

Design of an Improved Type Rotary Inductive Coupling Structure for Rotatable Contactless Power Transfer System

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Abstract. This paper is aimed at analyzing the rotary inductive coupling structure of contactless rotary transformer. The main feature of the proposed rotatable contactless power transfer system is which winding is coaxial-interlayered for improving the magnetic coupling capability. There is no ferrite core used in the secondary-side of the rotary inductive coupling structure, this helps to ease the exerted force that is stress by the secondary-side on spindle. In order to verify the feasibility of the proposed contactless power transfer system for rotary applications, an inductive powered rotary machinery and the control system have been integrated. The experimental results show that the maximum power transfer efficiency of the proposed rotary inductive coupling structure is about 94.8%. The maximum output power received in the load end is 1030 W with transmission efficiency of 88%.

1 Introduction

The need of resources from earth is growing day to day. For the construction of all industrial civilization and the exploitation of resources such as mineral mining, oil drilling, aerospace engineering, and wind power, they all need the industrial machinery with rotary motion. In most cases, the action of those rotating machinery is rotated in single direction and do not have the back rotation function. The power supplied to a rotating shaft is usually by mechanical slip-ring assemblies, which is always followed the risk of tear and wear of assemblies caused by the inherent high friction between the metallic conductors. If the power supplied to a rotating shaft by general wire assemblies, it may cause the entanglement of power supply wire. According to this reason, there is required to find a way that the power supply wire will not entangle with rotary part of machinery while operating.

The solution for supplying power to rotary machinery can be divided into the contact and contactless ways, respectively. The common solution of the contact way is to supply power by mechanical slip-ring assemblies, which is always led to the wear of assemblies. It will increase the cost of equipment maintenance and add the probability of replacing consumables [1]. In addition, the temperature of slip-ring joints may rise in the process of rotary status, in turns, it may cause the conductive joints burning. The flying sparks are also generated by surface friction, increasing the risk of special working environment such as the refineries, wet and conductive environment, high temperature treatment, and clean room. Therefore, it is necessary to develop the contactless power transfer method for rotary machinery with high reliability to reduce the risk and disaster while operating

under hard environment. The contactless power supply techniques can be divided into two ways: the inductive power transfer techniques [2-3] and the capacitive power transfer techniques [4-5]. Figure 1 shows the illustrations of these two different contactless power transfer ways for rotary machinery.

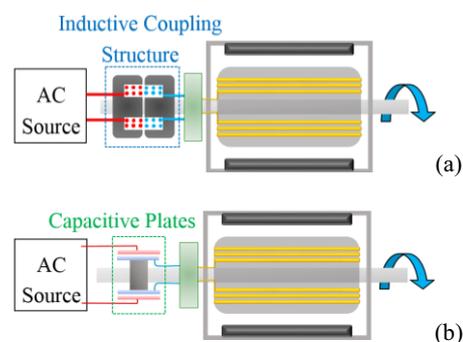


Figure 1. Contactless ways for rotary machinery. (a) Inductive. (b) Capacitive.

The inductive power supply technique is used to transfer power by alternating magnetic field between the different coils. It has the advantage of low maintenance requirement and high power transmission capacity, but it still requires installing coil windings and the magnetic material on the rotating shaft which adds additional stress on shaft equipment. The stability of power transmission may also be affected by the rotational speed that is depending on the design of the coupling structure. In the other hand, the capacitive power supply technique is used to transfer power by alternating electric field between two conductive plates. It depends on the amount of electric charge that accumulated between two plates, but it still

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has a bottleneck to manufacture the plate capacitor with enough capacitance to apply high power. For the high power requirements in such industrial application nowadays, the contactless inductive power transmission technique is utilized to develop and implement an improved type rotary inductive coupling structure for rotatable contactless power transfer system that is not sensitive to the rotational speed and can transfer power to the rotary load steadily.

2 Contactless power transfer system

The general application of contactless power transmission technology in the overall system architecture is shown in Figure 2. The whole system can be divided into the primary-side power supply part, the inductive coupling structure, and the secondary-side pickup part, respectively. By applying a high frequency exciting circuit, the dc power source can be converted into a high frequency alternating power source that supplies a high frequency current into the primary-side coil and generates a high frequency magnetic field by the resonant compensation circuit. Then the magnetic field is captured by the secondary-side inductive coil and transferred to a high frequency inductive current. The inductive current will be compensated by resonant circuit and rectified as a dc power source for supplying the power to output load.

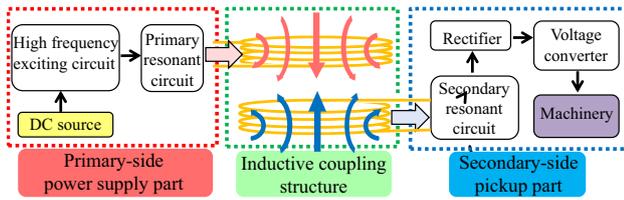


Figure 2. Block diagram of a contactless power transfer system.

The difference between the inductive coupling structure and the general transformer is that the air-gap within the coils of the primary-side and the secondary-side. In general, the air-gap of an inductive coupling structure is larger than a transformer, which means the inductive coupling capability is weaker than the transformer. Besides, the larger air-gap causes a larger leakage inductance, thus reduces not only the coupling effect but also the transmission capacity of power. In view of this, a contactless inductive power transfer system may add resonant capacitors in the circuit of both sides for compensation to enhance the power transfer capability [6]. While the system circuit is operated at the resonant frequency, the inductive reactance and the capacitive reactance formed by the inductive coils of two sides and compensative capacitors will be offset by each other, it makes the system impedance of circuit purely resistive.

Due to the inductive power transfer characteristic, it is not sensitive with the variation of output load under the following two compensation topologies of Figure 3. In this paper, these two resonant topologies are taken into analysis and design for the proposed system. First, the inductive coils of both sides are in series with resonant

capacitors as shown in Figure 3(a), which is called as S-S resonant topology. Figure 3(b) shows the S-P resonant topology, its inductive coil of the secondary-side is paralleled with resonant capacitor. In Figure 3, the subscript symbol P represents the primary-side, S represents the secondary-side. L_P and L_S are the self-inductances of the primary-side and the secondary-side, respectively. Besides, r_P and r_S are the coil resistances of the primary-side and the secondary-side, respectively. i_P and i_S are the currents of the primary-side and the secondary-side, respectively. R_L is the output load. The impedance of the secondary-side is different which depends on the compensation topology of secondary-side as illustrated in Figure 4.

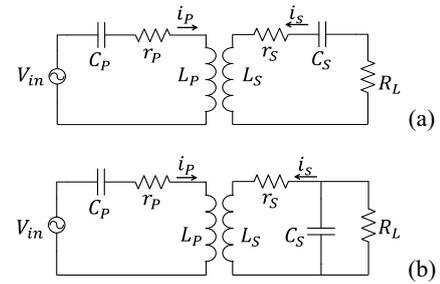


Figure 3. Two types of resonant topologies. (a) S-S. (b) S-P.

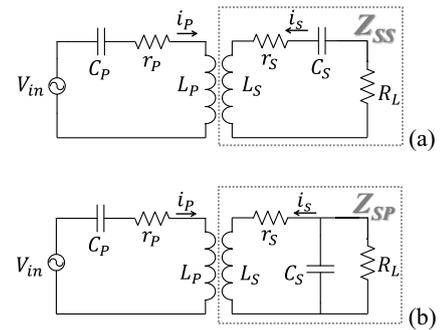


Figure 4. Equivalent impedance of the secondary-side circuit. (a) S-S. (b) S-P.

The equivalent impedance of the secondary-side while the resonant topology is under S-S and S-P, respectively, can be expressed as:

$$Z_{SS} = j\omega L_S + r_S + \frac{1}{j\omega C_S} + R_L \quad (1)$$

$$Z_{SP} = j\omega L_S + r_S + \frac{1}{j\omega C_S + 1/R_L} \quad (2)$$

When the frequency of system is operated at the resonant frequency $\omega_0 = 1/\sqrt{L_S C_S}$, the equivalent impedance of the secondary-side will be based on the relationship between the frequency and the mutual inductance M reflected to the primary-side circuit, where Z_X can be expressed as Z_{SS} or Z_{SP} . The reflection impedance Z_r is given as:

$$Z_r = \frac{\omega^2 M^2}{Z_X} \quad (3)$$

15 turns of winding, a woven Litz wire is used to reduce the equivalent series resistance of winding. The practical prototype is illustrated as Figure 8. After the rotary machinery is installed with secondary winding, the rotary part can be assembled with primary-side fixed part freely as shown in Figure 9.

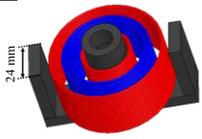
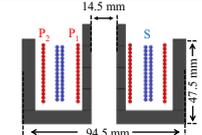
Proposed Rotary Inductive Coupling Structure			
Oblique view		Measuring Frequency(kHz)	40
		Litz Wire	0.13mm×80
Section view		k	0.9
		$L_p(\mu\text{H})$	138
		$L_s(\mu\text{H})$	126
		$M(\mu\text{H})$	120
Coil turns	Primary: (P_1)=16, (P_2)=16 Secondary:(S)=15	$r_p(\Omega)$	0.21
		$r_s(\Omega)$	0.2

Figure 7. Specification and measurement parameters.

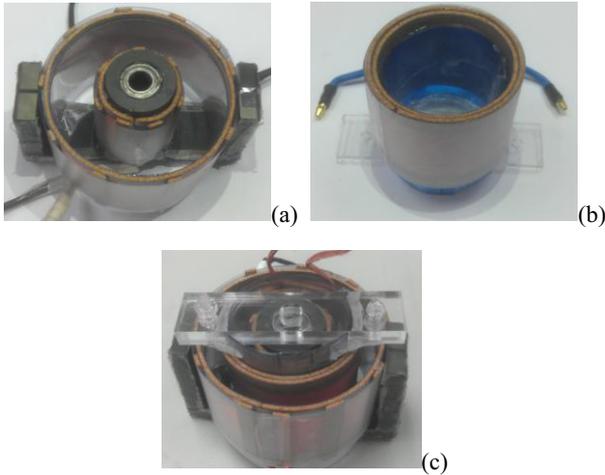


Figure 8. Practical prototype. (a) Ferrite core and coil of primary-side. (b) Secondary coil. (c) Combination of both sides.

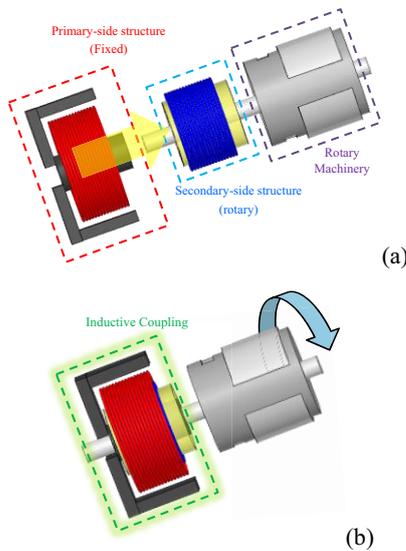


Figure 9. Assemble illustration of coupling structure and rotary machinery. (a) Before and (b) after assemble completely.

The calculated transmission power and efficiency of prototype is shown in Figure 10. Figure 11 is the calculated the output voltage and current with two different resonant topologies. From the results of calculation, in the case of adopting S-S topology, the output current is not change obviously with the variation of load. The output voltage is increased with the larger load impedance, which means that the output power is increased while the output impedance increase. While adopting S-P topology, the output voltage is changed merely with the variation of load. The output current is increased while the impedance of load is reduced, which means that the output power is increased with the decrease of output impedance. From the results of above analysis, the output load of proposed system is treated as rotary armatures. The torque of armatures is changed with the input current, thus the S-P topology is more appropriate.

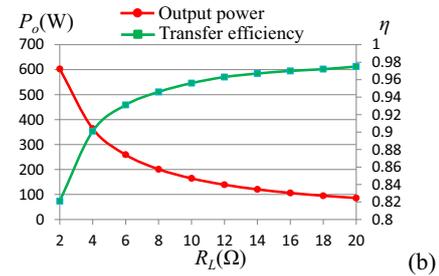
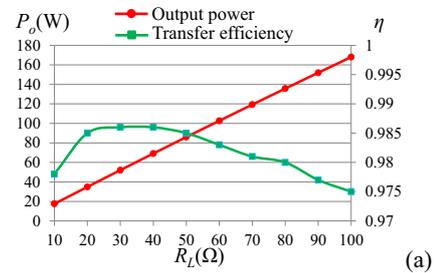


Figure 10. Calculated output power and transfer efficiency. (a) S-S. (b) S-P.

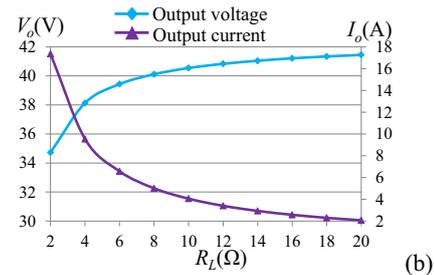
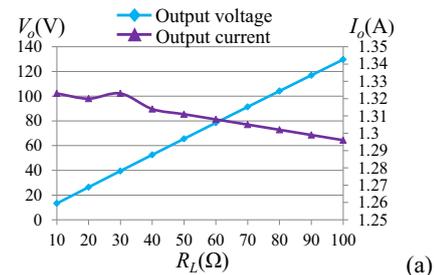


Figure 11. Calculated output voltage and current. (a) S-S. (b) S-P.

4 Contactless rotary machinery systems

Figure 12 shows the block diagram of the proposed rotatable contactless power transfer system. The architecture of the control system used in the output rotary machinery is shown in Figure 13. The rotary machinery is homemade synchronous motor with three-phase armatures. In design of control system, a hall sensor fixed on rotary shaft is used to determine the position of the armatures and sending signal to control the switches of three-phase bridge inverter.

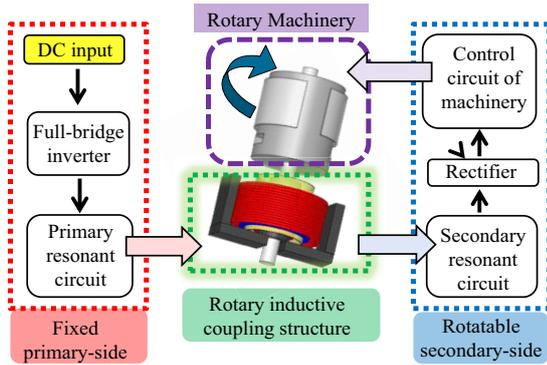


Figure 12. Proposed rotatable contactless power transfer system.

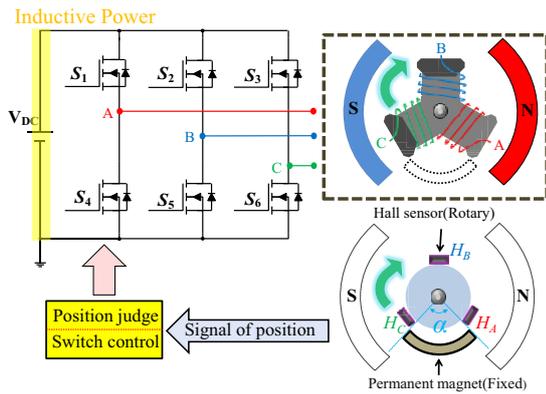


Figure 13. Architecture of the control system.

5 Experimental results

To verify the feasibility of the contactless power transfer system for rotary application, a platform of Figure 14 is built for experiment and measurement while the secondary-coil is rotated by a dc motor. The slip-rings are used to transfer the power to resonant, rectifier and resistance load. Thus, the voltage and current waveform on secondary-side could be measured. Figure 15 shows the practical experiment setup.

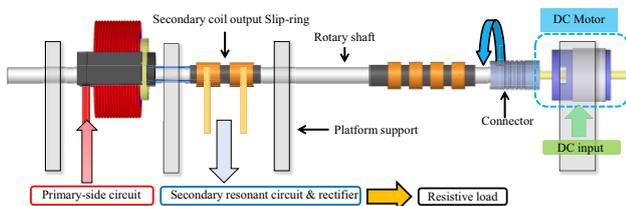


Figure 14. Platform setup for measurement.

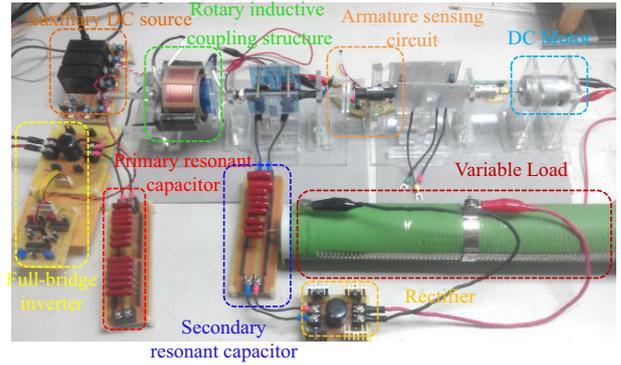


Figure 15. Practical experiment setup for measurement.

The waveforms of the primary and secondary sides while the secondary-side is under fixed and rotary status are measured. The voltage and current waveforms are not varied obviously while the secondary-side is under fixed and in rotary condition. It means that the inductive coupling effect between both coils would not be affected by the rotary motion. Therefore, the power can be transferred from the primary-side to the secondary-side stably while using the proposed rotary inductive coupling structure. The experimental results show that when the input voltage is fixed at 84 V, the rotatable contactless power transfer system can transfer the maximum power about 1030 W with energy transfer efficiency of 88%. In case of the output power received is less than 300 W, the transmission efficiency is reached to 94.8%. Figure 16 shows the output power and energy transfer efficiency with the variation of output load.

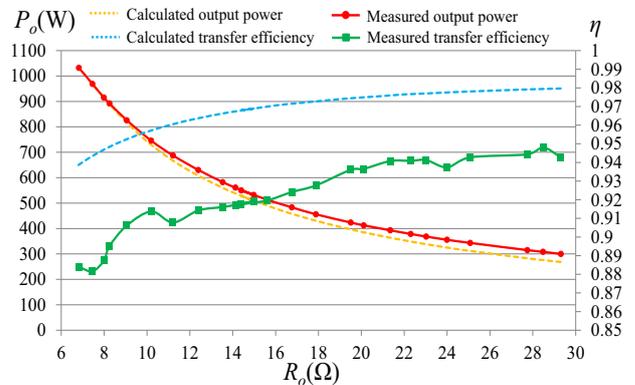


Figure 16. Output power and energy transfer efficiency.

The calculated results do not consider the switching loss at the primary-side, and the energy loss of rectifier at the secondary-side also does not included either. As the results of calculation and measurement, the calculated power transfer efficiency is higher than measured one. In the comparison of output power, the measured curve is closed to the calculated curve, but the measured one is lower than the calculated result. It can be estimated that the rectifier circuit connected with output load, the reflected impedance of output load is nonlinear, it makes the variation of reflected impedance from the output to the secondary-side circuit, thus the sending power is higher than calculated amount. In addition, while using the proposed contactless power transfer system to

motivate the handmade rotary machinery. The secondary-side inductive coil fixed on shaft is rotated while the rotary machinery powered by the proposed system. The resonance and rectifier circuits of the secondary-side are integrated with driving circuit of machinery fixed on rotary shaft.

From the measured voltage and current waveforms on resonant circuit of both sides, it can be observed that the resonant tank has reached the resonance condition. The voltage of secondary-side resonant capacitor v_{CS} is 11.7 V, which is able to estimate that the input voltage of three-phase bridge inverter is about 11 V. Besides, the voltage period of armature are measured as 56.6 ms. It can be estimated that the rotation speed of armature is 1071 rpm. Figure 17 shows the practical experiment setup for the measurement of voltage and current signals while the handmade rotary machinery is motivated by proposed contactless power transfer system. The practical setup situation of the driving circuit of rotary machinery fixed on shaft as shown in Figure 18.

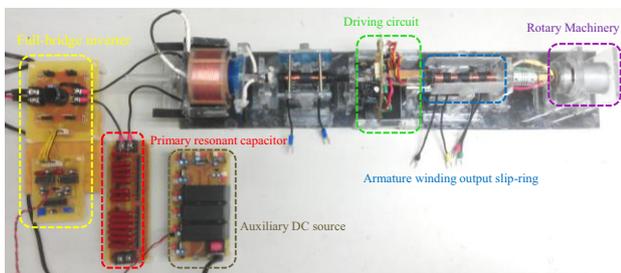


Figure 17. Practical experiment setup.

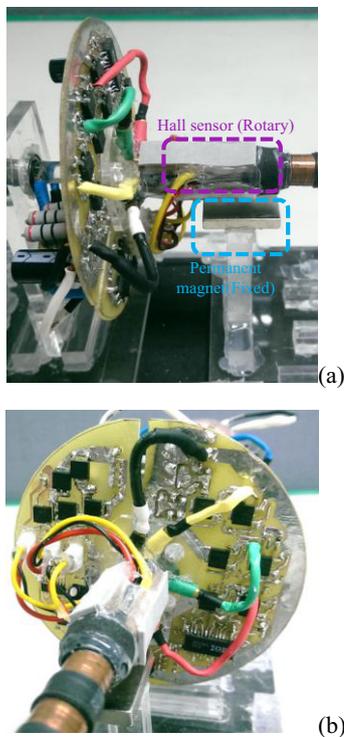


Figure 18. Practical setup of fixed driving circuit on shaft. (a) Oblique view. (b) Center view.

6 Conclusions

This paper is aimed at carrying out an improved design of rotary inductive coupling structure for rotatable contactless power transfer system, which can steady transfers power to the rotary load. In order to study and analysis the magnetic properties of inductive coupling structure, the finite-element-method software Maxwell is used. The main feature of the proposed rotary inductive coupling structure is that the windings are coaxial-interlayered to each other to improve the magnetic crossing area between the two coils and boost the magnetic coupling capability of structure. The ferrite core located at the primary-side is designed as an extended sharp to increase the launching distance of magnetic field. In order to verify the feasibility of the proposed system, a platform is built for experiment and measurement when the secondary-coil rotates. In addition, a synchronous motor with rotary armature and the control system has been integrated with the rotatable contactless power transfer system. In the design of control system, a hall sensor is used to determine the position of the rotary armature and send the position signal to control the switch of three-phase bridge inverter to keep armature rotate continuously.

References

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