Compensation topology for flat spiral coil inductive power transfer systems

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Abstract: Inductive power transfer technology is now widely used to provide power into various devices, such as battery based vehicles, implant devices, portable equipment etc. Despite the rapid development of power electronics components, inductive power transfer technology still has some drawbacks. The output power is vulnerable to the magnetic coupling efficiency of two coils. If misalignment and displacement of the coils occur the output power can drop sharply. This study proposes a new design that can transfer rated power at various coupling coefficients. The characteristics of the proposed topology are discussed. All discussions and conclusions are obtained for the condition that the coil self-inductance remains unchanged during misalignment. Analytical and experimental results are presented in this article, to support the proposed design.

1 Introduction

Inductive power transfer (IPT) is a contact-less method to transmit electrical energy without any mechanical contact between two magnetic coils. It is designed to send power from the primary winding to the secondary winding by using a transient magnetic field. Nowadays, with the enormous development of modern power electronics, IPT techniques are applied more efficiently. The fundamental principle that the IPT system is based on, which is also used in conventional transformers, is the well-known electromagnetic theory. Yet IPT has some inherent advantages. Since the transmitter and the receiver are electrically isolated and completely sealed, power can be delivered without any safety risks and reliability issues in harsh environments. In addition, the coupled coils are separated from each other making the power transmission more flexible, mobile and convenient. The IPT system has been applied to many kinds of movable occasions such as implant devices [1–4] and portable equipment [5–7], rail systems [8–10].

Compared with the traditional transformer system, the structure and feature of the magnetic coupling device for an IPT system are very different. The severe and sensitive coupling condition is a ubiquitous problem in IPT systems. Commonly, IPT systems might be classified as track-based systems and concentrated coil system according to the designed of primary side [11]. The transmitter coil of track-based system is often an elongated coil designed as track-based systems and concentrated coil system according to the designed of primary side [11]. The transmitter coil of track-based system is often an elongated coil distributed as a track and one or more receiver coils that usually appear as sliding transformers are coupled to it [12]. The track design was firstly introduced to continuously power a moving electric vehicle (EV) [8, 13–15]. In this type of system, the power will be transferred when pickups move along the track. Power transfer of these systems is very sensitive to lateral misalignment. Some methods have been developed to increase the tolerance of lateral misalignment of such IPT systems, including special track design [10, 16] and multi-phase systems [17, 18].

The concentrated coil system often has a better coupling condition, tuning condition and electromagnetic compatibility (EMC). This kind of system is widely used in portable devices [5], stationary battery charging and some segmented roadbed systems [19, 20]. In practical systems, transmitter and receiver are often shaped as disc or square coil and the position of the transmitter and receiver is relatively fixed on working condition [11, 21]. As the horizontal and vertical misalignment of secondary coil increase, the power transfer drops [22, 23]. In this circumstance, the power can only be transferred when the transmitter coil and secondary coil are exactly aligned and certain coupling coefficient is attained [11].

In paper [6, 7, 24], coil arrays are adopted to overcome this problem. The charging platform performs as a position free system. Yet, this approach is only used in portable device battery charging instead of high power systems because of its complexity in mechanism and control strategy. In [25] the authors introduce a hybrid structure for planar charging platform. This structure can produce an even magnetic flux distribution resulting a high misalignment.

Frequency control method is used in [26, 27] to achieve a good tolerance of air gap or lateral misalignment. Resulting in this control method, the system works on resonance condition while the coupling coefficient is changing. Authors of paper [28] present a compensation topology for high misalignment application.

In this paper, a concept of compensation topology for high misalignment IPT system without shielding method and ferrite is proposed. By selecting appropriate compensation capacitor values, the IPT system can obtain good misalignment behaviour. The potential usage of this system is underwater vehicles where humans are not present. Shielding method and ferrite object are not necessary and open coil structures can be used in this situation. As such, the variation in self-inductance of coils are assumed to be negligible. The underwater environment and other factors can have different effects upon the system. However, the research of these effects is beyond the scope of this paper. This paper is organised as follows: Section 2 introduces the basic theory and topologies of the IPT system; the concept of topology design is introduced and examined in Section 3; the calculated and experimental results are discussed in Section 4.

2 Overview of IPT

Most IPT systems consist of two different parts: the transmitter and the receiver. Typically the transmitter contains a power inverter network operating at the resonant frequency and supplying current for the compensated coil or track (Fig. 1). The power inverter changes direct current (DC) to alternating current (AC) at high
frequency. Commonly, the preferred inverter network is half bridge topology or full-bridge topology. For the full-bridge topology, the inverter is built with four switches \( (S1, S2, S3, S4) \) as shown in Fig. 2. By alternately closing switch pair \( (S1, S4) \) and pair \( (S2, S3) \), AC voltage is produced. After the band-pass filter \( LfCf \), sinusoidal voltage will be supplied to the resonant tank. To prevent short circuit of the input voltage source, \( S1 \) and \( S2 \) should never be closed at the same time. The same principle applies to switch \( S3 \) and \( S4 \).

The receiver comprises of receiver coil, resonant circuit, rectifier circuit, filter circuit and load module. Resonant circuit has the same function as on the transmitter side. The rectifier converts the induced AC to DC, which is suitable for the load. The filter circuit is designed to remove the AC ripple remaining in the output.

The two most important electromagnetic units in IPT system are the transmitter coil and the receiver coil. The effectiveness of two coil’s magnetic geometries is reflected by the coupling factor \( k \) \[29\]. Which is defined as

\[
k = \frac{M}{\sqrt{LpLs}}
\]

where \( M \) is the mutual inductance between primary coil and secondary coil. \( Lp, Ls \) are self-inductance of primary and secondary side, respectively.

The power capability of the system is highly dependent on coupling factor. Unfortunately, a large air gap often exists between transmitter coil and receiver coil. This phenomenon leads to a very poor coupling condition. As a result, the leakage inductance are much larger than magnetic inductance causing large excitation current and high winding losses. What is more, the EMC also becomes an issue because of the high leakage flux.

### 2.1 Basic topologies

To minimise the voltage-ampere rating of supply and improve the power transfer capability, compensation circuits are needed in the primary and secondary side of IPT systems. A lot of effort has been spent on compensation circuit topology. Using the combination of series and parallel compensation in primary and secondary side, four basic topologies were developed \[30\]. These four basic compensation topologies are SS, SP, PP and PS compensation. Fig. 3 shows the configuration of four basic topologies. In these four compensation topologies, the secondary capacitors are often chosen to resonate with coil inductance at high frequency while primary compensation capacitors to guarantee the primary zero phase angle (ZPA) condition.

Generally, secondary with series compensation represent voltage source characteristics and reflect no reactance to primary. Parallel compensated Secondary has current source features and the primary side has capacitive reactance reflected from secondary \[30\]. For series compensated primary system, the primary current will surge when secondary is uncoupled to primary makes the system unstable. The output power of primary parallel compensated system is highly dependent on coupling condition \[28\]. Furthermore, the output voltage of fully tuned SS topology is independent with the coupling condition. However, the system will be extremely unstable. Some systems use frequency shift control methods to maintain system stability \[26\]. Note that, A SS leakage inductance compensation which can be designed independent of the load is also used in many IPT systems \[26, 31\]. The parallel–parallel topology have higher impedance in primary and secondary side and better stability \[32\].

### 2.2 Special topologies

In practice, special compensation topologies are proposed for different applications. A unity power factor (UPF) compensation topology for high power IPT pickup is presented in paper \[33, 34\]. The UPF pickup uses a series-parallel topology called LCL circuit. It reflects no reactance to the track and reduce rectifier switching losses and resistive losses in the pickup winding owing to the soft-switching circuit characteristic.

Lee et al., \[19\] propose a new topology appropriate for roadbed wireless charging. In this system, the transmitter coil is series compensated and LCC receiver is series-parallel compensated. This topology is designed to automatically control the main circuit current as receivers are uncoupling with the transmitter. The
The parallel capacitor can reduce the current rating in main circuit. In primary side, the coil is discussed in this section. Capacitor reactance of secondary side is zero. Capacitor can eliminate the high order current harmonics. In secondary side, the filter inductance and filter capacitor. The equivalent circuit of the proposed topology is illustrated in Fig. 4. \( Z_0 \) is the impedance reflected from the compensated secondary winding. \( Z_0 \) is the winding impedance after partly series compensation. \( Z_p \) can be derived as

\[
Z_p = j\omega_0 L_p + \frac{1}{j\omega_0 C_p} + r_p
\]

\[
= j\omega_0 M + r_p
\]

where \( r_p \) is the parasitic in primary side. It is obvious that \( Z_p \) is inductive when using partly compensation capacitor \( C_p \). The impedance reflected from the secondary side is \( Z_s \)

\[
Z_s = \frac{\omega_0^2 M^2}{R_{eq} + r_s}
\]

where \( M = k_1 L_p L_s \), \( r_s \) is the secondary parasitic resistance. \( R_{eq} \) is the equivalent resistance of the full-bridge rectifier with capacitive filter and the load. If the load is a DC resistor, the relationship

\[
\omega_0 = 2\pi f_0
\]

Based on paper \([30]\), the value of capacitor \( C_{ps} \) in conventional series-series compensation topology named \( C \) is determined as follow

\[
C_{ps} = \frac{1}{\omega_0^2 L_p a^0}
\]

where \( a \) is an auxiliary parameter and constrained by inequality \( 0 < a < 1 \).

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\[
\omega_0 = 2\pi f_0
\]
between $R_0$ and $R_{eq}$ can be described as [46]

$$R_{eq} = \frac{8}{\pi} R_0$$  \hspace{1cm} (10)

The filter formed by $L_t$ and $C_t$ is adopted to eliminate the high order current harmonics. The selection of two components should follow $\omega_0^2 L_t C_t = 1$. The impedance of the filter in selected frequency will be $j\omega_0 L_t(1/j\omega_0 C_t)$ which is equal to zero. Furthermore, the impedance seen by source can be calculated as

$$Z_{source} = \frac{Z_p + Z_i(1/j\omega_0 C_{pp})}{(1/j\omega_0 C_{pp}) + Z_p + Z_t} + j\omega_0 L_t + \frac{1}{j\omega_0 C_t}$$  \hspace{1cm} (11)

When two coils are exactly in position, the main circuit should be working in ZPA condition. Selecting a suitable $C_{pp}$, we can guarantee that the reactance of $Z_{source}$ is zero. According to (6), (7), (9)--(11), $C_{pp}$ will be given by

$$C_{pp} = \frac{aL_p}{(a\omega_0 L_p)^2 + (a\omega_0 M_{max}/R_{eq})}$$  \hspace{1cm} (12)

The value of $M_{max}$ is achieved when two coils are precisely aligned (the coupling coefficient $k$ reaches a peak). Parasitic resistance $r_p$ and $r_t$ are ignored in the calculation process.

### 3.2 Misalignment consideration

Assuming the parasitic resistance $r_p$ and $r_t$ is zero in this section, we can derive the output voltage transferred to the load $R_0$ from Fig. 4 as

$$u_{out} = \frac{R_{eq}}{R_{eq} + j\omega_0 M_{ip}} v_{in} = j\omega_0 M_{ip}$$  \hspace{1cm} (13)

where $i_p$ is primary branch current as shown in Fig. 4. Since bandpass filter $L_t C_t$ works on resonance condition, $i_p$ can be calculated using (7), (9), (11), (12) as

$$i_p = \frac{v_{in}}{Z_{source} - (1/j\omega_0 C_t) - j\omega_0 L_t} Z_p + Z_t = \frac{v_{in}}{j\omega_0 L_t + (a\omega_0 M^2/R_{eq})}$$  \hspace{1cm} (14)

Substituting (14) into (13), we have

$$u_{out} = \frac{j\omega_0 M}{j\omega_0 L_t + (a\omega_0 M^2/R_{eq})} v_{in}$$  \hspace{1cm} (15)

Substituting (1) into (15), the voltage transfer ratio $G(k)$ can be expressed as

$$G(k) = \frac{|u_{out}|}{|v_{in}|} = \frac{1}{\sqrt{(a^2 L_p/L_s)(1/k)^2 + ((\omega_0 \sqrt{L_p}/R_{eq})k)^2}}$$  \hspace{1cm} (16)

Then, we have the simplified voltage transfer function

$$G(k) = \frac{1}{\sqrt{(b \cdot (1/k))^2 + (q \cdot k)^2}}$$  \hspace{1cm} (17)

where

$$b = \frac{\omega_0 \sqrt{L_p/L_s}}{R_{eq}}$$  \hspace{1cm} (18)

$$q = \frac{\omega_0 \sqrt{L_p/L_s}}{R_{eq}}$$  \hspace{1cm} (19)

The derivative of $G(k)$ respective to $k$ is written as

$$g(k) = \frac{dG(k)}{dk} = \frac{(b^2/k^3) - kq^2}{((b/k)^2 + (qk)^2)^{3/2}}$$  \hspace{1cm} (20)

It is obvious that $G(k)$ obtains the maximum when $g = 0$. The value of the peak point is $k_0$.

$$k_0 = \left[ \frac{b}{q} \right] = \sqrt{\frac{R_{eq}}{a\omega_0 L_p}}$$  \hspace{1cm} (21)

The maximum of voltage transfer ratio is named $G(k)_{max}$. The value of $G(k)_{max}$ is

$$G(k)_{max} = \frac{1}{\sqrt{2bq}} = \sqrt{\frac{R_{eq}}{2a\omega_0 L_p}}$$  \hspace{1cm} (22)

The output voltage $u_{out}$ is proportional to $G(k)$ when $v_{in}$ is fixed. Therefore the ratio of output voltage to its maximum will be equal to the ratio of $G(k)$ to $G(k)_{max}$. Through the ratio, output voltage drop when misalignment happens can be investigated. The ratio is defined as

$$H(k) = \frac{u_{out}}{u_{out\max}} = \frac{G(k)}{G(k)_{max}} = \sqrt{\frac{2k_0^2}{k^2 + (qk_0)^2}}$$  \hspace{1cm} (23)

Fig. 5 shows the relationship between $H(k)$ and $k$. For $k < k_0$, $H(k)$ increases monotonically with increasing in coupling coefficient $k$. $H(k)$ peaks at $k_0$. $H(k)$ decreases slightly as the coupling coefficient increases continuously.
To give a better understanding of this, we take (shown in Fig.6) voltage are guaranteed and no specific variation interval of drop will be less than 5% as example. When this set of parameters is given, coupling condition. When this set of parameters is given, output voltage is determined by which means that the AC voltage should lead the inverter current.

By introducing an auxiliary parameter $0 < \zeta < 1$, output voltage $u_{\text{out}}$ can be designed to be always larger than $\zeta u_{\text{out,max}}$ for a specific coupling range $[k_{\text{min}}, k_{\text{max}}]$. In this condition, the following inequality should be satisfied

$$\zeta < \sqrt{\frac{2k_0^2}{k^2 + (k_0^2/k^2)}}$$  \hspace{1cm} (24)$$

By solving (24), the boundaries of coupling coefficient can be given as

$$k_{\text{max}} = \frac{k_0 \zeta}{\sqrt{1 + \sqrt{1 - \zeta^2}}}$$ \hspace{1cm} (25)$$

$$k_{\text{max}} = \frac{k_0 \zeta}{\sqrt{1 - \sqrt{1 - \zeta^2}}}$$ \hspace{1cm} (26)$$

The maximum variation rate of $k$ will be

$$\delta_k = \frac{k_{\text{max}} - k_{\text{min}}}{k_{\text{max}}} = 1 - \left[\frac{1 - \sqrt{1 - \zeta^2}}{1 + \sqrt{1 - \zeta^2}}\right]$$ \hspace{1cm} (27)$$

To give a better understanding of this, we take $k_0 = 0.2$, $\zeta = 0.95$ as an example. When this set of parameters is given, $k_{\text{min}}$ and $k_{\text{max}}$ are calculated as 0.1588 and 0.2518. That means the output voltage drop will be less than 5% as $k$ varies in [0.1588, 0.2518]. The variation interval of $k$ can up to 36.9% of the total interval when voltage are guaranteed and no specific control is installed as shown in Fig. 6a.

In practice, we need to choose an appropriate $k_0$ for the different coupling condition. When $k_0$ is decided, the curve of output voltage drop will be determined. The maximum of voltage gain $G(k)$ at has relationship to $q$ and $b$ which means the maximum output voltage is determined by $q$ and $b$ when $v_{\text{in}}$ is a constant. Therefore an appropriate $q$ and $b$ should be selected for different power condition. Fig. 6 shows that $G(k)_{\text{max}}$ decreases as $q$ increases.

**3.3 Input phase angle**

In this study, we employ a full-bridge as inverter topology and inductive circuit will result in soft switching inverter and better efficiency [46]. The main circuit should be designed to achieve an inductive impedance which means that the AC voltage should lead the inverter current.

When using the compensation capacitors in Section 3.1, the real part of $Z_{\text{source}}$ can be calculated as

$$R_{\text{in}} = \frac{\omega_0^2 M^2 / R_{\text{eq}}}{(1 - \omega_0^2 a L_p C_{pp})^2 + (\omega_0 C_{pp})^2 (\omega_0^2 M^2 / R_{\text{eq}})^2}$$ \hspace{1cm} (28)$$

the imaginary of $Z_{\text{source}}$ is

$$X_{\text{in}} = \frac{\omega_0 a L_p (1 - \omega_0^2 a L_p C_{pp}) - (\omega_0^2 M^2 / R_{\text{eq}})^2 \omega_0 C_{pp}}{(1 - \omega_0^2 a L_p C_{pp})^2 + (\omega_0 C_{pp})^2 (\omega_0^2 M^2 / R_{\text{eq}})^2}$$ \hspace{1cm} (29)$$

The phase of the impedance which is given the symbol $\theta$ is determined through the following relations

$$\theta = \frac{180^\circ}{\pi} \arctan \frac{X_{\text{in}}}{R_{\text{in}}}$$ \hspace{1cm} (30)$$

Substituting (28)–(30)\hspace{1cm}$$

$$\theta = \frac{180^\circ}{\pi} \arctan \frac{\omega_0^2 \cdot (\omega_0 a L_p / R_{\text{eq}}) \cdot ((M_{\text{max}}^2 - M^4) / M^2)}{(\omega_0 a L_p)^2 + (\omega_0 M_{\text{max}}^2 / R_{\text{eq}})^2}$$ \hspace{1cm} (31)$$

where $M = k \sqrt{L_p L_s}$ and $M_{\text{max}}$ is the mutual inductance of maximum $k$. Eventually, we have

$$\theta = \frac{180^\circ}{\pi} \arctan \left(\frac{k_0^2}{k_0^2 + k_{\text{max}}^4 / k_{\text{max}}^2}\right)$$ \hspace{1cm} (32)$$

where $k_0$ is defined in (21) Section 3.2 and $k_{\text{max}} = M_{\text{max}} / \sqrt{L_p L_s}$. 

**Fig. 5** Output voltage fluctuation of different $k$

**Fig. 6** Voltage transfer ratio $G(k)$ against $k$, when

$a) k_0 = 0.2$

$b) k_0 = 0.4$
Equivalent circuit of the proposed system is depicted in Fig. 8. System efficiency is to be constant in the analysis of this article. However, the change in relative position between primary and secondary can result in the variations in the magnetic coupling and self-inductance [44, 47]. These changes may result in a drop in efficiency within the system.

3.4 Efficiency analysis

System efficiency is a very important aspect of system design. Equivalent circuit of the proposed system is depicted in Fig. 8.

The total power losses caused by parasitic can be calculated as

\[ P_{\text{loss}} = I_{s}^{2}r_{o} + I_{1}^{2}r_{1} + I_{p}^{2}r_{p} + I_{s}^{2}r_{s} \]  

(33)

The output power can be expressed as

\[ P_{\text{out}} = I_{1}^{2}R_{eq} \]  

(34)

It is known that

\[ \left| \frac{I_{s}}{I_{p}} \right| = \left| \frac{Z_{t} + j\omega_{0}L_{pp}}{1/\omega_{0}C_{pp}} \right| = \frac{k_{0}^{2}}{k_{0}^{2} + k_{\text{max}}^{4}} \sqrt{k_{0}^{2} + k_{\text{max}}^{4}} \]  

(35)

\[ \left| \frac{I_{s}}{I_{p}} \right| = \left| \frac{I_{1} + I_{s}}{I_{p}} \right| \simeq 1 + \frac{k_{0}^{2}}{k_{0}^{2} + k_{\text{max}}^{4}} \sqrt{k_{0}^{2} + k_{\text{max}}^{4}} \]  

(36)

\[ \left| \frac{I_{1}}{I_{p}} \right| \simeq kq \]  

(37)

Considering only parasitic resistance loss, the efficiency of the system \( \eta \) can be calculated as

\[ \eta = \frac{P_{\text{out}}}{P_{\text{loss}} + P_{\text{out}}} \]  

(38)

Substituting (33)-(38), \( \eta \) is given by (see (39))

The inductance of \( L_{p} \) and \( L_{q} \) are assumed to be constant in the analysis of this article. However, the change in relative position between primary and secondary can result in the variations in the magnetic coupling and self-inductance [44, 47]. These changes may result in a drop in efficiency within the system.

4 Experiment

4.1 Coil geometry

The coupling transformer is one of the most important components in IPT system. Mostly, transformer structure and geometry are determined and manufactured for specified applications. The coupling coils often have to meet the requirements of applications such as power level, dimensional limitation, EMC and efficiency. The concentrated coil system used in EV should use shielding method and ferrite to protect the passengers and improve the quality of the system [11]. The shielding also prevent the system from interacting with other structures [21]. Design and optimisation of circular coils are presented in paper [48].

An experimental coil design of this paper is specified in this section. The adopted coil has an annular geometry with no core. If shielding and ferrite are used, the influence of variations in the magnetic coupling and self-inductance should be considered. In our experimental system, the secondary coil and primary coil are identical. Its outer diameter \( D \) and inner diameter \( d \) is determined to be \( D = 140 \text{ mm}, \ d = 40 \text{ mm} \). The thickness \( t_{h} \) is \( 2 \text{ mm} \). Two winding are assembled with Litz wire (100 × 0.1 mm) in 34 turns. As shown in Fig. 9, \( g \) denotes the air gap between primary coil and secondary coil and \( x \) denotes the horizontal misalignment of the receiver coil (Fig. 10).

Two common factors that affect the magnetic coupling are lateral misalignment and air gap. Usually, self-inductance and mutual inductance of two coils are obtained by finite element analysis tool for its simplification. Figs. 10a and b show simulated mutual inductance of two coils with different misalignment \( x \) and air gap \( g \), respectively. The air gap \( g \) is 40 mm when lateral misalignment varies. Self-inductance of two coils are measured as \( L_{p} = 96 \mu \text{H} \) and \( L_{q} = 95.8 \mu \text{H} \).

4.2 Circuit parameters

According to the coil design of the experimental system, the maximum of the coupling coefficient is 0.25. Then, \( k_{0} \) is selected
to be 0.2 by (21) in Section 3.2. When \( k_0 \) is fixed, \( q \) will be selected for power condition. As we discussed before, \( k_0 \) is related to \( b \) and \( q \). After we select suitable values of parameter \( k_0 \) and \( q \), parameter \( b \) will be affirmative. In our experimental system, secondary coil and primary coil are identical, parameter \( b \) is equal to parameter \( a \). Parameter \( b \) and \( q \) are determined by \( L_p, L_s, C_{ps}, R \). By choosing appropriate circuit parameters, \( k_0 \) and \( q \) will be appropriate for the application. In the experimental prototype parameters are selected as: \( q = 6, \quad k_0 = 0.2, \quad b = a = 0.25 \). Table 1 gives electronic components and other parameters of the prototype.

4.3 Results

The measured and simulated output voltage \( V_{out} \) when lateral misalignment \( x \) varies are illustrated in Fig. 11a. The air gap between two coils is maintained at 40 mm for different lateral misalignment \( x \). As shown in the experimental curves, the output voltage slightly increases and arrives its maximum value with a lateral misalignment of 30 mm. It is worth nothing that the maximum lateral misalignment can up to 30% of coil diameter \( D \) showing a good position tolerance and validating the applicability of the proposed concept. Fig. 11b shows the measured and simulated results of varying gap \( g \) with a zero lateral misalignment. As air gap increasing, the output increases. After that, the decrease in voltage is relatively linear for air gap varying

![Simulated magnetic coupling with different coils](image)

![Output voltage and Primary coil current with different position](image)

**Table 1** Circuit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>( L_p )</td>
<td>96 ( \mu )H</td>
<td>inductance of primary</td>
</tr>
<tr>
<td>( C_{ps} )</td>
<td>35.2 nF</td>
<td>series capacitor of primary</td>
</tr>
<tr>
<td>( C_{gap} )</td>
<td>30.9 nF</td>
<td>parallel capacitor of primary</td>
</tr>
<tr>
<td>( L_s )</td>
<td>100 ( \mu )H</td>
<td>filter inductance</td>
</tr>
<tr>
<td>( C_f )</td>
<td>25.3 nF</td>
<td>filter capacitor</td>
</tr>
<tr>
<td>( L_s )</td>
<td>95.8 ( \mu )H</td>
<td>inductance of secondary</td>
</tr>
<tr>
<td>( C_{sp} )</td>
<td>26.4 nF</td>
<td>series capacitor of secondary</td>
</tr>
<tr>
<td>( R_s )</td>
<td>12.4 ( \Omega )</td>
<td>load resistance</td>
</tr>
<tr>
<td>( V_i )</td>
<td>24 V</td>
<td>input voltage</td>
</tr>
<tr>
<td>( f_0 )</td>
<td>100 kHz</td>
<td>operating frequency</td>
</tr>
<tr>
<td>power MOSFET</td>
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<td>power switches</td>
</tr>
<tr>
<td>schottky diode</td>
<td>MUR1660CT</td>
<td>rectifier diodes</td>
</tr>
</tbody>
</table>
from 60 to 120 mm. The RMS current of primary coil for different misalignment is presented in Fig. 11c. The current of primary coil maintains nearly constant when misalignment larger than 60 mm, owing to the sharp decrease of reflected impedance of secondary side. The wave form of main circuit in nominal position and maximum misalignment position is shown in Fig. 12. The figure shows a slight increase in current, and a growth in phase angle between voltage and current according to Fig. 7.

5 Conclusion

A new concept of compensation topology has been presented in this paper to improve misalignment tolerance in IPT system with open coil structures. The detailed analysis of voltage transfer ratio, input phase angle and efficiency about this new concept of compensation is presented in this paper. The circuit parameters are selected for high lateral misalignment of secondary coil. The variation interval of coupling coefficient $k$ can go up to 36.9% of the total interval when voltage are guaranteed and no specific control is installed. A system experiment has been conducted to test the effectiveness of the compensation concept. The simulated and measured results further demonstrate the effectiveness of the proposed topology for underwater vehicles.

6 Acknowledgement

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