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

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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 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 (ICT) due to its higher efficiency [7].

The performance of ICT 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 fulfill 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.

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]
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.

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.

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

2 Conventional residential ICET system with multiple mobile clamps

![Diagram of ICET system with sliding transformer and various mobile loads](image)
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 \( v_{o1}, \ldots, v_{on} \) 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 \( C_{pi} \) 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. 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
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. \( Z_{LC}=R_o \)), 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

\[
  i_r = \frac{\pi}{2}I_{ref}\sin(\omega t)
\]

where \( \omega_{r} \) 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

\[
  v_p = v_i \cdot \text{sgn}(i_r)
\]

In the proposed topology, the two waveforms \( (i_r, v_p) \) are completely in phase. Therefore, circulating reactive current is completely avoided, thus achieving unity power factor operation. Also, at \( f_c=f_{ac} \), 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.

The principle of operation of the inverter allows that the voltage \( v_i \) automatically changes according to the required output power while the current \( i_r \) 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.

### 4.1 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 \( i_0 \) to the inverter input side. Besides, the controlled voltage source models the effect of the input voltage \( v_i \) on the inverter output side. For simplicity, the magnetising inductance, parallel capacitors and leakage inductance are assumed equal in all clamps \( (L_m=L_m, C_p=C_p \text{ and } L_{ss}=L_s) \). Also, a unity turns ratio is assumed for transformers \( (n_t=1) \). Moreover, the effect of dissipative nature of the loads is modelled by the equivalent AC resistors \( (R_{ac_1}, \ldots, R_{ac_n}) \). The value of \( R_{ac_i} \) under steady-state condition can be expressed as [36]

\[
  R_{ac_i} = \frac{R_i^2}{\omega i}, \quad i = 1, \ldots, n.
\]

where \( R_{ac_i} \) is the output resistor and \( n \) stands for the number of clamps.

### 4.2 Angular resonant frequency

The proposed topology operates at \( \omega = \omega_{r0} \) where \( \omega \) is the angular frequency. Therefore, to design and analyse the proposed system, an accurate expression for \( \omega_{r0} \) should be obtained as an initial step to calculate the design parameters.

First \( \omega_{r0} \) should be determined by analysing the total impedance \( Z_t \) 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:

\[
  Z_i = j\omega L_s - \frac{1}{\omega C_{ac}} + \sum_{i=1}^{n} Z_{ac_i}
\]

where \( L_s \) and \( C_{ac} \) are the series components and \( Z_{ac_i} \) 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)

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

\[
  a = \frac{R_{ac_i}L_m + 2L_m\sqrt{R_{ac_i}^2(2+L_m(L_m+L_s)) + (L_m+L_s)^2\omega^2}}{2R_{ac_i}L_m}
\]

\[
  b = \frac{\omega L_m + L_s}{R_{ac_i}}
\]

In this case, the input impedance can be represented as

\[
  Z_i = \left[ \frac{\omega L_s - \frac{1}{\omega C_{ac}} + n \cdot \frac{\omega L_m C_p(L_m + L_s) - 1}{\omega^2 C_p(L_m + L_s) + 1}}{\omega^2 C_p(L_m + L_s) + 1} \right]
\]

The resonant angular frequency is obtained by setting (8) equal to zero (then by definition \( \omega = \omega_{r0} \)) and solving for \( \omega_{r0} \). The expression for \( \omega_{r0} \) is written as (see (9))

### 4.3 Output voltages

In Fig. 4, the output voltage \( v_{ac_i} \) 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

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**Fig. 4** Equivalent circuit of the proposed topology
From (13), the value for \( v_L \) can be expressed as:

\[
v_L = \left( \frac{1}{Z_{eq}} \right) \cdot \left( \frac{1}{L_{eq}} \right) \cdot \frac{1}{(1/C_{eq})} = \frac{\omega_0 L_{eq} \omega_0 C_{eq} - 1}{\omega_0 C_{eq} (L_{eq} + L_s) + \omega_0 L_{eq} - 1} \cdot \pi v_{\text{ref}} \tag{10}
\]

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

\[
v_{si} = \frac{1}{\pi} v_{si} = \frac{\omega_0 L_{\text{eq}} (\omega_0 C_{\text{eq}} - 1)}{\omega_0 C_{\text{eq}} (L_{\text{eq}} + L_s) + \omega_0 L_{\text{eq}} - 1} \cdot I_{\text{ref}} \tag{11}
\]

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 \( I_{\text{ref}} \). As described above, the voltage \( v_L \) varies as a function of the load. Once the input current to the resonant converter \( I_{\text{ref}} \) is constant, the variations in the input power produced by load changes modify the voltage \( v_L \). In the worst-case scenario (i.e. \( R_{\text{min}} = R_{\text{max}} \)), the relation between these variables can be expressed, assuming an ideal efficiency (100%) as:

\[
v_L I_{\text{ref}} = \sum_{i=1}^{n_{\text{si}}} v_{\text{di}} R_{\text{max}} \tag{12}
\]

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 \( v_{\text{si}} \). According to this condition, (12) can be re-written as follows:

\[
\sum_{i=1}^{n_{\text{si}}} \frac{v_{\text{di}}^2}{R_{\text{max}}} \leq V_b I_{\text{ref}} \tag{13}
\]

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

\[
I_{\text{ref}} \geq \sum_{i=1}^{n_{\text{si}}} \frac{v_{\text{di}}^2}{R_{\text{max}}} V_b \tag{14}
\]

In practice, the value of \( I_{\text{ref}} \) 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. \( R_{\text{si}} = R_{\text{mmax}} \)) and it is presented in the following steps:

1. **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 \( I_{\text{ref}} = 0.64 \text{ A} \). This value introduces the minimum current for a correct operation of the buck converter.

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

3. **Step 3:** In the final step, the values for \( C_{\text{r}} \) and \( L_s \) are obtained. It should be noticed 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, \( L_s \) should be chosen noticeably higher. In this example, \( L_s \) is chosen equal to 40 \text{ \mu H} which is drastically >2.5 \text{ \mu H}.

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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>input voltage</td>
<td>( V_b )</td>
<td>15</td>
<td>V</td>
</tr>
<tr>
<td>magnetising inductance</td>
<td>( L_m )</td>
<td>50</td>
<td>\mu H</td>
</tr>
<tr>
<td>leakage inductance</td>
<td>( L_L )</td>
<td>2.5</td>
<td>\mu H</td>
</tr>
<tr>
<td>switching frequency</td>
<td>( f_s )</td>
<td>110</td>
<td>kHz</td>
</tr>
<tr>
<td>minimum load resistor</td>
<td>( R_{\text{mmin}} )</td>
<td>100</td>
<td>\Omega</td>
</tr>
<tr>
<td>output voltage</td>
<td>( v_{\text{di}} )</td>
<td>22</td>
<td>V</td>
</tr>
</tbody>
</table>

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. \( R_{\text{si}} = R_{\text{mmax}} \)) and it is presented in the following steps:

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

### 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 comparison 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.
Fig. 7 shows the output waveforms of the RI (voltage $v_{r}$ 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
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</thead>
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<td>input voltage of buck converter</td>
<td>$V_{b}$</td>
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<td>V</td>
</tr>
<tr>
<td>buck converter inductor</td>
<td>$L_{b}$</td>
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<td>$\mu$H</td>
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<tr>
<td>buck converter capacitor</td>
<td>$C_{0}$</td>
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<td>series resonant capacitor</td>
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<td>nF</td>
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<tr>
<td>series resonant inductor</td>
<td>$L_{r}$</td>
<td>40</td>
<td>$\mu$H</td>
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<td>$\mu$H</td>
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<tr>
<td>leakage inductance</td>
<td>$L_{s}$</td>
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<td>$\mu$H</td>
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<tr>
<td>gap distance</td>
<td>$G_{d}$</td>
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<td>cm</td>
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<tr>
<td>transformer turn-ratio</td>
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<td>parallel resonant capacitor</td>
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<td>nF</td>
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<td>output inductor filter</td>
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<td>4</td>
<td>mH</td>
</tr>
<tr>
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<td>50</td>
<td>kHz</td>
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<tr>
<td>buck converter diode</td>
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<td>buck converter and RI switches</td>
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<tr>
<td>driver</td>
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<tr>
<td>diode rectifier</td>
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<td>KBU4M</td>
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<tr>
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<td>$\mu$H</td>
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<tr>
<td>magnetising inductance</td>
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<td>$\mu$H</td>
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<td>gap distance</td>
<td>$G_{d}$</td>
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<td>output capacitor filter</td>
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<td>100</td>
<td>$\Omega$</td>
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<tr>
<td>transformer turn-ratio</td>
<td>$r_{n}$</td>
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</tr>
<tr>
<td>switching frequency</td>
<td>$f_s$</td>
<td>110</td>
<td>kHz</td>
</tr>
<tr>
<td>output voltage</td>
<td>$V_{o1}, V_{o2}$</td>
<td>22</td>
<td>V</td>
</tr>
</tbody>
</table>
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

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

Table 4 Comparison between conventional and proposed topologies

<table>
<thead>
<tr>
<th>Components</th>
<th>Conventional number of elements</th>
<th>Proposed number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>switch</td>
<td>$4 + 4n$</td>
<td>5</td>
</tr>
<tr>
<td>diode</td>
<td>0</td>
<td>$1 + 4n$</td>
</tr>
<tr>
<td>capacitor</td>
<td>$1 + n$</td>
<td>$2 + 2n$</td>
</tr>
<tr>
<td>inductor</td>
<td>1</td>
<td>$2 + n$</td>
</tr>
<tr>
<td>transformer</td>
<td>$n$</td>
<td>$n$</td>
</tr>
<tr>
<td>control system</td>
<td>$1 + n$</td>
<td>2</td>
</tr>
<tr>
<td>driver</td>
<td>$1 + n$</td>
<td>2</td>
</tr>
</tbody>
</table>

9 References


[34] Huang, T., Bui, 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
