Experimental Verification of Sensor-less Coil Position Control System and its Gap Deviation Tolerance Improvement Method in Wireless Power Transmission System of Electrical Trains

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Abstract

Based on coil-misalignment information detected form position sensor-less method using magnetic coupling information between primary and secondary coils proposed in our previous publication. We built a test-bench for on-board coil positioning for static wireless power transmission in railway application. A method to improve tolerance to gap deviation of positioning has also be proposed. Performance of both positioning and gap deviation tolerance improving have been experimentally verified.

Key words: wireless power transmission, sensor-less, position control, robustness improvement, gap deviation, position control

1. Introduction

Wireless Power Transmission (WPT) is a technology which can be used to transmit power without physical contact. By applying this technology into railway system, merits such as lower cost, more convenient, safer and less visual obstacle can be achieved. Therefore it has become a popular research topic in recent years.

Inductive Power Transfer, a basic type of WPT, is mostly applied to WPT system designed for railway application due to its high power transmission ability. And its application can be roughly classified as dynamic WPT and stationary WPT[2][3].

Tab_1.1 Comparison of dynamic and stationary WPT system

Type	dynamic	stationary
power [kW]	△	○
efficiency	△	○
safety	○	○
all-envirnoment performance	○	○
install	×	○
maintenance	△	○
misalignment tolerance	○	×

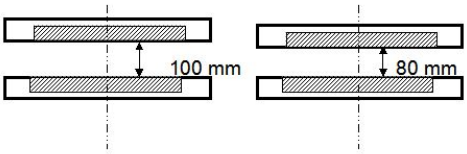
Tab_1.1 shows the comparison of dynamic and stationary WPT system[4][5]. Though stationary WPT system has the advantages such as lower cost and higher efficiency, dynamic WPT is mostly used in commercial applications due to its higher tolerance to misalignment. Therefore, if the misalignment tolerance of stationary WPT system can be enhanced, it will become a more attractive selection for railway WPT system.

Therefore, in our previously published paper[1], we proposed a position sensor-less method which uses magnetic coupling information between primary and secondary coils to detect the position of on-board coils in our previous study. From theoretical analysis, we found that the performance of such system will be affected by gap deviation.In this paper, we proposed a method which can be used to improve the tolerance to gap deviation of the detection system. And then verified both the detection and robustness improving method by experiment.

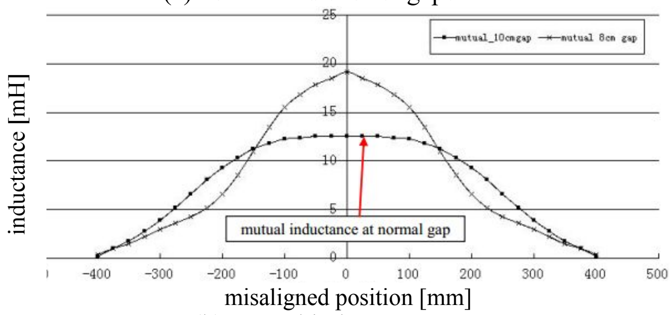
2. Gap deviation tolerance improving method

In our previously published paper. The designed method uses the spatial offset between primary and secondary coils to detect the direction of misalignment, and uses the combination of induced voltage in secondary coils to calculate the misaligned distance. Finally the misaligned position can be obtained by multiplying the direction and distance signal. However, the performance of the designed system will be affected by vertical gap deviation between coils. And detailed analysis is shown below:

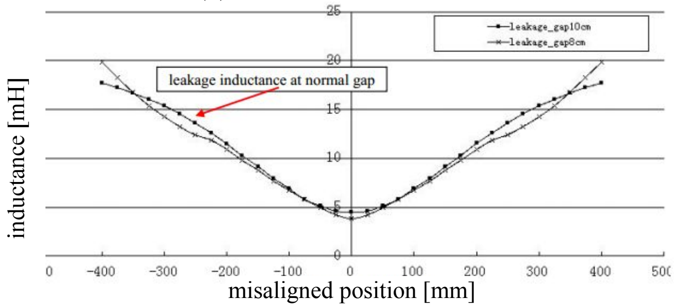
2.1 Effect of gap deviation Vertical gap deviation will occur due to the lean of train body or difference in implementation. And it will affect the accuracy of position detection. Fig_2.1.1 shows the analysis of magnetic field at gap deviation. Figure (a)~(c) shows the condition of different gap length, mutual inductance and leakage inductance, respectively. From the result, mutual inductance increases quickly with the decreasing of gap length, while leakage inductance changes very slow. As a consequence, the coupling coefficient will also change fast with gap deviation.



(a) normal and shorter gaps



(b) mutual inductance

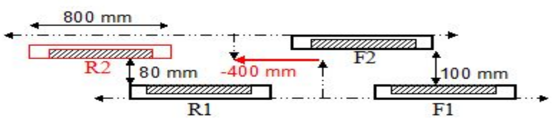


(c) leakage inductance

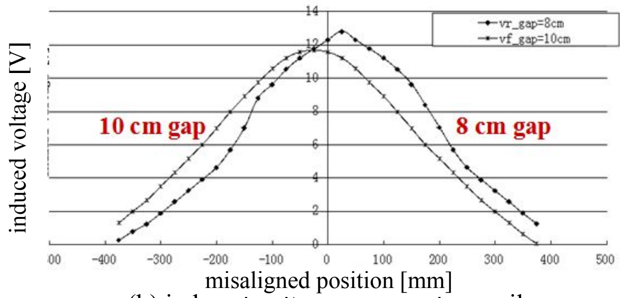
Fig_2.1.1 Magnetic field analysis of gap deviation

If we apply such gap deviation into the proposed detection system, like Fig_2.1.2(a), the detected position will be like Fig_2.1.2(b)~(c).

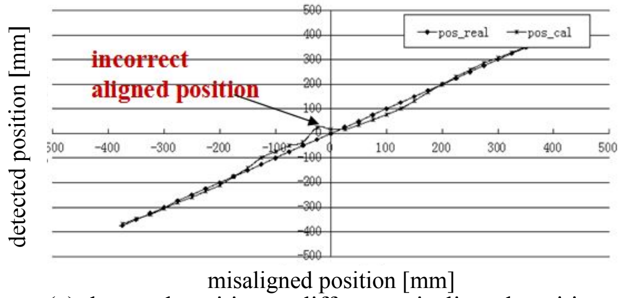
According to such result, the detected aligned position is inaccurate, so the position controlled by using such detection data will still be misaligned. Therefore, a method is needed to eliminate such detection error.



(a) arrangement of coils



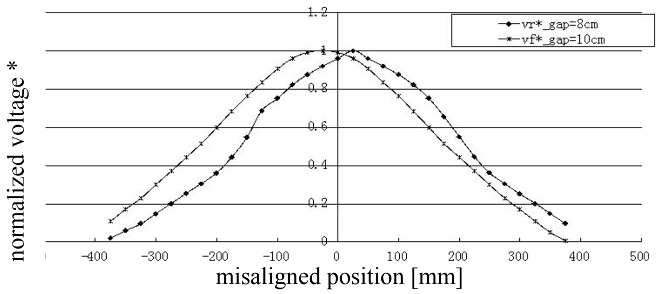
(b) induced voltage in secondary coils



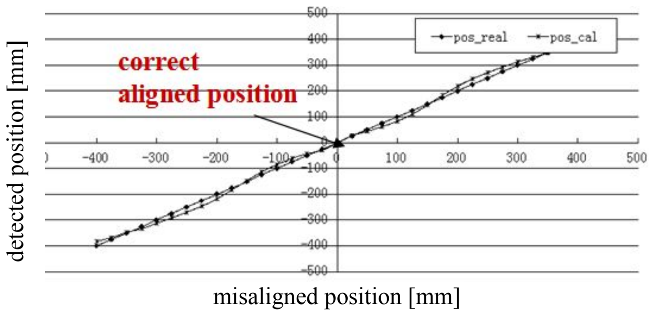
(c) detected position at different misaligned position

Fig_2.1.2 Effect of gap deviation on position detection

2.2 Method designed to eliminate effect of gap deviation



(a) normalized curve of induced voltage



(b) detected position

Fig_2.2.1 Comparison of detected position based on curve normalizing method

By observing the curve in Fig_2.1.2(b), detection error is mainly caused by the changed maximum amplitude of induced voltage. If such change in maximum induced voltage can be eliminated, detection errors will be eliminated as well. To achieve such objective, a method which uses curve normalizing is proposed. If dividing amplitude of the induced voltage at each misaligned position by their maximum value, a new normalized voltage-position characteristic curve can be obtained. The equation is as eq.(2-1), normalized curve and position detected based on this curve is shown in Fig_2.2.1. From this result, the detected aligned position is corrected, and error in distance detection is also reduced.

$$V_2^* = \frac{V_2}{Max[V_2]} \tag{2-1}$$

2.3 Position control sequence Position control will be executed after coil position is obtained. From the above analysis, the proposed method is able to detect the correct position with tolerance to gap length change, if the maximum amplitude of the induced voltage is known. However, since the execution of positioning starts after train stops, the maximum value is unknown at the first. This means the a scanning is needed to obtain the maximum value of the voltages. Thus the position control is divided as three phases:

Phase.I. Preliminary approach to aligned position (close loop)

Purpose of this step is to reduced the scanning range. According to the above analysis, scanning is needed to obtain the maximum amplitude of the value of induced voltage. However, extremely large range is necessity to ensure the necessity data can be obtained if scanning is executed as the first, due to the lacking the initial position, especially direction information. On the other hand, though the position detected by original amplitude-position characteristic curve is inaccurate, it is not totally wrong. Misaligned position can be limited to a smaller range based on the original curve, thus the inaccurate aligned position can be regarded as an "approximately aligned" position in this system. By starting from this relatively aligned position, scanning range will be reduced.

Phase.II. Scanning (open loop)

Scanning will be started after coil stops at the approximately aligned position, in this system, scanning is set fixed based on the maximum error. Thus the maximum value can be obtained in all situations.

Phase III. Accessing accurate aligned position (close loop)

Finally, coil position will be controlled by using the normalized curve. Detected position will be used as feedback and compared with the position reference (0 mm). After the coil reaches aligned position, operation is finished.

3. Experiment verification

3.1 Hardware selection In real application, ferrite cores and coils at the scale of 800*800 mm are used for transmission of high power (100 kW) . Since this experiment is built to verified the position detection method but not the power transfer ability, and position of coils are detected based on the shape of inductance-position characteristic curve of the coil. Smaller scale equipment set can be selected if it can be used to verified the proposed position detection method.

In this experiment, as shown in Fig_3.1.1, the equipment at 1:5 ratio of the real size are used. Gap length is also reduced at the same ratio to remain the ratio at vertical direction.

Coil turns number is kept as the same as the real one. Turns of coils are selected as 20 (turns) x 5 (layers). Wires are ϕ 1.6 copper wire, which are used in usual WPT applications. Parameters of the core and coils are as shown in Tab_3.1.1.

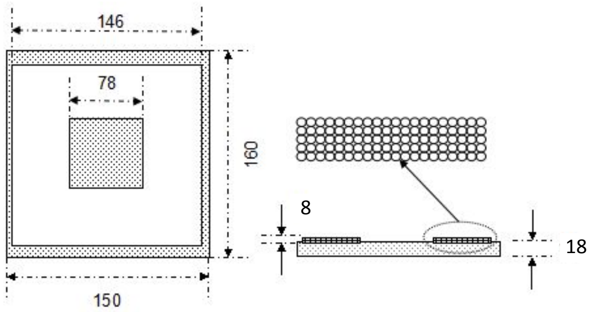


Fig_3.1.1 Coil&core used in experimental bench

Tab_3.1.1 Parameter of core&coil

Parameter		Value	Unit
Core	length	160	mm
	width	150	mm
	height	10	mm
	material	ferrite	/
Coil	turns	20	/
	layers	5	/
	material	Φ 1.6 copper wire	mm
gap		20	mm

About moving device, 300 mm ball screw and stepping motor are selected, as shown in Fig_3.1.2

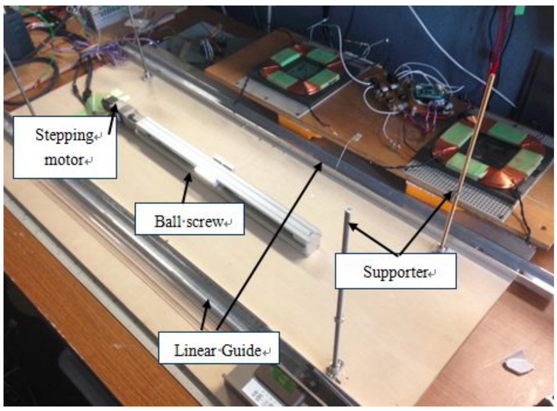


Fig_3.1.2 Ball screw and stepping motor

Finally, based on the reduced size of experiment bench and target of real system designing. Target of this system can be summarized like following:

(1) Verify if the designed system can detect coil position accurately within the range of 80 mm, and control the misalignment within 10 mm.

(2) Make assessment of system robustness against gap deviation.

3.2 Position detection and control Three cases are studied in this section, case 1 is the ideal condition in which no gap deviation happens. While case 2 and 3 are common conditions in which coil gap length are changed by vertical gap deviation.

Case 1: R1&R2 gap=20 mm, F1&F2 gap=20 mm.

Firstly, both gap length are set as 20 mm. Fig_3.2.1 shows the situation when misaligned position is -80 mm as an example. Power source at primary side is set as $V1$=40 V, f=5 kHz.

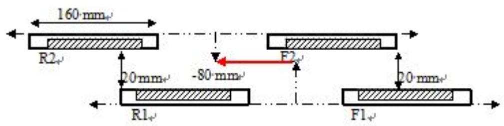


Fig_3.2.1 Coil arrangement

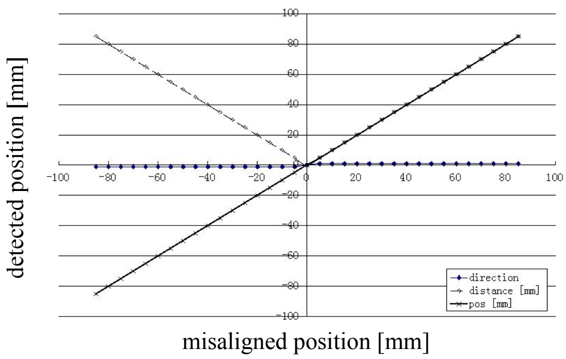


Fig_3.2.2 Detected position

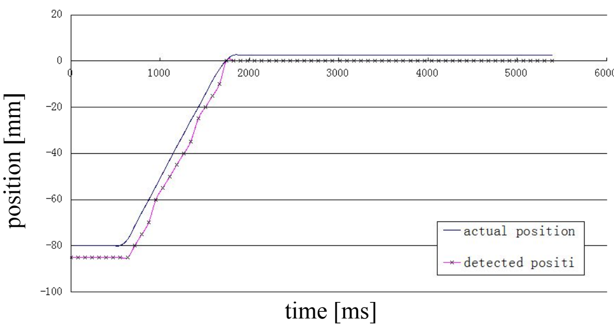


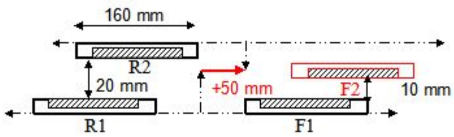
Fig_3.2.3 Performance of position control

Fig_3.2.2 shows the detected position when secondary side is set at each misaligned position. Form this figure that the position can be detected accurately.

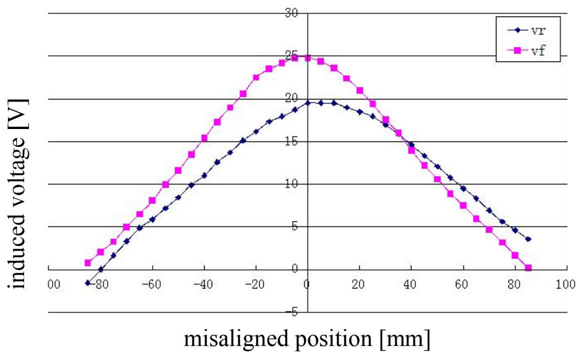
Fig_3.2.3 shows detailed performance when secondary side stops at -80 mm, the most rear condition. Also experiments are made at other starting positions. Among them the maximum execution time is less tan 2 s, 6.67% of dwelling time, if the average dwelling time is 30 s. The final misalignment of all these cases can be controlled within 5 mm.

Case 2: R1&R2 gap=20 mm, F1&F2 gap=10 mm.

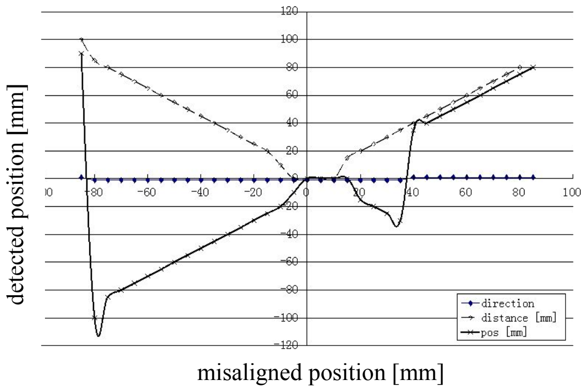
This case studies the system performance with reduced gap length. For instance, arrangement of coils at +50 mm misaligned position is shown in Fig_3.2.4(a). Power source at primary side is still set as $V1$=40 V, f=5 kHz



(a) Coil arrangement



(b) Induced voltage in two secondary coils



(c) Detected position

Fig_3.2.4 Performance of position detection with reduced gap length

Induced voltage and detected position are shown in Fig_3.2.4(b) and Fig_3.2.4(c), respectively. Unlike the curve in Fig_3.2.2, it is easy to notice the difference between detected position in this curve. Since gap of R1&R2 is much larger than gap of F1&F2, amplitude of Vr is much smaller. In Fig_3.2.4(c) the aligned position, which is obtained by comparing amplitude of two voltage, are moved forward by about 40 mm, 25% of the coil length.

Which means huge errors of position occurs due to such gap deviation. Also from the same figure, direction signal becomes useless due to its low value, thus detectable range in this condition is (-80 mm, +80 mm).

Firstly, position will be only controlled based on this unnormalized amplitude-position characteristic curve to evaluate the error. Here the starting position is selected at +80 misaligned position. Result is shown in Fig_3.2.5. Coils are stopped at a inaccurate aligned position due to the inaccurate position detection. Final misalignment of secondary coils is at about +50 mm, which means that this position control is not successful. Several tests at other position are made and have the similar results. As a conclusion, gap deviation must be considered to make this system reliable.

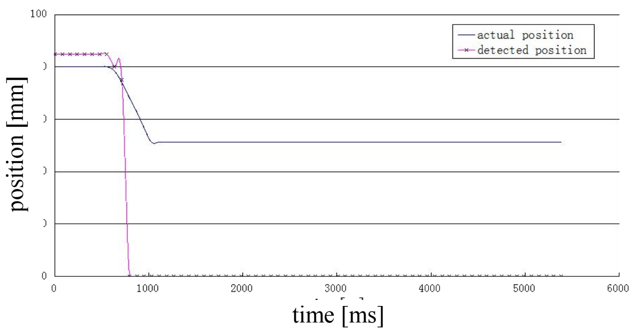
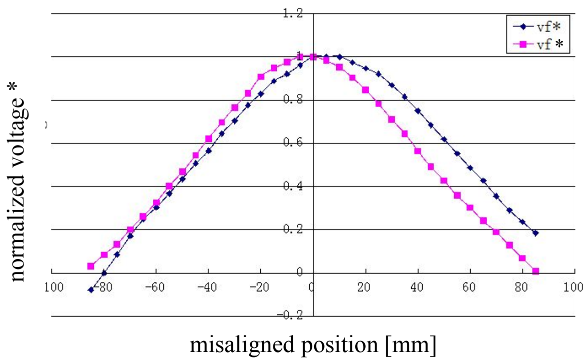
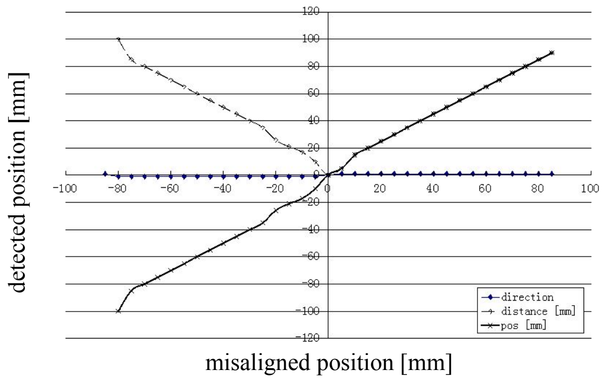


Fig_3.2.5 Position controlled by using original curve

Then, the proposed curve normalization method is used to improve performance of position detection and control. Normalized curve is in Fig_3.2.6(a), detected position is in Fig_3.2.6(b). From this figure, the detected aligned position is moved back to the correct position by using the curve normalization method. Small errors of distance detection are still existing but also reduced greatly.



(a) Normalized curve



(b) Detected position

Fig_3.2.6 Performance of position detection based on normalized curve

Then the coil position is controlled by using the normalized curve, and the result is shown in Fig_3.2.7. From this figure, the error of controlled position is less than 3 mm, which satisfied the design target. Experiments are also made at other starting positions, and the errors are all less than 3mm, which can satisfy our design target.

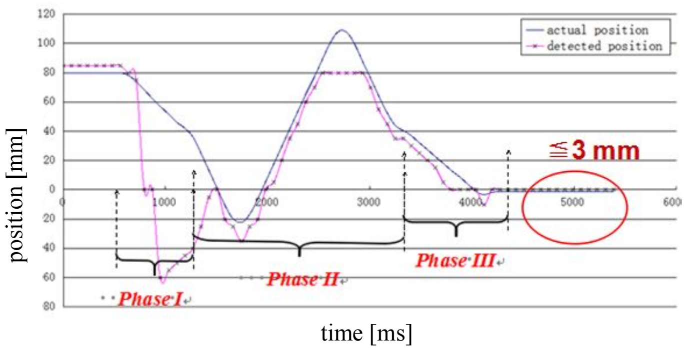


Fig_3.2.7 Performance of position control based on normalized curve

Case 3: R1&R2=20 mm, F1&F2=40 mm.

This case studies system performance when gap length is increased by gap deviation. Coil arrangement is shown in Fig_3.2.8.

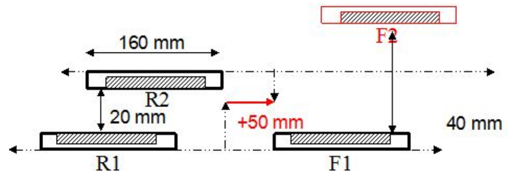
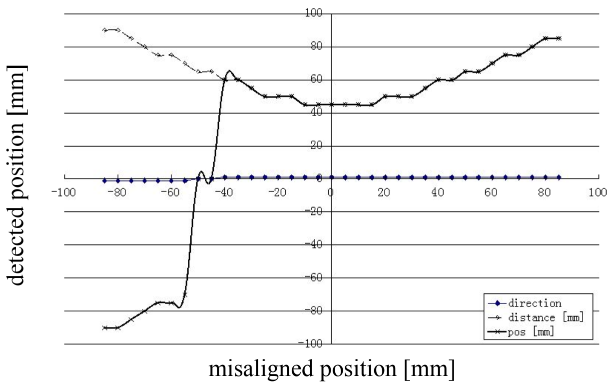
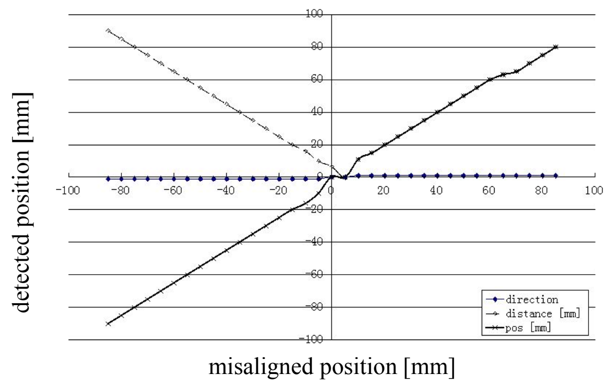


Fig_3.2.8 Coil arrangement with increased gap length

By using the same curve normalization method in case 2. The detected position information can also be corrected. Fig_3.2.9 shows the comparison of position detected by original and normalized curve. From this comparison, the error of detected position is reduced greatly.



(a) Position detected based on original curve



(b) Position detected based on normalized curve

Fig_3.2.9 Comparison of position detection based on original and normalized curve

Finally, coil position is controlled by using the designed control method. Fig_3.2.10 shows the result of position control from the misaligned position at -80 mm. The misaligned position can be controlled within 3 mm in the end, which satisfies the design target. Experiments made at other starting position have the similar results. Which verify the robustness of the designed position detection and control method.

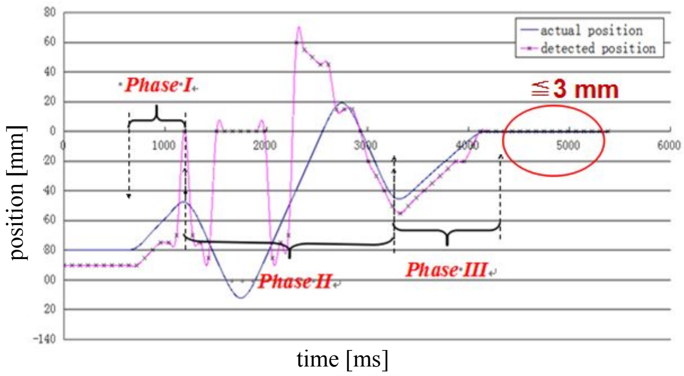


Fig_3.2.10 Performance of position control based on normalized curve

4. Conclusions

For stationary WPT system used for electrical trains, we proposed a system which can control on-board coils by using a sensorless position detection method to achieve maximum charging performance in previous paper[1]. In this paper, an experiment bench is built to verify the proposed method. From the result, the proposed method can satisfy the designed target with the normal gap length. However, error will occur when gap deviation happens. Therefore, a new proposal for compensating gap difference with preliminary scanning is used. As the result, the system can detect misalignment within the range of 50% core length and finally control it within 6.25% core length, when the gap deviation happens within the range of -50%~+100%, which means both accuracy and robustness of the proposed system are improved.

Reference

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