Decomposition and Synthesis of High-Order Compensated Inductive Power Transfer Systems for Improved Output Controllability

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Abstract—High-order compensation provides more design freedom for inductive power transfer systems and can help improve output voltage/current controllability. This paper develops a simplified decomposition and synthesis method for high-order-compensated inductive power transfer systems. It can achieve load-independent (LI) output under coupling variation, and easily fulfill the various charging requirements, such as constant voltage or constant current. The coupling independent resonance is ensured by using the induced source model, and the whole resonant tank is effectively decomposed as three parts. The power transfer characteristics are discussed for each part, and the requirements for LI output and zero phase angle (ZPA) operation are combined to generate the compensation candidates for both sides. Two families of topologies are synthesized for four kinds of conversions, i.e., voltage to voltage, voltage to current, current to voltage, and current to current. Meanwhile, the proposed method dramatically simplifies the evaluation for the influence of the coil equivalent series resistors on the transfer function and efficiency. These resistor-caused effects are quite different for two families of topologies. Finally, a 6.78-MHz system with 10-W output is designed to verify the difference between two-family topologies.

Index Terms—Coupling-independent (CI) resonance, decomposition and synthesis, high-order compensation, inductive power transfer, load-independent (LI) output, zero phase angle (ZPA) operation.

I. INTRODUCTION

INDUCTIVE power transfer (IPT) has been widely applied to charge wearable devices, cellphones, and electric vehicles [1], [2]. Usually, each specific application has its own demands on the power level, efficiency, size, and spatial freedom, which would finally determine the suitable resonant frequency, topology, system configuration, and control scheme [3]–[5]. For all these IPT systems, the selection and design of proper compensation is a common issue. About 15 years ago, the group from the University of Auckland proposed four basic compensations, i.e., series-series (SS), parallel-series (PS), series-parallel (SP), and parallel-parallel (PP), to boost the power transfer capability and achieve zero phase angle (ZPA) operation [6], [7]. Since then, many IPT systems have been developed. However, most of the reported systems have to use complicated switch-mode circuits to maintain good controllability for various objectives, such as constant output voltage, dynamic impedance matching, and optimal efficiency tracking [8]–[10]. Recently, the four basic compensations are also explored for load-independent (LI) output voltage or current to improve the controllability and simplify the system configuration [11]–[14]. However, most systems cannot keep LI output and ZPA operation when the coupling varies. Therefore, it is challenging to achieve various objectives with simple circuits and control scheme.

In theory, the four basic compensations are difficult to meet various demands simultaneously because of the limited design freedom. Therefore, it is possible to employ high-order compensations to overcome this issue, and then additional objectives can be fulfilled [15]–[17]. For example, the LC compensation offers an input-voltage-controlled current to drive the transmitter (TX) coil, and then power demands of each receiver (RX) are effectively decoupled [15]. The LCC compensation is proposed in [16] for zero-current-switching (ZCS). The double-sided LCC compensation can achieve the LI output, zero-voltage-switching (ZVS), and ZPA operation simultaneously [17]. When the compensation order increases, the possible combination of resonant components would dramatically increase as well. Several papers are devoted to the design and selection of proper compensations. In [18], the basic circuit networks for LI output are summarized and used to explain the existing compensations. Based on these findings, several rules have been abstracted to synthesize high-order compensations by representing the coupling coils as a T-type circuit or classical transformer [19], [20]. However, this kind of coil modeling is hard to analyze the coupling variation cases. This issue is effectively avoided in [21] by using the induced source model, i.e., modeling the coils as the
combination of self-inductance and induced voltage source. Since the self-inductance is used for resonance, the derived frequencies for LI output and ZPA operation can be naturally coupling independent (CI).

This paper proposes a novel perspective to simplify the decomposition and synthesis for high-order-compensated IPT systems. All kinds of LI conversions, i.e., voltage to voltage (V2V), voltage to current (V2I), current to voltage (I2V), and current to current (I2I) are discussed based on the induced source model, which can naturally help analyze the CI resonance. The self-inductance of the TX coil is aborted by the TX compensation to form a resonant tank, so as for the RX side. The whole resonant tank can then be decomposed into three parts, i.e., a TX tank, a pair of induced voltage sources, and an RX tank. This system decomposition dramatically simplifies the system analysis and each part can be designed in a decoupled manner. Since the transfer functions of the induced voltage source are well known, the main challenge becomes how to develop high-order resonant tank candidates (for both sides) that enable LI output and ZPA operation. In order to solve this challenge, many well-developed methods for conventional high-order resonant converters can be modified and applied in this paper [22]. The basic requirements for LI output and ZPA operation are gradually applied to generate all the tank candidates. To the best of author’s knowledge, it is the first time to propose a rule to generate all the tank candidates. To the best of author’s knowledge, it is the first time to propose a rule to generate all the tank candidates (up to fourth order) for all kinds of conversions, which would finally help synthesize the high-order IPT topology. Finally, two families of fundamental topologies for all kinds of conversions are found, and two example topologies for V2V conversion are studied and compared.

II. COUPLING-INDEPENDENT (CI) RESONANCE

A. Limitation of Transformer Model or T Model

A typical IPT system is shown in Fig. 1. The power is coupled from the TX coil ($L_{tx}$) to the RX coil ($L_{rx}$). Since the mutual inductance ($M$) is small, both TX and RX compensations are necessary to boost the power transfer capability. In this paper, high-order compensations are employed to improve the system controllability. In practice, the output current or voltage should be regulated to meet specific power demand and port requirements. When a resonant tank is able to provide LI transfer function under coupling variation, the output regulation complexity could be significantly reduced. For example, if the resonant tank can offer LI V2V gain and its associated operation frequency will not shift under coupling variation (i.e., coupling-independent resonance), it means the input voltage $v_{in}$ can be used to directly control the output voltage $v_{o}$. Therefore, this paper is devoted to the decomposition and synthesis of high-order compensation with LI output, CI resonance, and ZPA operation.

In order to analyze the resonant tank, a straightforward and convenient method is to apply the classical transformer model for the coupling coils, and then an IPT system can be treated as an entity, which is actually a special isolated resonant converter. Fig. 1 shows the transformer model, in which the magnetizing inductance $L_m$, the leakage inductance $L_l$, and the equivalent turn ratio $N$ (not the real one) can be represented in terms of the self-inductance and mutual inductance (i.e., $L_{tx}$, $L_{rx}$, and $M$)

$$L_m = M^2 / L_{tx}$$

$$L_l = L_{tx} - M^2 / L_{rx}$$

$$N = M / L_{tx}.$$  (1)

It shows all the transformer parameters are actually coupling-dependent. Once these varied inductances join the resonance, the resonance frequency will shift when the coil position varies. The T-type model has similar issues (refer to Fig. 1). Therefore, all the compensation analysis based on these models (including coupling-dependent inductance) naturally face more challenges [19], [20].

B. System Decomposition

In order to achieve CI resonance, the resonant components have to be coupling-independent. Since fixed compensation networks (i.e., lumped capacitors or inductors with fixed value) are usually used, the only uncertain components come from the coupling coils (refer to Fig. 1). To avoid this issue, the coupling coils should be modeled with fixed components [21]. Therefore, as shown in the gray part of Fig. 2, the coupling coils are represented by the well-known induced source model, i.e., a combination of the two self-inductances ($L_{tx}$ and $L_{rx}$) and a pair of induced voltage sources ($v_{tx}$ and $v_{rx}$). $i_{tx}$ and $i_{rx}$ are the current of $L_{tx}$ and $L_{rx}$. It has

$$v_{tx} = -j\omega_s i_{tx}M$$

$$v_{rx} = j\omega_s i_{tx}M$$  (2)

where $\omega_s$ is the angular switching frequency.

Using the induced source model, a classical system decomposition approach is proposed in Fig. 2, and the whole resonant tank is viewed as a cascaded connection of three parts, i.e., Tank TX, the induced source part, and Tank RX. $L_{tx}$ and $L_{rx}$ are in series with TX/RX compensations to form
Tank TX/RX, respectively. The induced source part only includes \( v_{tx} \) and \( i_{tx} \). For Tank TX, \( v_{tx} \) and \( i_{tx} \) are the input voltage and current. Similarly, \( v_{rx} \) and \( i_{rx} \) are the output voltage and current of Tank RX. In this paper, Tank TX and Tank RX can be analyzed individually for a target resonant frequency, and then various objectives (like loading-independent output and ZPA operation) can be achieved by proper selection and design of resonant tanks. Since all the resonant components are fixed, the proposed decomposition method can naturally help to synthesize all coupling-independent IPT topologies.

### III. Load-Independent Output

#### A. Transfer Function of the Induced Source Part

The LI output (voltage or current) is preferred for an IPT system due to its good controllability. In this paper, \( G \) is used to define the input to output transfer function, and the subscript is used to denote the conversion type (like V2V) and different parts of the IPT system. For example, \( G_{coil,vi} \) means the transfer function from \( v_{tx} \) to \( i_{rx} \) in Fig. 2. Since the system is a cascaded connection of three parts, the overall transfer function is the product of the gain of each sub part. According to (2), the induced source part can naturally provide LI transfer function, that is,

\[
G_{coil,iv} = \frac{v_{tx}}{i_{tx}} = j\omega_i M
\]

\[
G_{coil,vi} = \frac{i_{rx}}{v_{tx}} = -\frac{1}{j\omega_i M}
\]

It shows there are only two approaches to achieve LI voltage/current transfer. Therefore, two families of IPT topologies are defined. If an IPT topology is synthesized based on LI \( G_{coil,ii} \), it belongs to Family A, and LI \( G_{coil,vi} \) is used to generate the topologies of Family B.

#### B. Basic LI Resonant Networks

Given LI conversions for the induced source part, the next objective is to find the suitable LI resonant tanks for Tank TX/RX. Usually, the LI output happens at a certain frequency for a given resonant tank. For example, a LLC resonant converter provides a LI output voltage when working at its series resonant frequency. Many studies on high-order resonant converters can help to find proper candidates. The basic network with LI output has been discussed in [18] and shown in Fig. 3. The impedance requirements and the transfer function are summarized in Table I. For example, a LLC circuit provides LI \( G_{vi} \), which can be easily explained by the Norton’s theory [refer to Fig. 3(c)]. Note that \( Z_2 = \infty \) in Fig. 3(a) also provides LI \( G_{vv} \), and \( Z_1 = Z_3 = \infty \) in Fig. 3(b) offers LI \( G_{ii} \). These fundamental blocks are used to generate high-order network with LI transfer functions.

In [20], the overall IPT resonant tank can be viewed as a cascaded connection of these basic LI networks. As shown in Fig. 4, the coupling coils are usually modeled as a T-type network. Although this modeling method can help explain the existing high-order IPT systems, it is inconvenient to analyze the coupling-independent resonance. For example, Zhang et al. [11] and Costanzo et al. [14] used the SS compensation for LI output voltage. Two LI resonant frequencies (\( \omega_H \) and \( \omega_L \)) are analytically derived and shown in Fig. 5(a). Using the synthesis approach of [20], the corresponding resonant networks for each LI resonant frequency can be easily identified, i.e., the resonance of the red block used to derive \( \omega_H \) and the resonance of the green part used to derive \( \omega_L \). It is obvious that both \( \omega_H \) and \( \omega_L \) are coupling-dependent because of the varied \( M \).

The SS compensation is also used for LI \( G_{vi} \) as shown in Fig. 5(b) [13]. The proposed decomposition in this paper can be used to easily analyze the resonance condition. For Tank TX, the resonance between \( L_{tx} \) and \( C_{ti} \) makes \( v_{tx} \)
clamped by $v_{in}$, i.e., LI $G_{tx,vv}$, which further leads to a clamped $i_{rx}$, i.e., LI $G_{coil,vi}$ [refer to (3)]. Finally, Tank RX is also a series LC branch with LI $G_{rx,ii}$. Therefore, the overall voltage to current transfer function is a product form, i.e., $G_{vi} = G_{tx,vv}G_{coil,vi}G_{rx,ii}$. Instead of analyzing the whole tank, this paper chooses to analyze the LI transfer function of each parts, based on which the derived resonance frequency is naturally CI.

C. Candidate Resonant Tanks for Topology Synthesis

The proposed decomposition method can not only better explain the existing IPT topologies, but also provide an effective way for topology synthesis. It helps the IPT system to have LI output capability at CI resonant frequency. Due to the source or load type (i.e., voltage or current), there are totally four types of transfer functions (i.e., $G_{vv}$, $G_{ii}$, $G_{vi}$, and $G_{iv}$). For each type of conversion, there are two effective ways to utilize the coupling coils, i.e., $G_{coil,vi}$ and $G_{coil,iv}$, which are used to define two-family topologies. For example, the overall gain for V2V conversion ($G_{vv}$) can be decomposed either as $G_{vv} = G_{tx,vv}G_{coil,vi}G_{rx,iv}$ (belonging to Family A) or as $G_{vv} = G_{tx,vi}G_{coil,iv}G_{rx,vv}$ (belonging to Family B). Therefore, this paper needs to develop a candidate pool for Tank TX and Tank RX for all kinds of conversions (i.e., V2V, V2I, I2V, and I2I).

The study of high-order resonant converter is not new, and there is a continuous effort on topology synthesis for the traditional resonant converter. The major difference between the traditional resonant converter and the IPT system is the varied coupling. In this paper, the induced source and the fixed self-inductance of the coupling coils are treated separately, and it helps to directly utilize the analysis methods of the traditional high-order resonant converter. Up until now, there is no paper to summarize all the possible high-order compensated IPT systems for various conversions, i.e., V2V, V2I, I2V, and I2I.

D. Candidate Tank Classification

The LI transfer functions of the proposed candidates are determined based on Fig. 3. For example, if a candidate...
tank can be viewed as the T-type network and meets the requirement of Table I, it will offer LI $G_{yy}$. Similar rules are also valid for the other three kinds of conversions. Finally, Fig. 9 classifies the candidate tanks based on the conversion type. These tanks are able to explain most of the existing well-known IPT topologies. For example, the SS compensation can offer LI $G_{vi}$, which is a combination of Tank A₁ (as Tank TX, enabling LI $G_{coli,v1}$), the induced voltage (enabling LI $G_{coil,v1}$), and Tank A₁ (reversely used as Tank RX, enabling LI $G_{rx,i}$); the double-sided LCC compensation offers LI $G_{vi}$ based on the cascaded connection of Tank C₂₆ ($G_{tx,v1}$), induced source ($G_{iv}$), and reversed Tank C₂₆ ($G_{tx,v1}$).

**IV. ZERO PHASE ANGLE OPERATION**

Given the candidate pool, many new IPT topologies can be synthesized with LI output and CI resonance. However, the IPT system still needs to consider other significant objectives. Actually, at the very beginning of IPT research, the four basic compensations are developed only for sufficient power transfer. For example, the RX compensation is used to maximize the output capability, i.e., fully utilizing the induced voltage of the RX side, $v_{rx}$, and the TX compensation is used to achieve ZPA operation for minimum VA rating. The reduced circulating energy is helpful to lower the device stress and the conduction losses, which is particularly important for high-power applications. Therefore, it is still meaningful to achieve the ZPA operation, which can help narrow down the available candidates in Table I. By reviewing the four basic compensations, the RX compensation is either a shunt capacitor or series capacitor, whose capacitance is fixed and only determined by $L_{tx}$. However, the TX compensation capacitance is quite different, only the SS can achieve coupling and loading-independent compensation. Since the fixed compensation network is preferred, this part focuses on how to select and design the fixed compensation network with ZPA operation. If a half- or full-bridge inverter is used, ZVS or ZCS may be required. Then, the resonant tank with ZPA operation should be slightly modified to have an inductive $Z_{in}$ (ZVS) or capacitive $Z_{in}$ (ZCS). These considerations have been discussed in many papers and will not be elaborated here [16], [17].

Fig. 10 shows the port impedance of the IPT system. $Z_{in}$, $Z_{ref}$, $Z_{rx}$, and $R$ are the input impedance of Tank TX, the reflected impedance, the input impedance of Tank RX, and final load resistance. $r_{tx}$ and $r_{rx}$ are the ESRs of $L_{tx}$ and $L_{rx}$. In this paper, the coils’ ESRs are separated from the self-inductance and equivalently viewed as the source internal resistance. $\eta_{tx}$, $\eta_{rx}$, and $\eta_{coil}$ are the efficiency of the TX side, the RX side, and the whole tank, respectively. In order to achieve ZPA, Tank TX should be able to compensate the reactive part of $Z_{ref}$, that is,

$$Z_{ref} = \frac{\omega^2 k^2 L_{tx} L_{rx}}{Z_{rx} + r_{tx}}$$

(4)

where $k$ is the coupling coefficient and equals to $M/\sqrt{L_{tx} L_{rx}}$. A fixed TX compensation requires a resistive $Z_{ref}$, otherwise $Z_{ref}$ will include a coupling-dependent reactive part and can only be fully compensated by a dynamic impedance matching network. Based on this concern, $Z_{rx}$ has to be purely resistive as well, and then a resistive $Z_{ref}$ is obtained based on (4).

At the RX side, $Z_{rx}$ is determined by the load $R$ and Tank RX. In order to have a resistive $Z_{rx}$ at the resonant frequency, Tank RX should be a resistance transformation network without introducing any reactive components. Three simplest resistance transformation networks are given as shown in Fig. 11. A series branch (i.e., a $L$ tank) gives a noninverted input resistance, while a T-type or II-type network gives an inverted input resistance. Higher-order resistance transformation networks can be built based on these basic blocks. Therefore, the network requirement for ZPA operation actually helps narrow down the candidate tanks as shown in Fig. 12.

Based on the proposed synthesis method, a large number of topologies can be generated for four basic conversions. For each type of conversion, two families of topologies with lowest order are given in Fig. 13. The coupling coils can offer LI $G_{coli,v}$ and $G_{coil,v}$ [refer to (3)]. In this paper, $G_{coli,v}$ is used to generate Family-A topologies, while $G_{coil,v}$ can generate Family-B topologies. Among these topologies, only the clamped voltage/current is denoted. For example, Tank TX of VVA is designed for LI $G_{tx,v1}$ (from $v_{in}$ to $i_{tx}$), and Tank RX is responsible for LI $G_{tx,vv}$ (from $v_{rx}$ to $i_{rx}$).
The circuit components within the black block are designed for the LI transfer function, and Table I should be applied. Meanwhile, the circuit within the green block is responsible for the resistance transformation, and Fig. 11 should be used. These basic requirements are combined to design the component value. The proposed synthesis offers a very simple approach to get all possible high-order component value. The resistance transformation of TX side requires \( Q_{tx} \) and \( \frac{Q_{tx}}{r_{tx}} \), which are usually much smaller than that of the compensation components. Therefore, the whole resonant tank can be roughly decomposed as two lossless tanks (Tanks TX and RX) and a pair of induced voltage sources with internal resistance (i.e., \( r_{tx} \) and \( r_{rx} \)) (refer to Fig. 10). Since the ZPA operation is achieved, all the port impedances are resistive. The efficiency for both sides and the whole tank are easily derived as

\[
\eta_{\text{tx}} = \frac{Z_{\text{ref}}}{(Z_{\text{ref}} + r_{\text{tx}})} \\
\eta_{\text{rx}} = \frac{Z_{\text{tx}}}{(Z_{\text{tx}} + r_{\text{rx}})} \\
\eta_{\text{coil}} = \eta_{\text{tx}}\eta_{\text{rx}}.
\]  

Once the ESRs are considered, the transfer function of the induced source part is slightly different. (3) is modified as

\[
\begin{align*}
G_{\text{coil,iv}} & = \frac{v_{\text{iv}}}{i_{\text{iv}}} Z_{\text{tx}} \\
G_{\text{coil,vi}} & = \frac{i_{\text{vi}}}{v_{\text{ref}}} Z_{\text{rx}} \\
G & = G_{\text{coil,iv}} \ast \eta_{\text{tx}} \\
& = G_{\text{coil,vi}} \ast \eta_{\text{rx}}.
\end{align*}
\]  

For topologies of Family A, the accuracy of the transfer function is only determined by \( \eta_{\text{tx}} \), while \( \eta_{\text{rx}} \) affects the transfer function of Family B topologies. In this paper, a practical application should properly select and design the topology to minimize the influence of ESRs.

B. Family A Versus Family B

Two V2V topologies are selected to study the difference between Families A and B. The ESR of the coupling coils will not only affect the accuracy of the transfer function, but also leads to different efficiency characteristics for different families. As shown in Fig. 14, the example topologies are generated by VVA and VVB by adding one more capacitor (refer to Fig. 9). Without this capacitor, in practice, it is very difficult to make \( L_{\text{tx}} = L_{\text{tx1}} \) for VVA due to the fabrication. Besides, this additional capacitor helps to modify the gain. According to the impedance requirements for LI output and ZPA operation, the compensation components should be designed according to Table I and Fig. 11. For the TX side of VVA1, LI \( G_{\text{tx,vi}} \) is ensured by

\[
\frac{j \omega_{\text{tx}} L_{\text{tx1}}}{j \omega_{\text{tx}} C_{\text{tx1}}} = 0.
\]  

The resistance transformation of TX side requires

\[
\frac{1}{j \omega_{\text{tx}} C_{\text{tx1}}} = \frac{1}{j \omega_{\text{tx}} C_{\text{tx2}}}.
\]  

For the RX side, the LI \( G_{\text{rx,rx}} \) and resistance transformation can be fulfilled simultaneously by

\[
\frac{1}{j \omega_{\text{rx}} L_{\text{rx1}}} = 0.
\]  

Defining \( m_{\text{r}} = L_{\text{tx2}}/L_{\text{rx1}} \), the transfer function is then
Fig. 15. $G_{vv}$ comparison between VVA1 and VVB1 for different $G_{ideal}$. (a) $G_{ideal} = 0.5$. (b) $G_{ideal} = 1$. (c) $G_{ideal} = 2$.

Fig. 16. $\eta_{coil}$ comparison between VVA1 and VVB1 for different $G_{ideal}$. (a) $G_{ideal} = 0.5$. (b) $G_{ideal} = 1$. (c) $G_{ideal} = 2$.

Fig. 17. $G_{vv}$ and $\eta_{coil}$ of VVA1 when $k$ decreases. (a) $G_{vv}$. (b) $\eta_{coil}$.

Fig. 18. Experiment setup.

derived as

$$G_{tx,vi} = \frac{1}{jm_1 \omega s L_{tx}}$$

$$G_{coil,iv} = j \omega s k \sqrt{L_{tx} L_{rx}}$$

$$G_{rx,vv} = 1$$

$$G_{vv} = G_{tx,vi} G_{coil,iv} G_{rx,vv} = \frac{k}{m_r} \sqrt{\frac{L_{tx}}{L_{rx}}}$$

(10)

Fig. 19. Full-load waveforms of VVA1 and VVB1.

Similarly, the impedance requirement and the transfer function for VVB1 are derived as follows:

$$j \omega s L_{tx} + \frac{1}{j \omega s C_{t1}} = 0$$

$$j \omega s L_{r1} + \frac{1}{j \omega s C_{r1}} = 0$$

$$j \omega s L_{r1} = j \omega s L_{tx} + \frac{1}{j \omega s C_{r2}}$$

$$m_r = L_{r1} / L_{tx}$$

$$G_{vv} = \frac{m_r}{k} \sqrt{\frac{L_{tx}}{L_{rx}}}$$

(11)

For a specific application, the power level and output voltage together determine the range of $R$, i.e., from full load ($R = R_{min}$) to light load ($R = +\infty$). In this paper, both VVA1 and VVB1 can be properly designed for a target voltage gain, $G_{ideal}$. A simulation is built based on Table II, and all the other resonant components are designed according to (7)-(11).

For different $G_{ideal}$ in Fig. 15, there is an error between $G_{vv}$ and $G_{ideal}$ due to the coils’ ESRs. Heavier load causes larger error.

According to (6), the real gain of Family A topologies is only affected by $\eta_{rx}$. Since VVA1 uses series compensation at the RX side, all the $G_{vv}$ curves are exactly the same in Fig. 15. In a different manner, the real gain of Family-B topologies is
affected by $\eta_{tx}$, which means $G_{vv}$ of VVB1 is dependent on both-side ESRs. Therefore, the $G_{vv}$ curves of VVB1 are quite different in Fig. 15 for different $G_{ideal}$. Usually a low-cost and simple IPT system may prefer working in an open-loop manner, and no other switch-mode circuits are used. For this case, VVB1 is better than VVA1 when $G_{ideal} < 1$. When $G_{ideal} = 1$, both topologies have the same error due to the circuit duality. If $G_{ideal} > 1$, VVA1 works better. It should be noted that all the discussion above is valid for fixed or roughly fixed coupling case. If an IPT system has a large coupling variation or wants to achieve accurate $G_{vv}$, additional dc/dc converters are still required, as such a frond-end state at the TX side.

For high-power applications, $\eta_{coil}$ has to be considered when selecting the topology. For VVA1, the coil efficiency defined by (5) can be further derived as

$$\eta_{coil} = \frac{R}{\omega^2 L_{tx} L_{rx} + r_{tx}(R + r_{rx})} \ast \frac{R}{R + r_{rx}}$$

where $X = \omega k \sqrt{L_{tx} L_{rx} G_{ideal}}$. This efficiency depends on $G_{ideal}$. Fig. 16 compares $\eta_{coil}$ for different $G_{ideal}$. If $G_{ideal} < 1$, VVB1 works better than VVA1 for heavy load condition, but its efficiency drops much faster than that of VVA1 when the load becomes lighter [refer to Fig. 16(a)]. However, the conclusion is reversed when $G_{ideal} > 1$ [refer to Fig. 16(c)].
When \( k \) drops due to the position change, \( v_{in} \) should be used to compensate the decreased \( G_{vv} \) for constant \( v_o \) [refer to (10)]. Here VVA1 with \( G_{ideal} < 1 \) is used as a study case because it shows good efficiency for a wide load range [refer to Fig. 16(a)]. As shown in Fig. 17, \( G_{vv} \) is linearly proportional to \( k \), and decreased \( k \) directly leads to an efficiency drop.

C. Experimental Verification

The final experiment setup is shown in Fig. 18. A Class-A power amplifier (PA) is used to drive the high-order-compensated coils. This linear PA can provide a pure sinusoidal driving voltage. The coils’ parameters are given in Table II. High-Q capacitors (about 2000) and inductors (about 800) are used for compensation. A 6.78-MHz IPT system is built with \( k = 0.22, \ v_{in} = 20 \ V, \) and \( R_{min} = 10 \ \Omega \). It is hard to exactly achieve the same \( G_{ideal} \) for VVA1 and VVB1 under fixed \( k \), because it is impossible to continuously tune the compensation inductors (refer to \( L_{11} \) and \( L_{r1} \) in Fig. 14). In the experiment, the \( G_{ideal} < 1 \) case is studied. \( L_{11} \) of VVA1 is tuned at 1.47 \( \mu H \) to provide \( G_{ideal} = 0.5 \); \( L_{r1} \) of VVB1 is tuned at 0.35 \( \mu H \) to have \( G_{ideal} = 0.505 \).

First of all, both VVA1 and VVB1 are built to verify the ZPA operation. The waveforms of \( v_{in}, v_o, \) and \( i_A \) are measured for full-load condition as shown in Fig. 19. It clearly shows \( v_{in} \) is in phase with \( i_A \), and ZPA is achieved for both topologies. \( v_o \) is also in phase with \( v_{in} \) as predicted by (10) and (11).

The measured \( G_{vv} \) is compared with the simulation in Fig. 20(a) and (b). For both topologies, the measured \( G_{vv} \) are well-matched with the simulation results. In order to compare VVA1 and VVB1, the ratio between the achieved \( G_{vv} \) and the target gain \( G_{ideal} \) is defined as \( r = G_{vv}/G_{ideal} \). Then, the results of Fig. 20(a) and (b) can be converted and compared in Fig. 20(c). The difference between VVA1 and VVB1 validates that VVB1 has smaller error than VVA1 [refer to Fig. 15(a)]. The measured \( \eta_{coil} \) are compared in Fig. 21. A good consistency is also observed between the experiment and the simulation. The small error is mainly caused by the ESRs of other resonant components. The peak efficiencies for both topologies are all above 93%.

When \( k \) drops, the input source is tuned to ensure a constant output voltage. In this case, \( v_o \) is maintained at 10 \( V \) by manually fine tuning \( v_{in} \). Fig. 22 compares the measured \( G_{vv} \) and \( \eta_{coil} \) with the simulation results for different coupling conditions. When \( k \) drops from 0.22 to 0.11, the measured \( G_{vv} \) also drops as the simulation predicts. Besides, the measured \( \eta_{coil} \) are also well consistent with the simulation results, and the efficiency drop is observed due to the drop of \( k \).

VI. CONCLUSION

A novel and simple system deposition and synthesis method is proposed in this paper for IPT systems. The induced voltage source model is effectively employed to fully utilize the LI transfer functions between the coupling coils. The self-inductances are arbitrated by both-side compensations. Using this modeling approach, the high-order IPT resonant tank is no longer treated as an entity and is effectively decomposed as three parts. This paper modifies the mature topology synthesis method for the conventional resonant converter and applies this method for IPT compensation synthesis. The tank candidates are generated to achieve coupling-independent resonance, loading-independent output, and ZPA operation. Many novel topologies are developed for four kinds of conversion. Based on the coil transfer function, two families of IPT topologies are proposed and compared. Besides, the proposed modeling method can easily deal with the coil ESRs, and it shows that the actual transfer function and efficiency of two families of topologies are affected by the coil ESR in a quite different manner. Finally, the experimental results well explain the influence of ESRs on the two-family topologies. The proposed method dramatically simplifies the selection, analysis, and design of high-order-compensated IPT systems.

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