Position-Sensorless Detection of Coil Misalignment for Wireless Static Power Charging of Electric Trains

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Abstract

Misalignment between coils deteriorates power transfer performance in Wireless Power Transfer (WPT) system and one way to deal with such problem is moving the coils to aligned position. To make correct position control, this paper proposes a detection method using a 2-couple coils system which combines the information from the two induced voltages in respective receiving coils to detect the position of coils. The feasibility and robustness of designed detection system is verified by simulation.

Key words: wireless power transfer, electric train, misalignment, sensor-less, position detection, robustness

1 . Introduction

1.1. Static power charging system Wireless Power Transfer (WPT) has the merits such as safety and environment friendly, so it has been applied to many transportation systems, such as Electric Vehicle (EV) and electric railway [1]. In railway applications, two charging methods, called as dynamic charging and static charging, are mainly studied [2][3]. Fig.1 shows the configuration of a static charging system. The train is charged by the wireless charging system when it stops in the station, and powered by the Energy Storage Devices (ESD) when it runs from one station to another [4].

Several couples of coils are used to transfer the required power. As shown in Fig.1, power transmitting coils at the primary side are installed in stations and connected to the power source V_s, power receiving coils at the secondary side are installed under the train and moving with it. Power is transferred inductively via the electromagnetic field between primary and secondary coils.

For efficient charging and stable operating of this system, two basic requirements should be satisfied. Firstly, large power is needed to power the train from one station to the next, since the stopping time at one station is only about 20~30 seconds, charging power should be relatively high. In Light Rail Transit (LRT) condition, required charging capacity is about 100 kW. Further more, high charging efficiency should also be ensured to make this system more economical [5]. Due to the such requirements, Inductive Power Transfer (IPT) method is mostly used because it has higher power transfer capacity at the same scale, when compared with other methods such as electromagnetic resonance and microwave.

1.2 Problem statement and solutions Though IPT method has larger power transfer capacity, it also has demerits. In IPT, power is mainly transferred by magnetic coupling between the coils and power transfer performance depends heavily on coupling condition. If the misalignment between power transmitting and receiving coils is zero or very small, the influence to power transfer performance is small and acceptable. However, with the increase of misalignment, the efficiency decreases quickly and power transfer performance decreases quickly.

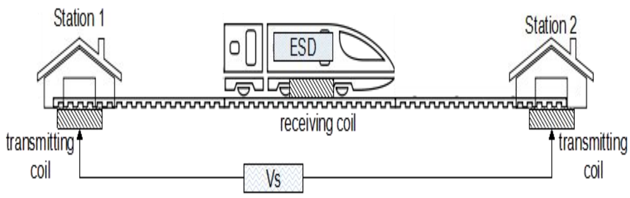

Fig.1 Configuration of static wireless charging system for railway

For railway application, controlling the precise stopping of a train is a difficult task if compared with EV. The misalignment can reach hundred millimeters. In this situation, charging performance will be extremely poor and nearly no power can be transferred, which means more ESD should be used as backup and increases the system cost [4]. As a result, intolerance to misalignment brings an obstacle in the way of commercializing wireless power transfer to railway applications.

Many studies were made to deal with misalignment problems [6]-[8]. Most of them can ensure power transfer performance until the misalignment reaches 1/4 diameter of the transformer. However, charging performance decreases more if misalignment becomes larger. In our study, a system with movable coils are proposed to deal with problems generated by large misalignment. To move the coils, their position should be detected at first. Position estimation and control of EV was studied in paper [9][10]. In paper [9], the authors used additional coils to detect the relative distance between coils, the additional coils make detection complex and they do not detect the relative direction of coils. In paper [10], position of EV is estimated and controlled before it stops. However, unlike EV, it is hard to control a train to stop at the aimed position precisely while it is moving, which means the position of coils should be controlled after the train stops, so a method is needed to detect the position of coils when they are static.

In this paper, to solve the problems mentioned above and make the system simple, a sensor-less method using only two-couple of coils to detect the position is designed and verified by MATLAB simulation. The paper is organized as follows: section 2 introduces the transformer used in the system and design objective, section 3 discusses the detailed detection method, section 4 analyzes the simulation result and the final section 5 shows the conclusion and future work.

2. Core selection and design objective

In section 1.1, the implementation of primary and secondary coils are introduced. To increase the power transfer capacity, ferrite cores are used to improve the magnetic coupling between primary and secondary coils. This system can be regarded as a separate transformer, and different core shape will lead to different charging performance. In this section, selected core for our study is discussed, as well as the design objective.

2.1 Core shapes and size In precedent research [6], characteristics of H, square and circle cores are analyzed by Finite Element Method (FEM) to study the relation between their shape and misalignment tolerance.

As the conclusion, circle core has the best tolerance to misalignment, but square core has the best charging performance within 200mm misalignment. The proposed system in this paper is to move the coils to a relatively aligned position, where the misalignment is very small when power is being charged. For a better charging performance at the aligned position, square cores are selected.

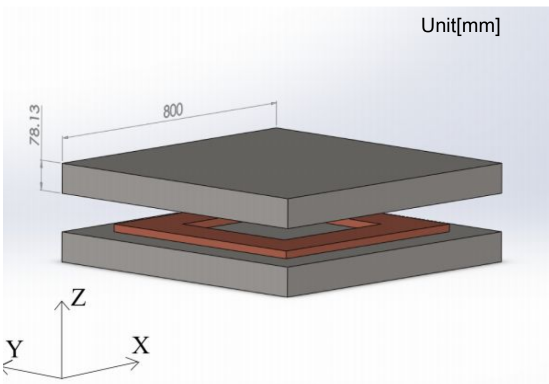

Fig.2 Structure and size of the transformer using square cores

Fig.2 shows the structure and size of the transformer which uses square cores. The maximum width and depth of the core is limited within 800 mm and 80 mm, considering the space where these WPT system is installed. The gap between primary side and secondary side is set to be 100 mm, which is enough to avoid collisions in railway application.

2.2 Equivalent circuit To analyze power charging performance, equivalent circuit of such separate transformer is studied, as shown in Fig.3. The part outside the frame are the topology of power source V_S, load R_L and capacitors C_C=C_S, which are used to compensate the reactive power generated by leakage inductance.

The part inside the frame is the transformer itself. r_1=r_2, X_1=X_2 and they represent the resistors and leakage inductance of primary and secondary sides, respectively. X_m is mutual inductance, through which power is transferred.

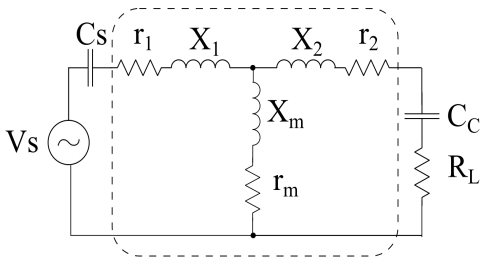

Fig.3 Equivalent circuit of the transformer

2.3 Calculation of power transfer ability and design objective Charging power and charging efficiency of square core transformer are calculated and shown in Fig.4. As discussed in section 1.1, the power needed is about 100 kW for each transformer, so the power requirement can only be satisfied when misalignment is less than 200 mm. Charging efficiency also decreases with the increase of misalignment and becomes extremely low when the misalignment is about 200 mm, which means reactive power is high. Thus the misalignment should be less than 100 mm to ensure charging efficiency.

Therefore, both required power and efficiency can be satisfied if the distance of misalignment can be controlled within 100 mm, which means the errors of position detection should be smaller than 100 mm.

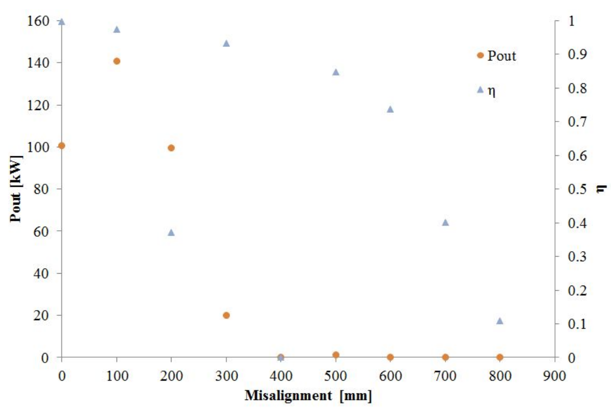

Fig.4 Power transfer performance of transformer using square cores

3. Design of Proposed detection system

In this section, the static electromagnetic characteristics of the system is analyzed to decide the parameter which can be used for position detection, then the details of the design of position detection are discussed.

3.1 Static electromagnetic characteristics of square shape core To design the position detection method, it is important to analyze the relation between electromagnetic characteristics and relative position of coils. Fig.5 shows how the mutual and leakage inductance vary with position in a square core transformer, respectively.

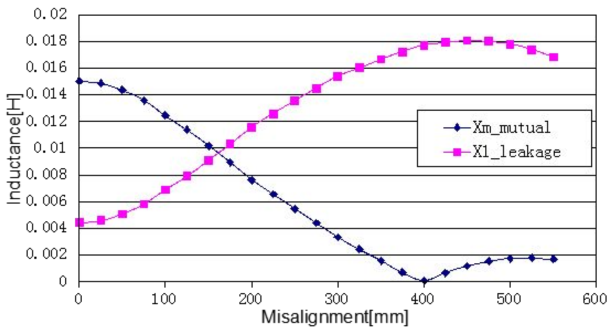

Fig.5 Inductance at each position

When the secondary side is open circuit, the induced secondary output voltage V_{oc} can be calculated by eq.(1), according to the equivalent circuit in Fig.3.

$$V_{oc} = \frac{j\omega X_m}{j\omega X_m + j\omega X_1 + r_1} V_s \approx \frac{X_m}{X_m + X_1} V_s \quad \text{.............(1)}$$

The power source V_s=15 V and frequency f=10 kHz, secondary side of the circuit is made open circuit. Then induced voltage in secondary coil V_{oc} is obtained in Fig.6.

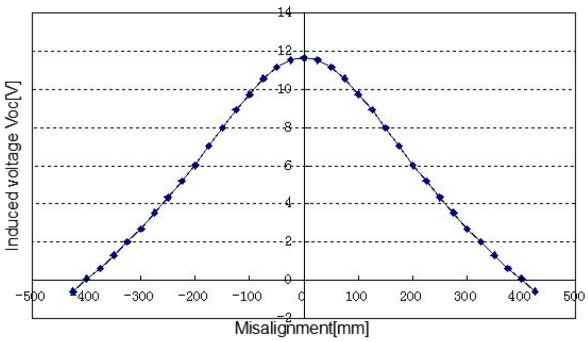

Fig.6 Voltage induced in secondary coil

Amplitude of the induced voltage is proportional to the misalignment in this figure. However, there will be some problems if only the amplitude of the induced voltage in a single couple of coils is used for position detection. Firstly, after train stops, the position of secondary coils may be either before or after primary coils along the moving direction of the train, but symmetry of this curve makes it impossible to detect the direction. Also, small deviations can happen between primary and secondary coils and change the gap length, which will also generate detecting errors if only the characteristic of a single couple of coil is used to detect the misalignment distance.

In this paper, the proposed system gives a way to detect the direction, and improves the robustness against deviation as well. It will be introduced as direction detection and distance detection, respectively.

3.2 Proposed direction detection method In this section, a 2-couple coil system is designed. This system includes two couple of coils: the rear couple of coils R_1,R_2 and the front couple of coils F_1,F_2. Their size and shape are discussed in section 2.2. Fig.7 shows how they are implemented.

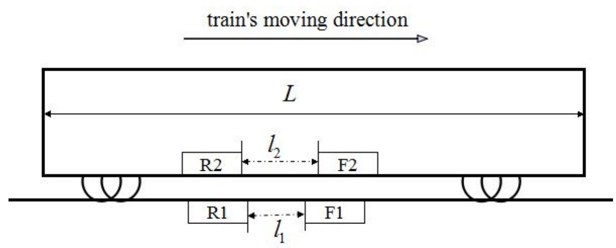

Fig.7 Implementation of designed system

The length of the vehicle L is 20 m, so intervals between the coils at the same side can be set large enough to ignore the interference between them. Then the voltage $V_{r\text{-}oc}$ induced in R2 and $V_{f\text{-}oc}$ induced in F_2 can be expressed by eq.(2)-(3).

$$\hat{V}_{r-oc} = \frac{X_{rm}}{X_{rm} + X_{r1}} \hat{V}_s \quad \text{..(2)}$$

$$\hat{V}_{f-oc} = \frac{X_{rm}}{X_{rm} + X_{f1}} \hat{V}_s \quad \text{..(3)}$$

To detect the direction of secondary coils, interval l_1 is set 50 mm wider than interval l_2 to generate a spatial offset between these two couple of coils. For example, in the moving direction of the train, when the position of F_2 is 100 mm before that of F_1, R_2 will be only 50 mm before R_1. This offset in misalignment will lead to different coupling condition between each couple of coils, as well as the induced voltage. If F_1 and R_1 are connected to the same power source, the induced voltage in F_2 and R_2 will have the same in phase but different amplitude. As expressed in eq.(4)-(5).

$$\hat{V}_{f-oc} = V_{f-oc} \cos(\omega t) \quad \text{..(4)}$$

$$\hat{V}_{r-oc} = V_{r-oc} \cos(\omega t) \quad \text{..(5)}$$

Fig.8 is obtained after calculating the amplitude of induced voltages when secondary coils are at different position. Comparison of voltages induced in different secondary coils is applied to detect the direction, details are defined as follows:

(1) In region A ($V_{f\text{-}oc} > V_{r\text{-}oc}$), the center of secondary coils is behind that of primary coils, the position of secondary coils is defined as negative.

(2) In region B ($V_{r\text{-}oc} > V_{f\text{-}oc}$), the center of secondary coils is before that of primary coils, the position of secondary coils is defined as positive.

(3) At point C ($V_{f\text{-}oc} = V_{r\text{-}oc}$), the center of secondary coils is just above the one of primary, position of secondary coils is defined as zero.

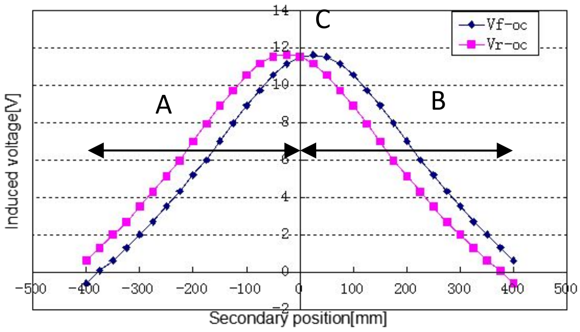

Fig.8 Voltage induced in secondary coils

To achieve such comparison and generate the direction signal V_a in our system, an analog processing circuit is used, the process is expressed by eq.(6)-(7).

V_{com} includes a constant part and an alternating part at double frequency of the power source. After passing a low pass filter, the constant part V_a is obtained. Positive V_a indicates that center of secondary coils is before that of primary ones, while negative V_a indicates the opposite condition.

$$\begin{aligned}\hat{V}_{com} &= (\hat{V}_{r-oc} + \hat{V}_{f-oc})(\hat{V}_{roc} - \hat{V}_{f-oc}) \\ &= (V_{r-oc}^2 - V_{f-oc}^2)\cos^2(\omega t) \\ &= (V_{r-oc}^2 - V_{f-oc}^2)\frac{(1+2\cos(2\omega t))}{2}\end{aligned} \quad \text{.............................(6)}$$

$$V_a = \frac{(V_{r-oc}^2 - V_{f-oc}^2)}{2} \quad \text{...(7)}$$

Function $sign(V_a)$ is used to represent the direction in a simple way. Here, positive, negative and zero position defined in section 3.2 can be represented as +1, -1 and 0 respectively, as in eq.(8).

$$sign(V_a) = \begin{cases} 1 & (V_a > 0) \\ 0 & (V_a = 0) \\ -1 & (V_a < 0) \end{cases} \quad \text{..................................(8)}$$

3.3 Designed distance detection method As mentioned in section 3.1, the induced voltage is almost proportional to the misaligned distance. So our basic idea is referring the detected voltage to this voltage-distance characteristic to calculate the distance.

However, this voltage-position characteristic of a single couple of coils can not be directly applied to distance calculation. In some cases, deviations of vehicle will change the gap length between the coils, as well as their coupling condition and the voltages induced. In this condition, errors will be generated if the voltage-distance characteristic obtained at the original gap length is still used to make distance calculation.

To reduce such detecting errors and increase the robustness of detection system, an analog processing is designed to generate the final distance signal V_b. It is expressed from eq.(9)-(11).

$$\begin{aligned}\hat{V}_n &= \hat{V}_{r-oc}\hat{V}_{f-oc} \\ &= V_{r-oc}V_{f-oc}\cos^2(\omega t) \\ &= V_{r-oc}V_{f-oc}\frac{(1+\cos(2\omega t))}{2}\end{aligned} \quad \text{.......................................(9)}$$

$$V_{nd} = \frac{1}{2}V_{r-oc}V_{f-oc} \quad \text{..(10)}$$

$$V_b = \sqrt{V_{nd}} = \sqrt{\frac{1}{2}V_{r-oc}V_{f-oc}} \quad \text{.......................................(11)}$$

Here, V_n is the product of $V_{r\text{-oc}}$ and $V_{f\text{-oc}}$. After passing a low pass filter, only the constant part V_{nd} is left. V_b is the root of V_{nd}, its value at different position is shown in Fig.9. By combing the processed voltage V_b and this voltage-position characteristic, the distance of misalignment D_m can be calculated.

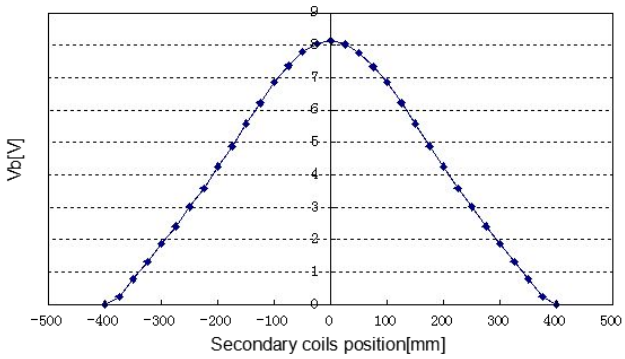

Fig. 9 V_b when secondary coils are at each position

After both $sign(V_a)$ and D_m are obtained, the final detected position information P_m can be obtained as in eq.(12).

$$P_m = D_m \cdot sign(V_a) \quad \text{..(12)}$$

4. Simulation results and analysis

In this section, simulation module of the designed system is built by using MATLAB. Induced voltages of secondary coils when they are at different positions are obtained and processed to generate the final position signal P_m. To analyze the tolerance of system when deviation happens, position detection is also made when gap length is changed.

4.1 Position detection without deviation In this case, gaps between each couple of coils are both set as 100 mm. The range of misalignment is set from -400 mm to +400 mm. Power source V_s=15 V, frequency f=10 kHz. Core structure and size are as discussed in section 2.2. V_a and V_b are obtained and processed to achieve the final position signal P_m.

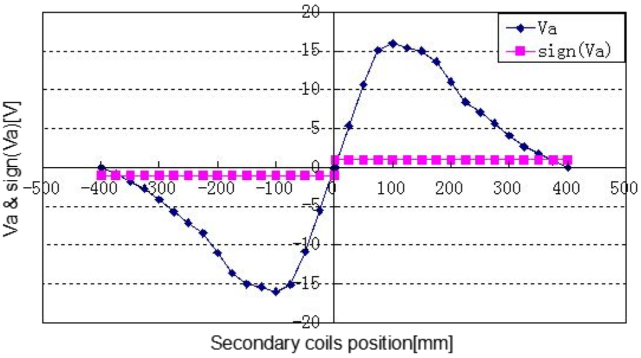

Fig.10 V_a and *sign(*V_a*)* at each position

Fig.10 shows V_a and *sign(*V_a*)* used in direction detection. This figure indicates that the direction of misalignment can be detected correctly when misalignment of secondary coils is from about -400 mm to 400 mm. However, when the distance of misalignment is near 400 mm, V_a is close to zero, which is the same as that when misalignment is zero. In order to avoid such mistake in detection, the maximum detectable misalignment in this paper is limited within the range of [-375 mm, +375 mm].

For distance detection, the induced secondary voltages are processed as discussed in section 3.3, a lookup table is used to generate the whole distance-voltage characteristic as shown in Fig.11. Then the distance of misalignment D_m is obtained by referring the processed V_b to this lookup table.

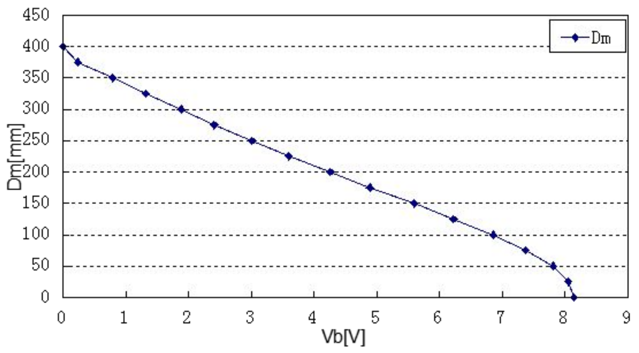

Fig.11 Distance-voltage characteristic

Finally, the position signal P_m is calculated by multiplying the direction signal *sing(*V_a*)* and distance signal D_m. Fig.12 shows the detected position when secondary coils are moved from -375 mm to 375 mm. The result shows that the designed method can detect both the relative direction and distance of coils when misalignment happens within the range of about 1/2 length of the transformer.

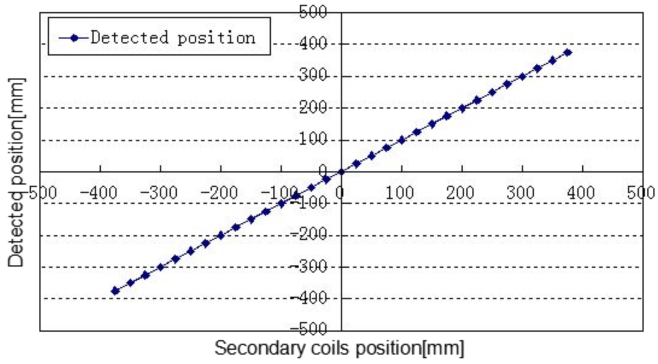

Fig.12 Detected position of secondary coils

4.2 Position detection with deviations The gap length will be changed if small deviation happens. Then the gap between each couple of coils may not be the same. And position detection is also made in such case to analyze the robustness of the designed method.

In this case, the gap between coil R_1 and R_2 is set to be 80 mm, while the gap between F_1 and F_2 is still 100 mm. Other parameters are the same as in section 4.1. Position of the secondary coils is detected when they are moved from -375 mm to 375 mm. Fig.13 shows the simulation result of position detection and detection errors. Although the average error in this system becomes larger, the biggest one is still less than 30 mm. As discussed in section 2.3, the design objective is to make the error smaller than 100 mm, so this detection method is robust against small deviations within 20 mm.

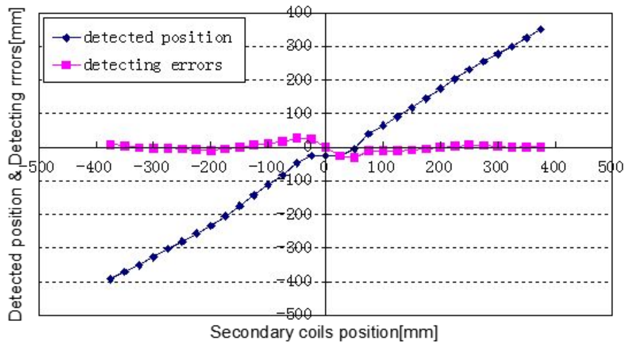

Fig.13 Detected position of secondary coils in case of deviation

Also, as discussed in section 3.3, significant errors may happen if only the induced voltage in a single secondary coil is used. So results of position detection with distance detected by single coil and double coils are also compared, detection errors are shown in Fig.14. From this figure, both average and maximum error are smaller if the voltage induced in two secondary coils are combined to calculate distance. Which means the system robustness against deviations is improved by using the designed method.

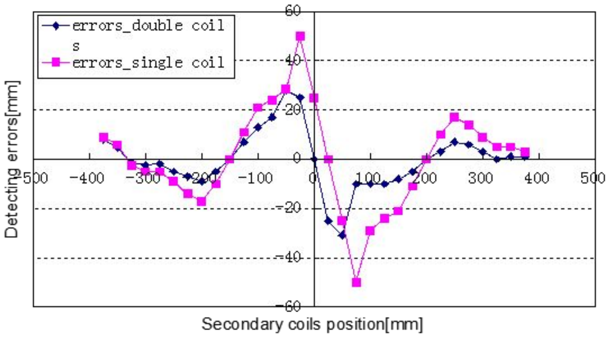

Fig.14 Errors of two distance detection methods

5. Conclusion and future work

In this paper, a coils position detection method is designed for wireless power transfer system in railway application. By only using a two-couple coil system, the detection system become more simple. From simulation results, this system can detect misalignment within the range of about 1/2 length of the transformer, 375 mm in this research. Errors are limited within 30mm even when gap length changes, which means the designed system is robust to small deviations within 20 mm. This detection allows a simple position control of the coils, which means it requires additional hardware for moving the coils. But this is still necessary if considering the misalignment can be significant big when train stops. Compared with precedent researches, this research helps make the charging system more tolerant to large misalignment. Also this research makes it possible to detect the direction when train is static.

In future work, the way to extend detectable range of position will be studied, and experiments will be made to verify the proposed detection method.

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