Single-Phase to Three-Phase Power Converters: State of the Art

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***Abstract*—Single-phase to three-phase conversion using power electronics converters is a well-known technology, especially when the configurations and control strategies already established in the technical literature are considered. Regarding the configurations conceived over the years, it can be observed two main tendencies: 1) configurations with a reduced number of components; and 2) configurations with an increased number of components. The search for topologies with a reduced number of components was the trend over a long period of time. This can be, in part, explained by the high cost of the power switch when compared to the capacitor used in the dc-link bus. Then, the converter leg was sometimes substituted for the midpoint capacitor. However, as far as the price of the semiconductor was going down, such tendency has been changed, and now the configurations with an increased number of components do appear as an interesting option, especially in terms of reliability, efficiency, and distortions improvement. A comprehensive review of the two possibilities (reduced and increased number of components) has been considered in this paper. Also, the single-phase to three-phase ac–ac direct conversion configurations and those which aim to reduce the dc-link voltage fluctuation have been included. The goal of this paper is to provide a complete range on the status of single-phase to three-phase power conversion technologies to professionals and researchers interested in this topic.**

***Index Terms*—Power conditioning, power electronics converters, pulse width modulation converters.**

I. INTRODUCTION

IN THE power distribution systems, the single-phase grid has been considered as an alternative for rural or remote areas [1], due to its lower cost feature [2], especially when compared with the three-phase solution. In huge countries like Brazil [3], the single-phase grid is quite common due to the large area to be covered. On the other hand, loads connected in a three-phase arrangement present some advantages when compared to single-phase loads. This is especially true when motors are considered [4], [5], due to their constant torque, constant power, reduced size, etc. [6]. There is a need for single-phase to three-phase conversion systems in this scenario.

In terms of application, the first thing that comes to mind when it is considered a single-phase to three-phase conversion, it is a three-phase motor drive system. However, the authors in [7] claim that, in rural application, feeding a three-phase induction motor is not anymore the main concern for the single-phase to three-phase conversion. Due to the evolution of the farm technology, some of the local loads (such as electronic power converters, computers, communication equipments, etc.) require high power quality, that is, sinusoidal, symmetrical, and balanced three-phase voltage.

In the past, single-phase to three-phase conversion systems were made possible by the connection of passive elements (capacitors and reactors) with autotransformer converters [8]–[10]. Such kind of system presents well-known disadvantages and limitations [10]. In those days, power electronics with silicon power diodes and thyristors was just emerging. As described in [11], the so-called power electronics, with gas tube and glass-bulb electronics, was known as industrial electronics, and the power electronics with silicon-controlled rectifiers began emerging in the market from the early 1960s.

Since the beginning of the solid-state power electronics, the semiconductor devices were the major technology used to drive the power processors [12]. Looking at the semiconductor devices used in the former controlled rectifiers [13] and comparing them with the new technologies [14], it makes possible to figure out the astonishing development. Beyond the improvement related to power switches, a great activity in terms of the circuit topology innovations in the field of three-phase to three-phase, single-phase to single-phase, and three-phase to single-phase conversion systems was also identified. [15]–[33] .

Among the single-phase to three-phase power conversion, two main tendencies can be observed: 1) configurations with a reduced number of components; and 2) configurations with an increased number of components. The first one (topologies with a reduced number of components) was the trend over a long period of time, which can be explained by the high cost of the power switches. Sometimes, the converter leg was substituted for the midpoint capacitor. However, as far as the price of the semiconductor was going down [34], such tendency of using the dc-link capacitor instead of leg has been changed. Now, the configurations with an increased number of components do appear as an interesting option, especially in terms of reliability, efficiency, and distortions improvement. Those two possibilities (reduced and increased number of components) have been comprehensively reviewed in this paper. Also, the single-phase to three-phase ac–ac direct conversion configurations (without dc-link capacitors) and that one's which aim reducing of the dc-link voltage fluctuation have been considered.

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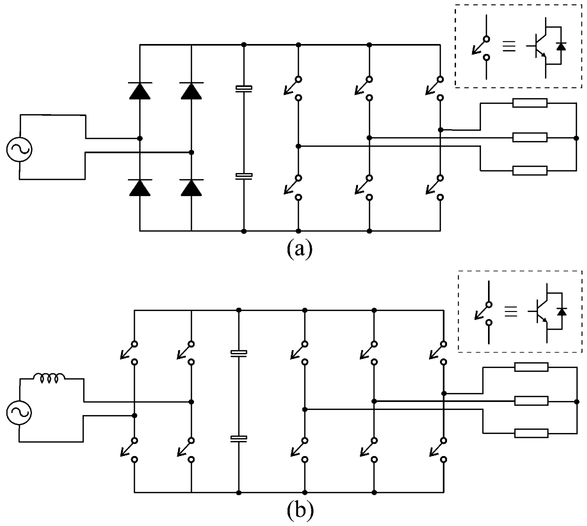
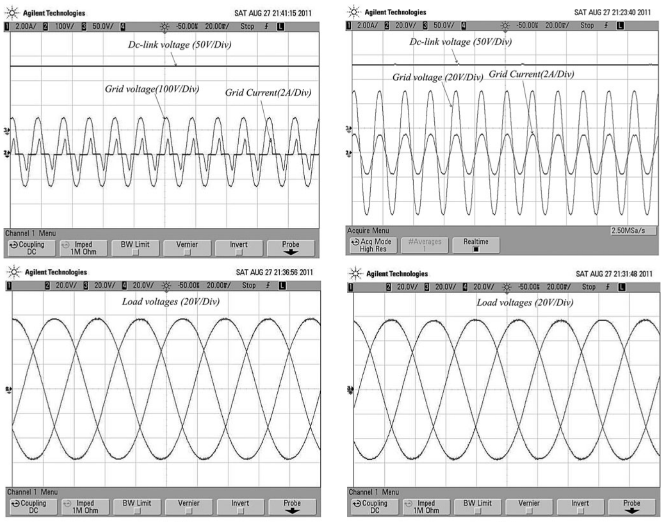


Fig. 1. Conventional single-phase to three-phase configurations. (a) Diode bridge in the input converter side (C1). (b) Controlled rectifier in the input converter side (C2).



(a) (b)

Fig. 2. Experimental results of the conventional single-phase to three-phase power conversion. (a) Configuration C1. (b) Configuration C2.

The goal of this paper is to provide a complete range on the status of single-phase to three-phase power conversion topologies to professionals and researchers interested in this topic. Authors are not aware of any investigation providing the state of the art given in this paper.

Two configurations will be considered as conventional ones, as observed in Fig. 1. It is worth to mention that each configuration will be renamed in this paper in order to facilitate the comparison: e.g., Fig. 1(a) will be called as C1, Fig. 1(b) will be called as C2, and so on.

Configuration C2 [see Fig. 1(b)] represents an interesting solution for single-phase to three-phase power conversion, since all variables at input–output converter sides can be controlled, as observed in Fig. 2, while the configuration C1 represents a cheaper solution but without any control of the input current and dc-link voltage. Fig. 2(a) and (b) shows the results for configurations C1 and C2, respectively. It is worth to mention that these two configurations are considered as the reference for the new proposals, i.e., the new topologies aim to generate waveforms closer of the configuration C1 and far away of the configuration C2.

A suitable control strategy employed to guarantee the control objectives of the configuration C2 is depicted in Fig. 3. The variables with "*" in this figure mean the reference variables. Notice from this figure that there exist three controllers and a synchronization block. Such control strategy will be considered as a reference to establish a figure of merit regarding the control complexity.

Other important characteristic observed in the single-phase to three-phase power converters which also has been considered in this paper is the irregular distribution of power among the switches of the converter, as observed in Fig. 4. It means that 63% of the total losses measured in the single-phase to three-phase converter [see Fig. 1(b)] is concentrated in the rectifier circuit, while the rest 37% is observed in inverter circuit.

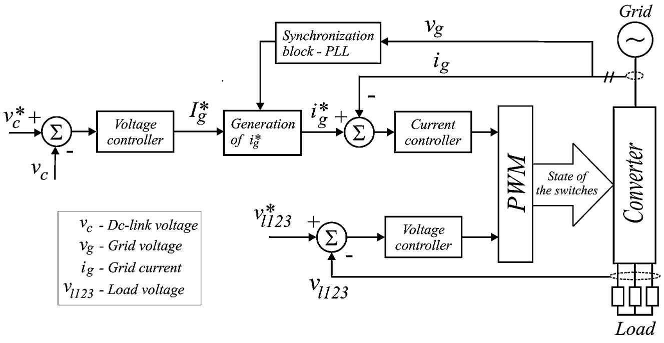


Fig. 3. Control block diagram of configuration C2.

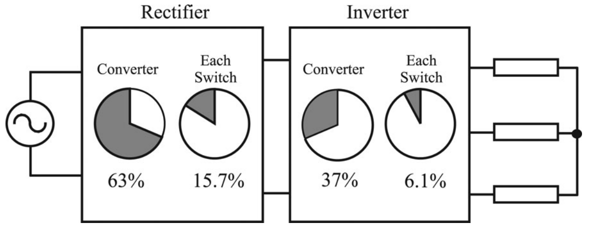


Fig. 4. Converter power losses distribution in both rectifier and inverter units: 63% in the rectifier circuit and 37% in the inverter one. Power losses in each switch of the rectifier (15.7%) and inverter (6.1%).

With those numbers, it is possible to measure the stress by switch, which means that each rectifier switch is responsible for 15.7% of the total converter losses, while each inverter switch is responsible for only 6.1%. The stress by switch gives an important parameter regarding the possibilities of failures in the power converters. Almost all configurations presented in this paper have this kind of trouble (considerable irregular power losses distribution). The exception is for the configurations with paralleled rectifiers, as will be described in Section III.

Different models for switch losses estimation have been presented in the literature [35]–[38]. In this paper, the loss

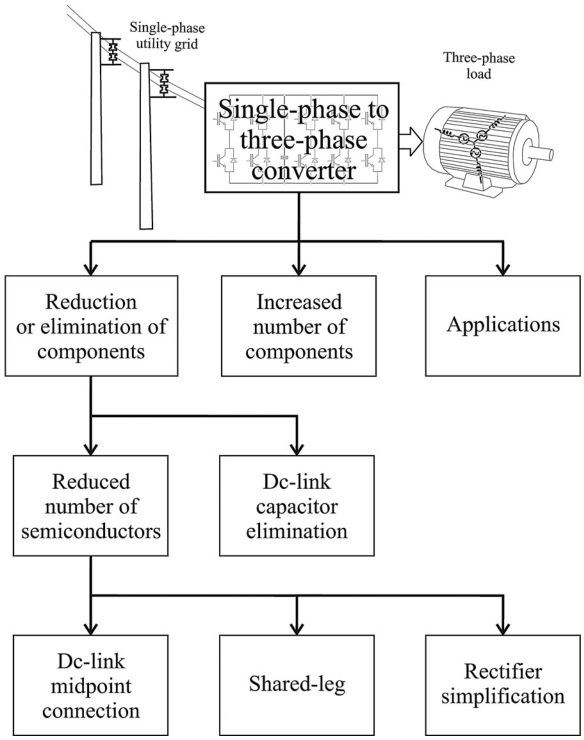


Fig. 5. Complete view of the paper organization.

estimation is obtained through regression model, which has been achieved by experimental tests, as presented in [39]. The power switch used in the experimental tests was insulated gate bipolar transistor (IGBT) dual module CM50DY-24H (POWEREX) driven by SKHI-10 (SEMIKRON). That switch losses model includes: 1) IGBT and diode conduction losses; 2) IGBT turn-on losses; 3) IGBT turn-off losses; and 4) diode turn-off energy.

Following this introduction, the rest of this paper is organized in six sections. In Section II, configurations with reduction or elimination of components will be considered. On the other hand, Section III presents those configurations with an increased number of components. Applications of the single-phase to three-phase conversion are brought up in Section IV. In Section V, a general comparison among the configurations is established, highlighting the main characteristics of each topology. Finally, in Section VI, conclusions are given. The section that deals with configurations with reduced number of components (see Section II) will be divided in two sections. A complete view of this paper organization is presented in Fig. 5. As far as possible, in each section, the papers are presented in a chronological way in order to give readers the idea of the single-phase to three-phase converter development.

II. CONFIGURATIONS WITH REDUCTION OR ELIMINATION OF COMPONENTS

Component count reduction without dramatically changing the quality of the converter waveforms was and still is the objective of many converter designers. This commitment is not often possible, especially in those solutions which eliminate many components of the converter. Even in these cases (radical component reduction), the impoverishment of waveforms is sometimes acceptable due to specific advantages presented in the proposed converter.

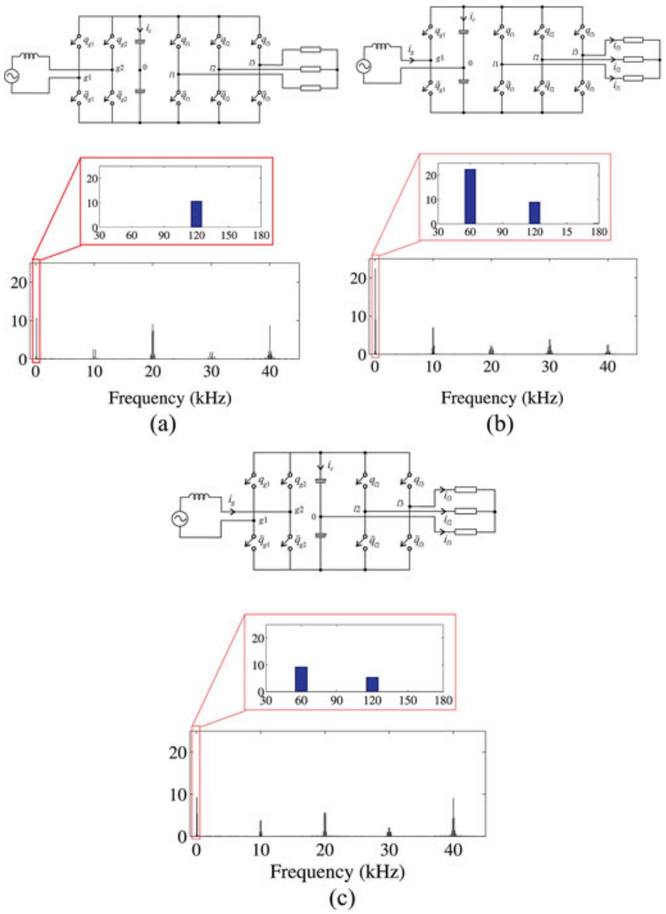


Fig. 6. Configurations and harmonic spectrums of the capacitor currents. (a) Full-bridge configuration. (b) Input half-bridge configuration. (c) Output half-bridge configuration.

A. *Configurations With a Reduced Number of Semiconductors*

1) Dc-Link Midpoint Connection: The dc-link midpoint connection has been employed in many ac converters to guarantee the reduction of the power switches. This means that at least one of the legs, constituted by two power switches, is not longer used. However, regarding cost reducing, this approach just make sense if what is saved by the number of power semiconductor devices is not lost in higher device ratings and more electrolytic capacitor energy storage [40], [41]. Another important aspect is the lifespan of the electrolyte capacitors, considered small when compared to that of the switches.

To highlight the impact of the dc-link midpoint connection over the lifespan and converter efficiency, the harmonic spectrums of the dc-link capacitor current for the conventional converter depicted in Fig. 6(a) and the half-bridge configurations presented in Fig. 6(b) and (c) will be considered.

From Fig. 6(a), the dc-link capacitor current is given by

$$\bar{i}_c = \frac{\tau_{g1}}{T_s} i_g - \frac{\tau_{g2}}{T_s} i_g - \frac{\tau_{l1}}{T_s} i_{l1} - \frac{\tau_{l2}}{T_s} i_{l2} - \frac{\tau_{l3}}{T_s} i_{l3} \tag{1}$$

where τ_{g1} to τ_{l3} are the time intervals in which switches q_{g1} to q_{l3} are closed, respectively, and T_s is the switching period. Assuming that the reference pole voltages can be constant over T_s, the time intervals τ_j ($j = g1$ to $l3$) can be written as a function of the reference pole voltages. For instance, τ_{g1} is given by

$$\tau_{g1} = \left(\frac{v^*_{g10}}{v^*_c} + \frac{1}{2}\right)T_s. \tag{2}$$

Thus, from (1) and (2), the dc-link capacitor current becomes

$$\bar{i}_c = \frac{1}{v^*_c}\left(i_g v^*_g - \sum_{k=1}^{3} i_{lk} v^*_{lk}\right) \tag{3}$$

where $v^*_g = v^*_{g10} - v^*_{g20}$. Similarly, for the input and output half-bridge topologies [see Fig. 6(b) and (c)], we find the following relations for the dc-link currents:

$$\bar{i}_c = \frac{1}{v^*_c}\left(i_g v^*_g + \frac{1}{2}v^*_c i_g - \sum_{k=1}^{3} i_{lk} v^*_{lk}\right) \tag{4}$$

$$\bar{i}_c = \frac{1}{v^*_c}\left(i_g v^*_g - \sum_{k=1}^{3} i_{lk} v^*_{lk} + \frac{1}{2}v^*_c i_{l1}\right). \tag{5}$$

The expressions of the capacitor current for the input and output half-bridge configurations are different to that of the conventional one, since there is an extra component depending on the grid current (input half-bridge) or the load current (output half-bridge). Such extra component can be observed in the zoom of Fig. 6. The dc-link high-frequency power losses are calculated by

$$P^{\mathrm{HO}}_{\mathrm{loss}} = 0.45\mathrm{ESR}_{(100\mathrm{Hz})}(I^{\mathrm{HO}}_{c,\mathrm{rms}})^2 \tag{6}$$

where $I^{\mathrm{HO}}_{c,\mathrm{rms}}$ is the component of high order of the root mean square (RMS) current on the dc link (with $h > 50$) and $\mathrm{ESR}_{(100\mathrm{Hz})}$ is the equivalent series resistance to frequency of 100 Hz. The ESR decreases with following parameters: rises at high frequencies, reducing of the ripple of current, and increasing temperature. The ESR can be considered constant for frequency higher than 3 kHz. It is equal to 0.45 times of the ESR value for 100 Hz [42], [43] . This means that $P^{\mathrm{HO}}_{\mathrm{loss}}$ depends only of $I^{\mathrm{HO}}_{c,\mathrm{rms}}$. Fig. 6 illustrates the harmonic spectrums of the dc-link capacitor currents of the full-bridge configuration, input half-bridge configuration, and output half-bridge configuration. Such simulated results were obtained considering 1 p.u. for the grid voltage and 1 p.u. for the load phase voltage. Furthermore, 1) the dc-link voltage equal to $\sqrt{3}$ times the amplitude of load phase voltage [for topology shown in Fig. 6(a)], 2) the dc-link voltage equal to two times the amplitude of load phase voltage [topology shown in Fig. 6(b)], and 3) the dc-link voltage equal to $2\sqrt{3}$ times the amplitude of load phase voltage [topology shown in Fig. 6(c)] have been considered. The low frequencies observed in the dc-link capacitor current of the topology C2 present only the second harmonic component, while the half-bridge topologies have a grid frequency component. On the other hand, the input and output half-bridge configurations showed a reduction of 24% and 8% in the high-frequency dc-link RMS current compared with a full-bridge topology, respectively. This means that the half-bridge topologies have a reduction in the dc-link high-frequency power losses.

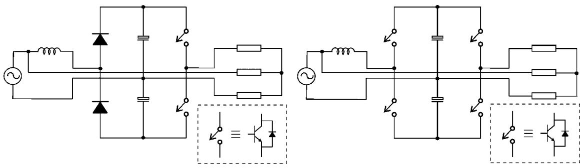

(a) (b)

Fig. 7. Economic single-phase to three-phase converter topologies for fixed frequency output proposed in [45] and [46]. (a) Half-bridge without active input current shaping (C3). (b) Half-bridge with active input current shaping (C4).

Again, the use of the midpoint connection of the capacitors is justifiable when the difference in the price of those devices (capacitor and switches) is enough to be considered [44]. Next, a review showing the appearance of single-phase to three-phase converters using a dc-link midpoint as an alternative will be given.

The works presented in [45] and [46] propose a family of single-phase to three-phase converters to be used when the output frequency is fixed and is equal to the utility grid (see Fig. 7). Notice that Enjeti *et al.* [45], [46] propose five new configurations, but just two of them will be presented in this section due to the dc-link midpoint connection; the other ones will be shown in Section II-A2. The topology in Fig. 7, in spite of reducing the number of power switches dramatically—compared with Fig. 1(a)—presents strong disadvantages: 1) the switches are subjected to twice the peak voltage of the single-phase mains; 2) the VA rating of the capacitors in the dc link is higher especially due to the low frequency current; and 3) active input current shaping cannot be obtained. This last disadvantage is not observed in the converter in Fig. 7(b).

Soon after, authors in [47] presented a configuration similar to that in Fig. 7(a), with a special approach for the machine start-up procedure (a switch and a capacitor were added). The impact of this kind of converter over the machine variables was studied in [48].

In those configurations, the machine operation is limited since the frequency is imposed by the grid (two machine phases are connected directly to grid). Then, the single-phase to three-phase converter with six switches, as observed in Fig. 8, was proposed and first investigated in [49] and [50] with a comprehensive analysis considering different figures of merit and deep comparison with the conventional converter. Years later, Covic *et al.* [51] suggested some improvements in the control, in terms of output voltage utilization of the circuit presented in Fig. 8. Regarding the application, Cruise *et al.* [52] indicated the topology in Fig. 8 as an alternative for motor drive systems in the rural area. This circuit was also considered in [53] for high-speed drive system and also in [54]–[58]. The authors in [59] employ a synchronization technique to reduce the capacitor current in the dc link; this technique was applied when the output frequency is equal to the input one.

A configuration with two dc-link midpoint connections (with two dc-link banks) was presented in [60]. This circuit operates as a soft-switched ac–dc–ac with high-frequency isolation, as

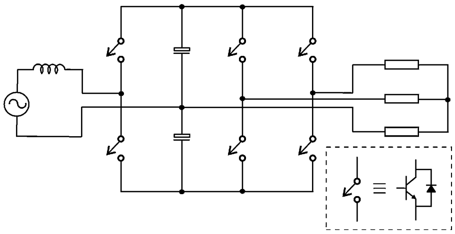


Fig. 8. Six switch converter proposed in [49] and [50] (C5).

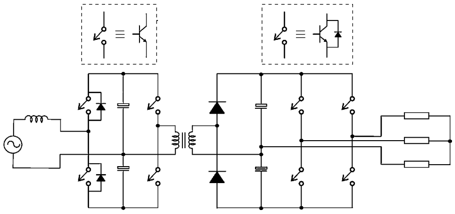


Fig. 9. Configuration with high-frequency isolation proposed in [60] (C6).

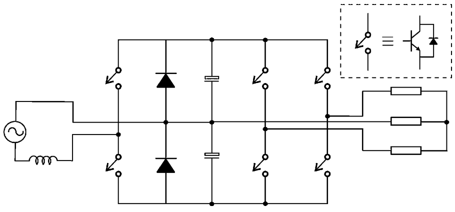
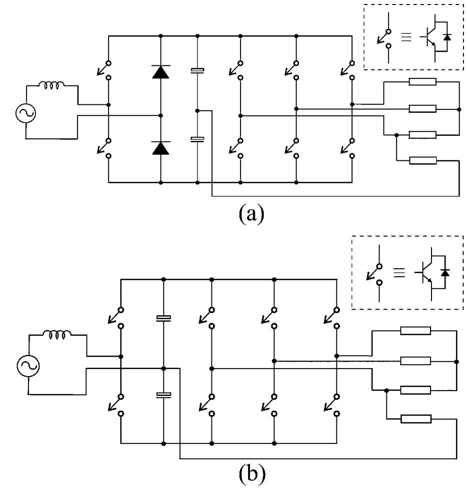


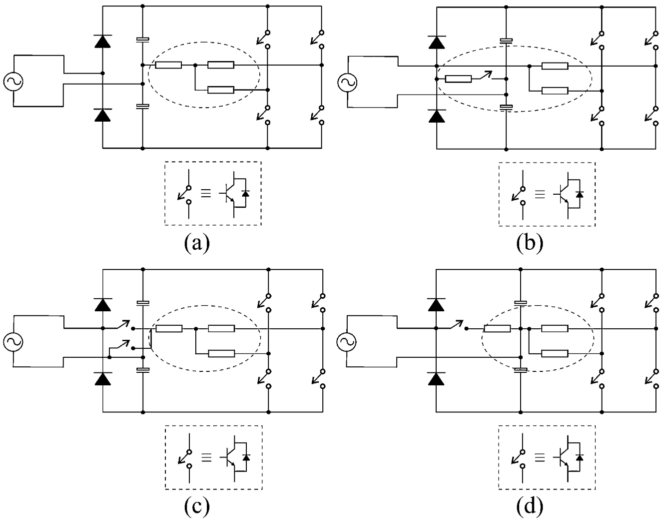
Fig. 10. Single-phase to three-phase bidirectional converter with six switches and a diode leg (C7).



(a)

(b)

Fig. 11. Single-phase to three-phase converter with semicontrolled PWM rectifier and four branch inverter proposed in [62] (C8 and C9).



(a) (b)

(c) (d)

Fig. 12. Configurations proposed in [63] (C10).

observed in Fig. 9. Its main characteristics are operation with zero-voltage switching, power factor control, and reversible power flow.

A single-phase to three-phase converter with six switches and a diode leg is presented in [61] (see Fig. 10).

Bellar *et al.* [62] proposed single-phase to three-phase four-wire configurations with dc-link midpoint connection, as observed in Fig. 11. The converter in Fig. 11(b) was also considered in the comparison presented in [62]. Notice that, in this case, a four-wire three-phase load has been considered.

The work presented in [63] brings a set of additional three-phase interconnections utilizing the B4 topology [see Fig. 12 (a)] with the possibility to supply a three-phase machine with a fixed or variable frequency. These configurations were named in that paper as B4f, B4vf, and B4vfz and they are shown, respectively, in Fig. 12(b)–(d). The main conclusions obtained in [63] in terms of those configurations were 1) the possible reduction in the capacitance under simple open-loop control methods; 2) having 2/3 of the pulsewidth modulation (PWM) switches as the conventional six-switch topology. Furthermore, for applications requiring line frequency operation, the B4vf is among the most practical. In some cases, the B4vfz may provide an advantage over the six-switch topology, when low power variable frequency, and rated power line frequency operation will suffice.

From the six-switch converter (see Fig. 8), which employs half-bridge connections at input–output converter sides, the authors in [64] consider two configurations changing the position of the half-bridge but using the same number of switches. The first configuration (proposed in [65]) employs the full-bridge converter at the load side and a half-bridge at the grid side [see Fig. 13(a)], while the second one employs a half-bridge converter at the load side and a full-bridge converter at the grid side [see Fig. 13(b)]. Notice that both circuits have a shared-leg between input and output converter sides. Furthermore, these topologies were compared with that proposed in [49] and [50] (see Fig. 4), and it was demonstrated that both present bidirectional power flow, sinusoidal input current with power factor close to one, and controlled output voltages. Unlike the conventional configuration, the advantages of the proposed converters are related to the reduced total harmonic distortion (THD) obtained at the input or output converter sides, since it could be chosen as the half-bridge for the input or output.

A comparison among a family of the single-phase to three-phase four-wire converters was addressed in [66]. The circuits

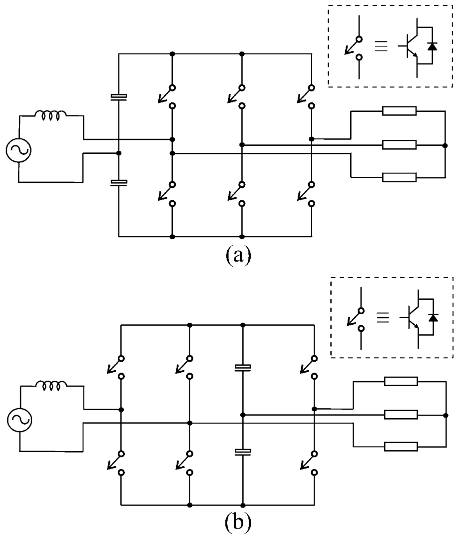


Fig. 13. Configurations proposed in [64] and [65] (C11).

considered in the work are depicted in Fig. 14. The use of the dc-link midpoint and share leg between input and output converter sides was the approach used to reduce the number of switches. All the proposed configurations have bidirectional power flow capability.

Table I shows the current and voltage ratings of the semiconductor devices for configurations C3–C12. A control complexity is also considered in this table and it is compared to the control block diagram used in the conventional configuration (see Fig. 3). In this table, D and S means diode and switch, respectively, i.e., 2D is two diodes while 4S is four switches. For instance, the current rating of the semiconductor devices in configuration C3 is two diodes with 2 p.u. and two switches with 1 p.u. In Tables I–V, the load phase voltage is 1 p.u. and the load current is 1 p.u. The grid voltage is also equal to 1 p.u.

2) Shared Leg Between Input–Output Converter Sides: The connection in the dc-link capacitors midpoint, as observed in the configurations shown in the last section, creates an extra low frequency current with 60 Hz flowing through the capacitor (see Fig. 6). This kind of connection must be avoided when the lifespan, voltage fluctuation, and stress in the capacitors are considered as critical issues.

In a general sense, the reduction of components without using the dc-link midpoint connection, in ac converters, means in leg shared between two stages of the converter [67]–[69]. Although, a reduced switch count converter with nine switches has been proposed recently in [70] for three-phase to three-phase conversion, such configuration was conceived without any shared leg.

Fig. 15 shows the configurations proposed in [45]. In these configurations, there is no connection in the dc-link midpoint with the objective of component reduction. The capacitor midpoint connection observed in Fig. 15(b) is established for the multilevel purposes. Such topologies were conceived to be used when the output frequency is fixed and must be equal to the utility grid frequency. Authors in [45] highlighted some advantages of these configurations including the bidirectional power flow between input–output converter sides, which could be useful in regenerative braking for motor type loads. The configuration in Fig. 15(a) was also studied in [71] considering the start-up procedure.

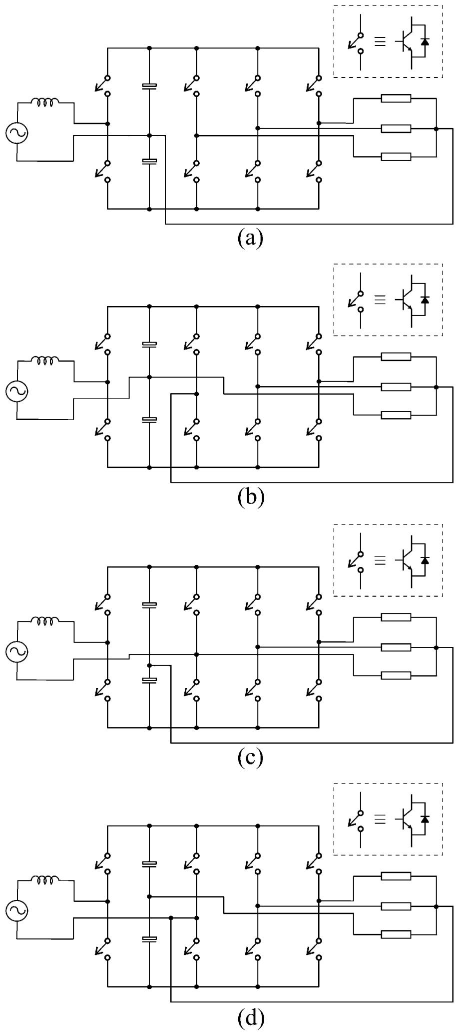


Fig. 14. Configurations proposed in [66] (C12).

In [72], a synchronization technique applied to the converter indicated in Fig. 16 was proposed. With this approach, it is possible to supply the three-phase machine with the same rated voltage of the conventional configuration, even with a shared leg between input and output converter sides.

The technique presented in [72] can be applied in all ac–dc–ac power converter configurations with a shared leg. As mentioned before, with this technique, the power converter with a reduced number of components will operate at the same conditions of the conventional configuration, but both sides of the converter must operate with the same frequency. The experimental results presented in Fig. 17 highlight this situation. Fig. 17(a) shows the power factor control of the grid current, while Fig. 17(b) shows the dc-link voltage control and the output phase voltage. Notice that, even using just four legs, the configuration C15 operates with the same dc-link voltage as the full-bridge configuration C2 would operate.

TABLE I
COMPARATIVE OF THE CONFIGURATIONS WITH DC-LINK MIDPOINT CONNECTION

	Topologies									
	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Current rating (p.u)	2.0(2D) 1.0(2S)	2.0(2D) 1.0(2S)	3.0(2S) 1.0(4S)	3.0(4S) 1.0(4S) 1.0(4S)	3.0(2S) 1.73(2D) 1.0(4S)	2.0(4S) 2.0(2D) 1.0(4S)	4.0(2S) 2.0(2S) 1.0(4S)	3.0(2D) 1.0(4S)	2.0(2S) 1.0(2S)	3.0(2S) 1.0(6S)
Voltage rating (p.u.) (p.u.)	$2\sqrt{3}$	$2\sqrt{3}$	$2\sqrt{3}$	2.0 (4S) $\sqrt{3}$(4S-2D)	$2\sqrt{3}$	$\sqrt{3}$	2.0	$2\sqrt{3}$	2.0	$\sqrt{3}$
Control Complexity	lower	higher	equival.	higher	higher	higher	higher	higher	higher	higher

Configurations C3–C12.

TABLE II
COMPARATIVE OF CONFIGURATIONS WITH SHARED LEG

	Topologies			
	C13	C14	C15	C16
Current rating (p.u)	2.0(4S) 1.0(2S)	2.0(2D) 2.0(4S) 1.0(1.0)	3.0(2S) 2.0(2S) 1.0(2S)	3.0(4S) 1.0(6S)
Voltage rating (p.u.)	$\sqrt{3}$	$\sqrt{3}$ (2D) $\sqrt{3}/2$(8S)	$\sqrt{3}$	$\sqrt{3}$
Complexity Control	higher	higher	higher	higher

Configurations C13–C16.

TABLE III
COMPARATIVE OF CONFIGURATIONS WITH RECTIFIER SIMPLIFICATION

	Topologies		
	C17	C18	C19
Current rating (p.u)	3.0(2S) 2.0(6S)	2.0(6s)	3.0(2S) 3.0(2D) 1.0(6S) 2.0(2S)
Voltage rating (p.u.)	$\sqrt{3}$	$2\sqrt{3}$	$\sqrt{3}$
Complexity Control	higher	higher	higher

Configurations C17–C19.

TABLE IV
COMPARATIVE OF CONFIGURATIONS WITH DC-LINK CAPACITOR ELIMINATION

	Topologies			
	C20	C21	C22	C23
Current rating (p.u)	$\sqrt{3}$(6S)	$\sqrt{3}$(4S)	1.0(9S)	
Voltage rating (p.u.)	1.0	$\sqrt{3}$	$\sqrt{3}$	$\sqrt{3}$
Complexity Control	lower	lower	higher	higher

Configurations C20–C23.

TABLE V
COMPARATIVE OF CONFIGURATIONS WITH INCREASED NUMBER OF COMPONENTS C24 TO C29

	Topologies				
	C24	C25	C26	C27	C29
Current rating (p.u)	3.0(2D) 1.0(6S)	3.0(4D) 1.0(6S)	1.5(8S) 1.0(6S)	1.5(4S) 2.0(2S) 1.0(4S)	1.5(8S) 0.5(12S)
Voltage rating (p.u.)	$\sqrt{3}$	$\sqrt{3}$	$\sqrt{3}$	$\sqrt{3}$	$\sqrt{3}$
Complexity Control	higher	higher	higher	higher	higher

In [73], a set of configurations for single-phase to three-phase four-wire converter was introduced. All configurations present one shared leg. Some of those were considered as conventional for comparison purposes and the proposed ones are depicted in Fig. 18. All the proposed configurations have bidirectional power flow capability.

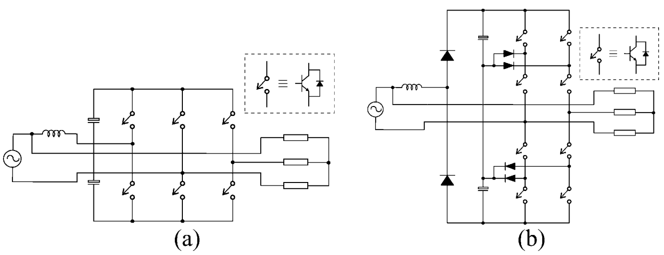


Fig. 15. Single-phase to three-phase converter configurations without dc-link midpoint connection proposed in [45]. (a) Full-bridge single-phase with active input current shaping (C13). (b) neutral point clamped (NPC) configuration (C14).

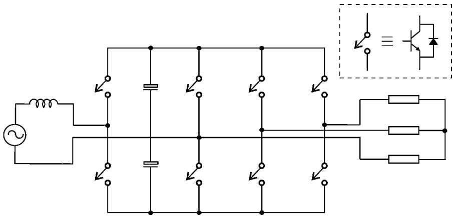


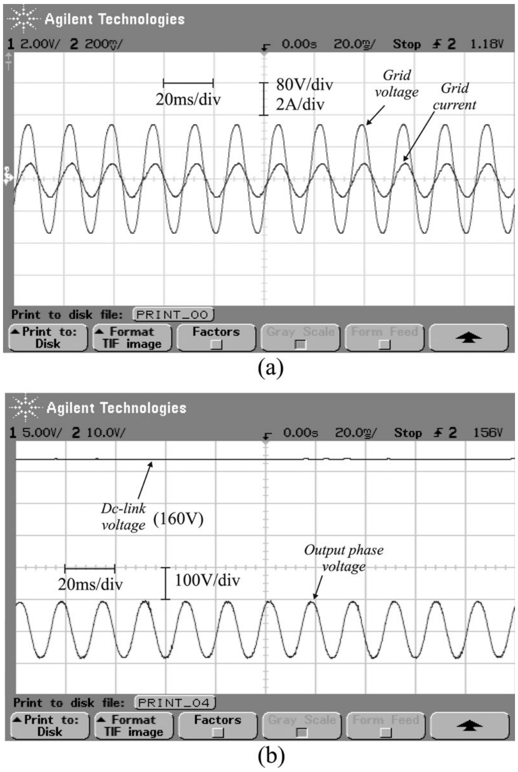
Fig. 16. Single-phase to three-phase converter with one shared leg (C15).

Table II shows the current and voltage ratings of the semiconductor devices for configurations C13–C16, as well as the control complexity.

3) Rectifier Simplification: After presenting configurations with a reduced number of semiconductors by using the dc-link midpoint connection and shared leg, topologies, which reduce the semiconductor devices by using other strategies, as, for example, simplification in the rectifier circuit, will be carried out.

Itoh and Fujita [74] proposed two ac motor drive systems fed from a single-phase grid, as observed in Fig. 19. Notice that, in those configurations, the neutral of the machine is directly connected to the grid neutral, which means 1/3 of the grid current circulating in each phase of the machine. This current increases the losses in the machine but does not affect its *dq* currents. Consequently, the torque is unaffected by the grid current. Despite this drawback, the systems present the merits of no inductor boost requirement in the rectifier circuit and of reduced number of switches.

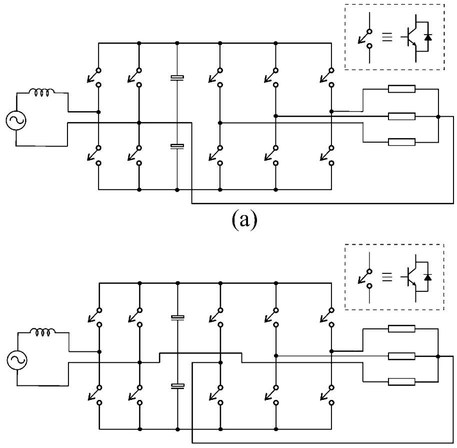
Fig. 20 shows the experimental results of the configuration C17. This configuration guarantees the same control goals of that in configuration C2, i.e., power factor control [see Fig. 20(a)], dc-link voltage control [see Fig. 20(b)], and balanced *dq* currents applied to the machine [see Fig. 20(c)].



(a)

(b)

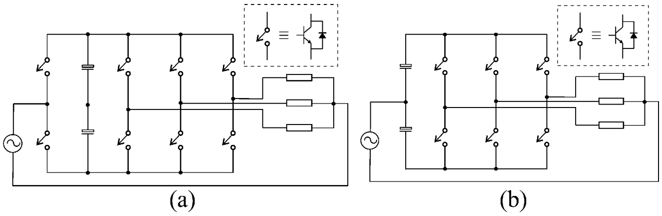
Fig. 17. Experimental results of the configuration C15. (a) Power factor control. (b) Dc link and output voltage controls.



(a)

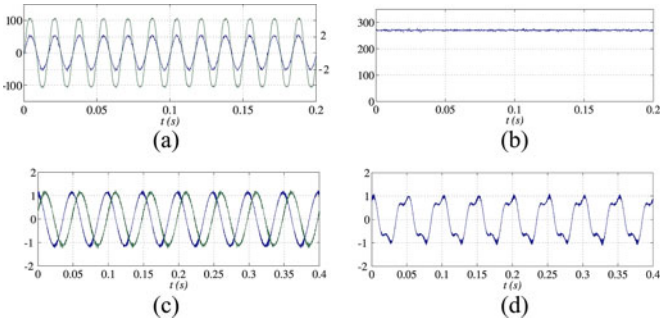
(b)

Fig. 18. Configurations proposed in [73]. (C16)



(a) (b)

Fig. 19. Single-phase to three-phase without boost inductor proposed in [74] (C17 and C18).



(a) (b)

(c) (d)

Fig. 20. Experimental results of the single-phase to three-phase converter without boost inductor. (a) Power factor control. (b) Dc-link voltage control. (c) dq currents. (d) Phase current of the machine.

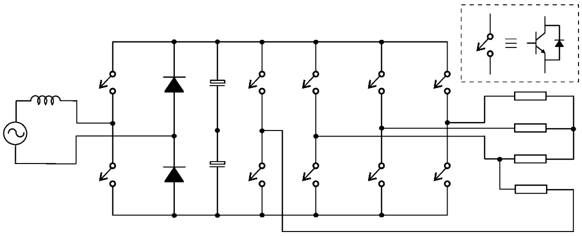


Fig. 21. Configuration proposed in [62] (C19).

However, the phase current of the machine presents low frequency distortions.

In spite of Fig. 19(b) utilizes the dc-link mid-point, this topology is considered in this section because its main feature is the total elimination of the rectifier. Two modulation techniques (sinusoidal and space vector) were investigated in [75] for these configurations.

Finally, a single-phase to three-phase four-wire converter with reduced component count in the rectifier was proposed in [62], as depicted in Fig. 21.

Table III shows the control complexity, current and voltage ratings of the semiconductor devices for configurations C17–C19.

B. DC-Link Capacitor Elimination

The matrix converter is a configuration with direct power conversion from an ac grid to an ac load [76]–[81], which means a power conversion with the dc-link capacitor elimination. Configurations have been proposed for three-phase to three-phase, three-phase to two-phase, and three-phase to single-phase conversion using the matrix converter approach [82]– [84].

The use of the matrix converter philosophy in a single-phase to three-phase conversion is more challenging than in the other conversions due to the voltage variation of the input voltage.

The authors in [85] can be considered the pioneers in the single-phase to three-phase conversion task without dc-link capacitors. The circuit proposed in [85] is presented in Fig. 22(a). The advantages and disadvantages of this circuit can be sorted as follows: 1) volts per hertz control capability; 2) input current nearly sinusoidal; 3) third-harmonic components in the output voltage; and 4) low voltage utilization. Years later, this

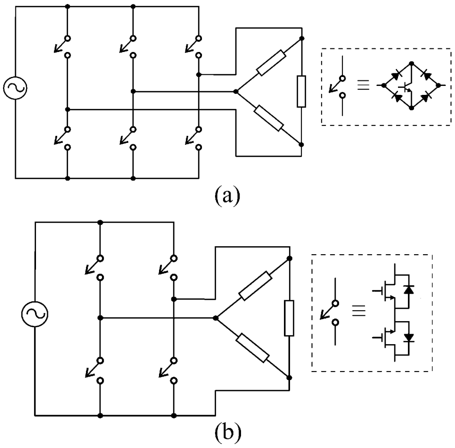


Fig. 22. Single-phase to three-phase matrix converter: (a) proposed in [85] (C20) and (b) proposed in [87] (C21).

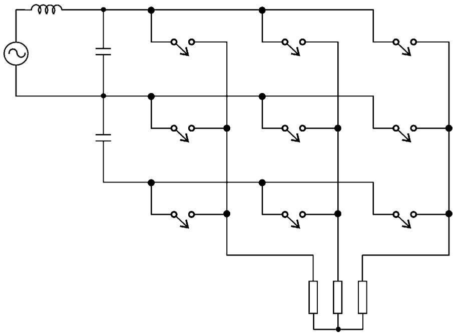


Fig. 23. Single-phase to three-phase matrix converter presented in [90] (C22).

configuration was explored in [86] considering a new operation strategy.

In terms of reduced component count, an improvement of the work in [85] is proposed in [87], with the reduction of 33% of the semiconductor devices. This configuration is presented in Fig. 22(b). In spite of that reduction, it is possible to control voltage and frequency of the three-phase motor. The disadvantages are that the voltage gain in input–output relation is low (just 63%) and low frequency harmonics are observed in the motor currents. A single-phase to three-phase cycloconverter was also presented in [88] and [89], where emphasis is given on the model and simulation by using PSPICE.

The matrix converter in its standard arrangement appears in [90]. This work dealt with the control and design methods for a single-phase to three-phase matrix converter, as observed in Fig. 23. Yamashita and Takeshita [91] propose a PWM strategy for this converter, aiming to reduce the number of commutations, while in [92] the delta–sigma modulator is employed, which is compared with a PWM approach.

Another single-phase to three-phase matrix converter configuration is proposed in [93], as depicted in Fig. 24. The topology proposed in [93] aims to reduce distortions in voltages and currents of the system proposed in [85] caused by the fluctuation of the single-phase instantaneous power at twice line frequency. Notice from Fig. 24 that the proposed topology has three additional bidirectional switches and one reactor.

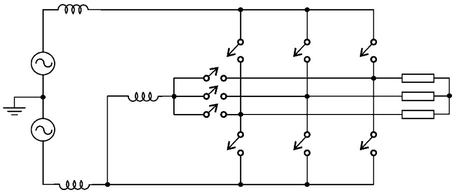


Fig. 24. Matrix converter configuration is proposed in [93]. (C23).

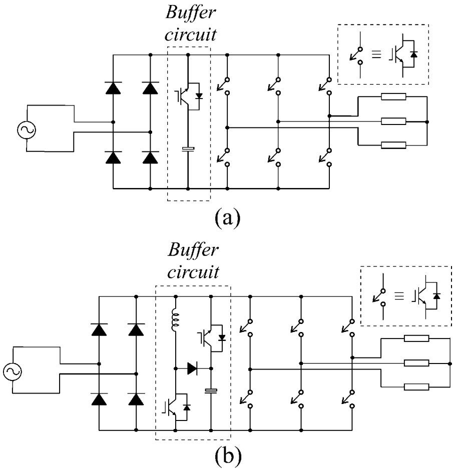


Fig. 25. Single-phase to three-phase converter with an active buffer and a charge circuit proposed in [101] (C24) and [102] (C25).

The configurations presented in [94] and [95] show a cycloconverter with seven thyristors and one balancer capacitor. These configurations cannot be applied in systems that demand soft torque due to unbalanced currents observed in the motor.

In [96], a configuration considering a current source type in the converter input side was proposed. Other works also realized a single-phase to three-phase conversion using ac–ac direct connection, as in [97] and [98].

Table IV shows the control complexity, current and voltage ratings of the semiconductor devices for configurations C20–C23.

III. CONFIGURATIONS WITH INCREASED NUMBER OF COMPONENTS

An increase in the number of components in ac converter is acceptable when benefits can be incorporated to the converter itself, as in the case of interleaved [99] or multilevel configurations [100], which improve the quality of the converter waveforms. Considering the single-phase to three-phase conversion, the component count increase can be further justified by the need of the dc-link voltage fluctuation reduction, which is no longer observed in three-phase to three-phase conversion systems.

The reduction of the power ripple with a frequency that is twice of the power supply was first investigated in [101] and soon after in [102] and [103] (see Fig. 25). The authors proposed configurations and the control method for a single-phase to three-phase power converter with power decoupling function. Such philosophy was also employed in a three-phase to single-phase conversion system in [104]. The main advantage of the

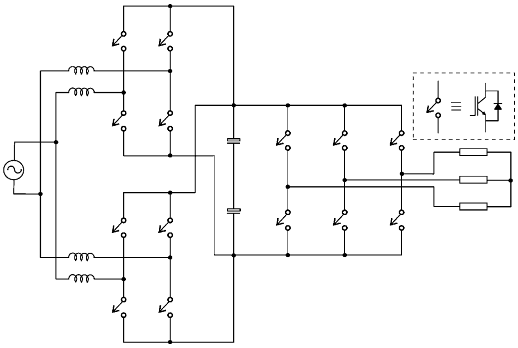


Fig. 26. Double rectifier stage proposed in [105] and [106] (C26).

proposed circuit is that it does not require a large reactor and large smoothing capacitors in the dc-link part. The proposed topology is constructed based on an indirect matrix converter with an active buffer to decouple the power ripple.

On the other hand, the single-phase to three-phase converter is characterized by the irregular distribution of current (and consequently of the power) among the semiconductor devices of the input and output converter sides (see Fig. 4). The conventional configurations (see Fig. 1) require rectifier power switches with current and power ratings larger than those switches in the inverter side.

This aspect has been considered in [105] and [106], with the proposal of a single-phase to three-phase with two parallel rectifiers, as observed in Fig. 26. In spite of increasing the number of components, such topology presents the following merits: 1) reduction of the rectifier current; 2) THD improvement in the grid side due to interleaved technique; and 3) reducing of stress in the dc-link capacitor and fault tolerance capability in the rectifier circuit. A circulating current appears in the rectifier stage, due to parallel connection, which was controlled by a proposed algorithm in [105] and [106].

Fig. 27 shows some experimental results for configuration C26 highlighting the interleaved operation. Fig. 27(a)–(c) depicts, respectively, grid and rectifiers currents, zoom of point 1, and zoom of point 2.

With the same philosophy, Jacobina *et al.* [107] propose a single-phase to three-phase converter composed of two parallel single-phase rectifiers and a shared leg between the input and output converter sides, as shown in Fig. 28. In applications where the input and output frequencies are equal, this circuit presents the following characteristics: 1) reduced power rating of the rectifier switches, which means switches operating at equivalent power rating; 2) reduced costs if the price of switches with different power ratings is higher than the cost of switches with close ratings; and 3) fault tolerance in the rectifier circuit.

Other solution employing parallel connection of the ac–dc–ac single-phase to three-phase converter was presented by Jacobina *et al.* [108]; this configuration is depicted in Fig. 29.

Table V shows the control complexity, current and voltage ratings of the semiconductor devices for configurations C24–C29.

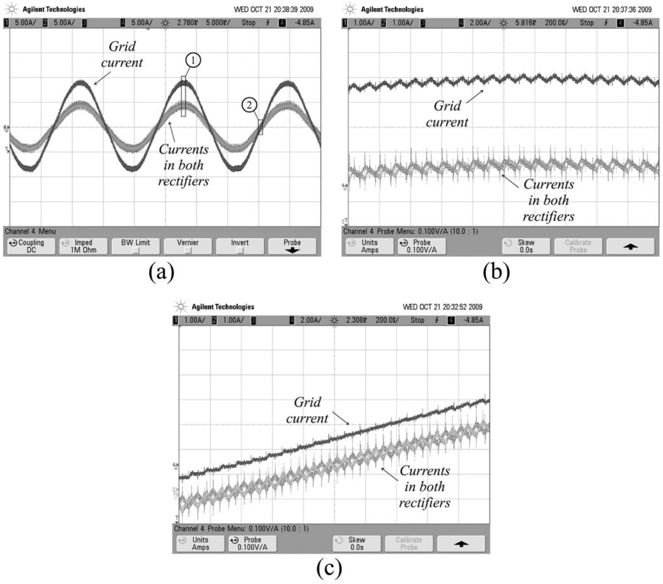


Fig. 27. Experimental results of the double rectifier stage proposed in [106].

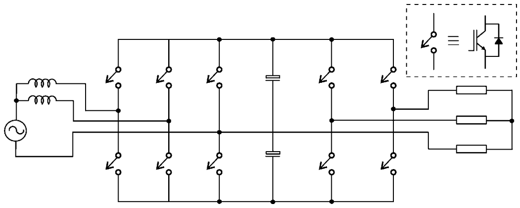


Fig. 28. Parallel rectifier with shared leg proposed in [107] C(27).

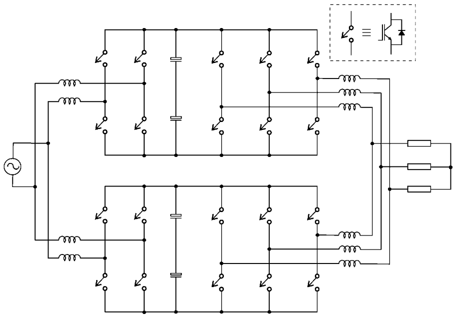


Fig. 29. Parallel ac–dc–ac single-phase to three-phase converter proposed by [108] (C28).

IV. APPLICATIONS

Many of the single-phase to three-phase topologies presented before have been used in different applications, for instance, power converter operating as an active power filter to reduce the amount of power processed by the switches, as done in [109]. This and other applications will be considered in this section.

The configuration proposed in [7] brings the idea of the active power filter applied to single-phase to three-phase conversion, as observed in Fig. 30. In fact, the configuration used in [7] was the same (in spite of the LC filter) of that in [45], but the final application and control was totally different. In this study, it was possible to improve the power quality for both linear and

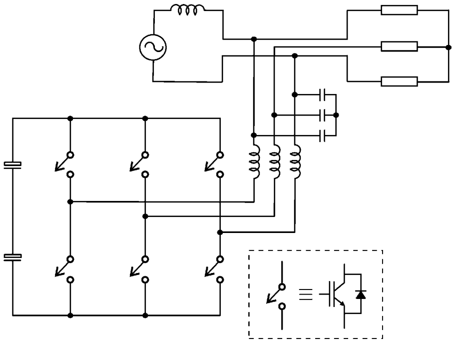
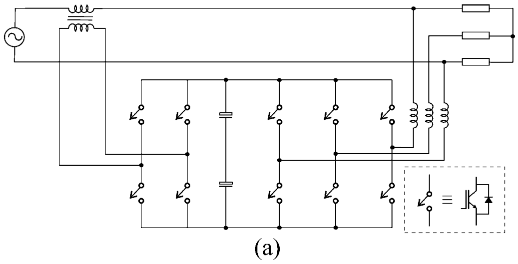
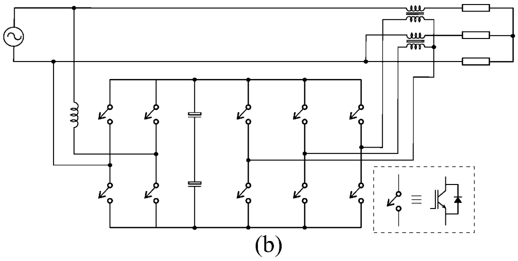


Fig. 30. Single-phase to three-phase system operating as an active power filter proposed in [7] (C29).



(a)



(b)

Fig. 31. Single-phase to three-phase converter operating as a universal active filter (C30). (a) Single-phase to three-phase active power filter proposed in [111]. (b) Single-phase to three-phase active power line conditioner proposed in [112].

nonlinear loads [7], as well as to guarantee the power factor correction. This approach was also considered in [110] for a three-phase to a single-phase conversion. A typical application for the system proposed in [7] is found in rural areas supplied by a single wire with earth return system. The main advantages of this system are 1) the power converter processes just a fraction of the load power and the energy necessary to regulate the dc-link voltage; and 2) none source at the dc side in the normal operation (if island mode operation is needed, a dc source must be available at the dc link to supply the load). Its main disadvantage is that the line-to-line voltage amplitude of the three-phase load is limited to the amplitude of the single-phase voltage. This could be minimized considering a delta connection of the three-phase load.

To solve the problem related to the low amplitude of the load voltages, Dos Santos, Jr., [111], [112] propose a universal power filter to be used in single-phase to three-phase systems, as depicted in Fig. 31(a) and (b). Both converters are conceived to compensate grid voltage distortions, and harmonic and reactive power drained by the load. The difference between these circuits is related to the position of the series and shunt filters. Notice that, in Fig. 31(a), the series filter is located at the grid side, while the shunt active power filter is located at the load side. Instead, in Fig. 31(b), the series filter is located at the load side, and the shunt active power filter is located at the grid side. The energy processed by each converter is lower than that processed by conventional topologies, since part of the power goes through the line. Consequently, the power ratings of the proposed systems are lower when compared to the conventional one. Other configurations were also established considering the same approach, as in [113] and [114].

Another possible application for a single-phase to three-phase converter is in electric traction where auxiliary fans and pumps need to be operated from the single-phase mains [45], or in [115] where it is considered as an auxiliary ac motor drives in electric locomotives (the application in a locomotive was also considered in [116]) and agricultural applications in rural areas.

The works in [117]–[120] explore the application of the single-phase to three-phase converter in a cogeneration system. The application of the single-phase to three-phase converter in a distributed generated plant with emphasis on maximum power pointer tracker was also presented in [121].

The application of the single-phase to three-phase converter in uninterruptible power system was treated in [122], while in [123], a single-phase to three-phase power converter with a mechanical three-terminal switch was proposed. The position of this switch must be selected depending on the speed motor operation. The authors of this work suggest air-conditioner systems as a possible application.

A fault tolerant system for a single-phase to three-phase conversion was evaluated in [124] and [125].

V. GENERAL COMPARISON

This section aims to bring a general comparison among the single-phase to three-phase configurations presented throughout this paper. This comparison includes the elements (switches, diodes, capacitors, etc.) employed in each configuration as well as their main features, like capability to provide the single-phase to three-phase conversion with input current shaping, output voltage with variable frequency, and fluctuation reduction in the dc-link voltage. Table VI shows a summary highlighting the more important points for each configuration. In this table, "$*$" in some configurations means that they are employed in a single-phase to three-phase with four-wire conversion.

Notice that, regarding the number of unidirectional switches used in each topology, the configuration C3 presents the smallest number of devices, two configurations (C4 and C10) employ just four switches, seven configurations (C1, C5, C7, C11, C13, C18, and C28) are conceived with six switches, one configuration (C24) with seven switches, eight topologies (C6, C8, C9, C12, C14, C15, C17, and C25) use eight switches, five configurations (C2, C16, C19, C27, and C29) are implemented with ten switches, and one configuration (C26) with 14 switches. Four configurations (C20–C23) do not use unidirectional switches. The other characteristics of each topology can be observed directly in the table.

TABLE VI
GENERAL COMPARISON AMONG CONFIGURATIONS

	Switch (Unid.)	*Switch (Bid.)*	*Diode*	*Dc-link bank*	*Boost inductor*	*Input current shaping*	*Fixed frequency output*	*Dc − link fluctuation reduction*
C1	6	0	4	1	0	no	no	no
C2	10	0	0	1	1	yes	no	no
C3	2	0	2	1	0	no	yes	no
C4	4	0	0	1	1	yes	yes	no
C5	6	0	0	1	1	yes	no	no
C6	8	0	2	2	1	yes	no	no
C7	6	0	2	1	1	yes	no	no
C8*	8	0	2	1	1	yes	no	no
C9*	8	0	0	1	1	yes	no	no
C10	4	0	2	1	0	no	yes/no	no
C11	6	0	0	1	1	yes	no	no
C12*	8	0	0	1	1	yes	no	no
C13	6	0	0	1	1	yes	yes	no
C14	8	0	6	1	0	no	yes	no
C15	8	0	0	1	1	yes	no	no
C16*	10	0	0	1	1	yes	no	no
C17	8	0	0	1	0	yes	no	no
C18	6	0	0	1	0	yes	no	no
C19*	10	0	2	1	1	yes	no	no
C20	0	6	0	0	0	no	no	no
C21	0	4	0	0	0	no	no	no
C22	0	9	0	0	0	yes	no	no
C23	0	6	0	0	0	yes	no	no
C24	7	0	4	0	0	no	no	yes
C25	8	0	5	0	0	no	no	yes
C26	14	0	0	1	4	yes	no	no
C27	10	0	0	1	2	yes	no	no
C28	20	0	0	2	2	yes	no	no
C29	6	0	0	1	0	yes	yes	no
C30	10	0	0	1	0	yes	yes	no

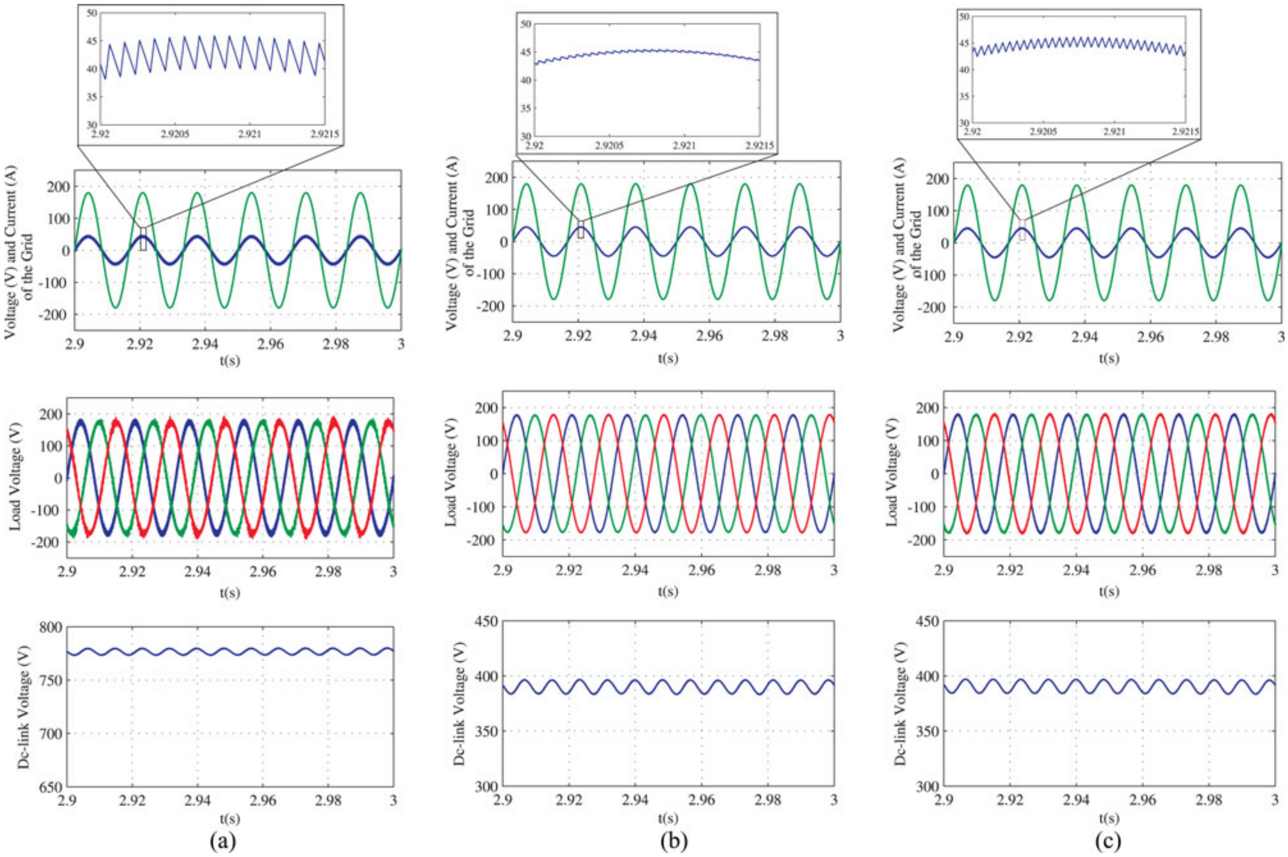


Fig. 32. Simulated results for (a) configuration C5, (b) configuration C28, and (c) configuration C2.

The comparison analysis among the configurations presented in this paper can be summarized considering the effect of component count reduction and increase in the converter waveforms. It is evident that both solutions (reduction and increase) affect other figures of merit of the converters, such as price and lifespan of each configuration. Indeed, it is possible to establish a rule among the configurations presented throughout this paper, i.e.,

1) component count reduction implies in a direct possible reduction of the initial price of the converter, as observed in Fig. 8 (configuration C5) and an impoverishment of the waveforms qualities, as observed in Fig. 32(a);
2) increasing the number of components implies in a direct rising prices of the converters, as observed in Fig. 29 (configuration C28) and it implies in an improvement of the waveforms qualities, as observed in Fig. 32(b).

Fig. 32(c) shows the same set of the waveforms for the conventional configuration—configuration C2. Such simulated results represent, in a general way, the influence of the approaches (component count reduction or increase) employed by authors in the technical literature.

VI. CONCLUSION

The proposal of this paper was to provide a state of the art for single-phase to three-phase conversion system, showing the most important configurations and their characteristics. It was observed two main tendencies over the years, i.e., configurations with reduced number of components and configurations with increased number of components. Such configurations were sorted throughout this paper and compared with each other. The general comparison among the configurations includes characteristics and elements employed in each topology. More than 110 papers were cited and the configurations were chronologically distributed in each section.

Among the configurations with a reduced number of semiconductors (C3–C19), the dc-link midpoint connection was found to be common in the first topology proposals (C3–C12); it was justified by the high price of the power switch compared to that of the dc-link capacitor. The other solution observed, when a semiconductor devices reduction is required, is the configurations with shared leg between input–output converter sides (C13–C16) which could be an interesting solution, especially when the input–output frequencies are equal.

In spite of single-phase to three-phase configurations with dc-link capacitor elimination (C20–C23) have been considered by many authors, it seems to be an unattractive option, especially regarding the applications in rural or remote area, since the high power density and reduction size obtained with the capacitor elimination is not a prime requirement in this kind of application.

The configurations with increased number of components (C24–C29) are an interesting option for single-phase to three-phase systems due to its inherent characteristics, such as THD improvements, high reliability, and efficiency. Furthermore, it is possible to solve a specific problem observed in single-phase to three-phase systems, i.e., dc-link voltage fluctuation (C24, C25).

Due to the power distribution system scenario in huge countries like Brazil and due to the advantages of the three-phase connected load (e.g., motor), instead of single-phase one, it suggests that single-phase to three-phase power conversion systems continue to be used in rural areas. In terms of future research, the configurations with increased number of components seem to be a trend due to their specific advantages.

REFERENCES

[1] B. Saint, “Rural distribution system planning using smart grid technologies,” in *Proc. IEEE Rural Electr. Power Conf.*, Apr. 2009, pp. B3–B3-8.

[2] H.-C. Chen, “Single-loop current sensorless control for single-phase boost-type SMR,” *IEEE Trans. Power Electron.*, vol. 24, no. 1, pp. 163–171, Jan. 2009.

[3] A. R. C. de L. M. Duarte, U. H. Bezerra, M. E. de L. Tostes, and G. N. da Rocha Filho, “Alternative energy sources in the Amazon,” *IEEE Power Energy Mag.*, vol. 5, no. 1, pp. 51–57, Jan./Feb. 2007.

[4] B. Zahedi and S. Vaez-Zadeh, “Efficiency optimization control of single-phase induction motor drives,” *IEEE Trans. Power Electron.*, vol. 24, no. 4, pp. 1062–1070, Apr. 2009.

[5] V. Kinnares and C. Charumit, “Modulating functions of space vector PWM for three-leg VSI-fed unbalanced two-phase induction motors,” *IEEE Trans. Power Electron.*, vol. 24, no. 4, pp. 1135–1139, Apr. 2009.

[6] X. Wang, H. Zhong, Y. Yang, and X. Mu, “Study of a novel energy efficient single-phase induction motor with three series-connected windings and two capacitors,” *IEEE Trans. Energy Convers.*, vol. 25, no. 2, pp. 433–440, Jun. 2010.

[7] R. Q. Machado, S. Buso, and J. A. Pomilio, “A line-interactive single-phase to three-phase converter system,” *IEEE Trans. Power Electron.*, vol. 21, no. 6, pp. 1628–1636, Nov. 2006.

[8] A. H. Maggs, “Single-phase to three-phase conversion by the ferrarisarno system,” *Electr. Eng.—Part I: Gen., J. Inst.*, vol. 93, no. 68, pp. 133–136, Aug. 1946.

[9] K. Hisano, H. Kobayashi, and T. Kobayashi, “A new type single-phase to three-phase converter,” *IEEE Trans. Magn.*, vol. 2, no. 3, pp. 643–647, Sep. 1966.

[10] S. Dewan and M. Showleh, “A novel static single-to three-phase converter,” *IEEE Trans. Magn.*, vol. 17, no. 6, pp. 3287–3289, Nov. 1981.

[11] M. Liserre, “Dr. Bimal K. Bose: A reference for generations [editor’s column],” *IEEE Ind. Electron. Mag.*, vol. 3, no. 2, pp. 2–5, Jun. 2009.

[12] F. Blaabjerg, A. Consoli, J. A. Ferreira, and J. D. van Wyk, “The future of electronic power processing and conversion,” *IEEE Trans. Ind. Appl.*, vol. 41, no. 1, pp. 3–8, Jan./Feb. 2005.

[13] F. W. Gutzwiller, “Thyristors and rectifier diodes—The semiconductor workhorses,” *IEEE Spectr.*, vol. 4, no. 8, pp. 102–111, Aug. 1967.

[14] A. Elasser, M. H. Kheraluwala, M. Ghezzo, R. L. Steigerwald, N. A. Evers, J. Kretchmer, and T. P. Chow, “A comparative evaluation of new silicon carbide diodes and state-of-the-art silicon diodes for power electronic applications,” *IEEE Trans. Ind. Appl.*, vol. 39, no. 4, pp. 915–921, Jul./Aug. 2003.

[15] S. B. Dewan, P. P. Biringer, and G. J. Bendzsak, “Harmonic analysis of ac-to-ac frequency converter,” *IEEE Trans. Ind. Gen. Appl.*, vol. IGA-5, no. 1, pp. 29–33, Jan. 1969.

[16] J. Quaicoe, S. Dewan, and P. Biringer, “A new three-phase to single-phase ac to ac frequency converter,” *IEEE Trans. Magn.*, vol. 15, no. 6, pp. 1779–1781, Nov. 1979.

[17] M. E. Fraser, C. D. Manning, and B. M. Wells, “Transformerless four-wire PWM rectifier and its application in ac–dc–ac converters,” *IEE Proc. Electr. Power Appl.*, vol. 142, no. 6, pp. 410–416, Nov. 1995.

[18] C. Klumpner, P. Nielsen, I. Boldea, and F. Blaabjerg, “New solutions for a low-cost power electronic building block for matrix converters,” *IEEE Trans. Ind. Electron.*, vol. 49, no. 2, pp. 336–344, Apr. 2002.

[19] L. Helle, K. B. Larsen, A. H. Jorgensen, S. Munk-Nielsen, and F. Blaabjerg, “Evaluation of modulation schemes for three-phase to three-phase matrix converters,” *IEEE Trans. Ind. Electron.*, vol. 51, no. 1, pp. 158–171, Feb. 2004.

[20] Z. Idris, M. K. Hamzah, and N. R. Hamzah, “Modelling simulation of a new single-phase to single-phase cycloconverter based on single-phase matrix converter topology with sinusoidal pulse width modulation using matlab/simulink,” in *Proc. Int. Conf. Power Electron. Drives Syst.*, Nov., 2005, vol. 2, pp. 1557–1562.

[21] C. B. Jacobina, I. S. de Freitas, and E. R. C. da Silva, "Reduced-switch-count six-leg converters for three-phase-to-three-phase/four-wire applications," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 963–973, Apr. 2007.

[22] C. B. Jacobina, I. S. de Freitas, and A. M. N. Lima, "DC-link three-phase-to-three-phase four-leg converters," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 1953–1961, Aug. 2007.

[23] C. B. Jacobina, E. C. dos Santos Jr., M. B. de Rossiter Correa, and E. R. C. da Silva, "AC motor drives with a reduced number of switches and boost inductors," *IEEE Trans. Ind. Appl.*, vol. 43, no. 1, pp. 30–39, Jan./Feb. 2007.

[24] M. Hagiwara, K. Wada, H. Fujita, and H. Akagi, "Dynamic behavior of a 21-level BTB-based power-flow controller under single-line-to-ground fault conditions," *IEEE Trans. Ind. Appl.*, vol. 43, no. 5, pp. 1379–1387, Sep./Oct. 2007.

[25] Y. Tang, S. Xie, and C. Zhang, "Z-source ac–ac converters solving commutation problem," *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2146–2154, Nov. 2007.

[26] C. Liu, B. Wu, N. Zargari, D. Xu, and J. Wang, "A novel three-phase three-leg ac/ac converter using nine IGBTs," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1151–1160, May 2009.

[27] P. C. Loh, F. Gao, P.-C. Tan, and F. Blaabjerg, "Three-level ac–dc–ac z-source converter using reduced passive component count," *IEEE Trans. Power Electron.*, vol. 24, no. 7, pp. 1671–1681, Jul. 2009.

[28] M.-K. Nguyen, Y.-G. Jung, and Y.-C. Lim, "Single-phase ac–ac converter based on quasi-z-source topology," *IEEE Trans. Power Electron.*, vol. 25, no. 8, pp. 2200–2210, Aug. 2010.

[29] M.-K. Nguyen, Y.-G. Jung, Y.-C. Lim, and Y.-M. Kim, "A single-phase z-source buck—boost matrix converter," *IEEE Trans. Power Electron.*, vol. 25, no. 2, pp. 453–462, Feb. 2010.

[30] X. P. Fang, Z. M. Qian, and F. Z. Peng, "Single-phase z-source PWM ac–ac converters," *IEEE Power Electron. Lett.*, vol. 3, no. 4, pp. 121–124, Dec. 2005.

[31] I. S. de Freitas, C. B. Jacobina, and E. C. dos Santos, Jr., "Single-phase to single-phase full-bridge converter operating with reduced ac power in the dc-link capacitor," *IEEE Trans. Power Electron.*, vol. 25, no. 2, pp. 272–279, Feb. 2010.

[32] S. M. Dehghan, M. Mohamadian, and A. Yazdian, "Hybrid electric vehicle based on bidirectional z-source nine-switch inverter," *IEEE Trans. Veh. Technol.*, vol. 59, no. 6, pp. 2641–2653, Jul. 2010.

[33] M. K. Nguyen, Y. G. Jung, H. Y. Yang, and Y. C. Lim, "Single-phase z-source cycloconverter with safe-commutation strategy," *IET Power Electron.*, vol. 3, no. 2, pp. 232–242, Mar. 2010.

[34] SEMIKRON Products. (2011). [Online]. Available: http://www.semikron.com.

[35] P. Grbovic, "An IGBT gate driver for feed-forward control of turn-on losses and reverse recovery current," *IEEE Trans. Power Electron.*, vol. 23, no. 2, pp. 643–652, Mar. 2008.

[36] W. Eberle, Z. Zhang, Y.-F. Liu, and P. Sen, "A practical switching loss model for buck voltage regulators," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 700–713, Mar. 2009.

[37] X. Mao, R. Ayyanar, and H. Krishnamurthy, "Optimal variable switching frequency scheme for reducing switching loss in single-phase inverters based on time-domain ripple analysis," *IEEE Trans. Power Electron*, vol. 24, no. 4, pp. 991–1001, Apr. 2009.

[38] D. Zhao, V. Hari, G. Narayanan, and R. Ayyanar, "Space-vector-based hybrid pulsewidth modulation techniques for reduced harmonic distortion and switching loss," *IEEE Trans. Power Electron.*, vol. 25, no. 3, pp. 760–774, Mar. 2010.

[39] M. C. Cavalcanti, E. da Silva, D. Boroyevich, W. Dong, and C. B. Jacobina, "A feasible loss model for IGBT in soft-switching inverters," in *Proc. IEEE Power Electron. Spec. Conf.*, 2003, pp. 1845–1850.

[40] F. Blaabjerg, S. Freysson, H. H. Hansen, and S. Hansen, "A new optimized space-vector modulation strategy for a component-minimized voltage source inverter," *IEEE Trans. Power Electron.*, vol. 12, no. 4, pp. 704–714, Jul. 1997.

[41] F. Blaabjerg, J. Sander-Larsen, J. K. Pedersen, and H. Kragh, "Reconstruction of output currents and fault detection in a b4-inverter with only one current sensor," in *Proc. IEEE 33rd IAS Annu. Meet. Ind. Appl. Conf.*, Oct. 1998, vol. 1, pp. 759–766.

[42] L. Asiminoaei, E. Aeloiza, P. N. Enjeti, F. Blaabjerg, and G. Danfoss, "Shunt active-power-filter topology based on parallel interleaved inverters," *IEEE Trans. Ind. Electron.*, vol. 55, no. 3, pp. 1175–1189, Mar. 2008.

[43] J. W. Kolar and S. D. Round, "Analytical calculation of the RMS current stress on the dc-link capacitor of voltage-PWM converter systems," *IEE Proc. Electr. Power Appl.*, vol. 153, no. 4, pp. 535–543, Jul. 2006.

[44] Y. Vuillermet, O. Chadebec, J. M. Lupin, A. Saker, G. Meunier, and J. L. Coulomb, "Optimization of low-voltage metallized film capacitor geometry," *IEEE Trans. Magn.*, vol. 43, no. 4, pp. 1569–1572, Apr. 2007.

[45] P. Enjeti, A. Rahman, and R. Jakkli, "Economic single phase to three phase converter topologies for fixed frequency output," in *Proc. 6th Annu. Appl. Power Electron. Conf. Expo.*, Mar. 1991, pp. 88–94.

[46] P. N. Enjeti, A. Rahman, and R. Jakkli, "Economic single-phase to three-phase converter topologies for fixed and variable frequency output," *IEEE Trans. Power Electron.*, vol. 8, no. 3, pp. 329–335, Jul. 1993.

[47] C. C. Chen, D. M. Divan, and D. W. Novotny, "A single phase to three phase power converter for motor drive applications," in *Proc. IEEE Ind. Appl. Soc. Annu. Meet. Conf. Rec.*, Oct. 1992, vol. 1, pp. 639–646.

[48] J. C. Yris and H. Calleja, "Calculated performance of ac motors in a single-phase to three-phase converter application," in *Proc. V IEEE Int. Power Electron. Congr. Tech. Proc.*, Oct. 1996, pp. 156–159.

[49] P. Enjeti and A. Rahman, "A new single phase to three phase converter with active input current shaping for low cost ac motor drives," in *Proc. IEEE Ind. Appl. Soc. Annu. Meet. Conf. Rec.*, Oct. 1990, vol. 2, pp. 935–942.

[50] P. N. Enjeti and A. Rahman, "A new single-phase to three-phase converter with active input current shaping for low cost ac motor drives," *IEEE Trans. Ind. Appl.*, vol. 29, no. 4, pp. 806–813, Jul./Aug. 1993.

[51] G. A. Covic, G. L. Peters, and J. T. Boys, "An improved single phase to three phase converter for low cost ac motor drives," in *Proc. Int. Conf. Power Electron. Drive Syst.*, Feb. 1995, vol. 1, pp. 549–554.

[52] R. J. Cruise, C. F. Landy, and M. D. McCulloch, "Evaluation of a reduced topology phase-converter operating a three-phase induction motor," in *Proc. Electr. Mach. Drives*, May 1999, pp. 466–468.

[53] T. Binkowski, M. Grad, M. Latka, W. Malska, and D. Sobczynski, "A drive system with high-speed single-phase supplied three-phase induction motor," in *Proc. 13th Power Electron. Motion Control Conf.*, Sep. 2008, pp. 714–717.

[54] D.-C. Lee, T.-Y. Kim, G.-M. Lee, and J.-K. Seok, "Low-cost single-phase to three-phase PWM ac/dc/ac converters without source voltage sensor," in *Proc. IEEE Int. Conf. Ind. Technol.*, Dec. 2002, vol. 2, pp. 792–797.

[55] D. T. W. Liang, "Novel modulation strategy for a four-switch three-phase inverter," in *Proc. Int. Conf. Power Electron. Drive Syst.*, May 1997, vol. 2, pp. 817–822.

[56] E. N. Tshivhilinge and M. Malengret, "A practical control of a cost reduced single phase to three phase converter," in *Proc. IEEE Int. Symp. Ind. Electron.*, Jul. 1998, vol. 2, pp. 445–449.

[57] J. Sander-Larsen, K. Jespersen, M. R. Pedersen, F. Blaabjerg, and J. K. Pedersen, "Control of a complete digital-based component-minimized single-phase to three-phase ac/dc/ac converter," in *Proc. IEEE 24th Annu. Conf. Ind. Electron. Soc.*, Aug./Sep. 1998, vol. 2, pp. 618–625.

[58] D.-C. Lee and Y.-S. Kim, "Control of single-phase-to-three-phase ac/dc/ac PWM converters for induction motor drives," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 797–804, Apr. 2007.

[59] C. B. Jacobina, E. C. dos Santos, Jr, I. S. de Freitas, M. B. R. Correa, and E. R. C. da Silva, "Single-phase to three-phase dc-link three-leg converter with minimization of the capacitor currents," in *Proc. 41st Ind. Appl. Soc. Annu. Meet. Conf. Rec. Ind. Appl. Conf.*, Oct. 2006, vol. 4, pp. 2109–2114.

[60] E. R. C. da Silva, S. B. de Souza Filho, and F. A. Coelho, "A single phase to three phase soft-switched converter, isolated and with active input current shaping," in *Proc. 26th Annu. IEEE Power Electron. Spec. Conf.*, Jun. 1995, vol. 2, pp. 1252–1257.

[61] T. Ohnishi, "PWM control method for single-phase to three-phase converter with a three-phase switching power module," in *Proc. 29th Annu. IEEE Power Electron. Spec. Conf.*, May 1998, vol. 1, pp. 464–469.

[62] M. D. Bellar, M. Aredes, J. L. Silva Neto, L. G. B. Rolim, F. C. Aquino, and V. C. Petersen, "Comparative analysis of single-phase to three-phase converters for rural electrification," in *Proc. IEEE Int. Symp. Ind. Electron.*, May 2004, vol. 2, pp. 1255–1260.

[63] T. B. Bashaw and T. A. Lipo, "B4 topology options for operating three phase induction machines on single phase grids," in *Proc. 20th Annu. IEEE Appl. Power Electron. Conf. Expo.*, Mar. 2005, vol. 3, pp. 1894–1902.

[64] C. B. Jacobina, E. C. dos Santos, Jr., M. B. R. Correa, and E. R. C. da Silva, "Single-phase input reduced switch count ac–ac drive systems," in *Proc. IEEE 40th Ind. Appl. Soc. Annu. Meet. Conf. Rec. Ind. Appl. Conf.*, Oct. 2005, vol. 4, pp. 2505–2511.

[65] H. Douglas and M. Malengret, "Symmetrical PWM with a split-capacitor single-phase to three-phase converter for rural electrification," in *Proc. IEEE Int. Symp. Ind. Electron.*, Jul. 1998, vol. 1, pp. 289–293.

[66] C. B. Jacobina, E. C. dos Santos, Jr., M. B. R. Correa, and A. M. N. Lima, "Component minimized ac–ac single-phase to three-phase-four-wire converters," in *Proc. IEEE Int. Conf. Electr. Mach. Drives*, May 2005, pp. 789–796.

[67] A. Bouscayrol, B. Francois, P. Delarue, and J. Niiranen, "Control implementation of a five-leg ac–ac converter to supply a three-phase induction machine," *IEEE Trans. Power Electron.*, vol. 20, no. 1, pp. 107–115, Jan. 2005.

[68] G.-J. Su and J. S. Hsu, "A five-leg inverter for driving a traction motor and a compressor motor," *IEEE Trans. Power Electron.*, vol. 21, no. 3, pp. 687–692, May 2006.

[69] C. B. Jacobina, E. C. dos Santos, Jr., E. R. C. da Silva, M. B. de Correa, A. M. N. Lima, and T. M. Oliveira, "Reduced switch count multiple three-phase ac machine drive systems," *IEEE Trans. Power Electron.*, vol. 23, no. 2, pp. 966–976, Mar. 2008.

[70] T. Kominami and Y. Fujimoto, "A novel nine-switch inverter for independent control of two three-phase loads," in *Proc. IEEE 42nd Ind. Appl. Soc. Annu. Meet. Conf. Rec. Ind. Appl. Conf.*, Sep. 2007, pp. 2346–2350.

[71] J. A. A. Dias, E. C. dos Santos, Jr., C. B. Jacobina, and M. B. R. Correa, "Soft-starting techniques for low cost single-phase to three-phase drive system configuration," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 3996–4002.

[72] C. B. Jacobina, E. C. dos Santos, Jr., and M. B. R. Correa, "Control of the single-phase to three-phase four-leg converter for constant frequency output voltage," in *Proc. IEEE 36th Power Electron. Spec. Conf.*, Jun. 2005, pp. 52–58.

[73] C. B. Jacobina, E. C. dos Santos, Jr., and M. B. R. Correa, "Single-phase to three-phase-four-wire ac–ac component minimized converters without capacitor dc-bus mid-point connection," in *Proc. IEEE 36th Power Electron. Spec. Conf.*, Jun. 2005, pp. 2415–2421.

[74] J. Itoh and K. Fujita, "Novel unity power factor circuits using zero-vector control for single-phase input systems," *IEEE Trans. Power Electron.*, vol. 15, no. 1, pp. 36–43, Jan. 2000.

[75] R. Madorell and J. Pou, "Modulation techniques for a low-cost single-phase to three-phase converter," in *Proc. IEEE Int. Symp. Ind. Electron.*, May 2004, vol. 2, pp. 1279–1284.

[76] M. Y. Lee, P. Wheeler, and C. Klumpner, "Space-vector modulated multilevel matrix converter," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3385–3394, Oct. 2010.

[77] A. Ecklebe, A. Lindemann, and S. Schulz, "Bidirectional switch commutation for a matrix converter supplying a series resonant load," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1173–1181, May 2009.

[78] J.-I. Itoh and K.-I. Nagayoshi, "A new bidirectional switch with regenerative snubber to realize a simple series connection for matrix converters," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 822–829, Mar. 2009.

[79] R. Vargas, U. Ammann, and J. Rodriguez, "Predictive approach to increase efficiency and reduce switching losses on matrix converters," *IEEE Trans. Power Electron.*, vol. 24, no. 4, pp. 894–902, Apr. 2009.

[80] S. Kwak, "Fault-tolerant structure and modulation strategies with fault detection method for matrix converters," *IEEE Trans. Power Electron.*, vol. 25, no. 5, pp. 1201–1210, May 2010.

[81] S. Kim, Y.-D. Yoon, and S.-K. Sul, "Pulsewidth modulation method of matrix converter for reducing output current ripple," *IEEE Trans. Power Electron.*, vol. 25, no. 10, pp. 2620–2629, Oct. 2010.

[82] S. Kwak and H. A. Toliyat, "Development of modulation strategy for two-phase ac–ac matrix converters," *IEEE Trans. Energy Convers.*, vol. 20, no. 2, pp. 493–494, Jun. 2005.

[83] J. W. Kolar, F. Schafmeister, S. D. Round, and H. Ertl, "Novel three-phase ac–ac sparse matrix converters," *IEEE Trans. Power Electron.*, vol. 22, no. 5, pp. 1649–1661, Sep. 2007.

[84] Y. Miura, S. Horie, S. Kokubo, T. Amano, T. Ise, T. Momose, and Y. Sato, "Application of three-phase to single-phase matrix converter to gas engine cogeneration system," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2009, pp. 3290–3297.

[85] S. I. Kahn, P. D. Ziogas, and M. H. Rashid, "A novel single- to three-phase static converter," *IEEE Trans. Ind. Appl.*, vol. 25, no. 1, pp. 143–152, Jan./Feb. 1989.

[86] J. Xiao, W. Zhang, H. Omori, and K. Matsui, "A novel operation strategy for single-to three-phase matrix converter," in *Proc. Int. Conf. Electr. Mach. Syst.*, Nov. 2009, pp. 1–6.

[87] P. N. Enjeti, W. Sulistyono, and S. Choi, "A new direct phase converter to power three phase induction motor from a single phase supply," in *Proc. 25th Annu. IEEE Power Electron. Spec. Conf.*, Jun. 1994, vol. 2, pp. 1173–1179.

[88] V. Agarwal and K. Kant, "An empirical formula for CCI for single-phase to three-phase cycloconverter," in *Proc. Int. Conf. Power Electron. Drives Energy Syst. Ind. Growth*, Dec. 1998, vol. 2, pp. 646–651.

[89] V. Agrawal, A. K. Agarwal, and K. Kant, "A study of single-phase to three-phase cycloconverters using PSpice," *IEEE Trans. Ind. Electron.*, vol. 39, no. 2, pp. 141–148, Apr. 1992.

[90] K. Iino, K. Kondo, and Y. Sato, "An experimental study on induction motor drive with a single phase—three phase matrix converter," in *Proc. 13th Eur. Conf. Power Electron. Appl.*, Sep. 2009, pp. 1–9.

[91] T. Yamashita and T. Takeshita, "PWM strategy of single-phase to three-phase matrix converters for reducing a number of commutations," in *Proc. Int. Power Electron. Conf.*, Jun. 2010, pp. 3057–3064.

[92] A. Hirota, S. Nagai, and M. Nakaoka, "Suppressing noise peak single phase to three phase ac–ac direct converter introducing deltasigma modulation technique," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 3320–3323.

[93] M. Saito, T. Takeshita, and N. Matsui, "A single to three phase matrix converter with a power decoupling capability," in *Proc. IEEE 35th Annu. Power Electron. Spec. Conf.*, Jun. 2004, vol. 3, pp. 2400–2405.

[94] X. Yang, R. Hao, X. You, and T. Zheng, "A new topology for operating three-phase induction motors connected to single-phase supply," in *Proc. Int. Conf. Electr. Mach. Syst.*, Oct. 2008, pp. 1391–1394.

[95] X. Yang, R. Hao, X. You, and T. Zheng, "A new single-phase to three-phase cycloconverter for low cost ac motor drives," in *Proc. 3rd IEEE Conf. Ind. Electron. Appl.*, Jun. 2008, pp. 1752–1756.

[96] H. Takahashi, R. Hisamichi, and H. Haga, "High power factor control for current-source type single-phase to three-phase matrix converter," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2009, pp. 3071–3076.

[97] J. Zhang, G. P. Hunter, and V. S. Ramsden, "Performance of a single-phase to three-phase cycloconverter drive," *IEE Proc. Electr. Power Appl.*, vol. 142, no. 3, pp. 169–175, May 1995.

[98] Vineeta and K. Kant, "Microcomputer-based single-phase to three-phase cycloconverter," *IEEE Trans. Ind. Electron.*, vol. 37, no. 4, pp. 310–316, Aug. 1990.

[99] B. Tamyurek and D. A. Torrey, "A three-phase unity power factor single-stage ac–dc converter based on an interleaved flyback topology," *IEEE Trans. Power Electron.*, vol. 26, no. 1, pp. 308–318, Jan. 2011.

[100] L. G. Franquelo, J. Rodriguez, J. I. Leon, S. Kouro, R. Portillo, and M. A. M. Prats, "The age of multilevel converters arrives," *IEEE Ind. Electron. Mag.*, vol. 2, no. 2, pp. 28–39, Jun. 2008.

[101] Y. Ohnuma and J. I. Itoh, "Novel control strategy for single-phase to three-phase power converter using an active buffer," in *Proc. 13th Eur. Conf. Power Electron. Appl.*, Sep. 2009, pp. 1–10.

[102] Y. Ohnuma and J. I. Itoh, "A control method for a single-to-three-phase power converter with an active buffer and a charge circuit," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2010, pp. 1801–1807.

[103] Y. Ohnuma and J. Itoh, "Space vector modulation for a single phase to three phase converter using an active buffer," in *Proc. Int. Power Electron. Conf.*, Jun. 2010, pp. 574–580.

[104] Y. Ohnuma and J. I. Itoh, "Control strategy for a three-phase to single-phase power converter using an active buffer with a small capacitor," in *Proc. IEEE 6th Int. Power Electron. Motion Control Conf.*, May 2009, pp. 1030–1035.

[105] C. B. Jacobina, E. C. dos Santos, Jr., and E. Fabricio, "Single-phase to three-phase drive system using two parallel single-phase rectifiers," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 901–905.

[106] C. B. Jacobina, E. C. dos Santos, Jr., N. Rocha, and E. L. Lopes Fabricio, "Single-phase to three-phase drive system using two parallel single-phase rectifiers," *IEEE Trans. Power Electron.*, vol. 25, no. 5, pp. 1285–1295, May 2010.

[107] C. B. Jacobina, E. C. dos Santos, Jr., N. Rocha, and E. Fabricio, "Single-phase to three-phase five-leg converter based on two parallel single-phase rectifiers," in *Proc. 35th Annu. Conf. IEEE Ind. Electron.*, Nov. 2009, pp. 850–855.

[108] C. Jacobina, E. Cipriano dos Santos, N. Rocha, de Sa, B. Gouveia, and E. da Silva, "Reversible ac drive systems based on parallel ac–ac dc-link converters," *IEEE Trans. Ind. Appl.*, vol. 46, no. 4, pp. 1456–1467, Jul./Aug. 2010.

[109] H. Fujita, "A single-phase active filter using an H-bridge PWM converter with a sampling frequency quadruple of the switching frequency," *IEEE Trans. Power Electron.*, vol. 24, no. 4, pp. 934–941, Apr. 2009.

[110] J. C. Wu and Y. H. Wang, "Three-phase to single-phase power-conversion system," *IEEE Trans. Power Electron.*, vol. 26, no. 2, pp. 453–461, Feb. 2011.

[111] E. C. dos Santos, Jr., C. B. Jacobina, D. F. Guedes, and A. C. Oliveira, "Single-phase to three-phase universal active power filter," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 3801–3806.

[112] E. C. dos Santos, Jr., C. B. Jacobina, and J. A. A. Dias, "Active power line conditioner applied to single-phase to three-phase systems," in *Proc. 35th Annu. Conf. IEEE Ind. Electron.*, Nov. 2009, pp. 148–153.

[113] J. A. A. Dias, E. C. dos Santos, Jr., C. Jacobina, and E. R. C. da Silva, "Application of single-phase to three-phase converter motor drive systems with IGBT dual module losses reduction," in *Proc. Brazilian Power Electron. Conf.*, Oct. 2009, pp. 1155–1162.

[114] J. A. A. Dias, E. C. dos Santos, Jr., and C. B. Jacobina, "A low investment single-phase to three-phase converter operating with reduced losses," in *Proc. 25th Annu. IEEE Appl. Power Electron. Conf. Expo.*, Feb. 2010, pp. 755–760.

[115] I. Cadirci, S. Varma, M. Ermis, and T. Gulsoy, "A 20 kW, 20 kHz unity power factor boost converter for three-phase motor drive applications from an unregulated single-phase supply," *IEEE Trans. Energy Convers.*, vol. 14, no. 3, pp. 471–478, Sep. 1999.

[116] N. V. V. R. Kumar, P. V. Rajgopal, S. N. Saxena, S. K. Mondal, B. P. Muni, and J. V. R. Vithal, "A new GTO-based single-phase to three-phase static converter for loco auxiliaries," in *Proc. Int. Conf. Power Electron., Drives Energy Syst. Ind. Growth*, Jan. 1996, vol. 2, pp. 713–719.

[117] E. G. Marra and J. A. Pomilio, "Self-excited induction generator controlled by a VS-PWM converter providing high power-factor current to a single-phase grid," in *Proc. 24th Annu. Conf. IEEE Ind. Electron. Soc.*, Aug./Sep. 1998, vol. 2, pp. 703–708.

[118] R. Quadros Machado, J. Antenor Pomilio, and E. Goncalves Marra, "Electronically controlled bi-directional connection of induction generator with a single-phase grid," in *Proc. 27th Annu. Conf. IEEE Ind. Electron. Soc.*, 2001, vol. 3, pp. 1982–1987.

[119] R. Q. Machado, S. Buso, J. A. Pomilio, and F. P. Marafao, "Three-phase to single-phase direct connection rural cogeneration systems," in *Proc. 19th Annu. IEEE Appl. Power Electron. Conf. Expo.*, vol. 3, pp. 1547–1553.

[120] E. C. dos Santos, Jr., C. B. Jacobina, N. Rocha, J. A. A. Dias, and M. B. R. Correa, "Single-phase to three-phase four-leg converter applied to distributed generation system," *IET Power Electron.*, vol. 3, no. 6, pp. 892–903, Nov. 2010.

[121] R. Bojoi, D. Roiu, G. Griva, and A. Tenconi, "Single-phase grid-connected distributed generation system with maximum power tracking," in *Proc. 12th Int. Conf. Optim. Electr. Electron. Equipment*, May 2010, pp. 1131–1137.

[122] S. B. Bekiarov and A. Emadi, "A new on-line single-phase to three-phase UPS topology with reduced number of switches," in *Proc. IEEE 34th Annu. Power Electron. Spec. Conf.*, Jun. 2003, vol. 1, pp. 451–456.

[123] H. Haga, K. Nishiya, S. Kondo, and K. Ohishi, "High power factor control of electrolytic capacitor less current-fed single-phase to three-phase power converter," in *Proc. Int. Power Electron. Conf.*, Jun. 2010, pp. 443–448.

[124] E. C. dos Santos, Jr., C. B. Jacobina, and M. B. R. Correa, "Fault tolerant ac–ac single-phase to three-phase dc-link converter," in *Proc. 22nd Annu IEEE Appl. Power Electron. Conf.*, Mar. 2007, pp. 1707–1713.

[125] E. C. dos Santos, Jr., C. B. Jacobina, M. B. R. Correa, and J. A. A. Dias, "AC drive fault tolerant system with single-phase grid," in *Proc. 23rd Annu. IEEE Appl. Power Electron. Conf. Expo.*, Feb. 2008, pp. 1839–1845.

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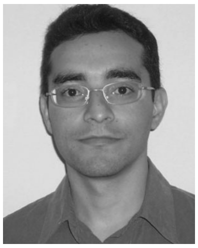

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