Control for Maximizing Efficiency of Three-Phase Wireless Power Transfer Systems At Misalignments

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This paper presents a control for maximizing the transfer efficiency of three-phase wireless power transfer systems at misalignments. The control conducts an imbalanced three-phase operation with positive- and negative-sequence components. The positive-sequence component is used to regulate the transferred power, and the negative-sequence component is used to improve the efficiency. The optimal value of the negative-sequence component is determined by a sequential search. A modulation technique for this control allows a three-phase inverter to generate imbalanced voltages required by the control in as few switching numbers as possible. The system employing the control is examined for wireless power transfer of 100 W at misalignments of 100 mm, the radius of the wireless transfer pad. The tests confirmed the wireless power transfer operation employing the control gains 3% improvement in the efficiency in comparison with a balanced three-phase operation.

Keywords: imbalanced three-phase operation, sequential search, transfer efficiency, wireless power transfer system

1. Introduction

Wireless power transfer systems enable convenient charging, prevent electrical shock and provide high tolerance in harsh environments. These advantages allow the systems to be applied to chargers of various applications such as for ships**, electric bicycles**, trains** and electric automobiles**. Conventional wireless power transfer pads used in these systems consist of single-phase coils. However, wireless power transfer pads with a multi-phase structure have been coming out in recent years. For example, there are a pad with a two-phase structure** and a pad with a three-phase structure**.

Misalignments of a primary side from a secondary side is inevitable issue of wireless power transfer systems. Misalignments could cause a significant decrease in transfer power and efficiency. However, a pad with multiple coils can have higher tolerance than a pad with single coil** because the coils in the pad can have uneven current, for example, a primary coil close to the secondary coil is given more current than other primary coils. For the same reason, a pad with a three-phase structure can have higher tolerance than one with a single-phase structure.

There are two methods for supplying power to a pad with a three-phase structure. One uses three single-phase inverters as shown in**. In this method, three phase-currents through three coils can be controlled independently. Therefore, the control for these inverters can be implemented simply and easily. Another method uses a three-phase inverter**, which is more compact than the former. The inverter of (**), however, is just in balanced three-phase operation and does not desterilize the advantage of wireless power transfer pad with three-phase structure.

This paper presents a control capable of maximizing transfer efficiency of three-phase wireless power transfer pads at misalignments. The control conducts an imbalanced three-phase operation with positive- and negative-sequence components. The optimal values of these components are given by a sequential search. Section 2 describes a circuit configuration of the system using the pads and describes the imbalanced operation using the circuit equations. Section 3 proposes the modulation technique for a three-phase inverter to output three-phase imbalanced voltages. Section 4 explains a control technique to achieve maximum efficiency, using sequential search. The system using the control is examined with a three-phase wireless power transfer pads in Section 5.

2. System Configuration

2.1 Three-phase Wireless Power Transfer Pads

Figure 1 shows a concept of three-phase wireless power transfer pads. The primary and secondary sides arrange three-phase coils (the primary coils are U1, V1 and W1 and the secondary coils are U2, V2 and W2), closely. Therefore, a coil affects a coil of the different side as well as one of the same side through mutual inductance. Mutual inductance of a coil with a coil of different side complicatedly changes.

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which is defined with the radius spectral to that of the primary is called horizontal misalignment, the displacement of the center of the secondary side with respect to that of the primary side through a vertical airgap, where the secondary side does not overlap the coil with the corresponding phase of the primary side. The misalignment of the center of the secondary side with respect to that of the primary is called horizontal misalignment, which is defined with the radius $r$ and polar angle $\beta$.

### 2.2 Circuit Configuration and Operation

Figure 3 shows a circuit configuration. The three-phase inverter feeds to a three-phase wireless power transfer pad through the power factor compensation circuit. The phasors of the inbalanced three-phase voltages, $V_{ui}$, $V_{vi}$ and $V_{wi}$, generated by the inverter are expressed as:

$$V_{ui} = |V_{pl}| e^{j\theta_{ui}} + |V_{nl}| e^{j\theta_{ui}}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (1a)$$

$$V_{vi} = |V_{pl}| e^{j(\theta_{ui} - \frac{\pi}{2})} + |V_{nl}| e^{j(\theta_{ui} + \frac{\pi}{2})}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (1b)$$

$$V_{wi} = |V_{pl}| e^{j(\theta_{ui} + \frac{\pi}{2})} + |V_{nl}| e^{j(\theta_{ui} - \frac{\pi}{2})}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (1c)$$

where $|V_{pl}|$ and $|V_{nl}|$, and $\theta_{ui}$ and $\theta_{ni}$ are the r.m.s values and the initial phase angles of positive- and negative-sequence voltages, respectively.

As a power factor compensation circuit, the primary side can use a three-phase LCL compensator or a three-phase LCL compensator with partial series tuning. This system of this paper employs a three-phase LCL compensator with partial series tuning, where the inductors $L_{c1}$ and the capacitors $C_{1}$ and $C_{L1}$ are set with the following relations:

$$\omega L_{c1} = \omega (L_1 + M_1) - \frac{1}{\omega C_{L1}}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (2a)$$

$$\omega L_{c1} = \frac{1}{\omega C_{1}}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (2b)$$

where $\omega$ is angular frequency, which is coincident with the operation frequency $2\pi f_{o}$ of the inverter. $L_1$ is the primary self-inductance of the wireless power transfer pad and $M_1$ is the mutual inductance between primary coils. As confirmed from (1), because

$$V_{ui} + V_{vi} + V_{wi} = 0 \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (3)$$

is satisfied, the three-phase LCL compensator can output the primary currents $I_{u1}$, $I_{v1}$ and $I_{w1}$ expressed as:

$$I_{u1} = \frac{V_{ui}}{\omega L_{c1}}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (4a)$$

$$I_{v1} = \frac{V_{vi}}{\omega L_{c1}}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (4b)$$

$$I_{w1} = \frac{V_{wi}}{\omega L_{c1}}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (4c)$$

Consequently, the primary currents are in proportion to the phase voltages and independent from the impedance of the pad.

The secondary induced voltages $V_{u2}$, $V_{v2}$ and $V_{w2}$ are expressed as:

$$V_{u2} = j\omega \begin{bmatrix} M_{uu} & M_{uv} & M_{uw} \\ M_{vu} & M_{vv} & M_{vw} \\ M_{wu} & M_{wv} & M_{ww} \end{bmatrix} \begin{bmatrix} I_{u1} \\ I_{v1} \\ I_{w1} \end{bmatrix}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (5)$$

where $M$ represents the mutual inductances between the primary and secondary sides. A subscript character on the left

![Fig. 1. A concept of three-phase wireless power transfer pads](image1)

![Fig. 2. Mutual inductances between the primary and the secondary sides under the misaligning conditions of $r = 100$ mm and $\alpha = \pi/6$](image2)

![Fig. 3. Configuration of three-phase wireless power transfer system](image3)
side indicates the primary phase coil and a character on the right side indicates the secondary phase coil. As shown in Fig. 2, mutual inductances under misaligning conditions have different offsets. This causes imbalanced induced voltages in the secondary even if the primary currents are balanced.

The secondary side can employ a three-phase parallel LC compensator, a three-phase LCL compensator, or a three-phase LCLC compensator. In this paper, the system employs a three-phase parallel LC compensator. When the capacitors \( C_2 \) are set with the mutual inductance \( M_2 \) between the secondary phase coils at

\[
C_2 = \frac{1}{\omega^2 (M_2 + L_2)},
\]

the parallel resonant circuits in the compensator can output the following currents independent of impedance of the load:

\[
I_{ur} = \frac{V_{w2} - V_{w2}}{3j\omega (L_2 + M_2)}, \quad (7a)
\]

\[
I_{vr} = \frac{V_{w2} - V_{w2}}{3j\omega (L_2 + M_2)}, \quad (7b)
\]

\[
I_{wr} = \frac{V_{w2} - V_{w2}}{3j\omega (L_2 + M_2)}, \quad (7c)
\]

where \( V_{w2} \) and \( V_{w2} \) are the line–to–line voltages and are defined as

\[
V_{w2} = V_{u2} - V_{v2}, \quad (8a)
\]

\[
V_{w2} = V_{u2} - V_{v2}, \quad (8b)
\]

\[
V_{w2} = V_{u2} - V_{v2}. \quad (8c)
\]

Connection of a neutral point in the secondary side of the pad and a neutral point of the \( y \)-connected capacitors allows (7) to be satisfied even if the sum of the induced voltages is non-zero.

When the voltages \( V_{w2}, \) \( V_{w2} \) and \( V_{w2} \) are much larger than the dc voltage \( V_o \) of the load, the instantaneous currents \( i_{ur}, i_{vr} \) and \( i_{wr} \) vary sinusoidally. Otherwise, the currents are distorted. For simplicity, these currents are assumed to vary sinusoidally in the following description. Figure 4 shows the waveforms of the instantaneous currents \( i_{ur}, i_{vr} \) and \( i_{wr} \) into the rectifier and the instantaneous line-to-line voltages \( v_{u2}, v_{v2} \) and \( v_{w2} \). The phasors of these currents are defined as

\[
I_{u2r} = I_{ur} - I_{ur} = |I_{uv2}e^{j\omega t}|, \quad (9a)
\]

\[
I_{v2r} = I_{vr} - I_{vr} = |I_{vw2}e^{j\omega t}|, \quad (9b)
\]

\[
I_{w2r} = I_{wr} - I_{wr} = |I_{ww2}e^{j\omega t}|. \quad (9c)
\]

The instantaneous voltages of the rectifier vary in square wave depending on relationships between these instantaneous currents, \( i_{u2r}, i_{v2r} \) and \( i_{w2r} \). The line-to-line phase with the highest instantaneous current has a voltage of \( V_o \). In contrast, the phase with the lowest instantaneous current has a voltage of \( -V_o \). Otherwise, the phase has a voltage of zero. The phase angles defined in Fig. 4, for example, \( \varphi_{uv2} \) and \( \varphi_{vw2} \) are available using

\[
\varphi_{uv2} = \frac{\pi}{2} + \gamma_v \text{ or } -\frac{\pi}{2} + \gamma_v, \quad (10a)
\]

\[
\varphi_{vw2} = \frac{\pi}{2} - \gamma_v \text{ or } \frac{\pi}{2} + \gamma_v, \quad (10b)
\]

where

\[
\gamma_v = \theta_{uv2} - \theta_{vw2}, \quad (10c)
\]

\[
\gamma_v = \tan^{-1}\left(\frac{|I_{uv2}|\sin\varphi_{uv2}}{|I_{vw2}|\cos\varphi_{vw2} - |I_{v2r}|}\right). \quad (10d)
\]

It is noted that the ranges of these phase angles are limited between \(-\pi/2\) and \(\pi/2\). Based on these phase angles, the output power \( P_o \) can be calculated with

\[
P_o = \frac{1}{3} (P_{u2o} + P_{v2o} + P_{w2o}), \quad (11a)
\]

where

\[
P_{u2o} = \sqrt{2} |I_{uv2}|' V_o \left[\sin \left(\varphi_{uv2}\right) + \sin \left(\varphi_{vw2}\right)\right], \quad (11b)
\]

\[
P_{v2o} = \sqrt{2} |I_{vw2}|' V_o \left[\sin \left(\varphi_{v2o}\right) + \sin \left(\varphi_{uw2}\right)\right], \quad (11c)
\]

\[
P_{w2o} = \sqrt{2} |I_{ww2}|' V_o \left[\sin \left(\varphi_{w2o}\right) + \sin \left(\varphi_{uw2}\right)\right]. \quad (11d)
\]

3. Modulation Technique for Imbalanced Operation

The three-phase inverter in this system is required to output imbalanced three-phase voltages. Considering that the system needs high-frequency voltages, the inverter switching needs to be as few as possible to suppress switching loss and influence of dead time on the control. Figure 5 shows modulation technique for the inverter to satisfy this requirement. The technique uses two pulses with a width of \(\pi/2\) during a cycle period. The pulses are shifted by phase angle \(\xi\) with respect to the initial phases angle \(\theta\). The phase angle \(\xi\) can be calculated using

\[
\xi = \theta_{uv2} - \theta_{vw2}, \quad (10c)
\]

\[
\xi = \tan^{-1}\left(\frac{|I_{uv2}|\sin\varphi_{uv2}}{|I_{vw2}|\cos\varphi_{vw2} - |I_{v2r}|}\right). \quad (10d)
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P_{u2o} = \sqrt{2} |I_{uv2}|' V_o \left[\sin \left(\varphi_{uv2}\right) + \sin \left(\varphi_{vw2}\right)\right], \quad (11b)
\]

\[
P_{v2o} = \sqrt{2} |I_{vw2}|' V_o \left[\sin \left(\varphi_{v2o}\right) + \sin \left(\varphi_{uw2}\right)\right], \quad (11c)
\]

\[
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\]

\[
\xi = \tan^{-1}\left(\frac{|I_{uv2}|\sin\varphi_{uv2}}{|I_{vw2}|\cos\varphi_{vw2} - |I_{v2r}|}\right). \quad (10d)
\]
output includes high harmonics, especially, in terms of \( V_{wi} \), the second harmonic is 17.6 V while its fundamental is less than it. Most of these harmonics can be suppressed by the LCL compensator in the primary side. Figure 7 shows the dependence of the impedance of the LCL compensator on the frequency. The value at 80 kHz matches \( \omega L_{c1} \), which supports (4). The impedance over 110 kHz increases with the frequency. This implies that the LCL circuit works as a low-pass filter and the high frequency component of the system can be suppressed. The resulting primary current can be approximately sinusoidal waves.

## 4. Control Technique

### 4.1 Variables for Control

According to (1), the imbalanced three-phase voltages can be represented by only four variables such as \( |V_{ul}|, |V_{vl}|, \theta_{ui} \) and \( \theta_{vi} \) by employing positive- and negative-components. Among these variables, the phase angle \( \theta_{ui} \) (otherwise, \( \theta_{vi} \)) can be fixed, for example, at zero. \( |V_{ui}| \) is normalized and then is represented by \( \lambda \), which is defined as the ratio of \( |V_{ui}| \) to \( |V_{pi}| \) and limited between 0 and 1.0.

### 4.2 Control Technique

Figure 8 shows the control block diagrams for the system. The \( \theta_{pi} \) is fixed at zero. \( |V_{pi}| \) is generated by the proportional-integral (PI) control block to control the output power \( P_o \) at a reference \( P_{oc} \). \( \theta_{ui} \) and \( \lambda \) are generated by the sequential search block to maximize the total efficiency of the system, which is defined as efficiency from the dc input to the dc output.

Figure 9 shows the flow chart of the sequential search. After initializing variables, the blocks in the shaded area are executed at every control period. Measured efficiency \( \eta \) is compared with \( \eta_{max} \), which is the largest efficiency before present control period. When \( \eta \) is larger than \( \eta_{max} \), \( \theta_{ui} \) and \( \lambda \) are memorized into the variables \( \theta_{ui,m} \) and \( \lambda_{m} \) as a point marking \( \eta_{mx} \). Then, the variation \( \Delta \theta_{ui} \) or \( \Delta \lambda \) of \( \theta_{ui} \) and \( \lambda \), respectively increases by being multiplied by \( k_{s} \) (\( k_{s} > 1.0 \)). The updated variation is used to further increase the corresponding variable in the next period. For example, when \( \theta_{ui} \) is changed in the previous period, \( \Delta \theta_{ui} \) is updated in the present period. Then, in the next period, \( \theta_{ui} \) is increased by \( \Delta \theta_{ui} \). When \( \eta \) is smaller than \( \eta_{mx} \), the variation \( \Delta \theta_{ui} \) or \( \Delta \lambda \) decreases and changes its sign by being multiplied by \( -k_{s} \) (\( k_{s} < 1.0 \)). Hence, the variable changes in opposite direction with smaller variation. Even when the variables are fixed, the measured efficiency changes due to measurement error and noise. In this control, the efficiency at \( \theta_{ui,m} \) and \( \lambda_{m} \) is updated repetitively. This frequent update prevents the efficiency value with large noise to survive. The sequential search block operates in lower frequency than that of the PI control block for regulating output power. Therefore, the output deviation caused by

### Figure 7

Dependence of impedance of the LCL circuit on frequency.

### Table 1

Parameters achieving maximum efficiency under a misalignment of \( r = 100 \) mm, \( \alpha = \pi/6 \) rad. and \( \beta = \pi/4 \) rad.

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>0.932</th>
</tr>
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<tbody>
<tr>
<td>(</td>
<td>V_{ul}</td>
</tr>
<tr>
<td>(</td>
<td>V_{vl}</td>
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<tr>
<td>(</td>
<td>V_{ul}</td>
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<td>(</td>
<td>V_{vl}</td>
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<tr>
<td>(</td>
<td>V_{ul}</td>
</tr>
</tbody>
</table>

where \( V_{max} = \sqrt{2} |V_{i}|/\pi \). The r.m.s voltages \( |V_{ul}|, |V_{vl}| \) and \( |V_{ui}| \) are given by (1): for example, the U-phase voltage \( |V_{ui}| \) is given by

\[
|V_{ui}| = \sqrt{V_{u,sin}^2 + V_{u,cos}^2}, \quad \theta_{ui} = \tan^{-1}\left(\frac{V_{u,sin}}{V_{u,cos}}\right),
\]

where

\[
V_{u,cos} = |V_{pi}| \cos \theta_{pi} + |V_{vi}| \cos \theta_{vi},
\]

\[
V_{u,sin} = |V_{pi}| \sin \theta_{pi} + |V_{vi}| \sin \theta_{vi},
\]

Figure 6(a) shows the waveforms of the phase voltages obtained by the modulation technique at the condition given by Table 1. This condition is marked as the maximum efficiency point of the test described later. The supplied voltage \( V_{in} \) is 100 V and the operating frequency \( f_{o} \) is 80 kHz. Figure 6(b) shows harmonics in these voltages. The fundamentals (the values at 80 kHz) of each phase voltage are equal to the reference voltages \( |V_{ul}|, |V_{vl}| \) and \( |V_{ui}| \). However, the following:

\[
\xi_{u} = \frac{1}{2} \sin^{-1}\left(1 - \left(\frac{|V_{ui}|}{|V_{max}|}\right)^2\right), \quad \xi_{v} = \frac{1}{2} \sin^{-1}\left(1 - \left(\frac{|V_{vi}|}{|V_{max}|}\right)^2\right), \quad \xi_{w} = \frac{1}{2} \sin^{-1}\left(1 - \left(\frac{|V_{wi}|}{|V_{max}|}\right)^2\right),
\]

where \( V_{max} = \sqrt{2} |V_{i}|/\pi \). The r.m.s voltages \( |V_{ul}|, |V_{vl}| \) and \( |V_{ui}| \) are given by (1): for example, the U-phase voltage \( |V_{ui}| \) is given by

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\]

where

\[
V_{u,cos} = |V_{pi}| \cos \theta_{pi} + |V_{vi}| \cos \theta_{vi},
\]

\[
V_{u,sin} = |V_{pi}| \sin \theta_{pi} + |V_{vi}| \sin \theta_{vi},
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5. Experiments

To validate the control, the system using a circular three-phase wireless power transfer pads with two layers\(^{(17)}\), shown in Fig. 10, was implemented. Its outer diameter is 200 mm and vertical gap between the primary and secondary side was set at 39 mm. The circuit constants are given by Table 2.

<table>
<thead>
<tr>
<th>Table 2. Circuit constants</th>
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<tbody>
<tr>
<td>( r_1 )</td>
</tr>
<tr>
<td>( L_1 )</td>
</tr>
<tr>
<td>( M_1 )</td>
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<tr>
<td>( C_1 )</td>
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<tr>
<td>( C_2 )</td>
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</tbody>
</table>

Figure 11 shows the transient waveforms during sequential search operation under \( r = 100 \) mm, \( \alpha = \pi/6 \) rad. and \( \beta = \pi/4 \) rad. The scale for \( |V_p|/V_{\text{max}} \) is 0.5/div., for \( \lambda \) is 0.5/div., for \( \theta_{\text{ini}} \) is \( \pi/2 \) rad/div., for \( P_o \) is 75 W/div. and for \( \eta \) is 10%/div.

Figure 12 shows distribution of the measured transfer efficiency on the complex plane. The vacant area that is inside the circle of \( \lambda = 1.0 \) denotes that the output power does not reach 100 W. The most of area gaining 100 W is in the first

input and output voltages \( V_1 \) and \( V_o \) were set at 100 V and 300 V. The operating frequency of the inverter was 80 kHz. The reference power \( P_{\text{ref}} \) was set at 100 W.

The point of negative-sequence component moves to the converged point listed in Table 1 from the origin.

Figure 13 shows distribution of the measured transfer efficiency on the complex plane. The vacant area that is inside the circle of \( \lambda = 1.0 \) denotes that the output power does not reach 100 W. The most of area gaining 100 W is in the first
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Fig. 13. Distribution of measured transfer efficiency under conditions of Fig. 11

Fig. 14. Measured waveforms at the point marking maximum efficiency under conditions of Fig. 11 (The scales for \( v_{u} \), \( v_{v} \) and \( v_{w} \) are 150 V/div., for \( i_{u} \), \( i_{v} \) and \( i_{w} \) are 8.0 A/div., for \( i_{u1} \), \( i_{v1} \), \( i_{w1} \), \( i_{u2} \) and \( i_{w2} \) are 12.0 A/div. and for \( i_{u1} \), \( i_{v1} \) and \( i_{w1} \) are 6.0 A/div.)

quadrant. The observation of this distribution describes that the efficiency monotonically increases. Such monotonical increase is observed in all of the misaligning conditions executed in this paper. However, even if there are several peaks on the distribution, for example, because of employing other type of wireless power transfer pads, addition of simulated annealing algorithm to the control would help convergence to the effective points. The comparison between Fig. 13 and Fig. 12 proves that the proposed control technique performs effectively.

Figure 14 shows the waveforms in the steady state at the point marking the maximum efficiency. Although the inverter currents \( i_{u} \), \( i_{v} \) and \( i_{w} \) are distorted, the primary currents \( i_{u1} \), \( i_{v1} \) and \( i_{w1} \) vary in sinusoidal wave. A brief calculation using table 1 and (4) proves that these primary currents are in proportion to output voltages. The rectifier currents \( i_{ur} \), \( i_{vr} \) and \( i_{wr} \) appear in pulse. The waveforms can be improved by employing a three-phase \( LCLC \) compensator in the secondary side. A leakage magnetic field density at this time, that is an average of magnetic field densities at several points 150 mm-away from the coils, is 2.42 \( \mu \)T. On the other hand, under the balanced operation, the leakage magnetic field density is 5.07 \( \mu \)T. Thus, the proposed control technique can reduce leakage magnetic field.

Figure 15 shows the points marking the maximum efficiency as the polar angle \( \beta \) increases from 0 to \( \pi \) at \( r = 100 \) mm. 70% of the points are near \( \lambda = 1.0 \). This means that the system is operated in significant imbalance condition for gaining higher efficiency. Most of points clearly tend to have more current for the phase in the primary side that highly links with the secondary side. For example, at a condition of \( \alpha = \pi/6, \beta = \pi/4 \), the magnitude of the mutual inductance \( M_{uv} \), which is of the u-phase in the primary side, is the largest, as shown in Fig. 2. The maximum efficiency for this condition is obtained at the point where the u-phase voltage is the largest as listed in Table 1. However, it is difficult to find exact regularity for the distribution of these points because imbalanced inducences of the coils and losses in the inverter significantly affect the position of these points. This means that the sequential search is effective approach.

Figure 16 shows the efficiencies under imbalanced operation based on the proposed control and under balanced operation.

6. Conclusion

This paper presents a control technique for the three-phase wireless power transfer systems at misalignments. The control technique is capable of maximizing transfer efficiency by conducting imbalanced operation. The control uses the positive-sequence component for regulating the output power. Negative-sequence component is used for gaining maximum transfer efficiency, which is determined by the
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sequential search. The modulation technique allows a three-phase inverter to generate imbalanced voltages following the reference the control gives. Tests using the circular wireless power transfer pads with two layers prove that the control can maximizes transfer efficiencies under a required power. The sequential search can be completed in several seconds. The resulting efficiencies are averagely 3% higher than those of the balanced three-phase operation over different misalignment conditions.

References


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