Three-phase Wireless Power Transfer for Dynamic Charging of Electric Vehicle for High Efficiency and Reducing Voltage Unbalancing Considering Magnetic Flux Canceling

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Most of the available Electric Vehicles (EVs) can hardly be driven for long distances due to battery limitations. Therefore, as one of the most promising solutions, dynamic-hcarging based wireless power transfer (WPT) from coils under the ground to EVs has been widely studied recently. For dynamic charging of EVs, high power transmission is needed, moreover, the charging system should be robust to large gap and large misalignment. Therefore, in this paper, three-phase alternating current WPT system is for dynamic charging of EVs. In this paper, specifically, V-minus type is proposed to increase efficiency and decrease the the rate of voltage unbalancing. The rectangular coil, which is suitable for dynamic charging, is applied to transmit three-phase power. The performance of proposed methods is verified by simulations and experiments.

Keywords: Wirelss Power Transfer, Magnetic Resonance Coupling, Three-phase Alternating Current, Electromagnetic Field, Cross Coupling

1. Introduction

Electric Vehicls(EVs) are considered to be better in comparison with internalcombustion engine-based vehicles in terms of controllability and enviromental-friendly [1]. Nevertheless, Nevertheless, most of the off-the-shelf EVs have short crusing range due to small capacity of batteries. In order to solve this problem, the concept of wireless power transfer (WPT) from coils under the grouond to EVs while driving is proposed [2] [3]. Dynamic charging can reduce the burden of battery charging, prevents electric shock, and enable EVs to drive longer.

As one of the WPT methods , magnetic resonance coupling, which was found in MIT (Massachusetts Institute of Technology) is gathering attentions [4]. This is the method of tuning resonance frequencies of the transmitter and the receiver. It can work over misalignment and long gap. It is considered to be applicable to dynamic charging. Besides, three-phase alternating current is suitable for high power transmission because it can reduce the number of semiconductor devices and the ohmic loss. Three-phase WPT, which integrates WPT via magnetic resonance coupling and three-phase alternating current, is a suitable method for the dynamic charging for EV [5].

However, the transmission of phase-different electric power from multiple coils has many difficulties. Cross coupling occours between another phases, and the fluxies generated by other phases disturbs each others [7]. This may lower the efficiency [8].

In this paper, firstly, a detailed account in three-phase WPT is explained. Secondly, new three-phase WPT method, V-minus type, is proposed for the dynamic charging. Thirdly, analysis method of three-phase WPT is shown. Finally, simulation and experiment results are provided to demonstrate the advantages of the proposed method.

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2. Outline of the three-phase wireless power transfer

2.1 Three-Phase WPT for dynamic charging

There were researches about three-phase WPT. However, these papers focused on only WPT of three-phase to single-phase [9] [10], studied limited coil shape such as circular coil [5] [6] or sector [11] [12], or ignoring the mutual inductances between coils which is not the same phases.

Assuming that dynamic charging for EVs, WPT from rectangular three-phase coils buried in the road to rectangular coils loaded on the bottom of EV as shown in Fig.1. In this paper, to simplifications, WPT to EV while stopping is considered. Fig.2 shows the equivalent circuit of three-phase WPT. In order to consider the premise of the accounting unbalanced three-phase, three-phase four-wire system is used.

3. Equation of three-phase wireless power transfer

Considering cross-coupling between several coils, three-phase WPT can be caluculated by Eq.(1). The parameteres and variables are defined as table.1.

$$\begin{bmatrix} V_{1a} \\ V_{1b} \\ V_{1c} \\ V_{2a} \\ V_{2b} \\ V_{2c} \end{bmatrix} = \begin{bmatrix} R_{1a} & j\omega M_{1a1b} & j\omega M_{1a1c} \\ j\omega M_{1b1a} & R_{1b} & j\omega M_{1b1c} \\ j\omega M_{1c1a} & j\omega M_{1c1b} & R_{1c} \\ j\omega M_{2a1a} & j\omega M_{2a1b} & j\omega M_{2a1c} \\ j\omega M_{2b1a} & j\omega M_{2b1b} & j\omega M_{2b1c} \\ j\omega M_{2c1a} & j\omega M_{2c1b} & j\omega M_{2c1c} \end{bmatrix}$$

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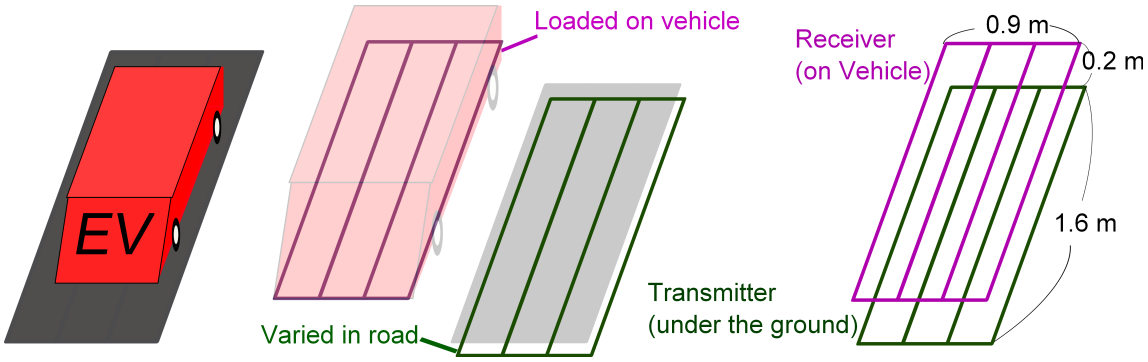


Fig. 1. Appearance of dynamic charging

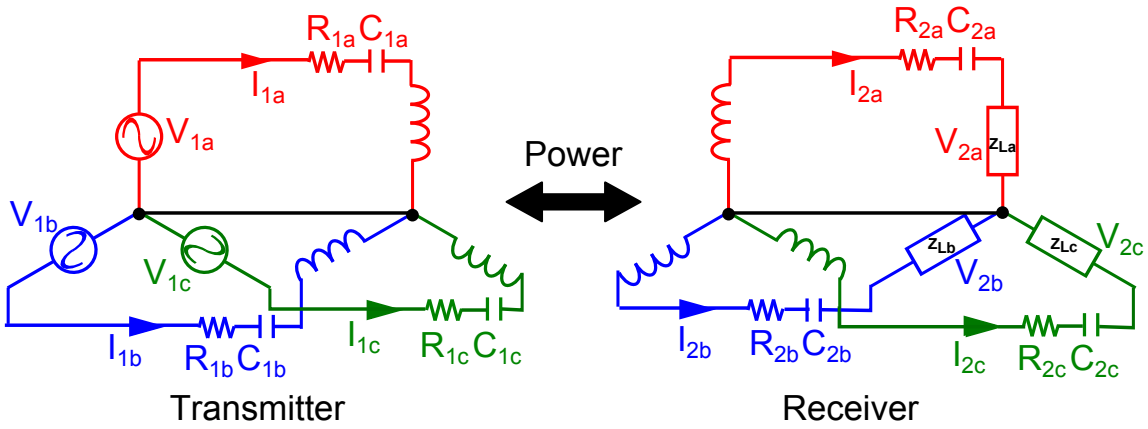


Fig. 2. Equivalent circuit of three-phase wireless power transfer

Table 1. Definition of the symbols

Symbols	Meaning
V_{1a},V_{1b},V_{1c}	Transmitter side voltage
V_{2a},V_{2b},V_{2c}	Receiver side voltage
I_{1a},I_{1b},I_{1c}	Transmitter side current
I_{2a},I_{2b},I_{2c}	Receiver side current
R_{1a},R_{1b},R_{1c}	Transmitter side resistance
R_{2a},R_{2b},R_{2c}	Receiver side resistance
R_{La},R_{Lb},R_{Lc}	Load resistance
C_{1a},C_{1b},C_{1c}	Transmitter side capacitance
C_{2a},C_{2b},C_{2c}	Receiver side capacitance
ω	Resonance angular frequency

$$\begin{bmatrix} j\omega M_{1a2a} & j\omega M_{1a2b} & j\omega M_{1a2c} \\ j\omega M_{1b2a} & j\omega M_{1b2b} & j\omega M_{1b2c} \\ j\omega M_{1c2a} & j\omega M_{1c2b} & j\omega M_{1c2c} \\ R_{2a} & j\omega M_{2a2b} & j\omega M_{2a2c} \\ j\omega M_{2b2a} & R_{2b} & j\omega M_{2b2c} \\ l\omega M_{2c2a} & j\omega M_{2c2b} & R_{2c} \end{bmatrix} \begin{bmatrix} I_{1a} \\ I_{1b} \\ I_{1c} \\ I_{2a} \\ I_{2b} \\ I_{2c} \end{bmatrix} \quad (1)$$

Diagonal elements of impedance matrix in Eq.(1) to be exact, has reactance component due to L and C. In this case, using resonance coupling method, the equation satisfies Eq.(2).

$$\omega = \frac{1}{\sqrt{LC}} \quad \cdots\cdots (2)$$

When deviding Impedance matrix in Eq.(1) into 3×3 matrix, and voltage and current vector into 1×3 matrix, the equation can be simplified to Eq.(3). Each bold-faced type means as shown in Eq.(4) ~ Eq.(9). Symbols as M_{1a2b} means mutual inductances between transmitter phase-A and receiver phase-B.

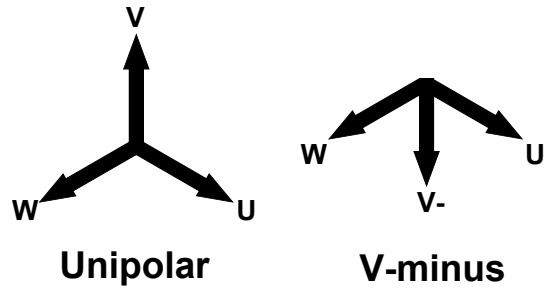


Fig. 3. Phaser of Unipolar-Type and V-minus Type

$$\begin{bmatrix} \boldsymbol{V_1} \\ \boldsymbol{V_2} \end{bmatrix} = \left[\begin{array}{c|c} \boldsymbol{Z_1} & \boldsymbol{M} \\ \hline \boldsymbol{M^T} & \boldsymbol{Z_2} \end{array}\right] \begin{bmatrix} \boldsymbol{I_1} \\ \boldsymbol{I_2} \end{bmatrix} \quad \cdots\cdots (3)$$

$$\boldsymbol{V_1} = \begin{bmatrix} V_{1a} \\ V_{1b} \\ V_{1c} \end{bmatrix}, \boldsymbol{V_2} = \begin{bmatrix} V_{2a} \\ V_{2b} \\ V_{2c} \end{bmatrix} \quad \cdots\cdots (4)$$

$$\boldsymbol{I_1} = \begin{bmatrix} I_{1a} \\ I_{1b} \\ I_{1c} \end{bmatrix}, \boldsymbol{I_2} = \begin{bmatrix} I_{2a} \\ I_{2b} \\ I_{2c} \end{bmatrix} \quad \cdots\cdots (5)$$

$$\boldsymbol{Z_1} = \begin{bmatrix} R_{1a} & j\omega M_{1a1b} & j\omega M_{1a1c} \\ j\omega M_{1b1a} & R_{1b} & j\omega M_{1b1c} \\ j\omega M_{1c1a} & j\omega M_{1c1b} & R_{1c} \end{bmatrix} \quad \cdots\cdots (6)$$

$$\boldsymbol{Z_2} = \begin{bmatrix} R_{2a} & j\omega M_{2a2b} & j\omega M_{2a2c} \\ j\omega M_{2b2a} & R_{2b} & j\omega M_{2b2c} \\ j\omega M_{2c2a} & j\omega M_{2c2b} & R_{2c} \end{bmatrix} \quad \cdots\cdots (7)$$

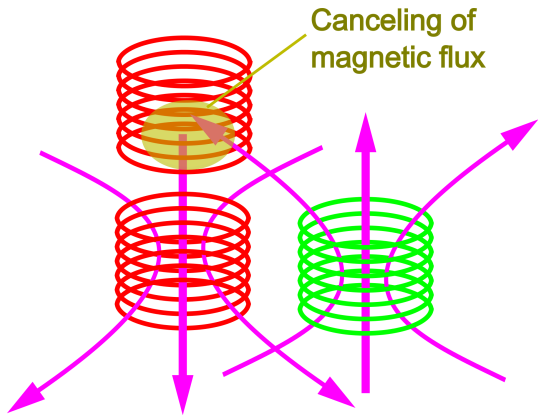


Fig. 4. The image of magnetic flux cancelation

$$\boldsymbol{Z_L} = \begin{bmatrix} R_{La} & 0 & 0 \\ 0 & R_{Lb} & 0 \\ 0 & 0 & R_{Lc} \end{bmatrix} \cdots\cdots (8)$$

$$\boldsymbol{M} = \begin{bmatrix} j\omega M_{1a2a} & j\omega M_{1a2b} & j\omega M_{1a2c} \\ j\omega M_{1b2a} & j\omega M_{1b2b} & j\omega M_{1b2c} \\ j\omega M_{1c2a} & j\omega M_{1c2b} & j\omega M_{1c2c} \end{bmatrix} \cdots\cdots (9)$$

$$\boldsymbol{V_2 = Z_L I_2} \cdots\cdots (10)$$

Defining input voltage as $\boldsymbol{V_1}$, and rearranging these equations order,$\boldsymbol{I_1}$,$\boldsymbol{I_2}$,$\boldsymbol{V_2}$ can be calculated by Eq.(11)~ Eq.(13).

$$\boldsymbol{I_1 = (Z_1 + M(-Z_L - Z_2)M^T)^{-1} V_1} \cdots\cdots (11)$$

$$\boldsymbol{I_2 = (-Z_L - Z_2)^{-1} M^T I_1} \cdots\cdots (12)$$

$$\boldsymbol{V_2 = Z_L(-Z_L - Z_2)^{-1} M^T I_1} \cdots\cdots (13)$$

4. Magnetic flux canceling by shifting phaser (proposed method)

In the previous research of three-phase WPT, three coils are adjacently aligned. Each coil has phase difference of 120 degrees namely the Phase U, Phase V, and Phase W. Because in this conventional method, the three phases has 120 degree difference, when a receiver coil receives the magnetic flux generated by adjacent transmitter coils, as shown in Fig.4, the magnetic flux canceling occurs and efficiency becomes lower. When using threefold asymmetry coils, mutual inductances differs. As a result, the three-phase will be unbalanced. The rectified voltage through three-phase rectifier will become low. And it causes a bad influence on electric power system.

In order to solve these problems, a new method is proposed. As seen in Fig.5 , the center phase is reversed and adjusted coils is only 60 degrees. This may decrease the magnetic flux canceling. In this method, even if horizontal misaligned , one receiver coil covers over two transmitter coils, efficiency is not as lower as the unipolar type as shown in Fig.6. The V-minus type can be realized by reversing the wiring of the central phase or turning the central coil in the other way. Wiring diagram of the each methods are shown in Fig.7. The conventional method is defined as the Unipolar type and the new center-reversed method is defined as the V-minus type. Fig.3 shows the phaser of the Unipolar type and the V-minus type. Fig.5 shows the outline of the coils of Unipolar-type and V-minus type.

Charastristics of the Unipolar type and V-minus type, are compared. Efficiency and rate of voltage unbalancing are considered to evaluate these methods.

5. Outcome measures

5.1 Transmission efficiency Efficiency A_p is the ratio of the sum of the input power to the sum of the output power, and it is shown as Eq.(14).

$$A_p = \frac{Re(\dot{I}_{2a}V_{2a} + \dot{I}_{2b}V_{2b} + \dot{I}_{2c}V_{2c})}{Re(\dot{I}_{1a}V_{1a} + \dot{I}_{1b}V_{1b} + \dot{I}_{1c}V_{1c})} \cdots\cdots (14)$$

5.2 Rate of voltage unbalancing By substituting Eq.(11) for Eq.(13), transformation equation from input voltage to output voltage is shown as Eq.(15).

$$\boldsymbol{V_2 = \Omega V_1} \cdots\cdots (15)$$

where

$$\boldsymbol{\Omega = Z_1(M^T)^{-1} - (Z_1(M^T)^{-1}Z_2 - M)Z_L^{-1}}$$

The Balance of three-phase is maintained when negative phase and zero phase of output voltage become zero. It is when Eq.(16) is given as input voltage. Negative phase and zero phase are calculated as Eq.(17). This is replaced as Eq.(18) where ψ is a complex number.

$$\boldsymbol{V_1} = \begin{bmatrix} 1 \\ \lambda \\ \lambda^2 \end{bmatrix} V \cdots\cdots (16)$$

$$\begin{bmatrix} V_{negative} \\ V_{zero} \end{bmatrix} = \begin{bmatrix} 1 & \lambda & \lambda^2 \\ 1 & 1 & 1 \end{bmatrix} \boldsymbol{\Omega} \begin{bmatrix} 1 \\ \lambda \\ \lambda^2 \end{bmatrix} \cdots\cdots (17)$$

$$\psi \begin{bmatrix} 1 \\ \lambda \\ \lambda^2 \end{bmatrix} = \boldsymbol{\Omega} \begin{bmatrix} 1 \\ \lambda \\ \lambda^2 \end{bmatrix} \cdots\cdots (18)$$

λ means 120 degree rotation as shown in Eq.(19).

$$\lambda = -\frac{1}{2} + \frac{\sqrt{3}}{2} j \cdots\cdots (19)$$

However, it is difficult to satisfy this qualification because the control of transmitter voltage and receiver voltage is needed. So, degree of collapse of three-phase is evaluated as rate of voltage unbalancing.

The rate of voltage unbalancing, k_{ub}, is 100 percentage of negative phase and positive phase, which is calculated by Eq.(20) ~ Eq.(21).

$$\begin{bmatrix} V_U \\ V_V \\ V_W \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \lambda^2 & \lambda & 1 \\ \lambda & \lambda^2 & 1 \end{bmatrix} \begin{bmatrix} V_{positive} \\ V_{negative} \\ V_{zero} \end{bmatrix} \cdots\cdots (20)$$

$$k_{ub} = \frac{|V_{negative}|}{|V_{positive}|} \cdots\cdots (21)$$

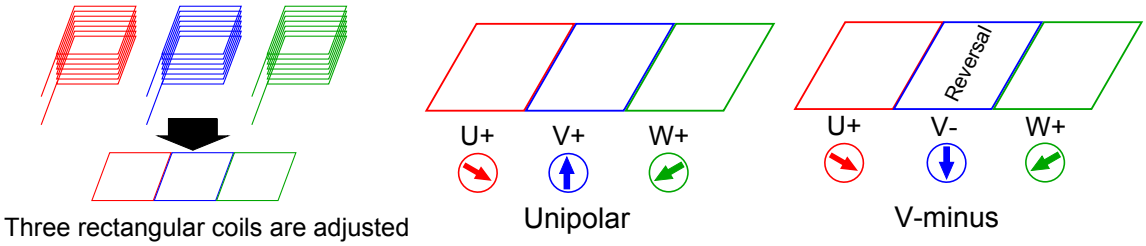


Fig. 5. The configuration of Unipolar-Type and V-minus Type

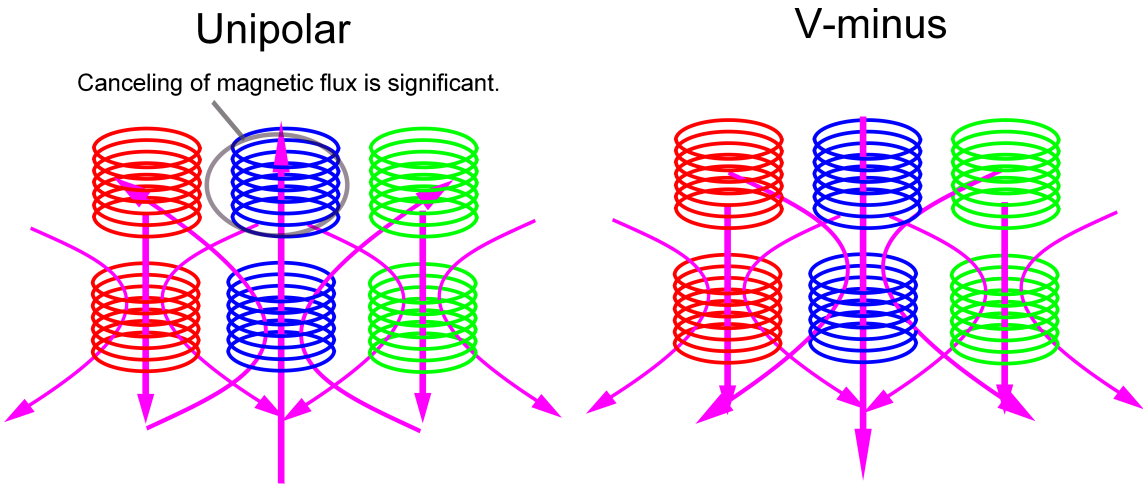
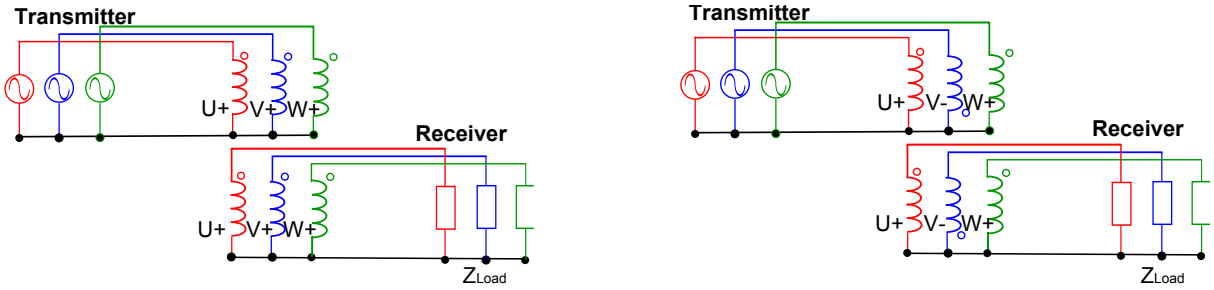


Fig. 6. Canceling of magnetic flux of Unipolar and V-minus



[1]Wiring of Unipolar [2]Wiring of V-minus

Fig. 7. Wiring of Unipolar and V-minus

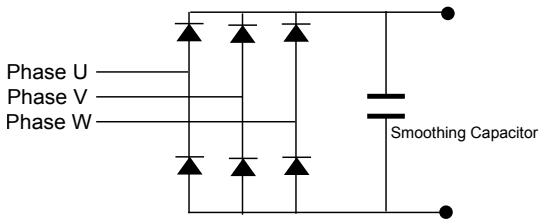


Fig. 8. Three-phase converter

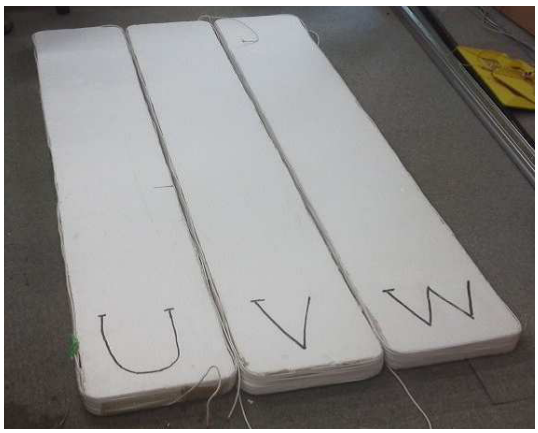


Fig. 9. Manufactured coils

5.3 Rectified voltage ratio For EV applications, three-phase power is charged to smoothing capaciter. Average voltage after rectified by rectifier Fig.8 is evalued. In this case, rectified voltage ratio is defined as the ratio of smoothing capaciter voltage and voltage amplitude of sin-wave source.

6. Experiment and Simulation

6.1 Conditions The shapes of transmitter and receiver coils are designed as 1600 × 900 mm consided from normal size EV. The size of one-phase coil is 1600 × 300 mm. table.2 shows the values of each parameter.

The coils are made by copper wire. The sectional area of the wire is in 2.0 mm unit(average inner radius is 1.8 mm, coating thickness is 0.8mm, conductor resistance is 9.91

Table 2. spec of coils

		Phase U	Phase V	Phase W
Transmitter	Number of turns	15	15	15
	size [m]	0.30 ×1.60	0.30 ×1.60	0.30 ×1.60
	Self Inductance [μH]	523.50	509.12	510.39
	Capacitance [nF]	6.6791	6.8870	6.8677
	Q factor	258	255	244
	Resistance [Ω]	1.090	1.050	1.217
Receiver	Number of turns	15	15	15
	size [m]	0.30 ×1.60	0.30 ×1.60	0.30 ×1.60
	Self Inductance [μH]	513.29	512.08	514.00
	Capacitance [nF]	6.8378	6.8467	6.8211
	Q factor	257	255	256
	Resistance [Ω]	1.058	1.075	1.070

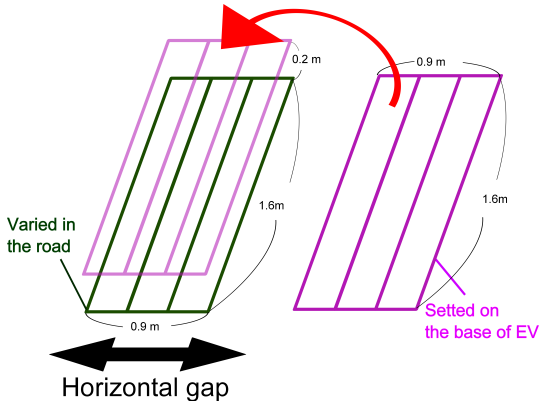


Fig. 10. Coil size of equipments

Ω/km). As the core of coils, expanded polystyrene is used.

Vertical gap between transmitter coil and receiver coil is set as 200 mm considering it is supposed to gap between road and bottom of vehicle. Considering that moving EV misalignes in the cross direction to movement, the x axis is set as horizontal misalignment of transmitter coil to receiver coil. The y axis is set as efficiency and rate of voltage unbalancing.

In the prior reserch of single phase WPT, it is showed that load of the receiver effects the efficiency. In order to maximize the efficiency, changing the receiver load by DC-DC converter is studied [13]. In this paper, the loads of three-phase of receiver is changed to same resistance by which the efficiency is the highest.

Resonance frequency is 85 kHz, which is promoted to standardize for dynamic charging for EV [14].

6.2 Experiment equipments Experiment equipment is shown in Fig.11. It is consisted of resonator coil, load, a stand which supports receiver coils. The 4ch signal generator whose impedance is 50 Ω is used as power source. Sin waves are generated by three-phase inverter Fig.12 so that their phase difference is 120 degree as $10V_{p-p}$. Power analyzer and oscilloscope are used to collect data.

6.3 Simulations and experiment result Mutual inductances between coils are measured by LCR meter. Simulation has done by using each value.

The results are shown in Fig.13, Fig.14, and Fig.15. It is found that proposed the V-minus type, is suitable for improving efficiency and reducing the rate of voltage unbalancing.

Using V-minus type, magnetic flux canceling is lower, the

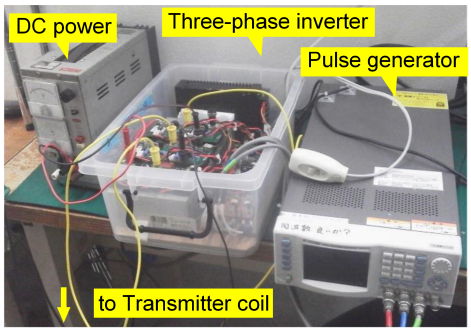


Fig. 11. Institution of experiment

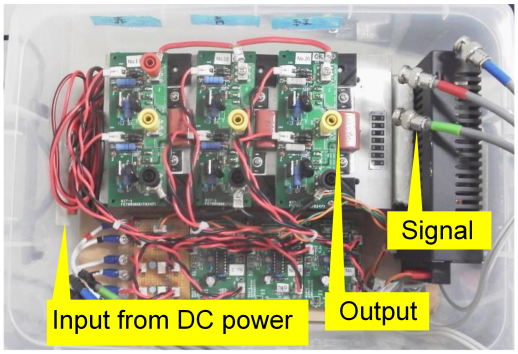


Fig. 12. Three-phase inverter

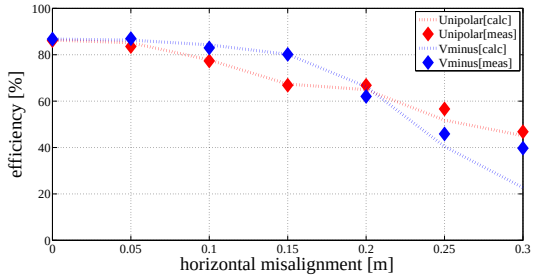


Fig. 13. Simulation result of horizontal misalignment vs efficicency

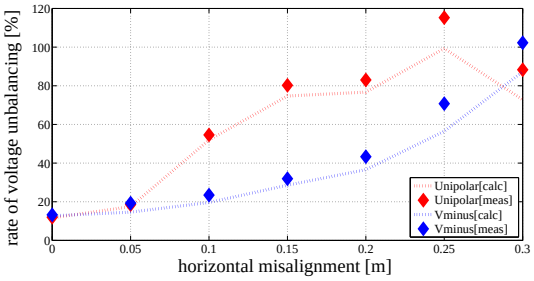


Fig. 14. Simulation result of horizontal misalignment vs rate of voltage unbalancing

induced voltage and the rectified voltage will be higher than using Unipolar type. Furthermore because difference of the phase of alternating magnetic flux is only 60 degree, disturbing by other phases is lowered, and voltage unbalancing occurs less than using Unipolar type.It is shown that proposed method is superior to achieve efficient and lowering of voltage unbalancing.

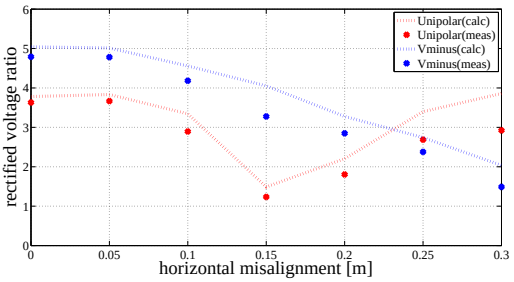


Fig. 15. Simulation result of horizontal misalignment vs rectified voltage

When horizontal gap is bigger than 0.2 m, rate of voltage unbalancing of V-minus became higher than that of Unipolar it is because when horizontal gap is bigger, zero phase becomes ruling of receiver voltage. Positive phase and negative phase will be similar to zero, and rate of voltage unbalancing, which is rate of positive phase and negative phase, fluctuates easily.

7. Conclusion

In this paper, the V-minus, a new method of three-phase WPT was proposed and its advantages were demonstrated. V-minus works more efficiently even there is horizontal gap. However, using unsymmetric shape coil, the rate of voltage unbalancing is still high. Therefore, in the further, controlling primary and secondary parameters to increase the efficiency and lower the rate of voltage unbalancing will be considered.

As one of the performance criteria, rectified voltage was evalued in this study. But considering that the voltage of the smoothing capaciter was measured in an unloaded condition. Another future works will be evaluating the system performance in the condition that the load resistance is controlled to have the maximum transfer efficiency.

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