A Study on Constant Voltage Design for Single-Frequency Two-Stream Contactless Power Transfer with Cross-Coupling

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Abstract This paper proposes a voltage stabilization scheme for feeding constant voltage to receiver in single-frequency two-stream contactless power transmission under the presence of cross coupling among couplers. We have demonstrated that the constant voltage could be provided to receiver load with mitigating cross coupling by inserting a compensation block followed couplers at receiver. In order to obtain more stable voltage rather than previous scheme, dividing a compensation block into two parts is newly proposed. A part of block is placed in the vicinity of transmitter couplers. Computer simulation including electro-magnetic and electric circuit was conducted for comparing the performance.

Keyword IPT, S-P Topology, Single-Frequency Two-Stream Contactless Power Transfer, Constant Voltage, π equivalent model

1. Introduction

Inductive power transfer (IPT) [1] technique has been put into various practical applications such as electric vehicles, electric toothbrushes, smartphones and so on [2]-[3]. These equipments use batteries to store power which is consumed by operation. However, equivalent resistance of battery usually varies during charging time. It causes the changes in behavior or working condition of IPT charging systems, leading to changes on the output voltage as well as the charging voltage for the battery. It will negatively affect charging process. For the above reasons, IPT charging systems need a technique that can enable transmitter to deliver constant voltage to the load of the receiver. Conventional IPT charging system, which utilized single transmitter to deliver power to single receiver and the receiver consists of one load, is called one-stream IPT system. For this kind of system, constant output voltage could be realized by using the compensation schemes of series-parallel (S-P) [4]. More specifically, the transmitting coil is connected in serial to a resonant capacitor while receiving coil is connected in parallel to another resonant capacitor. However, S-P topology cannot be applied for two-stream contactless power transfer system in which two separated transmitters are used to deliver differently constant voltages to two loads of one receiver. In this kind of system, the load voltages are unstable because of the cross-coupling among the coils.

In order to obtain constant voltages for two loads of a receiver in single-frequency two-stream constant power transfer systems, we have proposed a circuit that can suppress the effect of cross-coupling [5]. It can be implemented by adding compensation circuit to receiver-side to cancel out the self-inductances of transmitting and receiving coils as well as mutual inductances between them by symmetrically inserting capacitors if internal resistance in each element is negligibly small. In this study, we have further investigated constant voltage circuit on single-frequency two-stream contactless power transfer under the presence of cross-coupling among couplers as well as internal resistances of the coils.

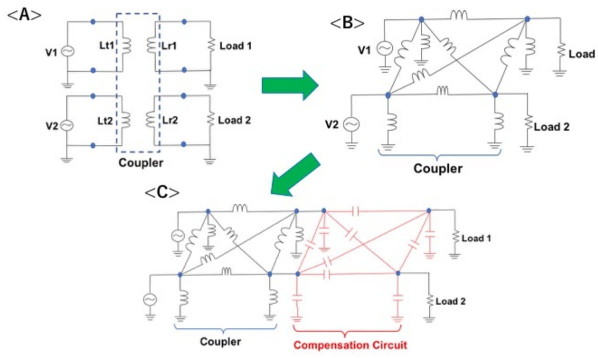

Fig. 1 Constant voltage circuit

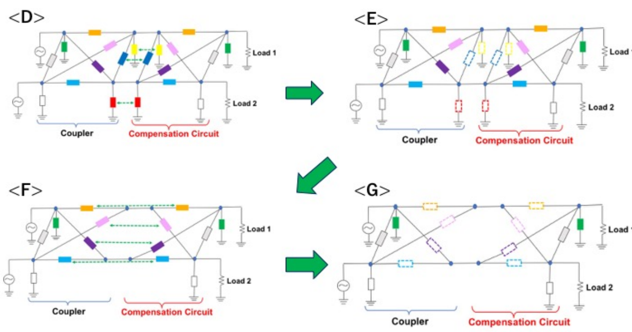

Fig. 2 Flow of canceling out reactance in the coupler

2. Constant Voltage Circuit

The schematic circuit of constant voltage circuit on

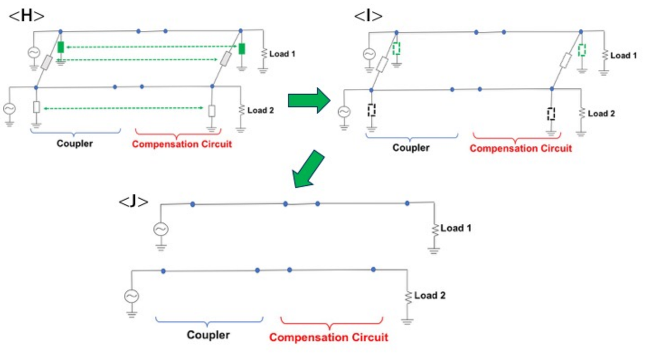

Fig. 3 Flow of canceling out reactance in the coupler

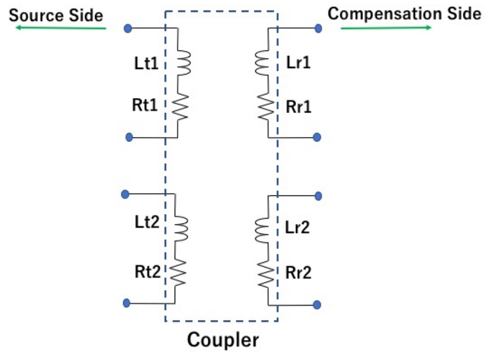

Fig. 4 Coupler including resistance

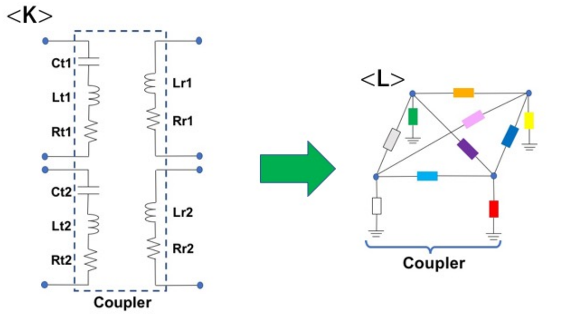

Fig. 5 Equivalent circuit of coupler including resistance

single-frequency two-stream contactless power transfer is shown in Fig. 1. In the figure, V1 and V2 denote the sine-wave constant voltages generated by the power sources. Lt1, Lt2, Lr1, Lr2 are respectively self- inductances of the transmitting and receiving coils. The circuit <A> is the single-frequency two-stream contactless power transfer system without compensation circuit. The circuit <A> is transformed to the circuit <B> by using π equivalent model. Inserting compensation circuit into receiver-side of the circuit <B>, we can obtain the circuit <C>. The value of each element in compensation circuit is determined to cancel out the corresponding reactance of the coupler as shown from Fig. 2 to Fig. 3. The reactance of the element in the coupler are canceled out by each compensation circuit element that have same color. From <D> to <E> in the Fig. 2, the blue element in the compensation circuit cancel out reactance of the one in the coupler. After canceling out the reactance, we can regard both blue elements as open. The same process is applied for the yellow and the red elements. From <F> to <G> in the Fig. 2, the purple element in compensation circuit cancels out reactance of the one in the coupler. Similarly, after canceling out reactance, we can regard both purple elements as open. The same process is applied for the pink elements. The orange element and the light blue element in compensation circuit are inserted into receiving- side in order to cancel out the reactance in the coupler. We can regard these elements as short. From <H> to <I> in the Fig. 3, the green element in the compensation circuit cancels out reactance of the one in the coupler. Canceling out the reactance, we can regard both green elements as open. The same process is applied for the gray elements and the white elements. Finally, we can obtain the circuit <J>, and the circuit <J> shows each load is directly connected to each power source and constant voltage is provided to each load. Therefore, we can design constant voltage circuit on single-frequency two-stream contactless power transfer.

In this paper, we hypothesize each coil in the coupler has internal resistance, as shown in Fig. 4. This resistance of the coil can cause the circuit we have proposed not to suppress the effect of cross-coupling, and prevent it from feeding constant voltage to receiving load. In this work, we propose the method of inserting another compensation block that cancels out the self-inductance of the transmitting coils in addition to using compensation circuit at receiving-side in the conventional method. The Fig. 5 shows the flow of converting the coupler including the internal resistances of the transmitting coils to π equivalent model. Same as the method of making the conventional constant voltage circuit in Fig. 2 and Fig. 3, inserting the compensation block after coupler, the load voltages keep stable at lower range of the loads in comparison with the conventional method. Each element of compensation circuit we proposed in this time can cancel out reactance of the element in the coupler that have same color as in the compensation circuit one by one same as conventional method. This method is expected to keep the load voltages against wider range of the load variations than the conventional method under the presence of the internal resistance in each coils of the coupler.

3. Simulation

We employ LTspice, a free computer software implementing a SPICE electronic circuit simulator, to compare and evaluate the proposed system and the co-

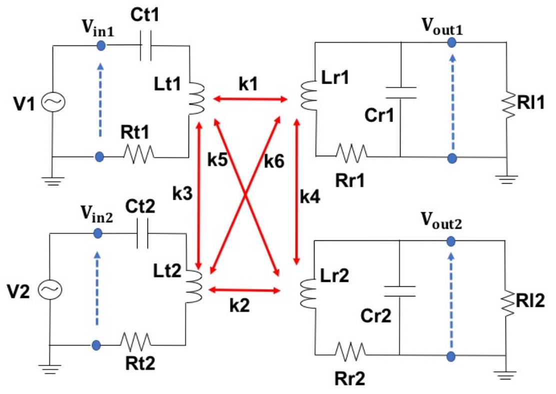

Fig. 6 Simulation model of SP method

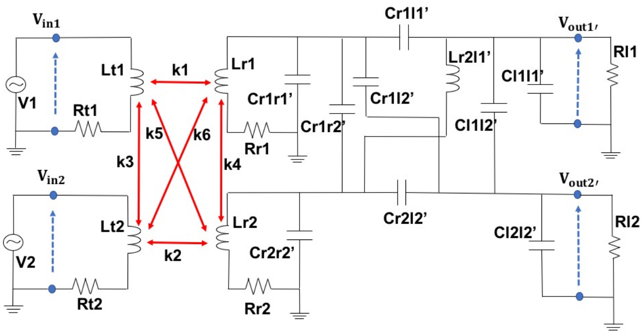

Fig. 7 Simulation of conventional method

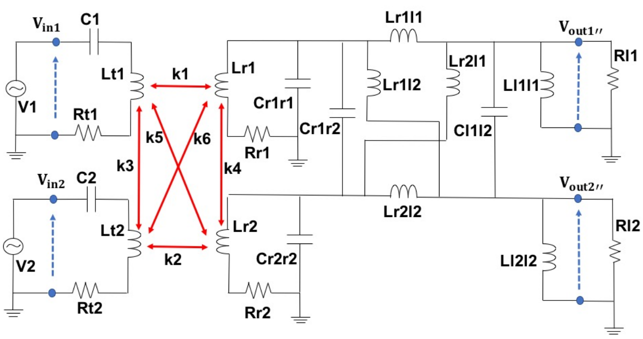

Fig. 8 Simulation model of proposed method

nventional system. The simulation models are shown in Fig. 6 Fig. 7 and Fig. 8. We design these models by using the value of TABLE Ⅰ and TABLE Ⅱ. TABLE Ⅰ shows the value of input voltage, desired voltage of load 1 and load 2, operation frequency, coupling coefficient and element that have in common among simulation models. V1 and V2 are the sources that generate sine wave. Input voltage on load 1 and load 2 are respectively 20 V and 15 V. Desired voltage on load 1 and load 2 are respectively 20 V and 15 V. Operation frequency of both sources is 200 kHz. The value of elements in compensation block on each circuit is shown in TABLE Ⅱ. Title 6 in TABLE Ⅱ shows the parameter of SP method. Title 7 in TABLE Ⅱ shows the parameter of conventional method. Title 8 in TABLE Ⅱ shows the parameter of proposed method. Aside to that, we regard internal re-

TABLE Ⅰ

Value of parameters that have in common among simulation models

Input voltage (V)	V1	20
	V2	15
Desired voltage on load 1 (V)		20
Desired voltage on load 2 (V)		15
Operation frequency (kHz)		200
Coupling coefficient	k1	0.6442
	k2	0.5423
	k3	0.2881
	k4	0.4063
	k5	0.2077
	k6	0.3414

Self inductance (μH)	Lt1	24.58
	Lt2	29.69
	Lr1	24.90
	Lr2	29.59
Resistance (Ω)	Rt1	2
	Rt2	2
	Rr1	2
	Rr2	2
	Rl1	20~200
	Rl2	20~200

TABLE Ⅱ

Parameter of each circuit

6	Capacitance (nF)	Ct1	44.037
		Ct2	30.213
		Cr1	25.432
		Cr2	21.401
7	Inductance (μH)	Lr2l1'	117.11
	Capacitance (nF)	Cr1r1'	7.1530
		Cr2r2'	10.800
		Cr1r2'	12.473
		Cr1l1'	29.290
		Cr1l2'	1.2554
		Cr2l2'	15.677
		Cl1l1'	15.780
		Cl2l2'	9.1094

8	Inductance (μH)	Lr1l1	13.505
		Lr1l2	26.669
		Lr2l1	128.99
		Lr2l2	18.36
		Ll1l1	19.513
		Ll2l2	18.96
	Capacitance (nF)	Cr1r1	46.015
		Cr2r2	28.537
		Cr1r2	20.084
		Cl1l2	18.188
		C1	25.763
		C2	21.329

sistances of compensation circuit as negligibly small. Fig. 9 shows the comparison of the output voltage against the variations of load 1 between the SP method, the conventional method and the proposed method. As shown in this figure, we can see the difference between the SP method, the conventional method and the proposed method when the value of both load increase. The proposed method is most stable around at the desired voltage in the three methods even when the loads vary in low values from 1 Ohm to 50 Ohm. Fig. 10 shows the comparison of the output voltage against the variations of load 2 between the SP method, the conventional method and the proposed method. The results indicate that the proposed method keeps the output voltages most stable around at the desired voltage in three methods even when the load 2 is lower than 50 Ohm. These simulation results demonstrate that the method of inserting compensation circuits into both transmitting-side and receiving-side in single-frequency two-stream contactless power transfer can keep the output voltages more stable than the SP method and the conventional method of only inserting compensation circuit into receiving side does.

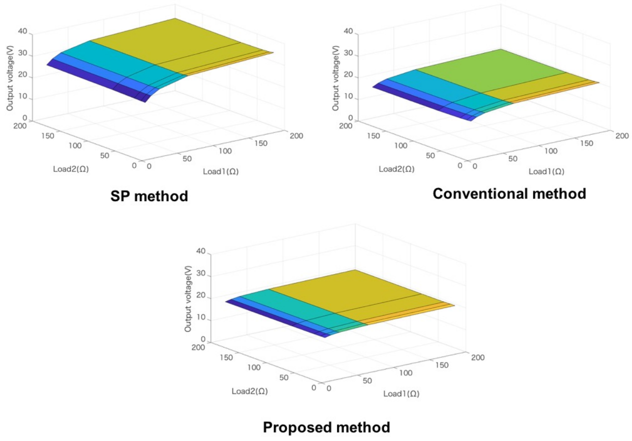

Fig. 9 Comparison of output voltage on load 1

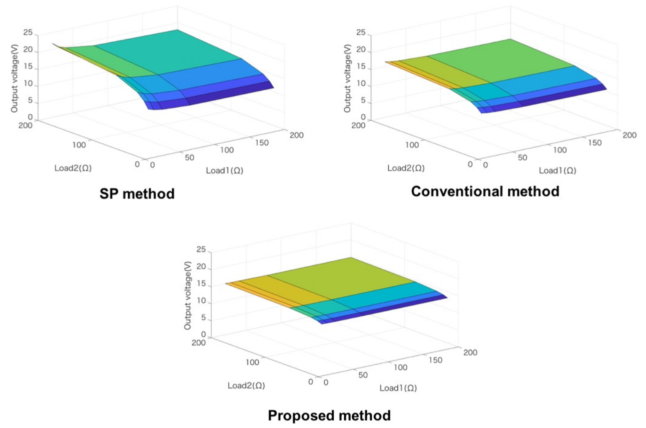

Fig. 10 Comparison of output voltage on load 2

4. CONCLUSION

In this paper, we proposed the compensation circuit on single-frequency two-stream contactless power transfer under the presence of the internal resistances of the coupler. The compensation circuits were inserted into transmitting-side in addition to receiving-side. Simulation results confirmed that inserting compensation circuits into transmitting-side and receiving-side can more efficiently reduce the effect of internal effect than SP method and the conventional method.

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