A New Converter Topology for Power Quality Improvement in Residential Induction Cooking System

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Abstract

This paper presents the analysis and design of a new ac–ac resonant converter for power quality improvement in residential induction cooking system. The proposed topology, based on the half-bridge series resonant inverter, uses only two diodes to rectify the mains voltage. The proposed converter can operate with zero-voltage switching during both switch-on and switch-off transitions. Moreover, this topology doubles the output voltage, and therefore, the current in the load is reduced for the same output power. As a consequence, the power quality of induction cooking system is significantly improved. The analytical and simulation results have been verified by using PSIM simulation software.

Keywords: Induction heating, power quality, inverter, resonant converter, AC-AC converter

1. Introduction

The Induction heating appliance market is increasing due to its fastest heating time and efficiency. Domestic induction cook tops are now becoming a standard option, especially in India.

The principle of operation is based on the generation of a variable magnetic field by means of a planar inductor below a metallic vessel [1], [2]. The mains voltage is rectified and after that an inverter provides a medium-frequency current to feed the inductor. The usual operating frequency is higher than 20 kHz to avoid the audible range and lower than 100 kHz to reduce switching losses. The most used device is the insulated gate bipolar transistor (IGBT) because of the operating frequency range and the output power range, up to 3 kW. Nowadays, most designs use the half-bridge series resonant topology because of its control simplicity and high efficiency [3]–[7].

In the past, several ac–ac topologies have been proposed to simplify the converter and improve the efficiency [8]–[10]. Considering the induction heating application, several resonant matrix converters featuring MOSFETs [11], [12], IGBTs [11], or RB-IGBTs [10], [12] have been proposed. However, the final efficiency and cost are compromised due to the use of a higher number of switching devices. Other approaches, commonly used in electronic ballasts, simplify the rectifier stage in order to improve the converter performance [10]–[12]. This topology, known as half-bridge boost rectifier, reduces the switch count. The aim of this paper is to propose a new topology to improve the efficiency while reducing the power device count for induction heating applications.

Proposed topology is based on the series resonant half-bridge topology and requires only two rectifier diodes. The effective output voltage is doubled, as in [9], [10], allowing a significant current reduction in the switching devices. Moreover, the proposed topology can operate with zero voltage switching conditions during turn-on for both switching devices, and also during turn-off transitions for one of them. As a consequence, the power quality is improved while the device count is reduced while keeping the same performance as more complex solutions.

2. Proposed Converter Topology

The proposed AC-AC converter topology as shown in Fig-1, employs two bidirectional switches S1 and S2 typically an IGBT. The mains voltage $V_{ac}$is rectified by two diodes D1and D2, but only one of them is activated at the same time. This operation improves power quality with regard to

classical topologies based on a full-bridge diode rectifier plus a dc-link inverter.

The proposed topology is a series–parallel resonant converter. The inductor–pot system is modelled as an equivalent series resistance R_{eq} and inductance L_{eq}, as shown in Fig-1.This topology implements resonant capacitors C_r and may use a source capacitor C_S. Due to the symmetry between positive and negative mains voltage, both resonant capacitors have the same value. An input inductor L_S is used to reduce the harmonic content to fulfil the electromagnetic compatibility regulations.
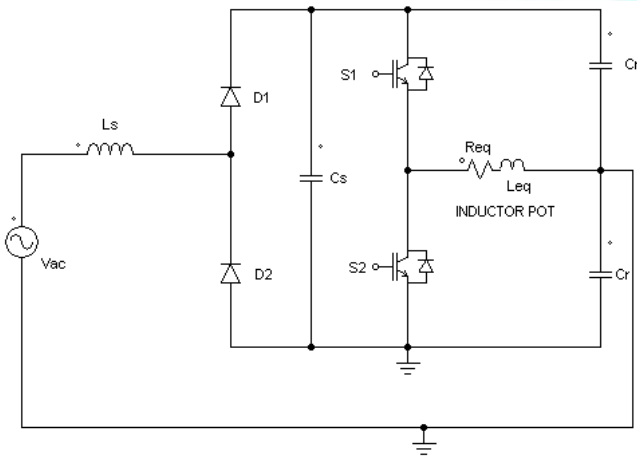

Fig. 1 Proposed AC – AC converter

3. Principle of Operation

The topology presents symmetry between positive and negative ac voltage supply. Its symmetry simplifies analysis and makes possible to redraw the circuit as shown in Fig. 2. Although this topology uses different resonant configurations, parallel and series, and different resonant tanks for each of them, it is possible to use a normalized nomenclature based on series resonance.

$$C_s = \alpha . C_r, \qquad \alpha \geq 0 \qquad (1)$$

$$L_s = \beta . L_{eq}, \qquad \beta \geq 0 \qquad (2)$$

$$\omega_0 = \frac{1}{\sqrt{L_{eq} . C_r}} \qquad (3)$$

$$\omega_n = \frac{\omega_{sw}}{\omega_0} \qquad (4)$$

$$Z_0 = \sqrt{\frac{L_{eq}}{C_r}} \qquad (5)$$

$$R_{eq} = \frac{\omega_0 . L_{eq}}{Q_{eq}} : \qquad (6)$$

$$C_{eq} = C_r \left(1 + \frac{C_s}{C_r + C_s}\right) = C_r \left(\frac{1 + 2\alpha}{1 + \alpha}\right) \qquad (7)$$

where α is the ratio between the dc-link and the resonant capacitors and β is the ratio between the input choke and the equivalent inductance of the inductor–pot system. The parameters $[\omega_0, \omega_{sw}, \omega_n]$ are the angular resonant frequency, the angular switching frequency, and the normalized angular switching frequency, respectively. Z_0 defines the equivalent impedance of the resonant circuit, defined by L_{eq} and Cr. Finally, Q_{eq} is the equivalent inductor–pot system quality factor at the resonant frequency.

Table 1: State and Transition Condition

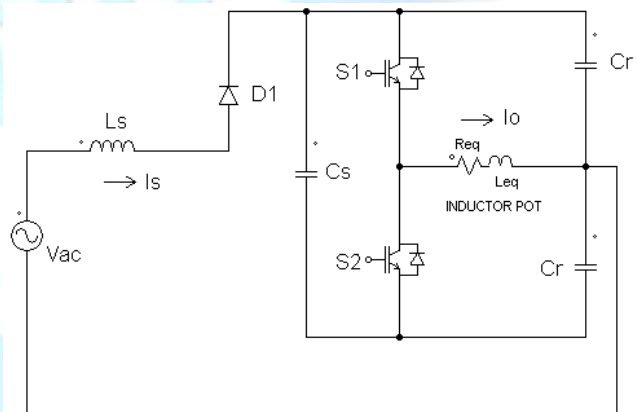| IGBT	STATE I	STATE II	STATE III
S1	Activated	Activated	Deactivated
S2	Deactivated	Deactivated	Activated

Fig. 2 Equivalent circuit

State I operate with the high-side switching device S1 triggered-on and activated and the low-side switching device S2 triggered-off. The parallel resonant circuit is set by an equivalent capacitor Ceq obtained from Cr and Cs and expressed in (7), and the inductor electrical parameters, Req and Leq. The current flowing through S1 is the same as the one flowing through the load.

State I begin when S2 is triggered OFF. Transitions from this state can lead either to state II or state III. If voltage across S2 reaches zero, the transition condition to state II is fulfilled. On the other hand, if S1is switched OFF, the next state is state III. State II is characterized by the conduction of both switching devices, although only S1 is

triggered ON. The equivalent parallel resonant circuit is set by the inductor electrical parameters in parallel with both resonant capacitors. *Cs*is short-circuited by both switching devices. This state starts when the voltage across S2 reaches zero. This state finishes when *SH* is triggered OFF and the next state is state III. The main benefit results of the lower switch-off current achieved when S1 is triggered OFF, due to the fact that the load current is supplied by both devices. In addition, S1 achieves ZVS conditions during both switch-on and switch-off transitions, reducing consequently the switching losses.
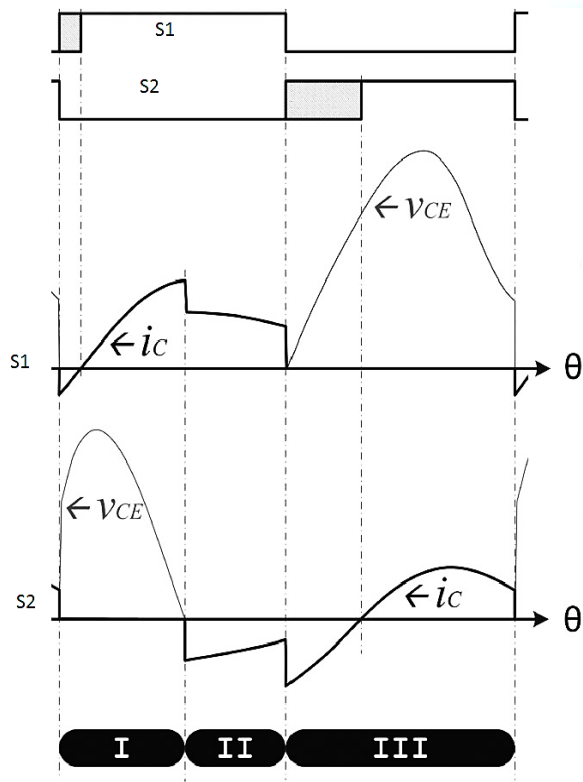

Fig. 3 Switching frequency control mode

State III is defined by the conduction of S2 while S1is deactivated. The equivalent resonant circuit is set by one resonant capacitor in parallel with the series connection of the *Cs* capacitor and the parallel connection of the inductor and the other one resonant capacitance. Note that when *Cs* is zero ($\alpha = 0$), the equivalent resonant circuit is a series RLC circuit composed of the inductor–pot system and one resonant capacitor. This state starts when S1is triggered OFF. At this moment, S2 can be triggered ON achieving ZVS switch-on conditions. This state finishes when S2 is deactivated, and the next state is state I.

The different state and transition conditions are described in table-1.

4. Simulation and Result

Principle of operation presented in previous section and operating modes can be described as shown in Fig-3, achieve ZVS switch-on conditions. The operation mode uses the three states described earlier: I, II, and III. It makes possible to achieve ZVS conditions for the high-side switch in state II. The low-side switch has non- ZVS turn-off characteristic. However, turn-off current is always lower than in the high-side switch.

Nowadays, the induction heating appliances power is limited by mains maximum current and voltage. The typical maximum output power is 3000W, and the power converter has been, therefore, designed to achieve 3000-W output power. Simulation parameters are *Cr* = 470 nF, and the inductor is modelled by *L*eq = 65 μH and 6.5 Ω for the series-equivalent resistor at switching frequency. The dc-link capacitor has been selected to be low enough to obtain a high power factor and a proper power control, as it is shown in this section and it can be neglected in this analysis.

The control strategies considered to control the output power is the square wave (SW) control, based on changing the switching frequency (SF) of the switching devices.
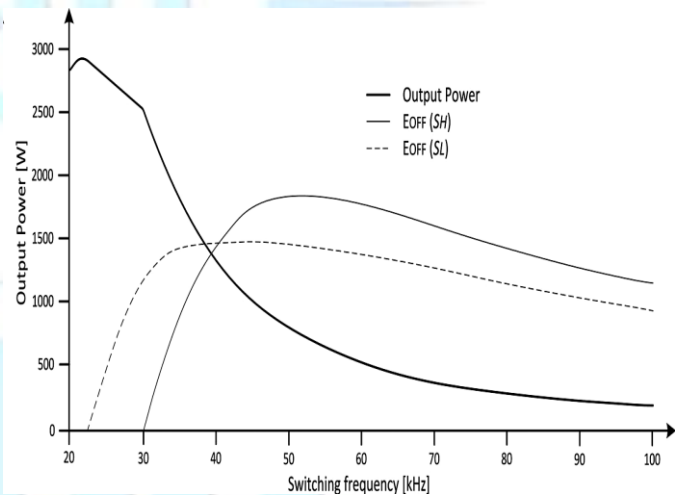

Fig. 4 Output power and switching losses in SF control mode

4.1 SF Control Strategies

The SF control modifies the output power by controlling the switching frequency. The switching frequency is higher than the resonant frequency to achieve switch-on ZVS, and the output power is reduced when the switching frequency is increased. As is shown in Fig. 4, the frequency range starts at 22 kHz, which is the resonant frequency determined by *L*eq and *Cr*, that ensures ZVS switching-on conditions, and can be increased to decrease the output power.

However, if the switching frequency reaches 30 kHz, switching-off losses increase because ZVS switching-off conditions are not achieved. As a result, the suitable switching frequency range and, therefore, the output power range is reduced. As is shown in Fig-5, the induction load must be carefully designed to avoid unfeasible high voltages.

As a conclusion, the output power in the proposed converter can be effectively controlled by means of SF control strategy. The output power can be reduced from the maximum value at the resonant frequency, 3000W, to 1000Wwithout degrading the converter efficiency. If further reduction is required, pulse density modulation (PDM) can be used to keep an improved power quality.
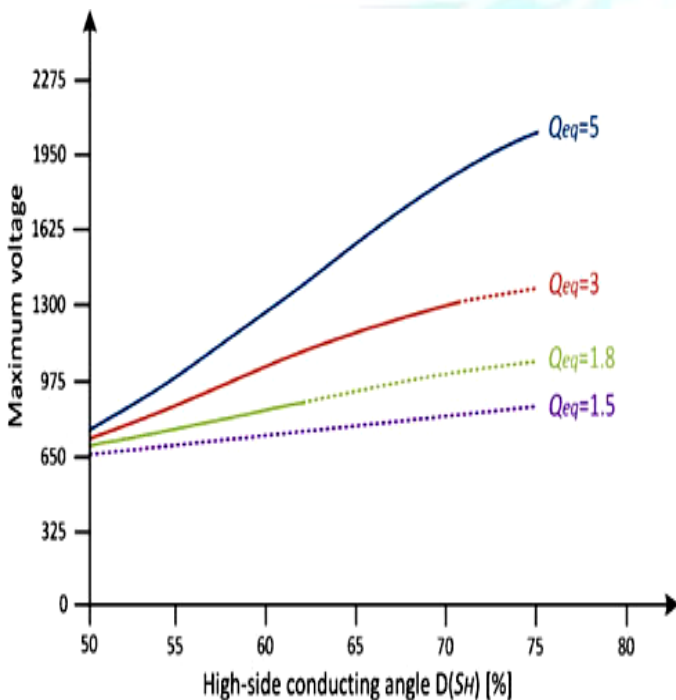

Fig. 5 Values for different load quality factor

5. Conclusions

This paper presents a new ac–ac converter topology applied to residential induction cooking system. An analytical analysis has been performed in order to obtain the equations and operation mode that describe the proposed converter. The converter can operate with zero-voltage switching during both turn-on and turn-off commutations. Besides, the output voltage is doubled compared to the classical half-bridge, reducing the current through the switching devices. As a consequence, the power converter power qualities improved in the whole operating range. A 3-kW prototype has been designed and

simulated in order to validate the analytical and results. The simulation measurements show a significant power quality improvement compared to the classical half-bridge topology and validate the feasibility of the proposed converter.

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