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Optimizing Wireless Power Transfer: High-Frequency Inverter Architecture for Variable Compensation

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Abstract: This paper introduces a new high-frequency inverter architecture that can compensate for coupling variations in wireless power transfer (WPT) systems while operating at a fixed frequency and maintaining high efficiency. This architecture, termed the variable compensation inverter (VCI), comprises multiple high-frequency inverters feeding a lossless resonant network, with the inputs of the inverters fed by controllable voltages. By appropriately controlling the input voltages of the individual inverters and their relative phase shift, the VCI can maintain near-resistive, and slightly inductive, loading of the inverters even as the reactance of the WPT coupler changes; hence, providing compensation while maintaining zero voltage and near-zero-current switching. The VCI also ensures that the output power of the WPT system is maintained at a fixed level, even duringcoupling variations. A prototype VCI is designed, built, and tested with a 1.5-MHz, 65-W capacitive WPT system for laptop charging applications. The system is able to fully compensate for up to 50% lateral misalignments in the capacitive coupler while maintaining a fixed output power level of 65 W and achieving 82% efficiency.

Keywords—wireless power transfer systems; coupling variations; variable compensation; variable compensation inverter; fixed output power; soft-switching; high efficiency.

1. INTRODUCTION

Wireless power transfer (WPT) can reduce the need for energy storage and enhance consumer convenience by enabling autonomous charging in applications ranging from electric vehicles (EVs) [1]–[8] to portable electronics [9]–[13]. WPT approaches can be categorized as inductive.WPT systems, which utilize a pair of magnetically coupled coils, and capacitive WPT systems, which utilize two pairs of electrically coupled plates as their coupler. Both inductive and capacitive WPT systems require circuit components that can compensate for the reactance of their couplers. To achieve effective power transfer, WPT systems need to operate at frequencies close to the resonance frequency of the resonant tank formed by the coupler and the compensation components. When the coupling reactance changes, either due to coupler misalignments or due to variations in the air gap, so does the resonance frequency. A typically used approach to maintaining effective power transfer in this scenario is to track the varying resonance frequency by changing the

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operating frequency of the system [14]. While this variable-frequency approach is effective, it makes the design of magnetics and gate driver circuitry challenging, as these are difficult to optimize for a wide range of frequencies, particularly when operating in the high-frequency (MHz) regime. Furthermore, in multi-MHz WPT systems, the operating frequency must stay within one of the designated industrial, scientific, and medical (ISM) bands (e.g., 6.78 MHz, 13.56 MHz, and 27.12 MHz), which have very restrictive bandwidths [15]. Alternative approaches to dealing with coupling variations include the use of banks of switchable capacitors [16], [17], or variable inductors [18] in the compensating network, which allow the resonance frequency to remain roughly unchanged in the event of coupling variations. These approaches also have significant demerits, including additional size, weight, and losses, particularly in high-power WPT systems. The recently introduced active variable reactance (AVR) rectifier [19] addresses these challenges through an innovative rectifier structure that can provide variable compensation at a fixed frequency efficiency.

while maintaining high efficiency. However, the AVR rectifier requires several circuit components to be incorporated on the receiving side of the WPT system, where space and weight are at a premium (for instance, on-board an EV or inside a smartphone). This paper introduces a new high-frequency inverter architecture, termed the variable compensation inverter (VCI), which can compensate for coupling variations in WPT systems while operating at a fixed frequency and maintaining high efficiency. This architecture incorporates two or more phase-shifted inverters fed by controllable input voltages and a lossless resonant network, all on the transmitting side of the WPT system. By appropriately controlling the input voltages of the inverters, the VCI can also maintain a fixed output power level during coupling variations. A prototype VCI is designed, built, and tested with a 1.5-MHz 65-W capacitive WPT system, and it is shown that the VCI can compensate for up to 50% lateral misalignments in the capacitive coupler while maintaining the system output power at a fixed level of 65 W and achieving 82%

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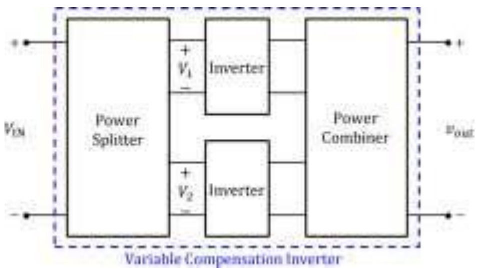


Fig. 1: Architecture of the proposed variable compensation inverter (VCI).

I. PROPOSED VARIABLE COMPENSATION INVERTER

The architecture of the proposed VCI is shown in Fig. 1. At the front end of the VCI is a power splitting circuit that is fed by a dc

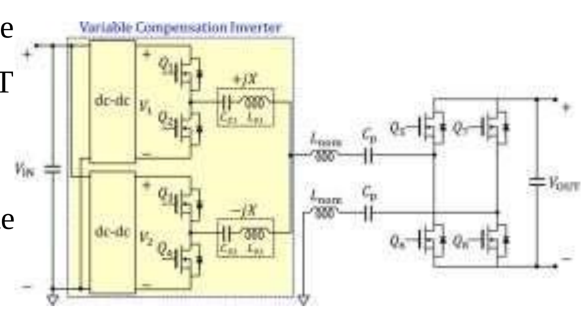
voltage (□IN in Fig. 1). This power splitting
circuit generates multiple controllable dc voltages (□1 and □2 in Fig. 1), which are supplied to high-frequency inverters. The outputs of the inverters feed a power combining circuit, which interfaces the VCI with the remainder of the WPT system. An example implementation of the VCI architecture in a capacitive WPT system is shown in Fig. 2. This system operates at a

fixed frequency, and the inductors □nom
compensate for the reactance of the capacitive coupler (labeled as □p in Fig. 2) under the nominal operating conditions; for

example, when the transmitting and receiving sides of the coupler are perfectly aligned. The CI shown in Fig. 2 comprises two dc-dc converters (which form the power splitting circuit) feeding Here, Here, VOUT and POUT are the dc output voltage and rated output power of the WPT system, respectively, and Krec is a constant associated with the topology of the rectifier (Krec = 8
π2 for the full-bridge rectifier shown in Fig. 2). When the coupling reactance XC changes from its nominal

two half-bridge inverters. The output power of the two bridge inverters is then combined using a lossless resonant network.

Fig. 2: Example implementation of the variable compensation inverter (VCI) in a capacitive WPT system.



comprising two branches having equal but opposite reactance (+X and −X). This

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Implementation of the VCI builds upon the concepts of an impedance control network (ICN) [20]; however, through its use of dc-dc converters, the VCI differs both topologically and functionally from an ICN.

$$2\Delta = \cos^{-1}\sqrt{1-\frac{X^2}{\frac{K_{rec}^2 V_{OUT}^4}{P_{OUT}^2}}}.$$

When the coupling reactance XC (= 1)1

p)) is at its nominal value, the two dc-dc

converters operate in pass-through mode, and the input voltages of the two bridge inverters (V1 and V2 in Fig2) are), botequal.al

the dc input voltage (IN). The phase-shift

between the two inverters under this nominal operating condition is given by

value by an amount of CC,

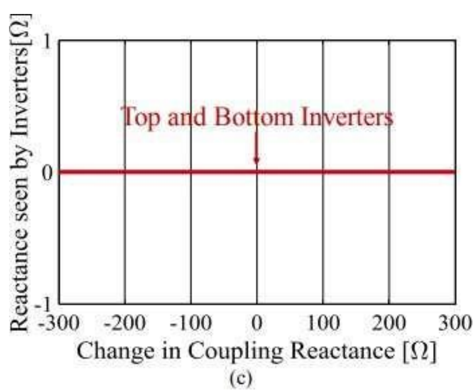

Fig. 3: Variation in operating parameters of the proposed variable compensation inverter (VCI) as the coupling reactance changes: (a) inverter relative phase-shift, (b) input voltages of top and bottom inverters, and (c) resultant reactance seen at the outputs of the two inverters.

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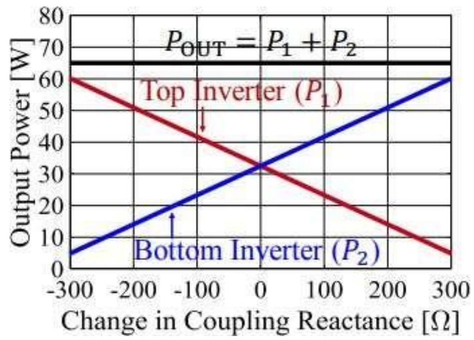

Fig. 4: Total output power and the power processed by the two inverters of the variable compensation inverter (VCI) as a function of the change in coupling reactance.

wide range of coupling variation in an example WPT application in Fig. 3. Therefore, the bridge inverters process purely real power, and the VCI fully compensates for coupling variations. Furthermore, the purely resistive impedances enable zero- current switching (ZCS) of the inverter transistors. By operating at a frequency slightly higher than the designed frequency, the inverter impedances become slightly inductive, facilitating zero-voltage switching (ZVS) and near-ZCS. This enables the VCI to fully compensate for coupling variations while maintaining soft switching.

The VCI in Fig. 2 is also capable of maintaining a fixed output power level during coupling variations. This can be achieved by imposing an additional constraint on the input

The value of the differential reactance X in

voltages of the two bridge rectifiers, given by: Here, Kinv is a voltage gain associate with the two bridgeinverters, and equals 2 π for the half-bridge inverters of the VCI in Fig.

The output power processed by the two bridge inverters of the VCI and the total output power of the WPT system with the inverter input voltages and phase-shift controlled according to (2)–(4) are shown as a function of the change in coupling.

reactance N��XCC in Fig. . As can be seeas

The coupling reactance varies over a wide range; the power processed by one of the inverters decreases while that processed by the other inverter increases, so that the total output power remains constant. This specific power-combining mechanism of the VCI enables it to maintain a fixed output power level even under coupling variations.

The VCI in Fig. 2 is selected to ensure that the WPT system delivers the required output.

power out unde nominal operatingg

conditions. This can be ensured by choosing the differential reactance to be:

$$X = \frac{K_{inv} V_{IN}}{P_{OUT}} \sqrt{2K_{rec} V_{OUT}^2 - K_{inv}^2 V_{IN}^2}.$$

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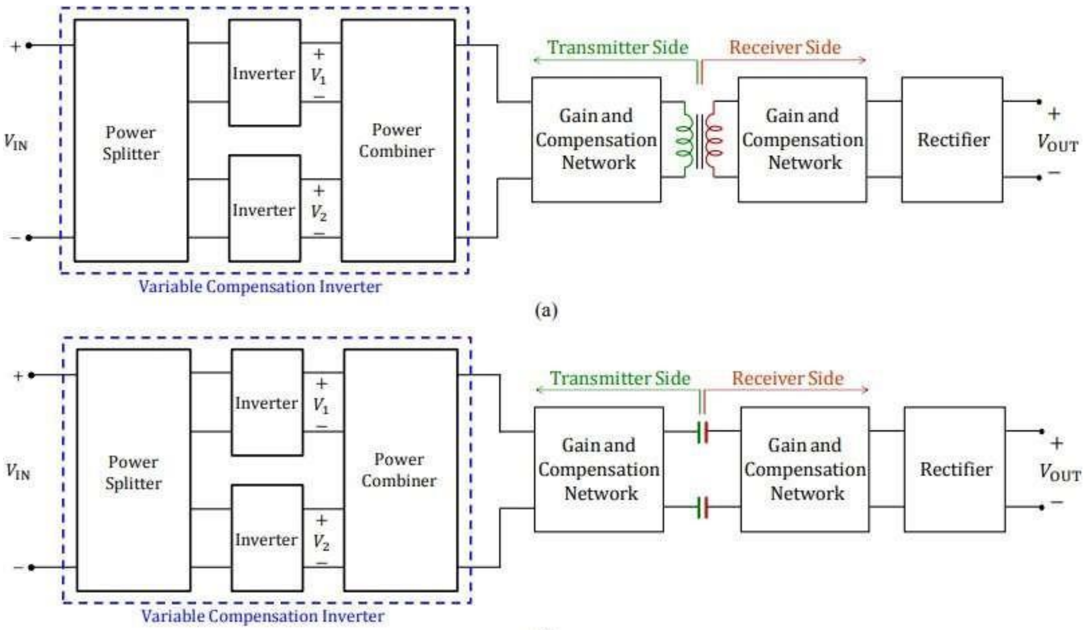
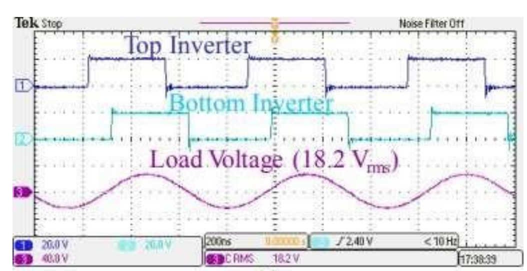


Fig. 5: Utilization of the proposed VCI in: (a) an inductive WPT system and (b) a capacitive WPT system comprising gain and compensation networks.

Various combinations of the inductances and capacitances of the two inverter tanks ($LX1$, $CX1$ and $LX2$, $CX2$ in Fig. 2) can realize this value of X , but with different deoffs. For instance, designs with relatively large inductance values may suffer from high inductor losses, but also exhibit highly sinusoidal currents that result in relatively low turn-off switching losses. On the reactance of the WPT coupler under nominal conditions. When the coupling reactance changes from its nominal value, the VCI provides the required additional compensation. The gain and compensation

networks in these WPT systems can havevarious topologies, including L-section matching networks [23]–[25], such as those shown in Fig. 6. When appropriately

1. PROTOTYPE DESIGN AND EXPERIMENTAL RESULTSA



(a)

prototype VCI similar to the one shown in Fig. 2 is designed, built, and tested with a 1.5-MHz, 65-W capacitive WPT system with dc input and output voltages of 20 V.

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suitable for a laptop charging application. A photograph of the prototype system is shown in Fig. 7. The capacitive coupler in the prototype system is implemented using two pairs of 10 cm × 10 cm plates separated by a 1-mm air gap. The dc-dc converters of the VCI are emulated using two independent power supplies, and the rectifier and laptop battery are emulated using an equivalent load resistor. The inductors in the prototype system are realized using AWG-48, 1000-strand Litz wire wound on RM14 cores of Ferroxcube's 3F46 material. The two inverters of the VCI are constructed using 80-V, 90-A EPC2021 enhancement-mode GaN transistors driven by TI LM5113 halfbridge gate drivers. The system is first tested under nominal operating conditions, that is, with the coupling plates perfectly aligned and with the input voltages of the two bridge rectifiers set equal to the dc input.

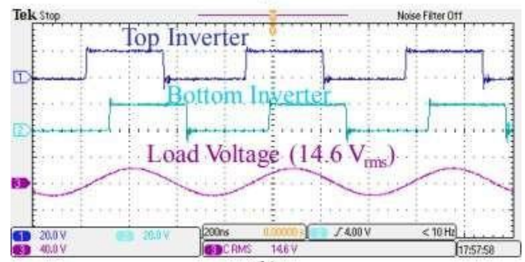
voltage VIN of 20V. The corresponding

The waveforms of the inverter switch-node voltages and the voltage across the load resistor are shown in Fig. 8(a). The system transfers the rated power of 65 W at an efficiency of 82% under these conditions. Fig. 8: Measured switch-node voltages of the two bridge inverters of the prototype variable compensation inverter (VCI) and the voltage across the resistive load for: (a) nominal operating condition with no misalignment, (b) 50% misalignment with no compensation, and (c) 50% misalignment fully compensated by the VCI.

compensates for coupling variations while maintaining fixed output power and high efficiency.

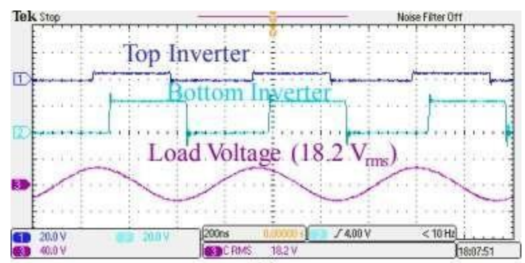
1. CONCLUSIONS

This paper introduces a new high-frequency inverter architecture that fully compensates for coupling variations in wireless power transfer (WPT) systems while operating at a fixed frequency and maintaining high efficiency. This architecture, termed the variable compensation inverter (VCI), comprises multiple high-frequency inverters fed by controllable voltages and feeding a lossless resonant network. By appropriately controlling the relative phase shift and the input voltages of the inverters, the VCI can provide variable compensation while maintaining zero-voltage and near-zero-current



(b)

switching. The VCI also ensures that the output power of the WPT system is maintained



(c)

at a fixed level even during coupling variations. A prototype VCI is

designed, built, and tested, and its performance validated, with a 1.5-MHz, 65-W capacitive WPT system for laptop charging applications.

The plates are then misaligned by 50% along a lateral dimension, and the resultant waveforms are shown in Fig. 8(b). It can be seen that the load voltage decreases; the

output power falls by 35% to 42 W, and the efficiency falls to 74%. The VCI then decreases the inverter phase shift, increases the input voltage of the bottom inverter, and decreases the input voltage of the top inverter in accordance with (2)–(4). The resultant waveforms are shown in Fig. 8(c). As can be seen, the load voltage is restored to the original level shown in Fig. 8(a); the output power is restored to 65 W; and the efficiency increases back to 82%. Hence, the prototype VCI designed, these networks can enhance the compensation provided by the VCI.

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