), a low immunity to power-grid disturbances, and a high number of power devices (18 IGBTs and 18 diodes) [8].

Recently, in 2001 [9], a new topology was proposed having the following advantages:

- Same performance benefits as the CMC, such as four quadrant operation, unity input power factor, pure sine waveforms with only high order harmonics in both input currents and output voltage;
- Pulse width modulation algorithms of conventional inverters can be utilized, greatly simplifying modulation operations;

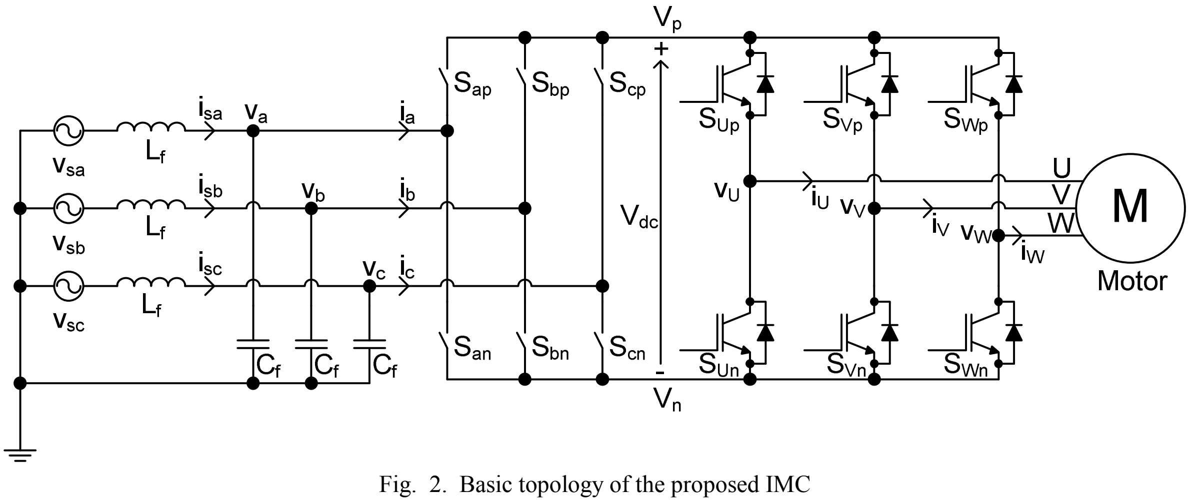

Fig. 2. Basic topology of the proposed IMC

- Commutation problems of CMC are considerably reduced, since all switches at the line side operate in zero-current switching (ZCS);
- No large reactive components are needed, since no energy storage is performed, except for relatively small size low-pass ac filter at line side.

Since this is a two-stage electronic power converter, it is known as indirect matrix converter (IMC). Fig. 2 illustrates the basic circuit for the IMC.

III. BIDIRECTIONAL SWITCH

Matrix converters require bidirectional AC switches to control the current and voltage in both directions. In the case of IMC, only the rectifier stage requires bidirectional switches. These switches are implemented by using one of the following configurations: a IGBT inside a diode bridge (see Fig. 3a), 2 anti-series connected IGBTs in a common collector (CC) configuration (Fig. 3b), or in a common emitter (CE) configuration (Fig. 3c). Reverse blocking (RB-) IGBTs can block voltage in both directions, also offering a convenient way to implement bidirectional switches using two RB-IGBTs in an anti-parallel connection (Fig. 3d) [10].

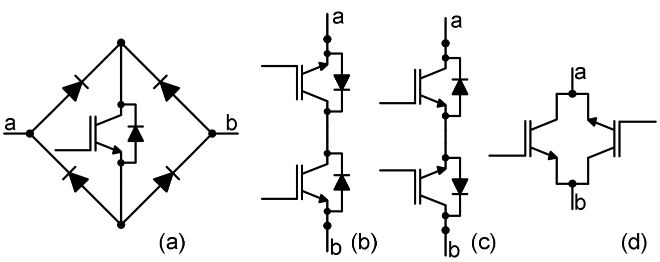

Fig. 3. Bidirectional switches configurations: a) bridge diode IGBT; b) CC-IGBT; c) CE-IGBT; d) anti-paralleled RB-IGBTs

In this work was chosen the CE-IGBT configuration due the possibility to implement independent power bidirectional switches modules and also because they achieve lower conduction losses than the bridge diode configuration. RB-IGBT configuration was not considered.

Detailed features and performance comparisons for these bidirectional switches configurations are presented in [10] and [11]. Reference [12] shows a commercially available integrated power module for 3Ø/3Ø CMC with a 9 CC-IGBT bidirectional switches configuration.

IV. SPACE VECTOR MODULATION

The proposed IMC topology consists of a rectification stage, which is actually a 3/2-phase matrix converter, directly connected to an inversion stage. This inversion stage is a IGBT bridge commonly used in three-phase VSI. Since unidirectional polarity of the voltage is required in the link between rectification and inversion stages, even considering there are no reactive components, it is proper to call it a dc-link [13]. An indirect space vector modulation (SVM) is often used for matrix converters, providing full control of both the output voltage vector and the instantaneous input current displacement angle [13]. Basically, a combination of two adjacent vectors and a zero-vector is used to synthesize a reference vector of variable amplitude and angle. The proportion between the two adjacent vectors gives the direction and the zero-vector duty-cycle determines the magnitude of the reference vector. See Fig. 5 and Fig. 7 for details.

A. Rectifier stage

For a proper VSI operation, it is mandatory that a dc-link be maintained, even considering the absence of reactive filtering components. The rectifier stage is responsible for convert the three-phase input voltage in a unidirectional voltage V_{dc} and also modulate the input currents. Fig. 4 shows the space-vector representation of the rectification stage [14].

The input reference vector is represented by an input current vector (I_{in}) that corresponds to the rectification stage. I_{in} is synthesized using two adjacent vectors I_γ and I_δ (Fig. 5). Duty-cycle of I_γ and I_δ are given by (1) and (2), where the rectification's modulation index $m_I = I_{in}/I_{dc}$ is set to unity and θ^*_{in} is the angle of I_{in} within the respective sector [15].

$$d_\gamma = m_I \cdot \sin\left(\frac{\pi}{3} - \theta^*_{in}\right) \quad (1)$$

$$d_\delta = m_I \cdot \sin \theta^*_{in} \quad (2)$$

Synchronizing θ^*_{in} with the input voltages, is possible to achieve any desirable input displacement factor, even the unity. The average dc-link voltage may also be controlled by

θ^*_{in}, as expressed in (3) [9], where Vm is the peak value if input phases voltage:

$$V_{dc} = \frac{3 \cdot Vm}{2 \cdot \cos\theta^*_{in}} \tag{3}$$

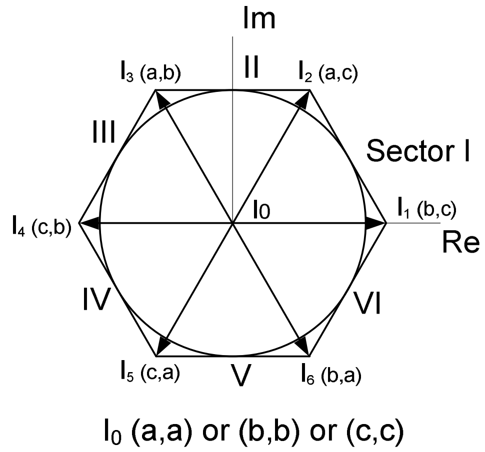

Fig. 4. SVM sectors and voltage vectors of switching states of the rectification stage

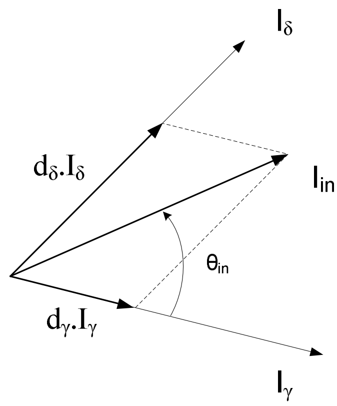

Fig. 5. Input current reference vector synthesis

B. Inverter stage

Space-vector modulation techniques are widely used in inverters because they reduce the switching steps, the harmonic content of the output voltage and provide a better voltage transfer from dc-link to the output of the converter [16].

The reference vector for the inversion stage is V_{out} and the modulation of the output voltages is made based on this vector. This space-vector representation is shown in Fig. 6. The output reference vector V_{out} is synthesized with two adjacent vectors V_α e V_β (Fig. 7). The duty-cycle of V_α e V_β are given by (4) and (5), where the inversion's modulation index is m_U and θ^*_{out} is the angle of V_{out} within the respective sector.

$$d_\alpha = m_U \cdot \sin\left(\frac{\pi}{3} - \theta^*_{out}\right) \tag{4}$$

$$d_\beta = m_U \cdot \sin\theta^*_{out} \tag{5}$$

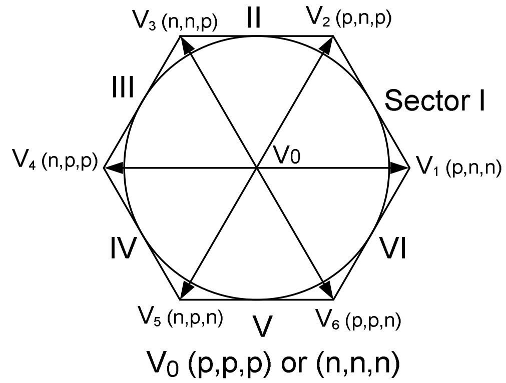

Fig. 6. SVM sectors and voltage vectors of switching states of the inversion stage

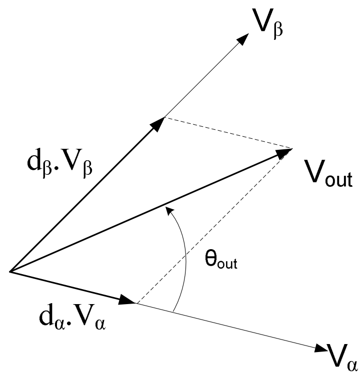

Fig. 7. Output voltage reference vector synthesis

C. Two-stage matrix converter

To balance the input currents and the output voltages properly in the same switching period, the modulation pattern should combine the rectification and inversion vectors uniformly, producing the following switching pattern: α γ-α δ-β γ-0. The combined duty-cycles of the rectification and inversion stages, using the previously presented switching pattern, are obtained as a cross product of their independent duty-cycles as shown in (6), (7), (8) and (9). The zero-vector duty-cycle is determined as the complement of all active states combined (10).

$$d_{\alpha\gamma} = d_\alpha \cdot d_\gamma \tag{6}$$

$$d_{\alpha\delta} = d_\alpha \cdot d_\delta \tag{7}$$

$$d_{\beta\delta} = d_\beta \cdot d_\delta \tag{8}$$

$$d_{\beta\gamma} = d_\beta \cdot d_\gamma \tag{9}$$

$$d_0 = 1 - \left(d_{\alpha\gamma} + d_{\alpha\delta} + d_{\beta\delta} + d_{\beta\gamma}\right) \tag{10}$$

The on-state time of each sequence is obtained by multiplying the corresponding duty-cycle by the switching period.

In a two-stage matrix converter, the zero vector is eliminated from the rectification stage and the switching sequence consists only of the two adjacent active current vectors defined in (1) and (2), resized in such way (11) and (12) that they occupy the whole switching period.

$$d_{\gamma}^{R} = \frac{d_{\gamma}}{d_{\gamma} + d\delta} \quad (11)$$

$$d_{\delta}^{R} = \frac{d_{\delta}}{d_{\gamma} + d\delta} \quad (12)$$

Since the average voltage on the dc-link is no longer constant (Fig. 8) due the cancellation of the zero-vector in the rectification stage, the modulation index of the inversion stage need to be compensated;

$$V_{PN-avrg} = d_{\gamma}^{R} \cdot V_{line-\gamma} + d_{\delta}^{R} \cdot V_{line-\delta} \quad (13)$$

$$m_{U} = \sqrt{2} \cdot \frac{V_{out}}{V_{PN-avrg}} \quad (14)$$

This compensation in m_U corrects the duty-cycles calculated in (4) and (5) with the momentary average dc-link voltage $V_{PN\text{-}avrg}$. The inverter stage uses a double-sided asymmetric PWM switching sequence 0_{γ} -α_{γ}-$\beta_{\gamma+\delta}$ -α_{δ} -0_{δ}, with unequal sides.

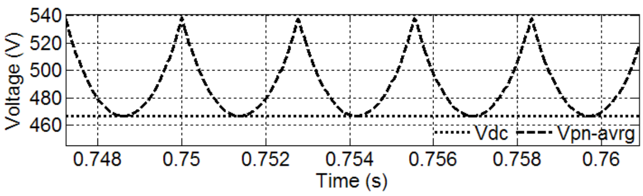

Fig. 8. V_{dc} compared with $V_{PN\text{-}avrg}$

The inversion duty-cycles are given in (15), (16), (17) and (18), with d_{α} and d_{β} compensated with m_U calculated in (14). The switching pattern for an IMC is presented in Fig. 9.

$$d_{0\gamma} = \frac{d_{\gamma} \cdot [1 - (d_{\gamma} + d_{\delta}) \cdot (d_{\alpha} + d_{\beta})]}{d_{\gamma} + d_{\delta}} \quad (15)$$

$$d_{\alpha\gamma} = d_{\gamma} \cdot d_{\alpha} \quad (16)$$

$$d_{\beta(\gamma+\delta)} = (d_{\gamma} + d_{\delta}) \cdot d_{\beta} \quad (17)$$

$$d_{\alpha\delta} = d_{\delta} \cdot d_{\alpha} \quad (18)$$

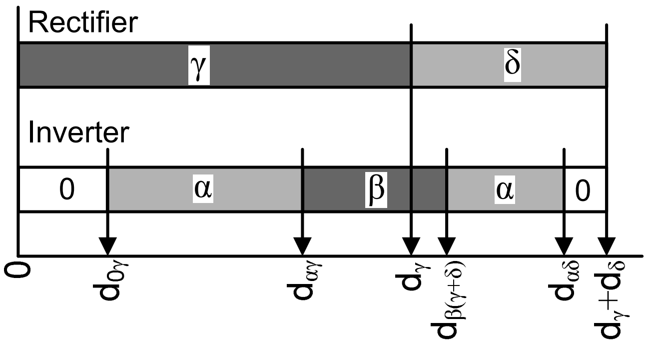

Fig. 9. Switching pattern for an IMC

V. SIMULATION RESULTS

To provide both a quantitative and a qualitative observation of converter's operation, some simulations were performed in MATLAB/SIMULINK. The following parameters were used to simulate the IMC:

Input line voltage:	380V;	Input frequency:	60Hz
Filter inductor:	200µH;	Line resistor:	0.2Ω
Filter capacitor:	30µF;	Output resistor:	10 Ω
Output inductance:	100mH;	Modulation level k:	0.80
Output frequency:	89Hz		

Fig. 10 shows input voltage and current for phase A, is important to note that the current is nearly sinusoidal and with a quasi-unity displacement factor. This greatly improves harmonic influence of the converter in the power grid. Voltage in dc-link (Fig. 11) has the line voltage envelope and is modulated in the switching frequency, load changes does impress great changes in dc-link voltage waveform.

Output line voltage is shown in Fig. 12. It does not differ from the output voltage waveform of a VSI feed by a filtered dc-link, except by the low frequency envelope from the input line voltage. Output currents are not affected by this low-frequency envelope, as shown in Fig. 13.

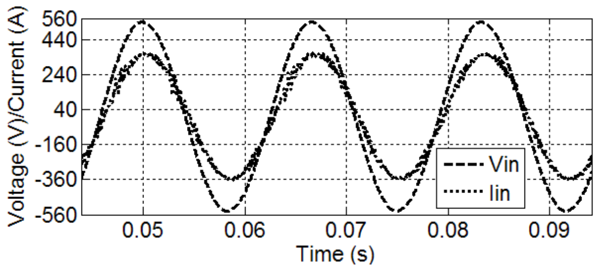

Fig. 10. Input voltage and current

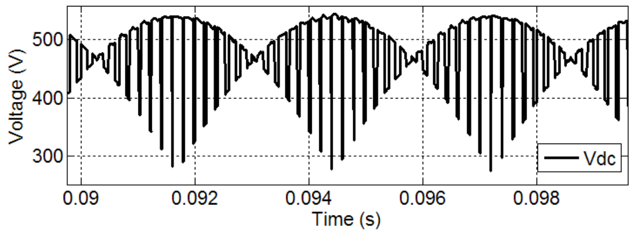

Fig. 11. Voltage at dc-link

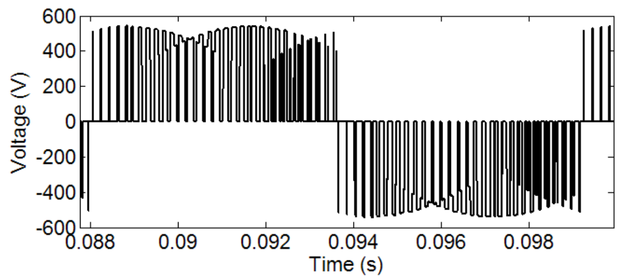

Fig. 12. Output voltage

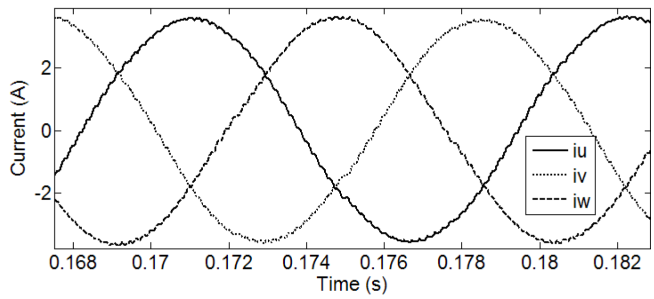

Fig. 13. Output currents

VI. EXPERIMENTAL EVALUATION

For the experimental evaluation of the IMC, building modules was designed. The current measure, voltage measure, bidirectional switch and power inverter boards are presented in Figures 14-18 respectively:

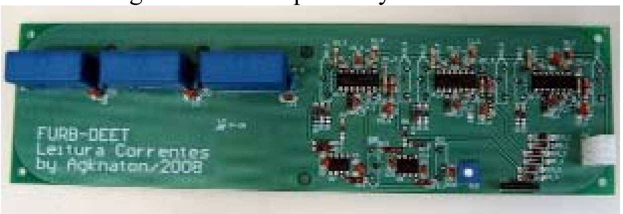

Fig. 14. Current measurement board

Fig. 15. Voltage measurement board

Fig. 16. TMS320C2812 DSP kit

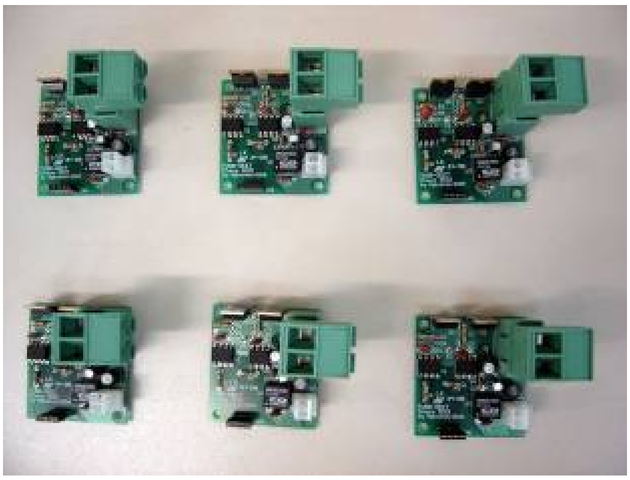

Fig. 17. Bidirectional switches boards

Fig. 18. Integrated inverter module board

The experimental prototype is under firmware development and testing.

Modular design of prototype allows further research on topology and control techniques, serving as starting point for new studies and developments on this type of converter.

VII. CONCLUSION

This indirect matrix converter topology driving an induction motor was investigated as a first approach to further studies on AC-AC direct power electronic converter. Hardware modules were designed as independent and versatile blocks, able to be used in other topologies such as sparse matrix converters and conventional matrix converters. Also different control and modulation strategies may be implemented using these same modules. On this study, simulation results were consistent with all major aspects described in the theory presented: quasi-unity displacement factor, sinusoidal input and output currents, proper modulation of output voltages and dc-link average voltage as expected.

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