Modelling of Single-Phase to Three-Phase Power Convertion System with Parallel Rectifier and Series Inverter

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Abstract: Single-phase to three-phase power conversion using power electronics converters is a well-known technology, when the configurations and control strategies already accomplished in the technical study are considered. This paper presents single-phase to three-phase with dc-link converters with parallel rectifier and series inverter for reduction in the input current and reduction of the output voltage processed by the rectifier circuit and inverter circuit respectively. In this paper we proposed better solution for single phase to three phase drive system by employing 2 parallel single phase rectifier stages, a 3-phase inverter stage. Parallel converters can be used to improve the power capability, reliability, efficiency and redundancy. An isolation transformer is not used for the reduction of circulating currents among different converter stages. It is an important objective in the system design. The complete comparison between the comprehensive model of proposed converter and standard configurations will be presented in this work. Simulation of this model will be carried out by using MATLAB/ Simulink.

Keywords: Power conversion, power electronics converters, parallel converter, pulse width modulation, three phase ac motordrive.

I. INTRODUCTION

In the past, single-phase to three-phase conversion systems were made possible by the connection of passive elements (capacitors and reactors) with auto transformer converters. Such kind of system presents well-known disadvantages and limitations. In present days, power electronics with silicon power diodes and thyristors are just emerging. So power electronics plays an important role day by day. In the power distribution systems, the single-phase source has been considered as an alternative for rural or remote areas, due to its lower cost feature, especially when compared with the three-phase solution. In huge countries like Brazil, the single-phase source is quite common due to the large area to be covered. On the other hand, loads connected in a three-phase arrangement presents some advantages when compared to single-phase loads. This is especially true in three-phase motor systems with variable-speed drives due to their constant torque characteristic. In this scenario, there is a need for single-phase to three-phase power conversion systems. The direct solutions for the single-phase to three-phase power converters are presented in Fig. 1. Fig. 1(b) shows a solution for single-phase to three-phase power conversion, in which all variables (e.g., input power factor and dc-link voltage) at input–output converter sides can be controlled, as observed in Fig. 2(b). On the other hand, the configuration presented in Fig. 1(a) represents a cheaper

solution but without any control of the input current and dc-link voltage, as observed in Fig. 2(a).
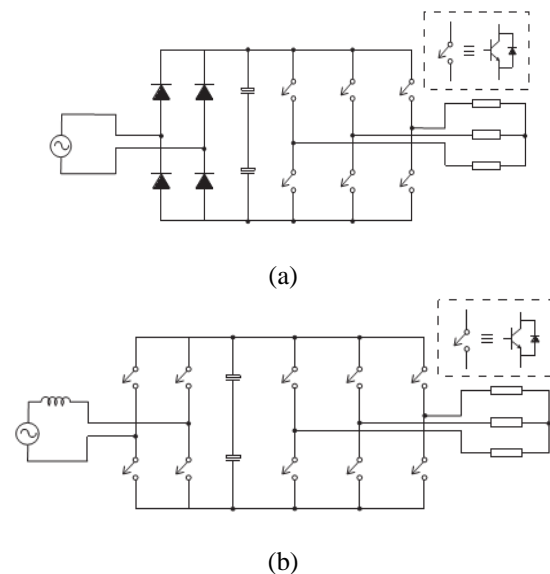

(a)

(b)

Fig. 1. Conventional single-phase to three-phase configurations: (a) Diode bridge at the inputconverter side (b) Controlled rectifier at the input converter side.In this paper, a single-phase to three-phase drive system composed of two parallel single-phase rectifiers and a three-phase inverter is proposed. The proposed system is conceived to operate where the single-phase utility source is the unique option available. Compared to the

conventional topology, the proposed system permits to reduce the rectifier switch currents, the total harmonic distortion (THD) of the grid current with same switching frequency or the switching frequency with same THD of the grid current, and to increase the fault tolerance characteristics. In addition, the losses of the proposed system may be lower than that of the conventional counterpart. The aforementioned benefits justify the initial investment of the proposed system, due to the increase of number of switches.

(b)

(c)

Fig. 3. Single-phase to three-phase power conversion. (a) Type of power processed by rectifier and inverter circuits. (b) Solution employed in [15]. (c) Solution employed in [16].

Fig 3. Shows the single-phase to three-phase power conversion with parallel configuration. Another important characteristic observed in the single-phase to three-phase power converters that also has been considered in this paper is the irregular distribution of power losses among the switches of the converter, as observed in Fig. 4.

It means that, for a 600 V 50A class of insulated gate bipolar transistor (IGBT), 63% of the total losses measured in the single-phase to three-phase converter is concentrated in the rectifier circuit, while the rest 37% is observed in the inverter circuit. 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 loss per switch gives an important parameter regarding the possibilities of failures in the power converters.
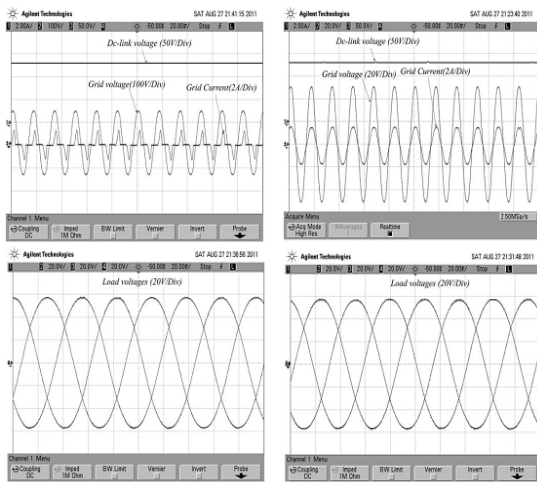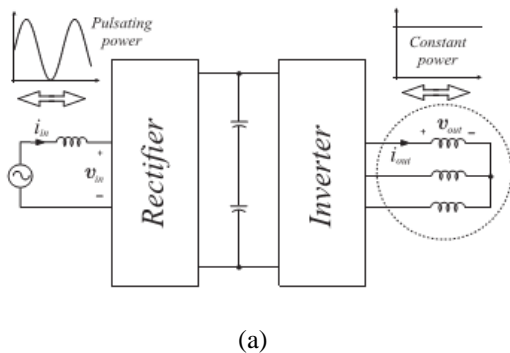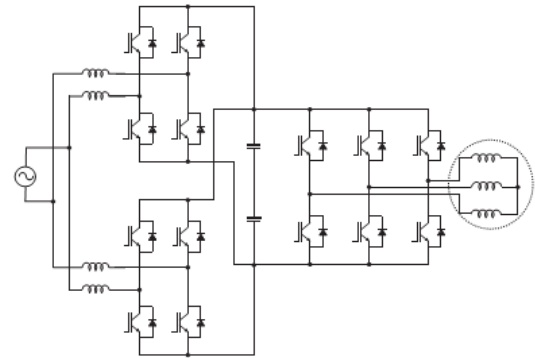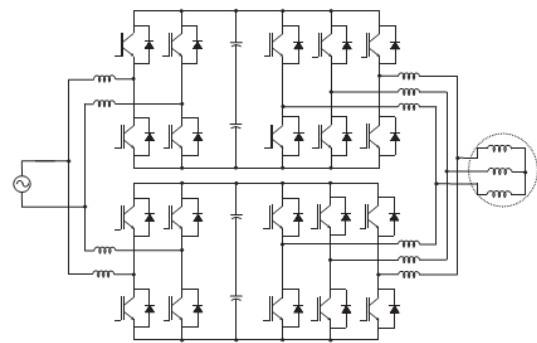

Fig. 2. Experimental results of the conventional single-phase to three-phase power conversion. (a) Configuration presented in Fig.1 (a). (b) Configuration presented in Fig. 1(b).
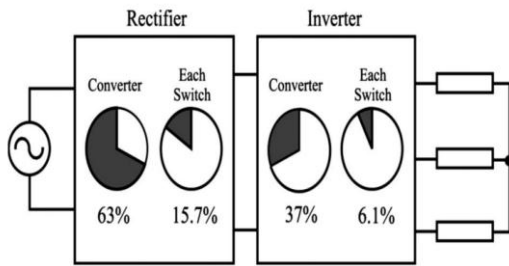

(a)

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%).

I. SYSTEM MODEL

This section will present the model of the proposed configuration. Such a configuration is constituted by a

single-phase source, one open-end three-phase motor, inductor filters (La, Lb, L'b, and L'a), converters 1, 2, 3, and 4, and two dc-link capacitor banks. If the legs are substituted by pulsed voltage sources, the proposed converter can be modelled as in Fig. 5.
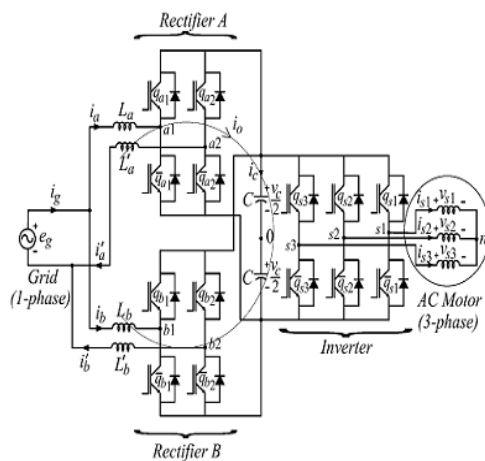

Fig. 5. Proposedsingle-phase to three-phase drive system.

To avoid the circulating current, the following three approaches are used commonly

i. Isolation. In this approach, the overall parallel system is bulky and costly because of additional power supplies or the ac line-frequency transformer.

ii. High impedance. They cannot prevent a low frequency circulating current.

iii. Synchronized control. This approach is not suitable for modular converter design. When more converters are in parallel, the system becomes very complicated to design and control.

In this proposed method the system is designed to reduce the circulating current (I_o). From fig.5.the following equations can be derived for the front end rectifier.

$$V_{a10} - V_{a20} = e_s - (r_a + l_a p)i_a - (r'_a + l'_a p)i'_a$$
$$V_{b10} - V_{b20} = e_s - (r_b + l_b p)i_b - (r'_b + l'_b p)i'_b$$
$$V_{a10} - V_{b10} = (r_a + l_a p)i_a - (r_b + l_b p)i_b$$

In this ideal case, the circulating current can be reduced to zero imposing

$$V_0 = V_{a10} + V_{a20} - V_{b10} - V_{b20} = 0$$

When Ia = 0 then $i_a = i'$ a and $i_b = i'_b$ and the system model reduced to

$$V_{a20} - V_{b20} = (r'_a + l'_a p)i'_a - (r'_b + l'_b p)i'_b$$
$$i_s = i_a + i_b = i'_a + i'_b$$

Where p = d/dt and symbols like r and l represent the resistances and inductances of the input inductors. The circulating current io can be defined from i_a and i' a or i_b and i'$_b$ i.e.

$$i_0 = i_a - i'_a = -i_b + i'_b$$

By solving the above equations,

$$V_a = e_s - [r_a + r'_a + (l_a + l'_a)p]i_a + (r'_a + l'_a p)$$
$$V_b = e_s - [r_b + r'_b + (l_b + l'_b)p]i_b + (r'_b + l'_b p)i_0$$
$$V_0 = -[r'_a + r'_b + (l'_a + l'_b)p]i_0$$
$$- [r_a - r'_a + (l_a + l'_a)p]i_a$$
$$+ [r_b - r'_b + (l_b + l'_b)p]i_b$$

Where

$$V_a = V_{a10} - V_{a20}$$
$$V_b = V_{b10} - V_{b20}$$
$$V_0 = V_{a10} + V_{a20} - V_{b10} - V_{b20}$$

In order to both facilitate the control and share equally current, voltage, power between the rectifiers, the four inductors should be equal. i.e. r'$_s$= ra = r'$_a$ = r$_b$= r'$_b$
And l'$_s$ =l$_a$ =l'$_a$ =l$_b$ =l'$_b$. In this case the equation can be simplified to the model given by

$$V_a + \frac{V_0}{2} = e_s - 2(r'_s + l'_s p)i_a$$
$$V_b + \frac{V_0}{2} = e_s - 2(r'_s + l'_s p)i_b$$
$$V_0 = -2(r'_s + l'_s p)i_0$$
$$V_{ab} = \frac{V_a + V_b}{2} = e_s - (r'_s + l'_s p)i_a$$
$$V_a - \frac{V_0}{2} = e_s - 2(r'_s + l'_s p)i'_a$$
$$V_b - \frac{V_0}{2} = e_s - 2(r'_s + l'_s p)i'_b$$

$$V_a = e_s - 2(r'_s + l'_s p)i_a$$
$$V_b = e_s - 2(r'_s + l'_s p)i_b$$

II. CONTROL STRATEGY

The gating signals are obtained by comparing pole voltages with one (vt1), two (vt1 and vt2) or more high-frequency triangular carrier signals. In the case of double-carrier approach, the phase shift of the two triangular carrier signals (vt1 and vt2) is 1800. The parameter μ changes the place of the voltage pulses related to v_a and v_b. When $v_x^* = v_x^*min$ (μ = 0) or $v_x^* = v_x^*max$ (μ = 1) are selected, the pulses are placed in the beginning or in the end of half period (Ts) of the control block diagram of Fig. 2, highlighting the control of the rectifier. To control the dc-link voltage and to guarantee the grid power factor close to one. Additionally, the circulating current io in the rectifier of the proposed system needs to be controlled.

In this way, the dc-link voltage vc is adjusted to its reference value v c* using the controller Rc, which is a standard PI type controller. This controller provides the amplitude of the reference grid current Is*. To control power factor and harmonics in the grid side, the instantaneous reference current Is* must be synchronized with voltage e.g., as given in the voltage-oriented control (VOC) for three-phase system. This is obtained via blocks Ge-ig, based on a PLL scheme Fig 6. The reference currents I $_a$*and i$_b$* are obtained by making i$_a$* = i$_b$* = Is* /2, which means that each rectifier receives half of the grid current. The control of the rectifier currents is implemented using the controllers indicated by blocks Ra and R$_b$. These current controllers define the input reference voltages v$_a$*and v$_b$*. The homo polar current is measured (i$_o$) and compared to its reference (i$_o$* = 0). The error is the input of PI controller Ro, that determines the voltage v$_o$*. The motor there-phase voltages are supplied from the inverter (VSI). Block VSI-Ctr indicates the inverter and its control. The control system is composed of the PWM command and a torque/flux control strategy (e.g., field-oriented control or volts/hertz control).
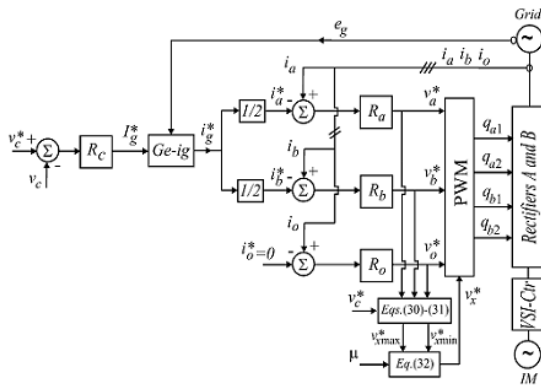

Fig. 6. Control block diagram

III. HARMONIC DISTORTION

As we know that harmonic distortion of the proposed converter and its voltages had been analysed with the help of weighted THD (WTHD). It is solved by using

$$WTHD(p) = 100/a_1 \sqrt{\sum_{i=2}^{p} (a_i/i)^2}$$

Where is treated as amplitude of fundamental voltage and is treated as amplitude of I$_{th}$ harmonic and also p may be number of harmonics in this consideration.

IV. SIMULATION MODEL

To study the operation of the Three-Phase Drive System, it is implemented in MATLAB/SIMULINK environment. The model is shown in Fig.7
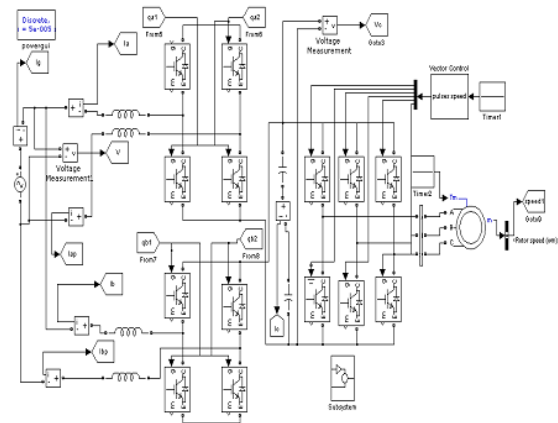

Fig. 7. Simulation model of single phase to three phase drive system using two parallel single phase rectifiers

V. RESULT

The simulation results were obtained with the grid- and machine-phase voltages equal to 127 V$_{rms}$, dc-link voltage of 225 V, capacitance of 2200 μ$_F$, and input inductor filters with resistance and inductance given respectively by 0.1Ω and 2.6 m$_H$. The load power was of 5 kVA. Fig. 8 shows selected simulation results for the proposed system. Such results were collected using double-carrier-based PWM with μ = 0 for the input converters (converters 1 and 3), while a single carrier-based PWM with μ = 0.5 is employed for the output converters (converters 2 and 4). Fig. 8 highlights the main control objectives handled by the proposed single-phase to three-phase power converter. Fig. 8 (a) shows the ability of the proposed converter to control the grid current with a sinusoidal waveform and power factor close to one. While Fig. 8 (b) and (c) demonstrate that the input rectifier currents (i1a and i$_{3a}$) are in fact half of the grid current due to the parallel connection at the grid side, Fig. 8 (d) shows the control of the circulating current. Both dc-link voltages are under control, as observed in Fig. 8 (e) and (f). As expected,there is a pulsating power at the dc-link capacitors due to the type of power from the single-phase grid. Since the three-phase power demanded by the three-phase machine is constant, the oscillating power from the grid appears at the capacitors. Fig. 8 (g) and (h) show the currents and voltages of the machine. Notice that the load voltages were filtered with a low-pass filter (LPF) to prove the converter's capability to generate 127 Vrms.

(a)

(b)

(c)

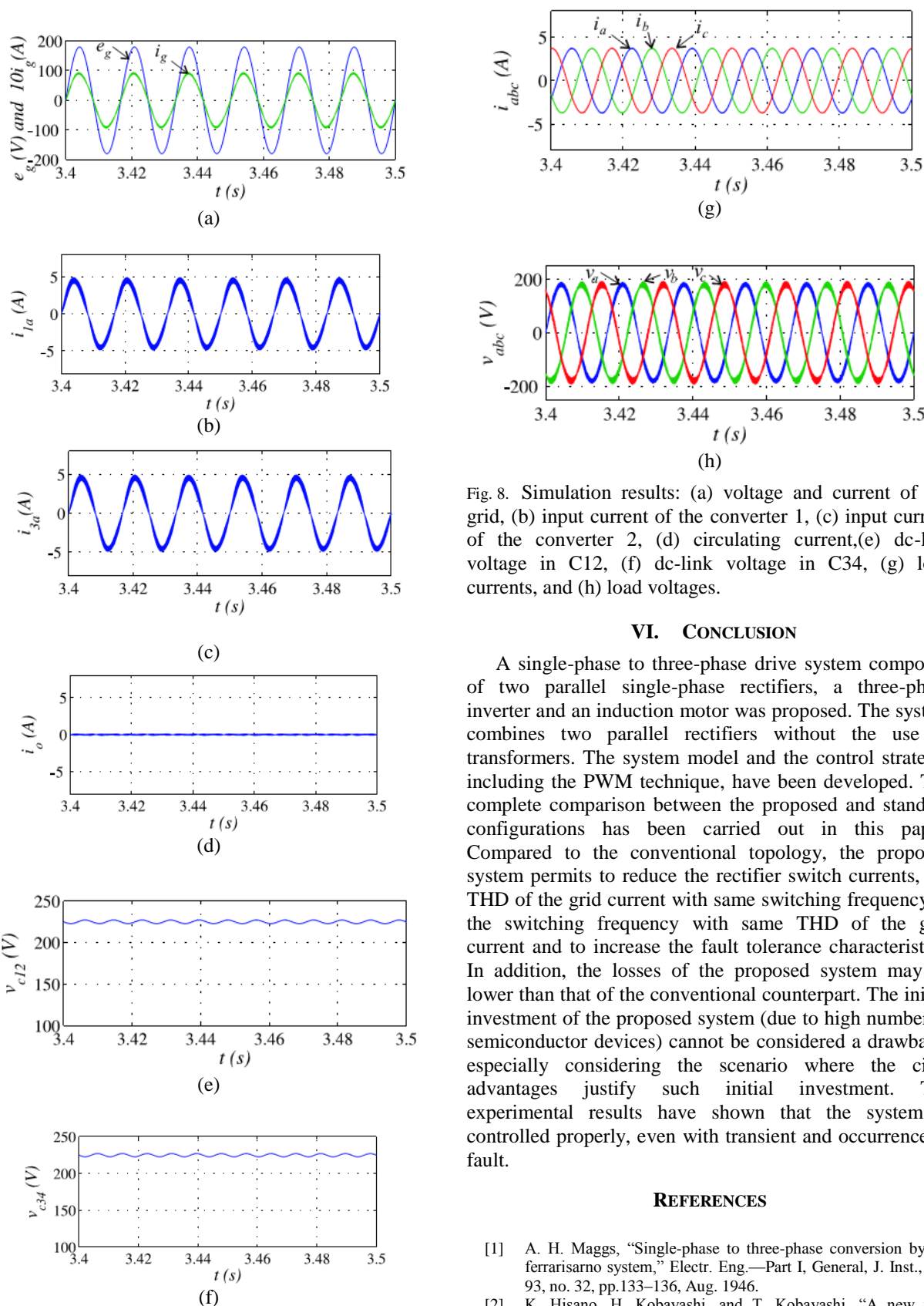(d)

(e)

(f)

(g)

(h)

Fig. 8. Simulation results: (a) voltage and current of the grid, (b) input current of the converter 1, (c) input current of the converter 2, (d) circulating current,(e) dc-link voltage in C12, (f) dc-link voltage in C34, (g) load currents, and (h) load voltages.

VI. CONCLUSION

A single-phase to three-phase drive system composed of two parallel single-phase rectifiers, a three-phase inverter and an induction motor was proposed. The system combines two parallel rectifiers without the use of transformers. The system model and the control strategy, including the PWM technique, have been developed. The complete comparison between the proposed and standard configurations has been carried out in this paper. Compared to the conventional topology, the proposed system permits to reduce the rectifier switch currents, the THD of the grid current with same switching frequency or the switching frequency with same THD of the grid current and to increase the fault tolerance characteristics. In addition, the losses of the proposed system may be lower than that of the conventional counterpart. The initial investment of the proposed system (due to high number of semiconductor devices) cannot be considered a drawback, especially considering the scenario where the cited advantages justify such initial investment. The experimental results have shown that the system is controlled properly, even with transient and occurrence of fault.

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