

# Soft-Transient Modulation Strategy for Improved Efficiency and EMC Performance of PFC Converters Applied to Flexible Induction Heating Appliances

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**Abstract**—Recent developments in domestic induction heating include flexible cooking surfaces that are demanding power factor corrector (PFC) converter for improved performance. In this paper, a soft-transient hybrid modulation strategy along with the converter control strategy is proposed to increase the efficiency and remove the zero-cross distortion, reaching a good balance between efficiency and EMC performance.

The proposed modulation strategy works with zero voltage switching (ZVS) at constant frequency in the mains cycle decreasing the switching losses and avoiding the intermodulation noise. Besides, for the same reason, avoiding acoustic noise, this frequency can be variable in order to synchronize the load inverter and the PFC stage. A 3.7 kW prototype is implemented and the experimental waveforms and efficiency are measured to prove the feasibility of this proposal.

**Keywords**—Home Appliances, Induction Heating, Resonant Power Conversion, Power Factor Corrector, Zero Voltage Switching, Modulation Strategies.

## I. INTRODUCTION

Domestic Induction Heating (IH) [1] is a leading heating technology due to its advantages, such as efficiency [2], fast and accurate heating, cleanness, and safety. Nowadays, flexible cooking surfaces (Fig. 1) [3] are becoming more relevant because of the increased freedom to select pot size, position, and shape. Some previous works have proposed cost-effective solutions either with multiplexed topologies [4, 5] or multi-inverter topologies [6-8]. However, these approaches suffer from limitations when operating with multiple loads in terms of output power control, intermodulation noise, and EMC performance.

The use of power factor corrector (PFC) converters has also been proposed in [9, 10]. A front-end PFC provides a common dc bus featuring low ripple and a higher adjustable bus voltage. This adjustable bus voltage allows controlling the power of a



Fig. 1. Flexible cooking surface.

multi-load system accurately. Besides, the higher voltage decreases the current through the switching devices and coils, improving the conduction losses. The PFC stage allows separating the mains from the induction load, easing the inverter control and assuring a high power factor (PF) at the input of the converter.

The PFC stage can be operated using different modulation strategies according to the application requirements. The zero voltage switching (ZVS) fixed frequency continuous conduction mode (CCM) is the preferred in IH applications to decrease the switching losses. Besides, the hybrid configuration is proposed in order to get a good balance between zero-cross distortion and efficiency [11]. However, the control of this proposal is not trivial because the change between the half-bridge and the full-bridge operation introduces a strong perturbation that the converter control cannot manage properly.

Therefore, the main aim of this work is to propose a soft-transient control strategy in order to overcome this issue. In this way, a PFC converter featuring high-efficiency and a fixed-frequency soft-switching control strategy is gotten, improving the efficiency, and meet the EMC regulations [12-17]. Besides, the intermodulation noise is avoided, since the multi-inverter, and the PFC stage can operate at the same frequency.

The remainder of this paper is organized as follows. Section II presents the topology for multi-load IH systems used in order to prove the proposed soft-transient modulation strategy. In Section III this modulation strategy is detailed along with the converter control. Section IV shows the implemented prototype

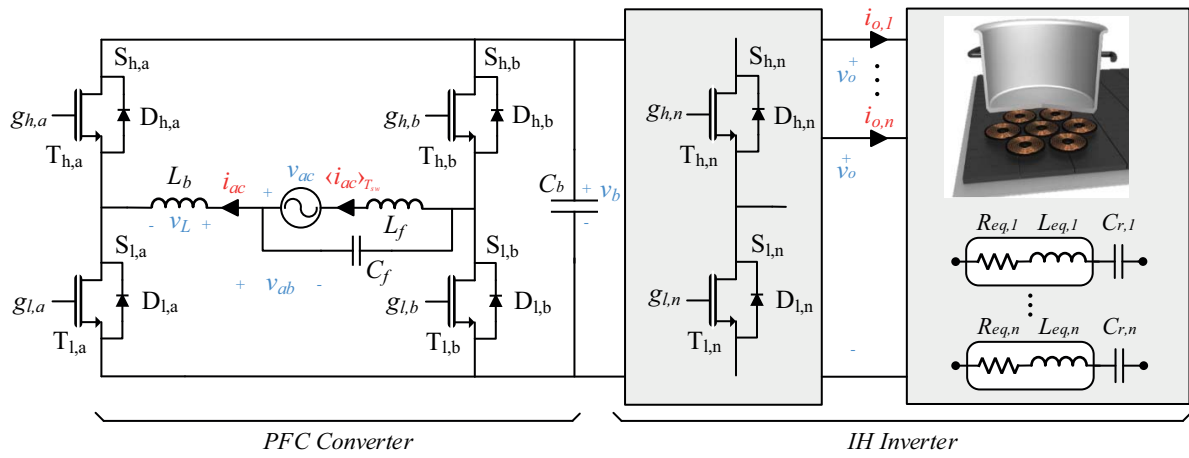


Fig. 2. PFC IH topology with  $n$  IH-loads.

and the main experimental results, including oscilloscope waveforms and measured efficiency. Finally, Section V summarizes the main conclusions of this paper.

## II. POWER FACTOR CORRECTOR FOR MULTI-LOAD IH SYSTEMS

The proposed PFC converter is shown in Fig. 2. It is based on the boost converter and it is composed of two half-bridge legs,  $a$  and  $b$ , which allow short-circuiting the boost inductance,  $L_b$ , with the mains voltage,  $v_{ac}$ , with a period  $T_{ac}$ , and/or the bus voltage,  $v_b$ . Each half-bridge is composed of two switching devices,  $S_h$  and  $S_l$ , implemented with MOSFETs,  $T_h$  and  $T_l$ , and antiparallel diodes,  $D_h$  and  $D_l$ . A filter between the mains and the PFC stage is placed, supplying the medium frequency currents and removing the high ripple of the boost coil current,  $i_{ac}$ . In this way, a fully filtered input current,  $\langle i_{ac} \rangle_{T_{sw}}$ , is achieved in the switching period  $T_{sw} \ll T_{ac}$ . In the proposed implementation, an inductor,  $L_f$ , and a capacitor,  $C_f$ , are used for filtering. Besides, a capacitor,  $C_b$ , filters the bus voltage, which powers the IH inverter. The set is composed of as many half-

bridge branches,  $S_{h,n}$  and  $S_{l,n}$ , as IH loads. Each IH load [18] is composed of the series equivalent resistance,  $R_{eq,n}$ , and inductance,  $L_{eq,n}$ , and the resonant capacitor,  $C_{r,n}$ .

This topology allows two configurations in order to perform the PFC modulation strategy: half-bridge or full-bridge configurations. In the half-bridge configuration, the  $a$  branch is activated at  $T_{sw}$ , while the  $b$  branch is activated at  $T_{ac}$  to get synchronous rectification. The main disadvantage is that the  $i_{ac}$  current control close to the mains-voltage zero crossing becomes difficult. In this case, the mains voltage is null ( $v_{ac}=0$ ) while the bus capacitor is fully charged, leading to extreme duty cycles and zero-cross distortion when the duty cycle is limited. The duty cycle,  $d$ , depends on the mains voltage sign as follows

$$d = \frac{v_{ac}}{v_b}, \quad v_{ac} > 0, \quad (1)$$

$$d = 1 + \frac{v_{ac}}{v_b}, \quad v_{ac} < 0.$$

The second approach, full-bridge configuration, is based on using the two inverter branches. In this way, both branches are

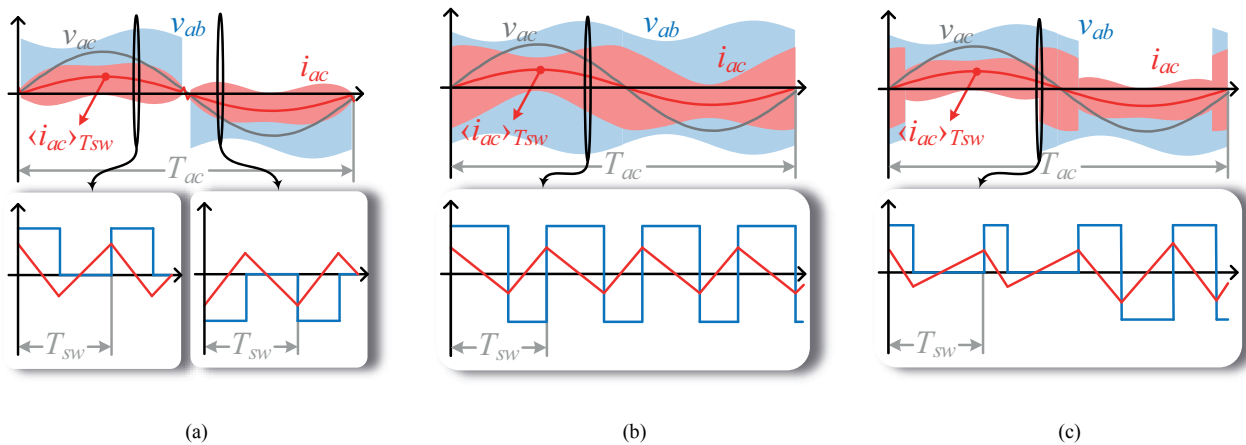


Fig. 3. ZVS and fixed-frequency modulation strategies using (a) half-bridge, (b) full-bridge, and (c) hybrid configuration.

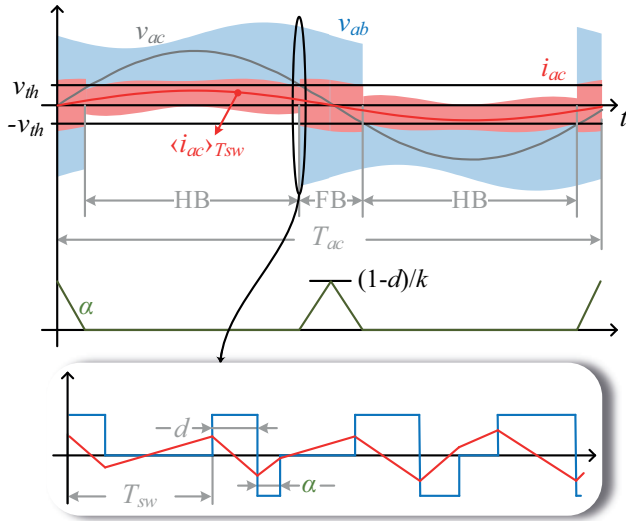


Fig. 4. Proposed soft-transient modulation strategy.

activated at  $T_{sw}$  and the bus voltage can be applied to the boost inductor. It allows avoiding the zero-cross distortion at the cost of higher switching and conduction losses due to the increased current ripple. As a consequence, this approach leads to lower efficiency results. In this case, the duty cycle does not depend on the mains voltage sign and its values are less extreme than in the half-bridge modulation, being 0.5 in the mains voltage zero crossing and easing the control. For each branch, the duty cycle in a CCM is defined as

$$\begin{aligned} d_a &= \frac{1}{2} \left( 1 + \frac{v_{ac}}{v_b} \right), \\ d_b &= \frac{1}{2} \left( 1 - \frac{v_{ac}}{v_b} \right). \end{aligned} \quad (2)$$

In order to improve both the efficiency and the zero-cross distortion, a combined approach is proposed: the hybrid configuration. It is based on using the half-bridge configuration and changing to the full-bridge configuration close to the zero crossing. In this way, the distortion is eliminated at the cost of additional control complexity. Besides, this approach obtains higher efficiency than the standard full-bridge configuration,

optimizing the overall performance of the converter. The combination of the two configurations achieves a good balance between efficiency and EMC performance. A competitive product of the domestic IH systems requires a high efficiency and a cost effective implementation. For this reason, the modulation strategy for performing the PFC control is based on getting ZVS soft-switching. Besides, the switching frequency of the PFC stage and the IH inverter has to be the same and fixed to avoid intermodulation noise. Fig. 3 shows the fixed-frequency soft-switching modulation strategies.

### III. PROPOSED SOFT-TRANSIENT MODULATION STRATEGY

The change from the half-bridge to the full-bridge configuration in the hybrid modulation must be carefully addressed to avoid current distortion. In order to decrease the effect of this configuration change, a soft-transient modulation strategy is proposed. This strategy is based on activating the rectifier branch at the switching frequency,  $T_{sw}$ , with a phase shift,  $\alpha$ , close to the mains voltage zero crossing. As it is shown in Fig. 4, the phase shift increases lightly from the change voltage,  $v_{th}$ , allowing that the converter control eliminates the perturbation. The maximum value of the phase shift is defined by the duty cycle and the  $k$  parameter.

The converter control (Fig. 5) is based on generating a sinusoidal reference current,  $i_{ac,ref}$ , in phase with the mains voltage and with the desired RMS current value,  $I_{ac,rms}$ . The regulator adjusts the mains current,  $\langle i_{ac} \rangle_{T_{sw}}$ , to follow the reference exactly. The output action of the proportional,  $K_p$ , and integral,  $K_i$ , regulator is the boost coil average voltage,  $\langle v_L \rangle_{T_{sw}}$ .

When the average voltage in an inductance differs from zero, it means a variation of its average current. According to the differential equation that models the boost coil behavior

$$i_{ac} \Big|_{t_0+T_{sw}} = i_{ac} \Big|_{t_0} + \frac{1}{L_b} \int_{t_0}^{t_0+T_{sw}} v_L dt. \quad (3)$$

Consequently, the  $v_L$  voltage makes possible controlling the boost-inductor average current,  $\langle i_{ac} \rangle_{T_{sw}}$ , linearly and, therefore, the mains current can be properly shaped. Keeping in mind the phase shift,  $\alpha$ , the duty cycle,  $d$ , can be calculated in a second step as

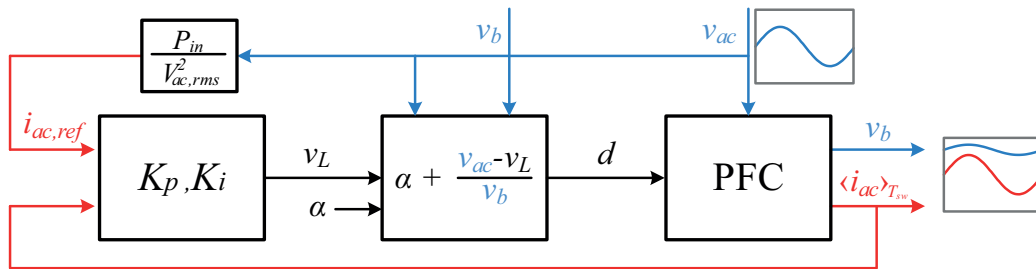


Fig. 5. Proposed digital control implementation where the output action of the proportional,  $k_p$ , and integral,  $k_i$ , regulator is the boost coil average voltage,  $v_L$ , and  $P_{in}$  is the desired input power. The duty cycle,  $d$ , is calculated in function of the  $\alpha$ ,  $v_b$ ,  $v_{ac}$ , and  $v_L$ .



Fig. 6. Implemented prototype.

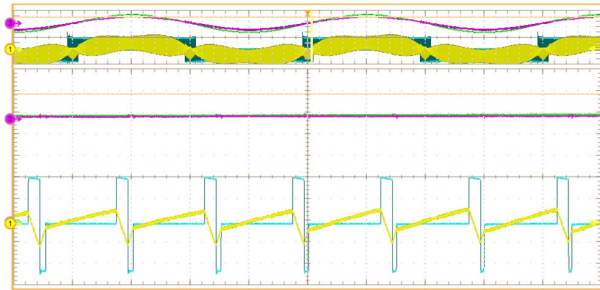


Fig. 8. A zoomed detail of the experimental waveforms:  $v_{ac}$  (200 V/div, green),  $\langle i_{ac} \rangle_{T_w}$  (20 A/div, purple),  $v_{ab}$  (200 V/div, blue), and  $i_{ac}$  (20 A/div, yellow). Time: 5 ms/div. Zoom time: 10  $\mu$ s/div.

$$d = \alpha + \frac{v_{ac} - v_L}{v_b}, \quad v_{ac} > 0, \quad (4)$$

$$d = 1 - \alpha + \frac{v_{ac} - v_L}{v_b}, \quad v_{ac} < 0.$$

The reference current,  $i_{ac,ref}$ , is obtained by the product of the mains voltage,  $v_{ac}$ , and the transconductance,  $G$ . This parameter is defined from the RMS mains voltage,  $V_{ac,rms}$ , and the desired input power,  $P_{in}$ , as

$$G = \frac{P_{in}}{V_{ac,rms}^2}. \quad (5)$$

#### IV. IMPLEMENTATION AND EXPERIMENTAL RESULTS

The proposed soft-transient modulation strategy has been implemented and tested using the prototype of Fig. 6. It is composed of a three-phase half-bridge module using CREE SiC MOSFETs [19]. An FPGA-based control architecture is used to control the prototype, taking advantage of speed and parallel-processing of FPGAs to perform IH appliance control [20-22]. The platform allows measuring the input current using a magneto-resistive current sensor and the voltage using resistive voltage dividers. A 1140- $\mu$ F bus capacitor, 26- $\mu$ H boost inductance, 5- $\mu$ F filter capacitor, and 200- $\mu$ H filter inductance have been used.

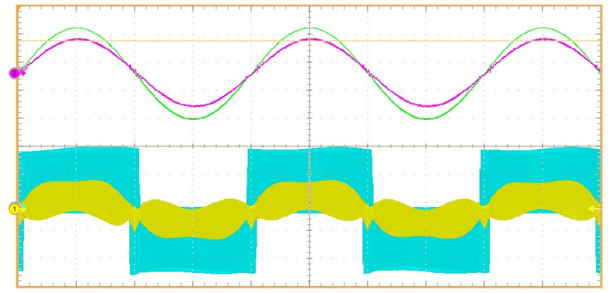


Fig. 7. Experimental waveforms:  $v_{ac}$  (200 V/div, green),  $\langle i_{ac} \rangle_{T_w}$  (20 A/div, purple),  $v_{ab}$  (200 V/div, blue), and  $i_{ac}$  (50 A/div, yellow). Time: 5 ms/div.

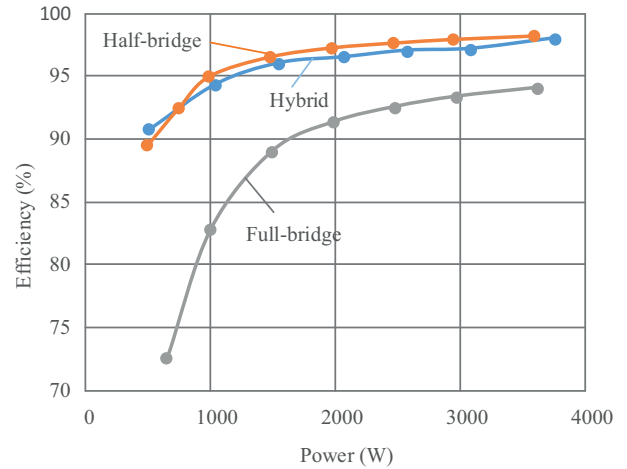


Fig. 9. Experimental efficiency.

Fig. 7 shows the experimental waveforms of the proposed hybrid modulation working at 67 kHz and at maximum power, i.e. 3.7 kW whereas Fig. 8 shows a zoomed detail. It can be appreciated that the rectifier branch works at the switching frequency with a phase shift,  $\alpha$ . The power factor is higher than 0.99 and the zero-cross distortion is avoided, fulfilling the EMC standards with a current Total Harmonic Distortion (THD<sub>i</sub>) lower than 1%.

Finally, Fig. 9 shows a comparison of the measured efficiency using each modulation strategy. The efficiency using hybrid configuration is similar than using the half-bridge configuration reaching 98% at maximum power, 3680 W.

#### V. CONCLUSIONS

In this paper, a soft-transient modulation strategy for improved efficiency and EMC performance of PFC converters applied to flexible induction heating appliances has been presented. The converter using the proposed modulation strategy, which also achieves soft-switching and fixed-frequency operation, has been designed and implemented, proving the feasibility of this proposal with a 3.7 kW prototype.

#### ACKNOWLEDGMENT

This work was partly supported by the Spanish MINECO under Project TEC2016-78358-R and Project RTC-2014-1847-6, by the DGA-FSE, by the Spanish MECED under the FPU grant FPU15/01590, by the University of Zaragoza under Project JIUZ-2017-TEC-05, and by the BSH Home Appliances Group.

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