Load Segment Tracking Control of IPT System Based on Power Efficiency Optimization

WENMEI HAO, LIWEI ZHANG, SANMU XIU, AND CHANGQING YANG

School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China

Corresponding authors: Liwei Zhang (lwzhang@bjtu.edu.cn) and Sanmu Xiu (smxiu@bjtu.edu.cn)

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ABSTRACT In the induction electric energy transmission system applied to fix point charging of vehicles, the mutual inductance change caused by position deviation or air gap change, and the equivalent load change caused by power demand change will make the output power and efficiency fluctuate, thus affecting the output stability of the system. In order to ensure the reliability of the charging process of the system and at the same time have a strong power output capacity, this paper proposes a load segmental tracking control strategy based on the optimal power efficiency. This control strategy adjusts the equivalent load to track different power efficiency indicator curves according to different mutual inductance states of the system and power demand when the vehicle is static charging, so that it can always maintain the optimal power efficiency state according to different charging conditions and improve the system performance. Finally, simulation and experimental verification are carried out under different states of mutual inductance. The results show that this method can achieve the equivalent load segmental tracking under different mutual inductance states, and always maintain the optimal power efficiency output.

INDEX TERMS Efficiency, inductive power transmission, load tracking, optimization, power.

I. INTRODUCTION

Inductive power transmission (IPT) technology transfers the power from the power supply to the load side in a non-contact way through electromagnetic induction, which has the advantages of safety, reliability and flexible power supply. It can not only overcome the problems of traditional contact power supply, such as electric spark, carbon accumulation and leakage, but also reduce the maintenance cost and improve the safety performance of the equipment. In recent years, IPT system has become a hot research field all over the world [1]–[3]. At present, IPT technology has been widely used in electric vehicles, medical devices, consumer electronics and other fields [4]–[7], and gradually develops towards high-power directions such as maglev train, urban rail transit vehicle, high-speed railway train [8]–[10].

In the case that IPT system is applied to static charging of vehicles, due to the high energy demand of vehicles and the shortest charging time. Therefore, it is required to have higher reliability and stronger power transmission capacity, and the output power level and efficiency level should be scheduled in a strict range [11]–[13]. However, the change of mutual inductance and equivalent load caused by air gap fluctuation and power demand, respectively, will cause fluctuations in output power and efficiency, and then the output stability of the system [14]. Currently, a certain achievements in the load identification of IPT system when the mutual inductance is invariable have gained by a number of scholars [15]–[18]. Literature [19] achieves the load and the mutual inductance identification of the S/S-type IPT system based on an additional compensating capacitor in the primary side. However, this method increases the complexity of the system and the control difficulty. In [20], the mutual inductance and load resistance of WPT system is identified when the operating frequency is different from resonant frequency of the receiver. Similarly, this method is focused only on the S/S-type IPT system. In [21] the authors treat a similar problem by applying the Particle Swarm Optimization (PSO) algorithm to identify the load parameters in an induction heating application. In [22], multiple coils mounted on the primary and secondary couplers are used to detect the position of the EV. Paper [23] introduces a load detection method for the voltage-fed IPT used in induction heating application systems by using the energy injection mode. In [24], a load detection scheme has been proposed for a wireless power transfer system based on the observation of the transmitter coil.
The basic structure of the inductive power transmission system. The high-frequency AC voltage $U_{in}$ in the figure is generated by the dc voltage of the primary side power grid through the single-phase high-frequency inverter circuit. Through the compensation topology of the primary side, high-frequency AC current $I_p$ is generated in the transmitting power coil $L_p$. The transceiver coil $L_p$ and $L_s$ are coupled with wireless energy transmission through the alternating magnetic field. The second side also adds the compensation topology, and finally the power is transmitted to the load. The load part converts alternating current into DC through high-frequency rectification and transfers it to the load through buck-boost.

For the target topology, the inductive power transmission system circuit can be simplified into the form shown in figure 2. Based on the mutual inductance equivalent model, the resonance coil is equivalent to series inductance and resistance, and the coupling of transmitting side and receiving side is represented by mutual inductance.

In figure 2, $C_p$ and $C_s$ are series resonant compensation capacitors of transmitting side and receiving side coil, $R_p$ and $R_s$ are self-resistance of coils, and $M$ is coupling mutual inductance between them. According to the relations of rectifier and buck-boost circuit, the relationship between the equivalent load $R_{eq}$ and the actual load $R_L$ can be expressed as follow:

$$R_{eq} = \frac{8}{\pi^2} \left( \frac{1-D}{D} \right)^2 R_L$$  \hfill (1)

Using the principle of mutual inductance equivalence, with the equivalent load of receiver side, the circuit on the transmitting side is shown in figure 3.

In figure 3, $Z_r = (\omega M)^2 / Z_2$, $\omega$ is the operating angular frequency of the system. $Z_2$ is the equivalent resistance of the receiving side, and its expression is as follows:

$$Z_2 = R_s + R_{eq} + j\omega L_s + \frac{1}{j\omega C_s}$$  \hfill (2)

In this paper, based on the traditional inductive power transmission circuit, an improved topology of adding DC–DC converter to the secondary side is adopted to make the whole system under control. This paper analyzes three power efficiency indicators of the system: power, efficiency and power efficiency product in detail, and proposes a load segmenting tracking control strategy based on the optimal power efficiency tracking. The equivalent load of the secondary side is adjusted according to different mutual inductance state of the system so as to achieve the optimal power efficiency tracking.

The structure of the paper is arranged as follows: the first chapter introduces the basic structure and related parameters of the induction power transmission system with DC–DC converter; Chapter 2 analyzes the output power, efficiency and power efficiency product parameters of the system within the allowable range of components in detail; According to the results of power efficiency analysis in chapter 2, the optimal power efficiency tracking control strategy of load segmentation is proposed in chapter 3; The fourth chapter carries on the simulation and the experiment, verifies the control strategy effectiveness; Finally, the conclusion is drawn.

II. ANALYSIS OF SEGMENT LOAD TRACKING IPT SYSTEM

The basic structure of the inductive power transmission system using segmental load tracking proposed in this paper is shown in figure 1. DC–DC voltage converter is added to traditional IPT system for real-time load tracking and adjustment. In order to achieve high power factor and high power density, it is necessary to add capacitor resonance compensation. In this paper, SS resonance compensation topology suitable for common high frequency and high power is selected.

The high-frequency AC voltage $U_{in}$ in the figure is generated by the dc voltage of the primary side power grid through the single-phase high-frequency inverter circuit. Through the compensation topology of the primary side, high-frequency AC current $I_p$ is generated in the transmitting power coil $L_p$. The transceiver coil $L_p$ and $L_s$ are coupled with wireless energy transmission through the alternating magnetic field. The second side also adds the compensation topology, and finally the power is transmitted to the load. The load part converts alternating current into DC through high-frequency rectification and transfers it to the load through buck-boost.

In the figure, $R_{eq}$ is the equivalent load before rectification circuit.

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$$Z_2 = R_s + R_{eq} + j\omega L_s + \frac{1}{j\omega C_s}$$  \hfill (2)
Substitute equation (2) into the reflected impedance $Z_r$. The real and imaginary parts are expressed as:

$$
\begin{align*}
\text{Re}(Z_r) &= \frac{\omega^2 C_s^2 M^2 (R_{eq} + R_s)}{\left(\omega^2 C_s L_s - 1\right)^2 + \omega^2 C_s^2 (R_{eq} + R_s)^2} \\
\text{Im}(Z_r) &= \frac{-\omega^2 C_s M^2 \left(\omega^2 C_s L_s - 1\right)}{\left(\omega^2 C_s L_s - 1\right)^2 + \omega^2 C_s^2 (R_{eq} + R_s)^2}
\end{align*}
$$

(3)

In order to maximize the transmitted power of the inductive power transmission system, the transmission of reactive power should be avoided as far as possible. In other words, the transmitting side and receiving side of the coupling coil are required to work together in the resonant state. The system needs to meet the condition of $\omega^2 C_s L_s = \omega^2 C_p L_p = 1$. Thus, equation (3) can be simplified to:

$$
\begin{align*}
\text{Re}(Z_r) &= \frac{\omega^2 M^2}{R_{eq} + R_s} \\
\text{Im}(Z_r) &= 0
\end{align*}
$$

(4)

At this point, it can be concluded that in the resonant state, the value of the primary side’s equivalent load $Z_1$ is as follows:

$$
Z_1 = R_p + \frac{\omega^2 M^2}{R_{eq} + R_s}
$$

(5)

As can be seen from equation (5), the equivalent load of the primary side of the system is determined by mutual inductance and equivalent load, and will change according to different operating states.

III. POWER AND EFFICIENCY ANALYSIS

As the mutual inductance is determined by the actual operation and environment. To avoid unnecessary waste, the rated voltage and current are designed by the high probability range of the mutual inductance, which is denoted as $U_{in\_rated}$ and $I_{p\_rated}$. In this case, there will also be a $Z_{1\_rated}$ equivalent load on the original side, with the value of:

$$
Z_{1\_rated} = \frac{U_{in\_rated}}{I_{p\_rated}}
$$

(6)

A. OPERATION MODE ANALYSIS

According to the relationship between rated $Z_{1\_rated}$ and actual $Z_1$ in the operation process of the system, the system is divided into two operating modes.

1) MODE ONE: $Z_1 > Z_{1\_rated}$

In this mode, $I_p$ is always less than $I_{p\_rated}$. Therefore, in order to ensure higher power output capacity, the primary side input voltage always keeps rated $U_{in\_rated}$ operation. Through calculation, the transmission efficiency and output power of the system can be expressed as follows:

$$
P_{out1} = \frac{U_{in\_rated}^2 \omega^2 M^2 R_{eq}}{\left[\omega^2 M^2 + R_p (R_s + R_{eq})\right]^2}
$$

(7)

$$
\eta_1 = \frac{P_{out1}}{P_{in1}} = \frac{\omega^2 M^2 R_{eq}}{\left[\omega^2 M^2 + R_p (R_s + R_{eq})\right]} \frac{R_s + R_{eq}}{R_s + R_{eq}}
$$

(8)

Output power and efficiency are the performance indicators to evaluate the output capacity of the system. To comprehensively evaluate the output capacity of the system, this paper introduces the product of output power and efficiency, namely power efficiency product $\lambda$, as the third indicator, whose expression is as follow:

$$
\lambda = \eta \times P_{out}
$$

(9)

In this mode, the power efficiency product is expressed as follows:

$$
\lambda_1 = \frac{U_{in\_rated}^2 \omega^2 M^2 R_{eq}}{\left[\omega^2 M^2 + R_p (R_s + R_{eq})\right]^2} \frac{R_s + R_{eq}}{R_s + R_{eq}}
$$

(10)

2) MODE TWO: $0 < Z_1 \leq Z_{1\_rated}$

In this mode, if the voltage is kept in rated $U_{in\_rated}$ operation, the primary side current $I_p$ will exceed the rated value $I_{p\_rated}$, causing irreversible damage to power electronic devices. Therefore, in order to protect power electronic devices and achieve higher power output capacity of the system, the primary side adopts phase-shifting control, making $I_p$ always keep rated $I_{p\_rated}$ operation. At this time, the input voltage of the primary side is less than or equal to $U_{in\_rated}$. Through calculation, the expression of transmission efficiency, output power and power efficiency product of the system can be obtained as follows:

$$
P_{out2} = \frac{I_{p\_rated}^2 \omega^2 M^2 R_{eq}}{\left(R_s + R_{eq}\right)^2}
$$

(11)

$$
\eta_2 = \frac{P_{out2}}{P_{in2}} = \frac{\omega^2 M^2 R_{eq}}{\left[\omega^2 M^2 + R_p (R_s + R_{eq})\right]} \frac{R_s + R_{eq}}{R_s + R_{eq}}
$$

(12)

$$
\lambda_2 = \frac{I_{p\_rated}^2 \omega^2 M^2 R_{eq}^2}{\left[\omega^2 M^2 + R_p (R_s + R_{eq})\right]} \frac{R_s + R_{eq}}{R_s + R_{eq}}
$$

(13)

B. POWER EFFICIENCY ANALYSIS

Next, power, efficiency and power efficiency product analysis are conducted for the above two modes respectively. The required parameters are shown in table 1. In the table, the relationship between $U_{dc}$ and $U_{in\_rated}$ is shown by equation (14). And the $I_{p\_rated}$ is determined by the power level of the system and $U_{in\_rated}$, as shown by equation (15).

$$
U_{in\_rated} = \frac{2 \sqrt{2}}{\pi} U_{dc}
$$

(14)

$$
I_{p\_rated} = \frac{P}{U_{in\_rated}}
$$

(15)

1) POWER

According to equations (7),(11) and their establishment conditions, the three-dimensional surface diagram of output power varying with mutual inductance $M$ and equivalent load $R_{eq}$ can be obtained, as shown in figure 4.

Based on theoretical analysis and engineering experience, combined with figure 4, when the system operates in rated state, that is, $Z_1 = Z_{1\_rated}$, the output power of the system is optimal. According to equations (5) and (6), the matching relationship between equivalent load and mutual inductance...
when the system output power is optimal can be obtained as follows:

\[
R_{eq} = \begin{cases} 
\omega^2 M^2 \left( \frac{U_{in, \text{rated}}}{I_{p, \text{rated}}} - R_p \right) - R_s & M > \frac{R_s}{\omega} \left( \frac{U_{in, \text{rated}}}{I_{p, \text{rated}}} - R_p \right) \\
0 & M \leq \frac{R_s}{\omega} \left( \frac{U_{in, \text{rated}}}{I_{p, \text{rated}}} - R_p \right)
\end{cases}
\]  

(16)

The curve is shown as the red line in figure 8, which is also the dividing line between mode 1 and mode 2.

2) EFFICIENCY

According to equations (8) and (12), the expressions of efficiency in the two modes are the same and independent of voltage and current. Therefore, the two modes are analyzed together. According to the equation (8) and (12), the three-dimensional surface diagram of efficiency changing with equivalent load and mutual inductance is shown in figure 5.

As can be seen from the image, the system also has a resistance mutual inductance curve with the best efficiency. To find out the curve, the efficiency of optimal load derivation, namely \( \frac{d\eta}{dR_{eq}} = 0 \), can be concluded that the system is to achieve the optimal efficiency of the load resistance expression is:

\[
R_{eq} = \omega M \sqrt{\frac{R_s}{R_p}}
\]  

(17)

Draw the curve shown in the black line in figure 8.

3) POWER EFFICIENCY PRODUCT

According to equations (10) and (13), as well as their respective conditions, a three-dimensional surface diagram for the power efficiency product \( \lambda \) is shown in figure 6.

It is difficult to intuitively see the curve of the optimal power efficiency product. This paper differentials the power efficiency product expression with respect to the load \( R_{eq} \), namely \( d\lambda/dR_{eq} = 0 \).

In mode 1, the optimal power efficiency product curve satisfies relation (18).

\[
R_{eq} = \frac{\omega^2 M^2}{4R_p} + \sqrt{\omega^4 M^4 + 16\omega^2 M^2 R_p R_s + 16R^2_p R^2_s}
\]  

(18)

In mode 2, the optimal power efficiency product curve satisfies relation (19).

\[
R_{eq} = \frac{-\omega^2 M^2}{4R_p} + \sqrt{\omega^4 M^4 + 16\omega^2 M^2 R_p R_s + 16R^2_p R^2_s}
\]  

(19)
In order to get the change rule of the optimal power efficiency product, the dividing curve equation (16) of mode 1 and mode 2, and the optimal power efficiency product curve equation (18) and (19) are drawn in figure 7.

In the figure, the red line is the dividing line between mode 1 and mode 2, as well as the optimal power curve. The area below the red line is the area of mode 1, and the area above the red line is the area of mode 2. The blue dotted line is the optimal power efficiency product curve under the mode 1, and it can be seen that it does not fall within the scope of the mode 1. Therefore, the optimal power efficiency product operation cannot be achieved under this mode. The solid blue line is the optimal power efficiency product curve under mode 2, and it can be seen that part of it is in the region of mode 2. By combining equations (16) and (19), the corresponding mutual inductance of the intersection point is denoted as $M_e$. Therefore, when the mutual inductance value is less than $M_e$, the optimal power efficiency product curve is a solid blue line; when the mutual inductance is greater than $M_e$, the optimal power efficiency product cannot be achieved. Thus, the optimal power efficiency product curve can be obtained, as shown in the blue line in figure 8. When the mutual inductance value is greater than $M_e$, the system cannot achieve the optimal power efficiency product operation, and the power efficiency product is no longer used as the power efficiency evaluation indicator.

4) SEGMENT POWER EFFICIENCY ANALYSIS

Based on the power efficiency relationship introduced in this chapter, the relationship between equivalent load and mutual inductance is shown in figure 8. In the figure, the red line is the optimal power curve, the black line is the optimal efficiency curve, and the blue line is the optimal power efficiency product curve. Combining equations (16) and (19), the intersection point of the optimal power efficiency product and the optimal power curve corresponds to the mutual inductance value of $M_e$, and combining equations (16) and (17), the intersection point of the optimal efficiency and the optimal power curve corresponds to the mutual inductance value of $M_p$.

Substitute the value of $M_p$ into equation (8) or (12). Through calculation, it can be concluded that the efficiency of working at the corresponding intersection point of $M_p$ is 87.5%. Then, an equal-efficiency curve of 87.5% is made,
as shown in the cyan line. For comparison, an equal-efficiency curve of 85% is made, as shown in the green line, and an equal-efficiency curve of 90% is shown in the purple line.

It can be seen from figure 8 that under different mutual inductance parameters, equivalent load can track different indicator parameters to maintain the overall optimal power efficiency state of the system. Different $M_p$ values can be selected according to different efficiency requirements. In this paper, 87.5% of the intersection point is selected as the efficiency indicator to simplify the segment interval.

When mutual inductance value is greater than $M_p$, the optimal power curve always keeps the operating efficiency of the system above 87.5%, and the transmission efficiency is at a high level. At this time, the power is taken as the power efficiency matching indicator, and the equivalent load is adjusted to track the operation of the optimal output power curve (red line). On the premise of sacrificing allowable efficiency, the power output of the system is guaranteed as much as possible.

When the mutual inductance value is between $M_e$ and $M_p$, no matter how to adjust the equivalent load, its efficiency is low. At this time, if the optimal power is tracked, its transmission efficiency will be lower, causing unnecessary waste. Therefore, in order to ensure the optimal power efficiency output of the system, the efficiency is taken as the power efficiency matching indicator, and the equivalent load is adjusted to make it track the operation of the optimal power efficiency curve (black line).

When the mutual inductance value is less than $M_e$, the efficiency is lower, the power curve also has a turning point. At this time, the tracking of optimal efficiency and optimal power are meaningless. It may be reasonable to choose a more comprehensive energy efficiency product as the optimization target. Therefore, the power efficiency product is selected as the power efficiency matching indicator, and the equivalent load is adjusted to track the operation of the optimal power efficiency product curve (blue line).

**IV. LOAD SEGMENT TRACKING CONTROL**

Based on the subsection matching relationship between equivalent load and mutual inductance in the previous chapter, a subsection tracking control strategy for IPT system with...
optimal power efficiency is proposed. Mutual inductance, as a quantity that cannot be measured directly, needs to be converted into a measureable quantity. According to the relationship between induced voltage and rectified output voltage, the calculation relation of mutual inductance obtained from the primary side current and rectified output voltage is as follows [27]:

\[ M = \frac{2\sqrt{2}U_{\text{rec}}}{\pi \omega I_p} \]

where, \( U_{\text{rec}} \) is the output dc voltage after rectification.

According to different mutual inductance intervals, the segmented control process is obtained as follows:

1) \( M > M_p \), optimal power tracking, in combination with equation (1) and equation (14), the duty ratio calculation equation is obtained:

\[ D = \frac{1}{\sqrt{\frac{\pi^2}{SK_e} \left( \frac{\omega^2 M^2}{\omega_p \text{rated}} - R_p \right) - R_s} + 1} \]

2) \( M_p \geq M > M_e \), optimal efficiency tracking, in combination with equation (1) and equation (17), the duty ratio calculation equation is obtained:

\[ D = \frac{1}{\sqrt{\frac{\pi^2 \omega^2 M}{SK_e} \sqrt{\frac{R}{R_p}} + 1}} \]
3) $M \leq M_e$, optimal power efficiency product tracking, in combination with equation (1) and equation (19), the duty ratio calculation equation is obtained:

$$D = \frac{1}{\sqrt{-\pi^2 \omega^2 M^2 + \pi^2 (\omega^2 M^2 + 16R_p R_s \omega^2 M^2 + 16R_p^2 R_s^2) + 1}}$$

In equation (21)-(23), once the system is determined, the primary and secondary side coils self-resistance $R_p$, $R_s$, operating angle frequency $\omega$, rated input voltage and current of the primary side $U_{in,\text{rated}}$ and $I_{p,\text{rated}}$, all can be regarded as known quantity. The actual load $R_L$ can be obtained by measuring the output voltage and output current of the system. The control flow chart is shown in figure 9.

At the beginning of operation, in order to ensure system safety, the high-frequency inverter of the primary side has the maximum phase shift angle, and the DC–DC converter of the secondary side has the minimum duty ratio. That is, minimum input voltage and maximum side equivalent load input.

V. SIMULATION AND EXPERIMENTAL VERIFICATION

Based on the above control algorithm, circuit schematics and block diagrams is shown as figure 10, and the experimental platform is built as shown in figure 11.

Simulation and experimental parameters are shown in table 2.

At this time, the primary and secondary side coils are all in the state of complete resonance, and the primary side voltage and current, the secondary side voltage and the secondary side current are all in the same phase. And because of $U_s = j \omega MI_p$, the secondary side current phase is ahead of the primary side voltage phase.

Next, the mutual inductance fluctuation will be verified. The change of mutual inductance is realized by adjusting air gap. Due to the addition of communication between the primary side and the secondary side to realize the transmission of the primary side current information to the secondary side, the secondary side data acquisition in the simulation and experiment needs to add the relevant delay compensation program to reduce the error and realize the control stability.

Keeping the load constant $R_L = 1 \Omega$, the working points located in three sections are selected for verification.
FIGURE 15. Simulation and experimental results of $M = 3 \, \mu H$, $R_L = 1 \, \Omega$.

The simulation and experimental waveforms are obtained as follows.

1) $M = 1 \, \mu H$: The curve of the system output power, efficiency and power efficiency product changing with the equivalent load $R_{eq}$ is shown in figure 12. Based on the control strategy in this paper, in order to ensure the optimal output capacity, at this point, the equivalent load tracks the optimal power efficiency product (the intersection of output power and efficiency), $D = 0.8$, $R_{eq} = 0.0507\, \Omega$. The simulation and experimental waveforms are shown in figure 13.

2) $M = 3 \, \mu H$: The curve of the system output power and efficiency changing with the equivalent load $R_{eq}$ is shown in figure 14. Based on the control strategy in this paper, in order to ensure the optimal output capacity, at this point, the equivalent load tracks the optimal efficiency, $D = 0.62$, $R_{eq} = 0.31\, \Omega$. The simulation and experimental waveforms are shown in figure 15.

3) $M = 6 \, \mu H$: The curve of the system output power and efficiency changing with the equivalent load $R_{eq}$ is shown in figure 16. Based on the control strategy in this paper, in order to ensure the optimal output capacity, at this point, the equivalent load tracks the optimal power, $D = 0.49$, $R_{eq} = 0.88\, \Omega$. The simulation and experimental waveforms are shown in figure 17.

The above results are summarized and analyzed to get table 3. By the FTT Analysis function in the Simulink, the RMS of the fundamental voltage and current can be obtain. As the inductance and capacitance are fully resonant, no reactive power loss, so transmission efficiency

$$\eta_{\text{simulation}} = \frac{U_{2\text{RMS}}I_{2\text{RMS}}}{(U_{1\text{RMS}}I_{1\text{RMS}})}:
$$

As shown in table 3, when mutual inductance is very low (Light vehicle load, very large air gap; Vehicle parking very inaccurate, coil deviation too large), efficiency and output power are both low. In order to ensure the optimal power efficiency of the system as far as possible, the optimal power efficiency product curve is tracked. Under this working state, the secondary side current is high, which will impact the device and increase the loss of DC–DC converter. Therefore, the working state with very low mutual inductance should be avoided.

When mutual inductance is low (Light load, large air gap; Vehicle parking inaccurate, coil offset), the efficiency cannot meet the system efficiency requirements. In order to avoid unnecessary waste, the system tracks the optimal
efficiency curve. Under this working state, the side current is relatively high, and the DC–DC loss is also large.

When mutual inductance is large (Heavy load, small air gap; Accurate vehicle parking), the system tracks the optimal power curve. At this time, the efficiency and power are both high, the primary side current will not be too large, the DC–DC loss is small, and the system works best.

To sum up, within the allowable range of rounding error, simulation and experiment verify the correctness of the theory, and the system can realize the control strategy of segment tracking. In practical application, the system should be kept within a reasonable range of mutual inductance.

### VI. CONCLUSION

When IPT system is applied to the fixed point charging of vehicles, the system mutual inductance and load change caused by the inevitable external factors such as inaccurate positioning and different load will affect the output energy efficiency of the system and reduce the output stability.

Aiming at the above problems, a segmental load tracking control strategy based on optimal power efficiency is proposed. Firstly, the topological characteristics of IPT system with DC–DC converter are analyzed, and then the power efficiency characteristics under different working modes are analyzed by taking power, efficiency and power efficiency product as indicators, next, the principle of load segmental tracking control is introduced in detail. Finally, the effectiveness of the control strategy is verified by simulation and experiment. The simulation and experiment draw the following conclusions:

1) Under reasonable mutual inductance range, the system will be in the best power efficiency state with high power and efficiency. When mutual inductance is low, the output power and efficiency of the system inevitably decrease.

2) By adjusting the DC–DC converter on the secondary side, it can achieve better power efficiency output in a large load range.

The method proposed in this paper can provide reference for the best mutual inductance working range and the matching relation between mutual inductance and load in the practical application of IPT system.

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WENMEI HAO was born in Hebei, China, in 1993. She received the B.Sc. degree in electrical engineering from Beijing Jiaotong University, China, in 2016, where she is currently pursuing the Ph.D. degree with the School of Electrical Engineering.

She is currently a Visiting Ph.D. Student with the Politecnico di Torino. Her current research interests include wireless charging technology and power electronics.

LIWEI ZHANG was born in Hebei, China, in 1977. He received the B.S. and M.S. degrees in electrical engineering from Beijing Jiaotong University, China, in 1999 and 2002, respectively, and the Ph.D. degree from the Institute of Electrical Engineering, Chinese Academy of Sciences, China, in 2006.

Since January 2006, he has been working at Beijing Jiaotong University, China, as a Professor. He had studied in the Politecnico di Torino as a Visiting Scholar, from December 2018 to November 2019. His current research interests include wireless charging technology, power electronics, and motor control.

SANMU XIU was born in Shandong, China, in 1975. He received the B.S. and M.S. degrees in electrical engineering from Beijing Jiaotong University, China, in 1997 and 2000, respectively.

Since July 2000, he has been working at Beijing Jiaotong University, China, as a Lecturer. His current research interests include wireless charging technology, power electronics, and ink-jet printing machine control.

CHANGQING YANG was born in Beijing, China, in 1994. He is currently pursuing the B.S. degree in electrical engineering with Beijing Jiaotong University, China. His research interests are power electronics and motor control.