A New Multiple-Output Resonant Matrix Converter Topology Applied To Domestic Induction Heating

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Abstract

Most of the ac-ac converters used in home-appliances are based on single-output dc-link inverters, which provides a cost-effective and straight-forward solution. However, this two-stage power conversion decreases power density and efficiency. Direct ac-ac conversion has been thoroughly studied in the past. However, the complex control scheme and higher cost has prevented it from being used in low-cost applications, such as home appliances.

This paper proposes the direct ac-ac conversion by means of a multiple-output resonant matrix converter applied to multiple-inductive load systems. The proposed topology reduces significantly the number of devices and complexity, leading to an efficient, versatile and cost-effective solution. The analytical and simulation results have been verified by means of a prototype applied to a novel total-active-surface induction heating appliance.

Keywords: Induction heating, resonant power conversion, matrix converter, digital control.

1. Introduction

Many electronic-fed home appliances are based on dc-link inverters which provide frequency-adjustable excitation required for motors, air conditioning systems, or induction heating devices (Wang et al. 2009). This architecture provides a straightforward implementation, but also implies a two-stage power conversion which decreases power density and efficiency.

Direct ac-ac conversion has been thoroughly studied in the past in order to provide an efficient and compact solution with no energy storage elements. These converters have been compared to other alternatives (Lai et al. 2008) and successfully applied to drives (Kolar et al. 2007), aerospace applications (Lee et al. 2010), or power supplies (Andreu et al. 2008; Ratanapanachote et al. 2006). Matrix converters have also been applied to series resonant loads for 3-phase systems in (Ecklebe et al. 2009). Considering the induction heating application, several resonant matrix converters featuring MOSFETs (Nguyen-Quang et al. 2006; Nguyen-Quang et al. 2007) or RB-IGBTs (Gang et al. 2008; Sugimura et al. 2008) have been proposed.

All the proposals previously described show some common positive points including improved power factor and harmonic distortion, increased power density, and reduction of electrolytic bus capacitors. However, the main drawback is the use of additional switching devices to implement the matrix converter, which lead to increased control complexity and cost. This issue becomes critical for certain cost-oriented applications. This may be the main reason...
for the low percentage of use of matrix converters compared to classical dc-link inverters in some areas as the home appliances segment.

The aim of this paper therefore is to propose a new multiple-output resonant matrix converter topology based on the series resonant multi-inverter (O. Lucía et al. 2010) to modify traditional power conversion based on a dc-link inverter (Fig. 1 (a)). The proposed multiple-output resonant matrix converter (Fig. 1 (b)) combines the advantages of matrix converters with the improved cost and power control of the series resonant multi-inverter. Since the matrix converter block is shared with a high number of induction loads, the overall cost is significant reduced, and the proposed topology can target the home appliances market.

This paper is organized as follows. Section II presents the proposed multiple-output resonant matrix converter topology, including the converter schematic and its control strategies. Section III summarizes the design procedure for the main components, and Section IV presents the main experimental results used to validate the converter operation. Finally, conclusions of this paper are drawn in Section V.

Fig. 1. Induction heating appliance block diagram: (a) classical dc-link resonant inverter and (b) proposed multiple-output resonant matrix converter.

2. Multiple-Output Resonant Matrix Converter

2.1 Topology

The proposed multiple-output resonant matrix converter (Fig. 2) is divided into two blocks: the common matrix converter block (CMCB) and the resonant load block (RLB). The CMCB has a half-bridge structure, and it is composed of the common switches $S_{m1}$ and $S_{m2}$. The switches have been implemented by means of two IGBTs with antiparallel diode featuring common-emitter configuration. This configuration has the best ratio between cost and efficiency.
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The resonant load block is composed of the electrical equivalent for each induction load $R_{eq,i}$ and $L_{eq,i}$, the resonant capacitor $C_{r,i}$, and the specific switches $S_i$. This provides adjustable output power for each load while reducing the number of devices.

The main benefit of the proposed topology lies in the use of the CMCB, as it significantly reduces the ratio of switching devices count per load, avoids the rectifier stage and energy...
storage elements, and simplifies the control strategy. Compared to the classical half-bridge inverter, and the single-phase single-output matrix converter, for an $n$-load system the proposed topology has $4 + n$ switching devices, while the others requires $2n$ and $4n$ respectively. This implies also a significant reduction in the auxiliary circuits such as control and driver circuits, and snubber networks.

### 2.2 Control strategy

The control strategy proposed for the multiple-output resonant matrix converter is based on the high frequency pulse density modulation (HF-PDM) (O. Lucía et al. 2010; O. Lucía et al. 2011). This scheme allows performing a fine output power tuning for each load while optimizing the power converter efficiency. The complete set of control parameters is $\psi = \{T_{hb}, D_{hb}, t_{d,bb1}, t_{d,bb2}, T_i, D_i, t_{di}, \phi_i | \ i = 1..n\}$ (Fig. 3). $T_{hb}$ and $D_{hb}$ are the CMCB switching period and duty cycle respectively, and $T_i$, $D_i$, $\phi_i$ are the RLB switching period, duty cycle, and phase shift respectively. Besides, a certain dead times $t_{d,bb1}$, $t_{d,bb2}$ and $t_{di}$ are defined for safety reasons.

The control signals of the CMCB, $c_{mh+}$, $c_{ml+}$, $c_{mh-}$, $c_{ml-}$, are modified according to the sign of the mains voltage. The CMCB operational conditions determines the overall output power delivered by the power converter to the set of induction loads. In addition to that, the specific switches $S_i$ are selectively switched on in order to activate the different heating areas and to perform precise output power control.

Fig. 4 shows the configuration sequence for the multiple output resonant matrix converter depending on the sign of the mains voltage. It is important to note that there are three switches activated at the same time. Besides, the common switches withstand the current for all the set of induction loads, whereas the specific switches only have to withstand the current associated to its induction load.

The main benefit of the proposed control scheme is the parallel load operation with a voltage source. This provides independent operation for each load and becomes a simple and effective method to control the output power for each induction load $P_{oi}$.

### 3. Design procedure

The following lines give a brief description of the design procedure for the proposed converter:
3.1 Resonant tank

The inductor-pot equivalent $R_{eq,i}L_{eq,i}$ and the resonant capacitor $C_{r,i}$ make up an individual resonant tank for each induction load. These have to be designed in order to obtain the desired output power and switching frequency range. The inductor is designed to achieve the $R_{eq,i}$ required to obtain the maximum output power $P_{o,i,max}$. Considering the output voltage provided by the CMCB, the necessary equivalent resistance is:

Fig. 4. Configuration sequence for the multiple output resonant matrix converter: (a) positive mains voltage and (b) negative mains voltage.
which leads to an inductor design with a certain number of turns and $L_{eq}$. Then, the resonant capacitor is chosen to set the resonant frequency $f_{o,i}$ above the audible range (20 kHz):

$$C_{o,i} = \frac{1}{4\pi^2 f_{o,i}^2 L_{eq,i}}.$$  

### 3.2 Switching devices

The switching devices are selected according to the converter specifications. The common switches operate with both switching and conduction losses, whereas the switching losses in the specific devices can be neglected (O. Lucia et al. 2010). Considering the usual switching frequencies and stress, 600-V IGBTs are selected.

The specific switches are selected considering the maximum output power per load. Then, the maximum current that they have to withstand is:

$$i_{S_{rms,\text{max}} \max} = \sqrt{P_{o,\text{max}}}/R_{eq,i}.$$  

The maximum current through the common switches $i_{S_{rms,\text{max}} \max}$ depends on the maximum converter output power $P_{o,\text{max}}$. Typically it is selected as $P_{o,\text{max}} < \sum P_{o,i,\text{max}}$ in order to avoid oversizing the converter. Considering symmetrical duty cycle and unity power factor (resonant conditions), the rms current can be estimated as:

$$i_{S_{rms,\text{max}} \max} = P_{o,\text{max}}/\sqrt{2V_{o,\text{rms}}}.$$  

### 3.3 Snubber network

The snubber network is intended to reduce the converter switching losses and therefore to increase the converter efficiency. Considering that the specific switches have no switching losses, and the common switches operate with zero voltage switching (ZVS) during the turn on, a capacitive snubber network ($C_s$) is selected to reduce the switching losses that occur during the common switches ($S_{mh}, S_{ml}$) switch-off transition. The maximum capacitance value is given by the ZVS condition, which can be calculated as:

$$C_{s,\text{max}} < \frac{2t_d i_{sw-off} \left| V_{\text{min}} \right|}{v_{\text{min}}},$$  

where $t_d$ is the dead time associated to that transistor and $i_{sw-off}$ is the switch-off current. As a consequence, $C_s$ is selected within this range order to optimize the efficiency and the power control region with the ZVS condition (O Lucia et al. 2009).

### 3.4 Control scheme

Control signals are generated using an FPGA-based control platform. The digital control block was described using VHDL. This block is based on a multi-phase Digital Pulse Width Modulator (DPWM) to control the common and specific switching devices. Besides, a mains-voltage feedback circuit provides the information needed to change the control signals according to the sign of the mains voltage ($nMCS$ signal). Fig. 5 shows the control block used to generate the CMCB control signals.
4. Experimental Results

A multiple-output resonant matrix converter was designed and implemented featuring 500-W output power per load, and switching frequency range between 30 and 150 kHz. The selected switching devices are IGBTs with antiparallel diode FAIRCHILD HGTG20N60. The resonant tanks are made up by 8-cm 48-turns coils and 44-nF resonant capacitors. Two 3.3-nF snubber capacitors have also been added in parallel with the common switches $S_{mh}$, $S_{ml}$.

The series resonant matrix converter prototype is shown in Fig. 6. Fig. 6 (a) shows a detailed view of the CMCB prototype, and Fig. 6 (b) shows the complete test bench for the 4-load series resonant matrix converter.
Fig. 6. Experimental 4-load induction heating test-bench: (a) Common Matrix Converter Block (CMCB), and (b) multiple induction heating load experiment.
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Fig. 7. Multiple-output resonant matrix converter prototype: (a) main control signals and waveforms (from top to bottom: \( c_{mh+}, c_{ml+}, c_{mh-}, c_{ml-}, nMCS, 40 \text{ V/div}, v_{\text{mains}}, 400 \text{ V/div}, i_{\text{o}}, 8 \text{ A/div}, \) and \( v_{\text{o}}, 400 \text{ V/div} \)), and (b) control signals transition (from top to bottom: \( c_{mh+}, c_{ml+}, c_{mh-}, c_{ml-}, nMCS, 40 \text{ V/div} \)).

Fig. 7 shows the main waveforms for the proposed converter. Fig. 7 (a) shows the control signals, mains voltage and voltage-sign signal, the output current, and the output voltage. This figure shows the proper converter operation during both, the positive and the negative mains cycle. In addition, a detailed view of the control signals transition is shown in Fig. 7 (b).

Finally, Fig. 8 shows the converter operation with different operational conditions for a load with \( R_{\text{eq},i} = 14 \Omega, L_{\text{eq},i} = 125 \mu\text{H}, \) and \( C_{r,i} = 44 \text{ nF} \). On one hand, Fig. 8 (a) shows the converter operation near the resonant frequency with \( f_{s,\text{bb}} = 75 \text{ kHz} \) and \( P_{\text{o,i}} = 500\text{W} \), where a sinusoidal output current can be seen. On the other hand, Fig. 8 (b) shows the converter operation with a higher switching frequency \( f_{s,\text{bb}} = 100 \text{ kHz} \) in order to reduce the output power to \( P_{\text{o,i}} = 100 \text{ W} \). For this condition, a higher harmonic content can be observed in the output current.
5. Conclusions

Direct ac-ac conversion has proven to be a convenient technique which can be extended to the ubiquitous dc-link inverters present in most household appliances. It combines higher power density with a reduced number of conversion stages and energy-storage elements. However, the higher number of switching devices and complex control scheme has prevented it from being widely used.

In this paper, a multiple-output resonant matrix converter has been proposed. It combines the benefits of matrix converters, with the improved control and cost reduction associated to this multiple output stage. The feasibility of this proposal has been tested by means of a 4-load prototype. As a conclusion, the multiple-output resonant matrix converter is proposed as a cost-effective and high-power density converter for multiple-load systems.
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References


