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DC-to-DC Converter Topologies for Wireless Power Transfer in Electric Vehicles

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Abstract—At present, about nineteen resonant compensation networks capable of operating as pulsating voltage source are utilized for wireless power transfer (WPT), in which all resonant elements participate in resonance. The majority of networks employ full-bridge or half-bridge topologies which suffer from significant stray and leakage inductances that trap the energy and limit the power transfer; hence, reduce the efficiency. Therefore, these topologies utilize additional resonant networks with many elements and switches to exploit all magnetic field-flux density curve quadrants to eliminate switching losses. Such an approach is less desirable as it adds cost and increases complexity. Therefore, this paper proposes four DC-DC converters that utilize resonant compensation networks without additional resonant tanks, targeting Electric Vehicles wireless charging applications. The proposed converters meet the requirements of charging time, cost, range and high efficiency without a dc flux bias as in existing solutions. The technical viability of the proposed dedicated dc-dc converters for wireless power transfer applications has been validated using preliminary simulations.

Keywords—Dc-to-dc converter, electric vehicles, resonant converters, wireless power transfer

I. INTRODUCTION

WPT is an emerging technology that is witnessing rapid development in recent years, and it is largely being implemented using the concept so called inductive power transfer. The basic concept of WPT using magnetic resonance originated over than a century ago, in works by Nicola Tesla published in 1898. The concept was further explored in 1921 based on a resonant circuit which consists of primary and secondary coils, transformer and pulse generator. The latest advancements in self-commutated power electronics devices and switching techniques have improved the efficiency of WPT technologies drastically.

The concept of WPT can be represented merely by a primary coil connected to AC excitation source, with part of the magnetic flux induced in the coil will eventually link and excite a secondary coil. Part of the flux that couples the primary and secondary coils is determined by the coupling coefficient or factor. The induced voltage in the secondary coil can be expressed in terms of the coupling coefficient k, the turns ratio of primary and secondary coils or the inductance values as follows: \( V_2 = \frac{n_2}{n_1} k V_1 \), where \( k < 1 \).

Fig. 1 shows a basic WPT system which consists of a transformer with leakage inductances. The smaller the coupling coefficient, the larger the leakage inductance and the smaller the secondary voltage. Similarly, the coupling coefficient is smaller when the transmission distance is greater than the primary coil dimension. The efficient WPT facilitates the power transfer between the primary to secondary coils with minimum losses. However, the considerable distance implies lower power transfer and the winding parasitic resistances reduce efficiency.

The topological approaches that can be adopted for WPT depend mainly on the application. Either input or output can be represented as a current or voltage source hence supply either voltage or current source respectively. The capacitor in the parallel resonant network can be considered as a voltage source, and the inductor in the series resonant network can be considered as a current source. Consequently, the primary and the secondary of the transformer can be either current or voltage source. If the input network is chosen to act as a current source, then the input will be able to supply considerable power since the resonant network, and the input voltage source is in series. In contrary, if the input network is chosen to act as a voltage source, then the large current will be circulating inside the parallel resonant network, and the input requires low power. In other words, the resonant impedance is significant for the parallel network, so the input current is low. On the load (secondary) side, the parallel resonant network is suitable for high voltage applications due to the voltage source existence or due to the sizeable resonant impedance. As shown in Fig. 2, the quality factor is significant enough for both parallel and series resonant networks. In order to achieve that, the resonant impedance should be significant for series networks but small for parallel networks. Consequently, the parallel resonant network is suitable for high voltage applications because the resonant impedance is smaller than the load impedance.

The challenge is that load is not a fixed resistor, and practically it is a dynamic load such as a rectifier or a battery. Accordingly, impedance matching and control is needed to achieve the optimum load requirements, and this changes the quality factor requirements as well. Besides, the coupling coefficient is variable with distance and the longer distance, the smaller the coupling coefficient and the lower power transfer and efficiency. Stray and leakage inductances play a crucial role in trapping the energy and limit the power transfer hence reduce the efficiency. Full bridge and half-bridge topologies are used to supply an AC waveform to a resonant network in order to operate on soft-switching and maximize the transferred power to the secondary side, and hence exploitation of the magnetic core is obtained by high-
frequency unbiased flux utilizing all magnetic field-flux density curve quadrants. However, variations of the half and full-bridge topologies involve many elements and switches and can have recourse to the complexity of resonant systems or snubber circuits to eliminate switching losses.

![Diagram](image)

Fig. 2. Resonant tank gain vs the normalized frequency at several Q factor values for a) series b) parallel, c) series-parallel and c) LLC resonant converters.

Traditionally, the buck-boost converter can utilize a coupled magnetic circuit to isolate the output, but the drawback is that magnetic energy is stored in the coupled winding core and that limit the maximum energy transfer according to the core volume. The core can transfer magnetic energy efficiently by an immediate transformer action rather than intermediate inductance. The conventional coupled SEPIC and Zeta converters involve turning a shunt inductor into a coupled transformer which always has a core dc bias current. Alternatively, a transformer-coupled with a split-capacitor that are utilized in the Ćuk converter family employs the transformer without a dc flux bias [1, 2].

This paper proposes converter topologies with buck-boost transfer functions that can be utilized for wireless power transfer without a dc flux bias. The proposed converters employ the resonant compensation networks without additional resonant tank components, with one switch, one diode only, and without a dc flux-bias employing a split capacitor approach. A transformer provides the same buck-boost transfer function and output polarity. The similarities and features of Ćuk converter family is compared with the traditional full-bridge resonator supported by time-domain simulations which conclude that these converters are suitable and attractive for Electric Vehicles wireless power charging and they have the following features: 1) meet the requirements of low cost and simple design, 2) fewer components utilizing one switch and one diode only, and 3) high efficiency by utilizing the soft-switching and operating the converter at resonance.

II. RESONANT NETWORK TOPOLOGIES

In power converters, increasing the switching frequency can dramatically reduce the size of passive components. However, there is a trade-off between the efficiency and volume of the converter. Since the frequency still limits the size of resonant network components, improving the topology by reducing the number of components or combining the resonant tank within the topology structure can be used to optimize performance. Resonant topologies became more popular in WPT applications, particularly, in electric vehicles charger, where some resonant tanks such as series resonant converter can act as a compensation network that cancels the leakage inductance at the resonant frequency.

A Capacitor-Capacitor-Inductor (CCL) resonant topology at the primary side of the converter is proposed to keep high current on the secondary side by providing a high equivalent impedance [3]. In the context of inductive power transfer, Series-Series (SS), Capacitor-Capacitor (CC), and Inductor-Capacitor-Capacitor (LCC) are compared and analyzed in [4]. A double-sided LCC resonant network at the constant switching frequency and soft-switching realization on the primary side shows that resonant frequency, load condition and coupling coefficient are independent [5]. An LCC resonant topology for electric vehicle wireless chargers offered a compact system at reduced coil size with high efficiency and a soft-switching realization by tuning the secondary side capacitor [6]. At variable coupling coefficient and a variable load, LCC-C topology with 0.3 coupling coefficient achieved high power transfer efficiency [7]. Both LLC and CC topologies show an enhanced power transfer efficiency at low mutual inductance, whereas the SS shows higher power transfer efficiency at high mutual inductance. Concerning high voltage gain and power transfer efficiency, LCC-Parallel (LCC-P) resonant topology is suitable for high voltage gain and presents robustness under small coupling factor [8]. A double-sided LCC topology has shown competent results lately. A bipolar coupler structure has been proposed in [9] to improve the compactness of the
compensation network with 95 kHz resonant frequency and nearly 95% peak efficiency.

At 85 kHz operating frequency, series-series resonant tank has shown high power transfer efficiency when compared to Inductor-Capacitor-Inductor (LCL)-LCL resonant network for 3.3kW electric vehicle charging application at 100 mm transfer distance whereas LCL-LCL recorded more robustness in terms of power factor when the frequency varies, or a misalignment occurs between coils [10]. At variable load, appropriate design for the topology is significant because it depends on load profile, frequency, and coil coupling characteristics. An LCL-Series converter with switched capacitor was designed and proposed to ensure continuous voltage/current for battery charging load profile [11]. Series LC and series-parallel LCL resonant topologies with full-bridge inverter working at 30 kHz switching frequency have been compared in terms of size, efficiency, cost, complexity, and design methodology [12]. The study has shown that the series LC topology is less costly than the series-parallel LCL, but LCL achieved 10% higher efficiency at minimum coupling whereas series LC recorded poor light load efficiency and high voltage stress. For capacitive power transfer with considerable air-gap distance, an LCL resonant topology provides high voltage for high power transfer with 150 mm air gap tested at 1.88 kW power and achieved close to 86% efficiency [13]. A CLC to a series-LC resonant network has been proposed for current source inverter in [14] to reduce the switching losses, the cost, and the stress on the switches to half when compared to parallel LC resonant network.

Parallel Resonant Converter (PRC) has high voltage gain at the resonant frequency and can achieve zero voltage switching while operating above the resonant frequency and zero current switching while operating below the resonant frequency. However, PRC suffers from the high circulating current. Similarly, Series Resonant Converter (SRC) can achieve zero voltage switching while operating above the resonant frequency and zero current switching while operating below the resonant frequency. SRC has the advantage of low circulating current at the resonant frequency. However, SRC suffers from both high circulating current at the high input voltage, and light load regulation [15, 16]. LCC is not sensitive to load changes and has less circulating current though it combines the advantages of PRC and SRC [17]. However, switching and conduction losses increase at high input voltage, whereas LLC can operate at low circulating current and achieve low switching losses as well [16].

Boost resonant converters have been proposed for their soft-switching characteristics. For achieving the required output voltage, resonant converter topologies use either step-up resonant tank circuits, medium frequency step-up transformers, or both to achieve higher voltage gain. To sufficiently increase the output voltage of the resonant converter, it is said to increase the submodules in power converter. The larger the number of power devices in the conduction path the more substantial the semiconductor losses. Therefore, soft-switching techniques provide the means to reduce conversion losses, through the elimination of switching losses by switching at zero voltage or current. In efforts to improve efficiency, many soft-switching topologies and techniques have been developed in recent years [18, 19]. In the quest for viable ways to reduce conversion losses, various bridgeless resonant converters have been proposed to reduce both conduction and switching losses [20-22].

From the literature above, the majority of the resonant tanks use a full-bridge inverter with a full bridge rectifier. The drawbacks of this approach are that it uses a large number of components, and the diode bridge rectifiers suffer from heat management issues and high conduction losses. These are general drawbacks that cannot be solved without replacing the topologies by a DC-to-DC simple converter. The DC-to-DC converters are limited by their structures through resonance cannot be attained if the resonant tank does not appear in the converter topology.

III. PROPOSED DC-TO-DC CONVERTERS

Nineteen resonant compensation networks that can work with a pulsating voltage source can be utilized for wireless power transfer with all resonant elements are participating in resonance. These resonant compensation circuits are shown and detailed in [23, 24]. Non-isolated and isolated versions of Ćuk and SEPIC converter have been used in the literature [25-30]. Magnetically coupled single-switch buck-boost converters (namely isolated Ćuk, Zeta, SEPIC, and P5) have been presented in [1]. Four DC-to-DC converters shown in Fig. 3 that utilize the resonant compensation networks without additional resonant tank components are proposed. These converter topologies are well-suited for Electric Vehicles.
wireless charging and meet the requirements of charging time, cost, range and high efficiency without a dc flux bias. The traditional way with Zeta and SEPIC converters is to utilize a magnetically coupled inductor for the circuit inductor. The core of coupled inductor still has flux bias because of the dc current. The flux bias can increase the power losses, and limit the permissible maximum power transfer. Hence, SEPIC and Zeta are not recommended for wireless power transfer and can be excluded from the proposed list for wireless power transfer.

The split-capacitor in the isolated Cuk and P5 converters plays an important role in blocking the dc components from the magnetic coupling component. The average capacitor current must be zero, and the average inductor voltage must be zero to achieve steady-state operation. Otherwise, the capacitor voltage will keep increasing until we lose control over the waveform, or the element is damaged. Nevertheless, the isolated Cuk converter still develops a dc component which can be overcome by using large capacitors. In contrary, P5 does not have any dc component neither on the primary nor the secondary windings, which maintains zero average voltage.

![Waveforms of the converters with continuous input current](image)

Fig.4. Waveforms of the converters with continuous input current; a) primary inductor current ripple and output voltage, and b) current waveform of the primary inductor current during resonance for both the isolated Cuk converter and the traditional Bridge converter at 10A input current. Note that the component tolerance is doubled because of the resonance operation.

IV. SIMULATION RESULTS

MATLAB simulations are used to verify the performance of the converters. The simulations are at a 100-kHz switching frequency. The simulation compares the input current ripple and output voltage for the four converters. The four converters are similar in terms of the equivalent circuits, operation, control design and performance.

Waveforms of primary inductor current ripple and output voltage with continuous input current are compared for the four converters. Overall efficiency at 0.5 duty cycle and current from for both Cuk and H-bridge converter are compared. H-bridge is extensively used in wireless power transfer due to several advantages such as cheaper cost, greater efficiency, and no shielding requirements. The current waveform of the primary inductor current for both the isolated Cuk converter and the traditional H-bridge converter at 10A input current has been compared at resonance. Due to the resonance operation, the tolerance of the components is doubled, which indicates a drawback. A 1 kW WPT system is designed to verify the ripple current, output voltage, and switching behavior for the converters. The system specifications that are used are as follows: Nominal input voltage is 400 V, the battery voltage is 200-350 V, rated output power is 1 kW, the nominal charging current is 3 A, and the equivalent load impedance is 60-120 Ω. Two resonators are located inside the primary and secondary transformer winding. In the proposed system, one switch and one diode are used to implement the converters in Fig. 3. Fig. 4 displays simulation waveforms of the proposed converters in continuous conduction mode at 1 kW of output power. Currents at the primary transmitter inductor and output voltage waveforms are shown in Fig. 4a. The primary current I_L1 for Cuk, Zeta SEPIC and P5 are clarified in the lower side of the figure. Cuk and Zeta share the same waveform while SEPIC and P5 share a similar one as well. Similar behavior for the output voltage waveforms V_o. Divided by a scale of 40 for clarifications purposes, Cuk and Zeta have the same voltage waveform whereas SEPIC and P5 share similar waveforms as well. Fig. 4b presents the current waveform for both Cuk converter and the conventional resonant bridge. It can be seen from the waveform that the switch turns ON with nearly zero-current switching and turns OFF with zero-voltage switching without a DC flux bias. Therefore, the aimed converter can produce reasonably high efficiency. Increasing the input current from 1A to 3A, for a given duty cycle and constant voltage results in improved efficiency (as shown in Fig. 5). However, for increased current, the I2R losses become more significant for the H-bridge circuit.

![Overall efficiency at 0.5 duty cycle and current from 1A to 7A for both Cuk and H bridge converter](image)

Fig.5. Overall efficiency at 0.5 duty cycle and current from 1A to 7A for both Cuk and H bridge converter.
V. CONCLUSION
A total of nineteen resonant networks that can work with a pulsating voltage source can be utilized for wireless power transfer with all resonant elements are participating in resonance. In this paper, four DC-to-DC WPT converters with central resonators are introduced, and a 1 kW simulation circuit has displayed their validity and features. All four converters employ two inductors and two split capacitors with a shunt transformer and have the same ac properties, but they are different in terms of mirroring capacitor dc bias. The proposed converters employ the resonant compensation networks without additional resonant tank components, with one switch, one diode only, and without a dc flux bias which concludes that these converters are suitable and attractive for Electric Vehicles wireless power charging and they meet the requirements of low cost, fewer components and high efficiency. The traditional way of coupling SEPIC and Zeta involves turning a shunt inductor into a coupled transformer to save on components. This approach may not be acceptable for wireless power transfer since the transformer is complicated by always having a dc bias current. In the results, future work experimental validation needs to provide information about the magnetic structure of the system such as the coil dimensions, number of turns, the self and mutual inductances. Also, a study will be conducted on cost analysis of the higher current power semiconductors and larger diameter litz wire that will be needed for increased current on the primary and secondary side of the transformer.

REFERENCES