Analysis, design and implementation of a residential inductive contactless energy transfer system with multiple mobile clamps

Arash Momeneh¹ ✉, Miguel Castilla¹, Mohammad Moradi Ghahderijani¹, Jaume Miret¹, Luis García de Vicuña¹

¹Department of Electronic Engineering, Technical University of Catalonia, Avda. Víctor Balaguer s/n, 08800 Vilanova i la Geltrú, Spain

✉ E-mail: arash.momeneh@upc.edu

Abstract: This study presents the analysis, design and implementation of a simple and cost-effective residential inductive contactless energy transfer system with multiple mobile clamps. The topology is based on the cascaded connection of a buck converter and a high-frequency resonant inverter loaded by several output passive rectifiers. The proposed system includes a sliding transformer to supply the mobile loads, leading to a safe and flexible location of loads. The theoretical analysis and design of the proposed system is based on a mathematical model derived using the first harmonic approximation. Selected experimental results are included to verify the system features. In comparison with conventional topology, the proposed system significantly improves efficiency, complexity and cost.

1 Introduction

In recent years, contactless energy transfer (CET) systems have been developed and investigated widely [1–6]. A CET system is responsible to transfer energy from the primary source to the loads without physical connection. By means of CET system the distribution cables can be successfully removed. Hence, with the conventional energy delivery method, CET systems are more safe, convenient and flexible. Several types of CET systems have been utilised in industrial and commercial applications. However, the most commonly used one is inductive contactless energy transfer (ICET) due to its higher efficiency [7].

The performance of ICET system has been extensively studied from different perspectives such as high efficiency DC/DC converter [8, 9], magnetic shield [10], analysing and modelling of the coupling system [11–16], control method and proper system design [17–19], and high-efficiency coupling [20]. It should be mentioned that these achievements are applicable only to the single clamp system. In fact, there are many unsolved problems to apply these methods to a multiple-clamp system.

Feeding multiple loads is one of the interesting advantages besides eliminating the last wire. The practical application scenario considered here is a long winding loop with sliding transformers supplying power for various electronic devices such as wearable devices, mobile phones, and laptops. The characteristics of these devices are normally different in size, power requirement and charging conditions. Therefore, to fulfil the aforementioned situation several challengeable problems should be solved. Over the past few years, several research studies have been done to address such a multiple-clamp system from different perspectives [21–26]. For example to analyse a multiple-receivers system, a circuit model has been presented in [21]. This model is used for high-power low-frequency applications. The control power capability, controllability and sensitivity are discussed in [21]. However, the load variation analysis is not considered. In [22], a new model has been presented to design the circuit parameters. Also, a new solution has been provided to compensate the efficiency drop by frequency tracking method and improve the system performance. Nevertheless, this solution is a complex method for delivery energy to the multiple-clamp system. In [23], a power distribution method for two-receiver system has been discussed. However, the mathematic analysis for multiple numbers of receivers has not considered. The authors [24] discussed the coupled mode theory to explore the effect of multiple loads on

power transfer efficiency. References [25, 26] also discussed the optimal load analysis and effect of coupling between multiple clamps, respectively.

Despite of numerous publications in the field of ICET systems with multiple clamps, few attempts have been made to bring this technology into the residential area where the distribution system is traditionally based on copper cables and fixed point sockets [27–32]. In fact, this distribution system is a very good technical solution to the supply of fixed and heavy loads such as refrigerators, washing machines, air conditioning etc. However, for residential mobile loads such as laptops and mobile phones, ICET technology will drastically improve flexibility. Note that these kinds of loads include internal post-regulators (they are active loads), so that excellent output voltage regulation is not strictly required for ICET systems in this particular case [33, 34]. Besides improving flexibility, ICET systems prevent electrical shocks due to the inclusion of high-frequency transformers which provides an electrical isolation to ensure a higher safety system. This feature is significant in wet environment, where there is always a risk of electrical shocks.

The most challenging aspect for residential ICET system is the lack of a direct communication line to inform the resonant converter about the load consumption as a consequence of long primary winding loop and mobile loads flexibility. Therefore, as an alternative, a system without communication capability must be applied. As a specific task in these applications, the input current should be controlled in a special way to reach a high efficiency in all the load conditions. In [27], a fixed reference input current has been applied for multiple mobile clamps, resulting in a high efficiency for full load and very low efficiency for low load conditions. To improve the overall efficiency, the authors [28] present an adaptive control scheme that automatically updates the value of the reference input current making use only of local measures. However, a wrong estimation of reference input current could be obtained as a consequence of neglecting the effect of magnetising and leakage inductances. In addition, control complexity of this system increases exponentially when the number of clamps rises.

A common feature of previous solutions is the use of active rectifiers in the mobile clamps [21–29]. Note that each active clamp requires a control system including sensing circuitry, control circuit and driver. Therefore, the cost of the system will increase for the high number of clamps compared to the topology based on passive rectifiers. As an alternative solution, the authors [30]

Fig. 1 Conventional approach to supply the ICET system with multiple-receivers

(a) Diagram of ICET system with sliding transformer and various mobile loads, (b) Schematic of the conventional DC/DC converter with multiple mobile clamps

present a simple and cost-effective topology to supply ICET system with multiple clamps without the need for an active rectifier. The proposed system operates based on using frequency modulation technique, resulting in fixed output voltage in several load conditions. However, the voltage gain is highly depends on the resonant elements values. Therefore, a little change on the resonant elements (due to the temperature or external effects) has a big impact on the voltage gain. In [31], a new cost-effective topology to supply a high-power single clamp system has been presented. The proposed topology has a fix output voltage independent to the load condition. However, the complex mechanism of the clamp connection and expensive control system has been considered for this topology. In [32], this topology was extended and simplified to supply multiple clamps. However, the theoretical analysis and the experimental validation of this interesting topology were not presented.

The purpose of this paper is to present the analysis, design and implementation of a simple and cost-effective technique to supply the residential ICET system with multiple mobile loads. The proposed topology is based on the cascaded connection of a buck converter operating as a constant current source and a high-frequency resonant inverter (RI) operating in closed loop with only feedforward term and loaded by passive rectifiers. The most promising features of the proposed topology is that the output voltages are nearly constant for all the load conditions even using passive rectifiers at the output side of the proposed ICET system. The drawback of this configuration is the poor transient response. For this reason, the topology is well suited to supply active DC loads with internal post-regulators such as laptops, mobile phones and other loads taking advantage of a flexible location. The analysis of the proposed topology is carried out with a mathematical model based on the first harmonic approximation. By using the derived model, a systematic design procedure is introduced to get constant output voltages in all the loads and also for different load conditions. Moreover, to validate the performance of the proposed system, selected experimental results are compared to those obtained from the conventional topology.

The main contributions of this paper are: (i) a simple, efficient and cost-effective topology to supply residential loads with multiple clamps, (ii) a mathematical model derived by using the first harmonic approximation which includes the effect of magnetising and leakage inductances and (iii) a systematic design procedure for the resonant components.

This paper is structured as follows: Section 2 describes the conventional topology to supply multiple mobile clamps. Section 3 presents the proposed topology and describes its principle of operation. Section 4 derives the mathematical model of the proposed system. Section 5 introduces the design procedure of the proposed system with a numerical example. The predicted theoretical results are verified experimentally in Section 6 with measurements obtained from an experimental setup. A comparison with the conventional topology is also included. Finally, the paper is concluded in Section 7 with remarks regarding the results.

2 Conventional residential ICET system with multiple mobile clamps

This section discusses the configuration, control and efficiency issues of the conventional residential ICET topology to supply a multiple mobile clamp system. Note that, there are several topologies such as series, parallel and series-parallel resonant converter for dual active bridge system. However, for this specific application series resonant converter has been selected due to higher efficiency and good performance [17, 27–29]. Moreover, in series resonant topology, the primary leakage inductance of the sliding transformers could be absorbed by the large discrete series resonant inductance. So, the effect of these elements could be reduced in the case of high number of clamps and variation of transformer air gap.

A diagram of the conventional topology with sliding transformer and various mobile loads is shown in Fig. 1a. This system consists of a RI, a primary winding loop, secondary side transformer and various mobile clamps. The RI is responsible to generate a high-frequency AC voltage to supply the mobile loads through the long primary winding loop of the sliding transformer. This feature offers the possibility to construct long ICET systems for mobile clamps.

Fig. 1b illustrates the complete electrical representation of the conventional residential ICET topology. It consists of a series resonant network connected in series with the primary side of n sliding transformers excited by the full-bridge RI. The secondary side of each clamp is formed by an active full-bridge rectifier and a capacitive filter. The magnetising inductances of the high-frequency transformers are modelled by parallel equivalent inductors ($L_{m1}, \dots, L_{mn}$). Note that in the primary side, the (small) leakage inductance of the transformer is absorbed by the large discrete inductance (L_r). The secondary side leakage inductance (L_{s1}) is included in the schematic. This conventional topology exhibits excellent output voltage regulation and transient response. Also, it has several drawbacks which will be presented as follows.

In this application, as a consequence of the long primary winding loop and the mobile load flexibility, the information about the load consumption is not available in the primary side of the full-bridge inverter. This problem can be solved by using a wireless communication system. However, this design will drastically increase the system cost due to the high bandwidth communication required to send output side data to the primary side controller. Therefore, the design and implementation of the control system that provides a high efficiency can be considered as a complex trend. On the one hand, several approaches can be adopted to regulate the inverter current including constant and variable i_{ref} [27, 28]. By using constant i_{ref} , high efficiency can be only reached at full load conditions [27]. With variable i_{ref} , the efficiency is improved for low load conditions, but at the expense of increasing the complexity of the current control loop. In [28], the current reference is online updated by estimating the load consumption through indirect measures. However, the estimation depends on a model that does not consider magnetising and leakage inductances, thus providing poor results in some circumstances. These parasitic elements are important in this application and they will be specially taken into consideration in this paper. On the other hand, the output voltages in the conventional topology depend on the load

Fig. 2 Schematic of the proposed ICET system with multiple mobile clamps

Fig. 3 Control diagram of the proposed system

(a) Buck converter current control, (b) RI control and (c) Output waveforms of the RI

conditions, so that a separated control system is required for each clamp. Although, the output voltage can be correctly regulated, the cost of the system is drastically increased in the case of high number of clamps (because of the sensing circuits, control system and driver needed by each active full-bridge rectifier). To sum-up, the conventional topology is complex and expensive, especially for a high number of clamps. In the next section, the proposed system that overcomes the aforementioned problems will be introduced.

3 Proposed residential ICET system with multiple mobile clamps

Fig. 2 shows the schematic of the proposed topology to supply n mobile clamps. The topology consists of a buck converter, RI, resonant elements, a high-frequency transformer, and diode bridge rectifiers with low-pass filters. In this system, the buck converter is responsible to inject a constant DC current (i_z) to the RI. This constant current is essential to guarantee fixed output voltages ($v_{o1}, \dots, v_{on}$) regardless of the load conditions. In practice, i_z is fixed by applying a conventional PWM closed-loop current-mode control to drive the switch S_b in accordance with the desired reference current (I_{ref}), as shown in Fig. 3a. As a consequence of the constant current, the voltage v_z changes automatically as a function of the load due to the power matching issue (i.e. the input power is roughly equal to the total output power supplied to the n loads). Therefore, based on the proposed system, the aforementioned efficiency problem is improved even for low load conditions. This property will be validated theoretically in the next sections. Note that the value of v_z should always be lower than the buck converter

input voltage (V_b). Once this issue is respected, a correct operation of the buck converter can be ensured ($v_z < V_b$).

On the other hand, the inverter operates with the simple zero-crossing detection (ZCD) modulation strategy shown in Fig. 3b. The resonant current i_r is used to match the switching frequency (f_s) with the resonant frequency (f_o) in a feedforward way by operating the converter continuously in energising mode [29]. This control strategy causes constant amplitude in i_r as shown in Fig. 3c. By applying ZCD to the inverter on the one side and using a passive diode rectifier on the other side, the input energy is completely transferred to the load as a unidirectional flow (from input side to the output side only) while in the conventional topology this current varies as a function of load following an amplitude modulation approach. This principle of operation avoids the transformer saturation problem by preventing the flowing of high currents into the transformers. Moreover, the voltage and current waveforms are perfectly in phase in the output side of the inverter, avoiding reactive power flowing into the resonant tank.

Additionally, a passive diode rectifier is used for each clamp instead of the controlled rectifier employed in the conventional topology. Also, a small parallel secondary side capacitor C_{p1} is included in the proposed topology to fix the output voltages. As a consequence of these changes, the cost and complexity of the proposed topology are reduced particularly in the case of high number of mobile clamps. Also, due to the second-order output filter, the current flowing through the filter capacitor is low, reducing the conduction losses in ESRs and consequently increasing the system efficiency.

The proper function of this topology is highly dependent on the performance of the buck converter in the first stage. The buck converter is a fundamental element to both guarantee a fixed output

Fig. 4 Equivalent circuit of the proposed topology

voltage and to increase efficiency. This converter in collaboration with RI is responsible to produce a fix current for the secondary side resonant elements (L_m , L_s and C_p). The total impedance of these elements (Z_{LC}) is in parallel with load (R_o). Therefore, by proper design of C_p the load effect can be neglected because of dominant value of Z_{LC} (i.e. $Z_{LC} \approx R_o$), resulting in fixed output voltage regardless of the load conditions. The design process of C_p to obtain a fix output voltage will be explained in Section 5.

The RI operates in closed-loop with only a feedforward term to detect the zero-crossing of the resonant current (Fig. 3c). The sinusoidal waveform is the resonant current i_r and the square waveform is the voltage v_p . In steady state, the current i_r can be expressed as

$$i_r = \frac{\pi}{2} I_{ref} \sin(\omega_o t) \quad (1)$$

where ω_o is the angular resonant frequency. Note that its amplitude is proportional to the output current of the buck converter. From Fig. 3c, the value of v_p can be expressed as

$$v_p = v_z \cdot \text{sgn}(i_r) \quad (2)$$

In the proposed topology, the two waveforms (i_r and v_p) are completely in phase. Therefore, circulating reactive current is completely avoided, thus achieving unity power factor operation. Also, at $f_s = f_o$, the switches turn on and off at zero current, reducing switching losses [35]. As a consequence of both issues, the efficiency of the proposed topology improves significantly. Also, the principle of operation of the inverter allows that the voltage v_z automatically changes according to the required output power while the current i_z is fixed by the buck converter. Therefore, the proposed system can regulate the input power without the need for a communication system.

It is worth mentioning that a fixed amplitude current can also be obtained in the resonant current using different approaches, for instance with a feedback control system including frequency or phase modulators. In these approaches, the input buck converter can be eliminated. However, in all these cases, the unity power factor provided by the proposed solution cannot be guaranteed, thus forcing the sliding transformer to operate in a more stressing condition. Taking into account the complex structure of the sliding transformer (long primary loop and several mobile secondary sides), the operation of the RI with only a single feedforward current term is an interesting option to eliminate the flowing of reactive power in the sliding transformer.

4 Mathematical modelling of the proposed topology

This section presents an equivalent model for the proposed topology. This model is employed to derive the main characteristics of the topology.

4.1 Model of the proposed topology

The proposed topology can be represented by the equivalent circuit model shown in Fig. 4. The model contains an input current source, two controlled sources, resonant components and equivalent resistors. The current source I_{ref} represents the operation of the buck converter while the controlled sources characterise the operation of the RI. Note that the controlled current source reflects the primary side resonant current i_r to the inverter input side. Besides, the controlled voltage source models the effect of the input voltage v_z on the inverter output side. For simplicity, the magnetising inductance, parallel capacitors and leakage inductance are assumed equal in all clamps ($L_{mi} = L_m$, $C_{pi} = C_p$ and $L_{si} = L_s$). Also, a unity turns ratio is assumed for transformers ($n_i = 1$). Moreover, the effect of dissipative nature of the loads is modelled by the equivalent AC resistors ($R_{ac1}, \dots, R_{acn}$). The value of R_{ac_i} under steady-state condition can be expressed as [36]

$$R_{ac_i} = \frac{\pi^2}{8} R_{oi}, \quad i = 1, \dots, n. \quad (3)$$

where R_{oi} is the output resistor and n stands for the number of clamps.

4.2 Angular resonant frequency

The proposed topology operates at $\omega = \omega_o$, where ω is the angular frequency. Therefore, to design and analyse the proposed system, an accurate expression for ω_o should be obtained as an initial step to calculate the design parameters.

First ω_o should be determined by analysing the total impedance Z_i marked in Fig. 4. In fact, the resonant frequency is defined as the frequency when the imaginary part of the total impedance is zero. The total impedance is a function of the series and parallel components which can be represented by the following equation:

$$Z_i = j\omega L_r - \frac{j}{\omega C_r} + \sum_{i=1}^n Z_{pi} \quad (4)$$

where L_r and C_r are the series components and Z_{pi} stands for the parallel impedances shown in Fig. 4. For the correct operation of the proposed converter, it is necessary that the parallel impedances are independent of the load resistors. This condition is satisfied when the parallel capacitor is designed according to (5)

$$C_p \gg \frac{1}{\omega^2 (L_m + L_s)} [1 + \text{Max}(a, b)] \quad (5)$$

$$a = \frac{R_{ac_i} L_m + 2L_s \sqrt{R_{ac_i}^2 (2 + L_m(L_m + L_s)) + (L_m + L_s)^2 \omega^2}}{2R_{ac_i} L_s} \quad (6)$$

$$b = \frac{\omega(L_m + L_s)}{R_{ac_i}} \quad (7)$$

In this case, the input impedance can be represented as

$$Z_i = j \left[\omega L_r - \frac{1}{\omega C_r} + n \cdot \frac{\omega L_m (\omega^2 L_s C_p - 1)}{\omega^2 C_p (L_m + L_s) - 1} \right] \quad (8)$$

The resonant angular frequency is obtained by setting (8) equal to zero (then by definition $\omega = \omega_o$) and solving for ω_o . The expression for ω_o is written as (see (9))

4.3 Output voltages

In Fig. 4, the output voltage v_{si} is a sinusoidal signal operating at the resonant frequency. Its amplitude relies on the parallel impedance (Z_p) and the amplitude of the resonant current

Table 1 Circuit parameters for the proposed design

Parameter	Symbol	Value	Units
input voltage	V_b	15	V
magnetising inductance	L_m	50	μH
leakage inductance	L_s	2.5	μH
switching frequency	f_s	110	kHz
minimum load resistor	R_{oi_min}	100	Ω
output voltage	v_{oi}	22	V

$$V_{si} = (|Z_{pi}| \cdot I_r) \cdot \frac{(1/C_p \omega_o)}{L_s \omega_o + (1/C_p \omega_o)} \quad (10)$$

$$= \frac{\omega_o L_m (\omega_o^2 L_s C_p - 1)}{\omega_o^4 C_p^2 (L_s L_m + L_s^2) + \omega_o^2 C_p L_m - 1} \cdot \frac{\pi}{2} I_{ref}$$

From Fig. 2, the output voltage v_{oi} is obtained by rectifying and filtering the sinusoidal voltage v_{si} . Therefore, v_{oi} can be expressed as

$$v_{oi} = \frac{2}{\pi} v_{si} = \frac{\omega_o L_m (\omega_o^2 L_s C_p - 1)}{\omega_o^4 C_p^2 (L_s L_m + L_s^2) + \omega_o^2 C_p L_m - 1} \cdot I_{ref} \quad (11)$$

It must be noticed that the output voltage is independent of the load conditions.

4.4 Design conditions for the reference current

The last step is to determine a design condition for I_{ref} . As described above, the voltage v_z varies as a function of the load. Once the input current to the resonant converter I_{ref} is constant, the variations in the input power produced by load changes modify the voltage v_z . In the worst-case scenario (i.e. $R_{oi} = R_{oi_min}$), the relation between these variables can be expressed, assuming an ideal efficiency (100%) as

$$v_z I_{ref} = \sum_{i=1}^n \frac{v_{oi}^2}{R_{oi_min}} \quad (12)$$

Moreover, to ensure a correct operation of the buck converter, its input voltage V_b must be always greater (or equal) than the output voltage v_z . According to this condition, (12) can be re-written as follows:

$$\sum_{i=1}^n \frac{v_{oi}^2}{R_{oi_min}} \leq V_b I_{ref} \quad (13)$$

From (13), the value for I_{ref} can be limited as

$$I_{ref} \geq \sum_{i=1}^n \frac{v_{oi}^2}{R_{oi_min} V_b} \quad (14)$$

In practice, the value of I_{ref} must be slightly over-dimensioned to compensate the ideal assumption of 100% efficiency. In the next section, a design example will be presented.

5 Design of the proposed topology

The necessary circuit parameters for starting the design process are listed in Table 1. Note that these values correspond to a low-power experimental prototype. The design process is based on the worst-case scenario (i.e. $R_{oi} = R_{oi_min}$) and it is presented in the following steps:

Step 1: In the first step, the reference current of the buck converter is determined based on Table 1 and (14). From (14), the minimum value of the reference current is $I_{ref} = 0.64$ A. This value introduces the minimum current for a correct operation of the buck converter.

Step 2: The value of the parallel capacitor C_p for each clamp can be obtained from (11) as $C_p = 80$ nF. According to (5), this value ensures a constant output voltage independent of the load condition.

Step 3: In the final step, the values for C_r and L_r are obtained. It should be noted that the primary leakage inductance has a small value. Also, this value may experience some changes during the operation of the system. Therefore, to eliminate the effect of this leakage inductance, L_r should be chosen noticeably higher. In this example, L_r is chosen equal to 40 μH which is drastically $> 2.5 \mu\text{H}$. By solving (9), $C_r = 68$ nF is calculated.

By following these steps, a proper design for the proposed topology is reached. The theoretical design is validated experimentally in the next section.

6 Experimental validation

The predicted theoretical results including principle of operation and performance of the proposed approach as well as the proposed design procedure are verified experimentally in this section. Also, a comparison between the proposed and conventional topologies is included.

A low-power high-frequency DC/DC resonant converter prototype with two clamps has been built and tested as shown in Fig. 5. The control system shown in Fig. 3 was implemented using analogue circuits. The main circuit parameters are given in Table 2. Note that the values are chosen based on the design process explained in the previous section. Moreover, some selected results for the conventional topology will be also presented for comparison purposes. It should be mentioned that a system with amplitude modulation control technique has been built and tested based on [29]. Table 3 lists the main circuit parameters of the conventional topology. To have a fair comparison, the values of this table are selected according to the design process presented in [29] to achieve the same output power, output voltage and switching frequency.

6.1 Comparison between the conventional and proposed topologies

Fig. 6 shows the main waveforms of the conventional and proposed topologies. As shown, the conventional topology has amplitude modulation in the resonant current which produces higher peak value in comparing with the proposed topology. In the conventional topology, the power flow from the input source to the resonant tank is decided by the closed-loop control system. When the amplitude current increases, the power is flowing into the resonant tank; when the amplitude current decreases, the input power is zero and the stored energy in the resonant tank is discharged in the loads. This principle of operation produces a higher peak current in all devices (including power switches and diodes). Conversely, in the proposed topology, the power flow is continuous and constant, reducing the stress of the devices.

$$\omega_o = \sqrt{\frac{L_m(nC_r + C_p) + C_p L_s + C_r L_r + \sqrt{c}}{2C_p C_r (L_m L_r + L_m L_s + nL_r L_s)}} \quad (9)$$

$$c = C_p [C_p L_m (L_m + 2L_s) + 2L_m C_r (nL_m - L_r - nL_s) + L_s (C_p L_s - 2C_r L_r)] + C_r^2 [nL_m (nL_m + 2L_r) + L_r^2]$$

Fig. 5 Experimental set-up with two mobile clamps

Fig. 7 shows the output waveforms of the RI (voltage v_p and current i_r) for the proposed topology in two different load conditions. Note that the current has a constant peak value independent of the load. The voltage is a (nearly) square wave and its amplitude depends on the load condition. As predicted by (12), this voltage changes according to the output power.

Table 2 Circuit parameters and components for the proposed topology

Parameter	Symbol	Value	Units
input voltage of buck converter	V_b	15	V
buck converter inductor	L_b	50	μH
buck converter capacitor	C_b	22	μF
series resonant capacitor	C_r	68	nF
series resonant inductor	L_r	40	μH
magnetising inductance	L_{m1}, L_{m2}	50	μH
leakage inductance	L_s	2.5	μH
gap distance	G_d	0.1	cm
transformer turn-ratio	n_t	1	—
parallel resonant capacitor	C_{p1}, C_{p2}	82	nF
output inductor filter	L_{o1}, L_{o2}	4	mH
output capacitor filter	C_{o1}, C_{o2}	10	μF
minimum resistive load	$R_{o1_{\min}}, R_{o2_{\min}}$	100	Ω
output voltage	v_{o1}, v_{o2}	22	V
reference current	I_{ref}	0.7	A
RI switching frequency	f_s	110	kHz
buck converter switching frequency	f_b	50	kHz
buck converter diode		1N5817	
buck converter and RI switches		MOSFET IRFP250N	
driver		HIP4081A	
diode rectifier		KBU4M	

Table 3 Circuit parameters and components for the conventional topology

Parameter	Symbol	Value	Units
input voltage	V_b	15	V
series resonant capacitor	C_r	68	nF
series resonant inductor	L_r	40	μH
magnetising inductance	L_{m1}, L_{m2}	50	μH
leakage inductance	L_s	2.5	μH
gap distance	G_d	0.1	cm
output capacitor filter	C_{o1}, C_{o2}	20	μF
minimum resistive load	$R_{o1_{\min}}, R_{o2_{\min}}$	100	Ω
transformer turn-ratio	n_t	1	—
switching frequency	f_s	110	kHz
output voltage	v_{o1}, v_{o2}	22	V

Fig. 8 shows the measured efficiency of the conventional and proposed topologies. Note that higher efficiency is obtained in the proposed topology. In particular, at 10% of full load, the proposed topology improves the efficiency in nearly 25 points compared with the conventional topology result. This increase is a consequence of the input voltage v_z variation according to the load consumption. In the conventional system, there is no adaptation to load condition. The maximum efficiency for the proposed topology is obtained at full load, being 80% in practice. Note that the power losses related to the buck converter are also included in this figure.

6.2 Performance in steady state

Fig. 9a shows the experimental results of output voltage as a function of loads 1 and 2 for the proposed topology. The measures for both output voltages roughly coincide ($v_{o1} = v_{o2}$) and, therefore, only the voltage v_{o1} is depicted in this figure. The results show that the output voltage is approximately constant in all the load conditions when using the proposed topology.

Fig. 9b illustrates the variation of output voltage v_{o1} for different clamp position along the primary winding loop. Note that the length of the primary winding loop is 120 cm. The experimental measurement for v_{o1} is obtained alongside the minimum (5 cm) to the maximum (60 cm) clamp distance from the RI. As evident, the output voltage is nearly constant in all the clamp positions. This interesting property is achieved due to the constant current i_r flowing through the primary winding loop.

Fig. 9c shows the output voltage as a function of air gap variation. It should be noticed that the air gap is defined as the distance between primary and secondary winding. From the figure, by increasing the air gap the output voltage is reduced. As predicted by (11), the output voltage is depending on the magnetising inductance and leakage inductance, which varies with the gap distance. Therefore, the mechanism of the clamp connection to the primary winding loop should be considered as an important issue. In fact, a robust mechanical connection to the primary winding loop is necessary to guarantee constant output voltage in the proposed system.

6.3 Performance in transient state

Fig. 10a shows the output voltage (top) and output current (bottom) during load step changes in conventional topology. The load is changed from the full load to 10% full load and vice versa, respectively. As it can be seen the conventional system operates correctly and regulate the output voltage according to the desired reference voltage ($V_{\text{oref}} = 20$ V). It should be mentioned that this principle of operation is achieved as a consequence of using the secondary side control system. Although, the output voltage can be correctly regulated, the cost of the system is drastically increased in the case of high number of clamps.

Fig. 10b shows the main waveforms of the proposed topology in transient state. Fig. 10b shows the output voltage v_{o1} and current i_{o1} , respectively, during the step load changes from full load to 10% and return to full load. As predicted theoretically, the output voltage in steady state is nearly independent of the load conditions and has a constant value even using passive rectifiers at the output side. As explained before, the proposed system as a consequence of using passive rectifiers instead of active full-bridge rectifiers has a slow transient system (for an easy comparison, note that the scales in Figs. 10a and b are different). This allows us to identify the practical application of the proposed topology for supplying active DC residential loads with internal post-regulators (laptops, mobile phones, etc) [33, 34].

Fig. 10c illustrates the i_r and v_z , respectively, during step load changes. According to the figure, the input voltage v_z is automatically changed according to the load conditions. Also, as a consequence of fixed input current provided by buck converter, the amplitude of the resonant current is fixed in all the load conditions. As it can be seen, the proposed system can regulate the input power without the need for a communication system. Therefore, the

Fig. 6 Measured output voltage v_{o1} (Top, 10 V/div) and resonant current i_r (500 mA, 50 μ s/div)
(a) Conventional topology, (b) Proposed topology

Fig. 7 Measured resonant current i_r (sinusoidal waveform, 200 mA/div, 2 μ s/div) and voltage v_p (square waveform, 5 V/div, 2 μ s/div) in two load conditions for the proposed topology
(a) Full load and (b) 10% full load

Fig. 8 Efficiency as a function of load. Conventional topology (grey), proposed topology (black)

efficiency of the proposed topology improves significantly in low load conditions.

6.4 Cost comparison

Table 4 lists the component count of the conventional and proposed topologies. From the point-of-view of cost, the negative point of the conventional topology is the increasing number of power switches with the number of clamps (n). In addition, the number of control systems, including voltage and current sensors, integrated control circuits and drivers also increase with the number of clamps. In the case of the proposed topology, only the number of power diodes, capacitors and inductors increase with the number of clamps. It is worth mentioning that for a low number of clamps, both topologies have similar cost. However, for a high number of clamps, the cost of the conventional topology increases drastically compared with the cost of the proposed topology. Consequently, the proposed topology is a cost-effective solution when a system with a high number of clamps is required.

7 Conclusion

In this paper, a new approach to supply the ICET system with multiple-receivers has been presented. It is based on the cascaded connection of a buck converter operating as a constant current source and high-frequency resonant current working with only a feedforward control system. A theoretical tool for the analysis and design of the proposed topology has been introduced. The analysis starts with the development of a static model of the resonant converter based on the first harmonic approximation. The model is simple, predicts accurately the particular properties of the proposed approach, and is useful for the derivation of the design conditions for the converter components. In addition, a systematic step-by-step procedure has been proposed to design the converter components. The theoretical analysis has been practically validated by selected experimental results. The properties of the proposed approach have been compared with the properties of the conventional approach, resulting in higher efficiency and lower cost. In particular, the cost is more competitive as the number of mobile receivers of the system increases.

8 Acknowledgments

This work has been supported by ELAC2014/ESE0034 from the European Union and its linked Spanish national project PCIN-2015-001. We also appreciate the support from the Ministry of Economy and Competitiveness of Spain under project ENE2015-64087-C2-1-R.

Fig. 9 Experimental results of output voltage in the steady-state condition (a) Steady-state output voltage v_{o1} , v_{o2} as a function of load demand: load 2 = 10% full load and load 1 changing (black), load 2 = load 1 both load changing (grey), load 2 = full load and load 1 changing (dash line), (b) The output voltage v_{o1} as a function of clamp position along the primary winding loop, (c) The output voltage v_{o1} as a function of clamp air gap

Table 4 Comparison between conventional and proposed topologies

Components	Conventional number of elements	Proposed number of elements
switch	$4 + 4n$	5
diode	0	$1 + 4n$
capacitor	$1 + n$	$2 + 2n$
inductor	1	$2 + n$
transformer	n	n
control system	$1 + n$	2
driver	$1 + n$	2

9 References

- [1] Lee, J.-Y., Shen, H.-Y., Lee, K.-W.: 'Design and implementation of weaving-type pad for contactless EV inductive charging system', *IET Power Electron.*, 2014, **7**, (10), pp. 2533–2542
- [2] Musavi, F., Eberle, W.: 'Overview of wireless power transfer technologies for electric vehicle battery charging', *IET Power Electron.*, 2014, **7**, (1), pp. 60–66
- [3] Namadmalan, A.: 'Bidirectional current-fed resonant inverter for contactless energy transfer systems', *IEEE Trans. Ind. Electron.*, 2015, **62**, (1), pp. 238–245
- [4] Trevisan, R., Costanzo, A.: 'A 1-kW contactless energy transfer system based on a rotary transformer for sealing rollers', *IEEE Trans. Ind. Appl.*, 2014, **61**, (11), pp. 6337–6345
- [5] Sibué, J.R., Kwimang, G., Ferrieux, J.P., *et al.*: 'A global study of a contactless energy transfer system: Analytical design, virtual prototyping, experimental validation', *IEEE Trans. Power Electron.*, 2013, **28**, (10), pp. 4690–4699

Fig. 10 Main waveforms of the conventional and proposed topology in transient state

(a) Output voltage v_{o1} and output current i_{o1} , respectively, for conventional topology, (b) Output voltage v_{o1} and output current i_{o1} , respectively, for proposed topology, (c) Resonant current i_r , input voltage v_z , respectively, for proposed topology

- [6] Lee, W.S., Son, W.I., Oh, K.S., *et al.*: 'Contactless energy transfer systems using antiparallel resonant loops', *IEEE Trans. Ind. Electron.*, 2013, **60**, (1), pp. 350–359
- [7] Liu, X.C., Wang, G.F., Ding, W.: 'Efficient circuit modelling of wireless power transfer to multiple devices', *IET Power Electron.*, 2014, **7**, (12), pp. 3017–3022
- [8] Twiname, R.P., Thrimawithana, D.J., Madawala, U.K., *et al.*: 'A new resonant bidirectional DC-DC converter topology', *IEEE Trans. Power Electron.*, 2014, **29**, (9), pp. 4733–4740
- [9] Aldhafer, S., Luk, P., Whidborne, J.: 'Tuning class E inverters applied in inductive links using saturable reactors', *IEEE Trans. Power Electron.*, 2014, **29**, (6), pp. 2969–2978

- [10] Kim, S., Park, H.-H., Kim, J., *et al.*: 'Design and analysis of a resonant reactive shield for a wireless power electric vehicle', *IEEE Trans. Microw. Theory Technol.*, 2014, **62**, (4), pp. 1057–1066
- [11] Imura, T., Hori, Y.: 'Maximizing air gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit and neumann formula', *IEEE Trans. Ind. Electron.*, 2011, **58**, (10), pp. 4746–4752
- [12] Sample, A.P., Meyer, D.A., Smith, J.R.: 'Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer', *IEEE Trans. Ind. Electron.*, 2011, **58**, (2), pp. 544–554
- [13] Park, S.W., Wake, K., Watanabe, S.: 'Incident electric field effect and numerical dosimetry for a wireless power transfer system using magnetically coupled resonances', *IEEE Trans. Microw. Theory Technol.*, 2013, **61**, (9), pp. 3461–3469
- [14] Nguyen, M.Q., Hughes, Z., Woods, P., *et al.*: 'Field distribution models of spiral coil for misalignment analysis in wireless power transfer systems', *IEEE Trans. Microw. Theory Technol.*, 2014, **62**, (4), pp. 920–930
- [15] Kiani, M., Jow, U.M., Ghovanloo, M.: 'Design and optimization of a 3-coil inductive link for efficient wireless power transmission', *IEEE Trans. Biomed. Circ. Syst.*, 2011, **5**, (6), pp. 579–591
- [16] Zhang, F., Hackworth, S.A., Fu, W., *et al.*: 'Relay effect of wireless power transfer using strongly coupled magnetic resonances', *IEEE Trans. Magn.*, 2011, **47**, (5), pp. 1478–1481
- [17] Pijl, F., Bauer, P., Castilla, M.: 'Control method for wireless inductive energy transfer systems with relatively large air gap', *IEEE Trans. Ind. Electron.*, 2013, **60**, (1), pp. 382–390
- [18] Madawala, U.K., Thrimawithana, D.J.: 'A bidirectional inductive power interface for electric vehicles in V2G systems', *IEEE Trans. Ind. Electron.*, 2011, **58**, (10), pp. 4789–4896
- [19] Madawala, U.K., Thrimawithana, D.J.: 'A single controller for inductive power transfer systems'. Proc. IEEE Ind. Electron. Conf., Porto, Portugal, November 2009, pp. 109–113
- [20] Low, Z.N., Chinga, R.A., Tseng, R., *et al.*: 'Design and test of a high-power high-efficiency loosely coupled planar wireless power transfer system', *IEEE Trans. Ind. Electron.*, 2009, **56**, (5), pp. 1801–1812
- [21] Wang, C.-S., Stielau, O.H., Covic, G.A.: 'Load models and their application in the design of loosely coupled inductive power transfer systems'. Proc. of IEEE Power System Technology Conf., Perth, WA, Australia, 2000, vol. **2**, pp. 1053–1058
- [22] Cannon, B.L., Hoburg, J.F., Stancil, D.D., *et al.*: 'Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers', *IEEE Trans. Power Electron.*, 2009, **24**, (7), pp. 1819–1825
- [23] Ean, K.K., Chuan, B.T., Imura, T., *et al.*: 'Impedance matching and power division algorithm considering cross coupling for wireless power transfer via magnetic resonance'. Proc. Int. IEEE 34th. Telecommunications Energy Conf., Scottsdale, USA, September 2012, pp. 1–5
- [24] Kurs, A., Moffatt, R., Soljačić, M.: 'Simultaneous mid-range power transfer to multiple devices', *Appl. Phys. Lett.*, 2010, **96**, (4), p. 044102
- [25] Zhang, T., Fu, M., Ma, C., *et al.*: 'Optimal load analysis for a two-receiver wireless power transfer system'. Proc. IEEE Wireless Power Transfer Conf., Jeju, Korea, May 2014, pp. 84–87
- [26] Ahn, D., Hong, S.: 'Effect of coupling between multiple transmitters or multiple receivers on wireless power transfer', *IEEE Trans. Ind. Electron.*, 2013, **60**, (7), pp. 2602–2613
- [27] Pijl, F., Bauer, P., Ferreira, J.A., *et al.*: 'Quantum control for an experimental contactless energy transfer system for multiple users'. Proc. IEEE PESC, Orlando, USA, June 2007, pp. 343–349
- [28] Pijl, F., Castilla, M., Bauer, P.: 'Adaptive sliding mode control for a multiple-user inductive power transfer system without need for communication', *IEEE Trans. Ind. Electron.*, 2013, **60**, (1), pp. 271–279
- [29] Pijl, F., Ferreira, J.A., Bauer, P., *et al.*: 'Design of an inductive contactless power system for multiple users'. Proc. Conf. Record of the IEEE 41st IAS Annual Meeting, Tampa, USA, October 2006, pp. 1876–1883
- [30] Momeni, A., Castilla, M., Pijl, F., *et al.*: 'Architecture and design of an inductive contactless energy transfer system with two mobile loads for residential applications'. Proc. 17th European Conf. Power Electronics and Applications, Geneva, Switzerland, September 2015, pp. 1–10
- [31] Meins, J.G., Sinsley, J.D.: 'Method and apparatus for supplying contactless power'. U.S. Patent 6 515 878 B1, February 2003
- [32] Momeni, A., Castilla, M., Pijl, F., *et al.*: 'New inductive contactless energy transfer system for residential distribution networks with multiple mobile loads'. Proc. 17th European Conf. Power Electronics and Applications, Geneva, Switzerland, September 2015, pp. 1–10
- [33] Wei, J., Lee, F.C.: 'Two-stage voltage regulator for laptop computer CPUs and the corresponding advanced control schemes to improve light-load performance'. Proc. Applied Power Electronics Conf. and Exposition, APEC '04, 2004, vol. **2**, pp. 1294–1300
- [34] Huang, T., Bai, Y.W., Kuan, H.-M.: 'Improvement of the power conversion efficiency of a personal computer'. IEEE Int. Symp. on Proc. Industrial Electronics (ISIE), 2013, pp. 1–6, ISSN 2163-5145
- [35] Kazimierzuk, M.K., Czarkowski, D.: 'Resonant power converters' (Wiley-Interscience, New York, 1995), pp. 149–199
- [36] Steigerwald, R.L.: 'A comparison of half-bridge resonant converter topologies', *IEEE Trans. Power Electron.*, 1988, **3**, (2), pp. 174–182