~~Design Considerations for Contactless Slip Ring~~

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***Abstract*—In this paper design of a modular, fault tolerant dynamic inductive power transfer(DIPT) system for contactless slip ring is investigated. After consideration of different compensation topologies, series-series(SS) compensation is selected due to its load and magnetic coupling independence of resonant frequency. Moreover a bifurcation free single transmitter(Tx) and single receiver(Rx) design methodology was discussed. However, in order to achieve N-1 contingency condition a modular multi-Tx and multi-Rx coil structure is employed. In this study 2Tx-4Rx and 3Tx-3Rx coil design is considered. During 3Tx-3Rx system, synchronous and 3 phase operation are also discussed. In the comparison proposed systems are compared in terms of fault tolerance, efficiency, number of semiconductor and control.**

***Index Terms*—dynamic inductive power transfer, series-series resonant converter, modular design, fault tolerant IPT coil design**

I. Introduction

Slip rings are used often in electrical machinery to transfer ~~electrical~~ power from stationary to rotating frame or visa versa. Most commonly they include copper rings and carbon brushes where constant friction is present during operation. Constant friction results faults in the systems ~~and~~ hence regular maintenance is required which may not be always feasible. In order to solve this problem synchronous exciters(SE) are used where a second electrical machine(EM) is connected to the shaft of a bigger EM where the power generated in the exciter is used to excite the field winding of the EM. Although they solve the friction problem, they cannot operate properly in low rotational speeds since no EMF is induced in the stator winding of the SE.

In this paper, design considerations for a modular axial dynamic inductive power transfer (DIPT) system will be presented which can solve both reliability and low-speed operation. In the first section, selection of compensation topology will be delivered. Then design methodology of a single transmitter (Tx) and single receiver (Rx) considering bifurcation free operation will be presented. In order to increase the reliability of the system a modular topology is considered and a single fault tolerant axial coil design is made.

In this study different number of Tx and Rx coil topologies will be investigated. The proposed end product can be mounted on any slip ring where the Tx coils are stationary and the Rx coils are rotating. The proposed system structure is presented in Fig. 1. Initial design parameters are presented in Table I.

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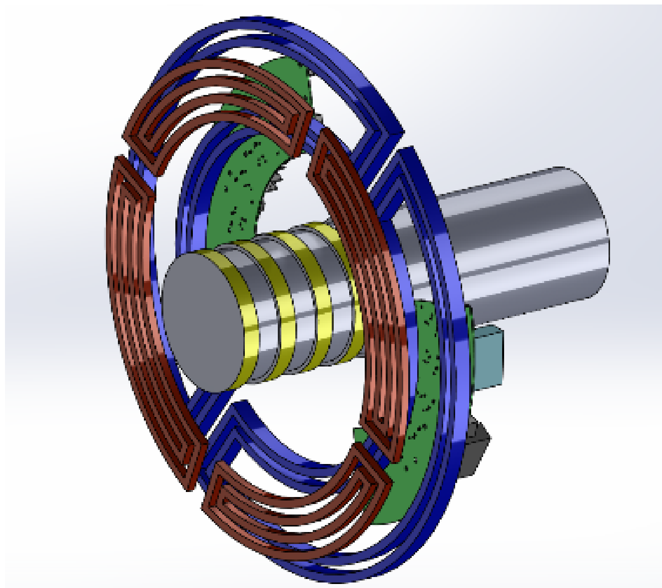


Fig. 1: Proposed DIPT system having 2-Tx and 4-Rx coils. The secondary AC/DC converter is omitted for better visualization.[ustune neyin ne oldugunu yazmayı unutma]

TABLE I: Initial System Design Parameters

Input Voltage	100 V_{DC}
Output Voltage	100 V_{DC}
Switching Frequency	150 kHz
Output Power	1 kW

II. Design Considerations

In loosely coupled IPT systems, reflected impedance is usually highly inductive and hence the power factor of the system is low. This results in a high primary current where the efficiencies are decreased significantly. To reduce the reactive power drawn from the supply side, dual side compensation is often employed both in the industry and in the literature. [1] In literature, there are four compensation methods named by Series-Series, Series-Parallel, Parallel-Series, Parallel-Parallel, to cancel reactive power [2]. Each compensation method has some advantages and disadvantages. They can be compared with respect to efficiency, no-load condition, resonance frequency stabilization, coupling factor. Table II for comparison of the four method is given. [3]

TABLE II: Comparison of The Four Compensation Method

	S-S	S-P	P-S	P-P
Load independence of ω_0	Yes	No	No	No
Coupling independence of ω_0	Yes	No	No	No
No load operation	No	Yes	Yes	Yes

In a rotating Rx frame, choosing any topology other than series-series compensation would result in a changing resonance frequency with changing coupling factor which is undesired in our application. Moreover, resonance frequency in series-series compensation is also independent of loading. However, a major drawback of this topology occurs when the coupling factor is low or the system operates near no load. Under the stated conditions and if the operating frequency is close to the resonance frequency, the Tx side is short circuited and all power is dissipated on the internal resistance of the IPT coil.

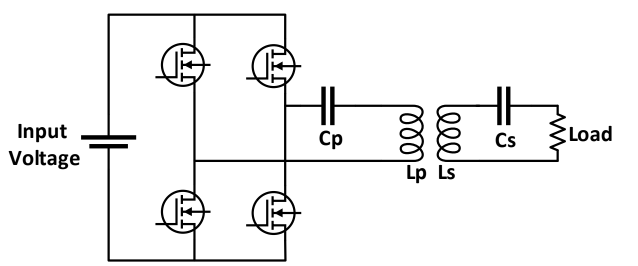


Fig. 2: Series-Series Compensated Full-Bridge Resonance Converter

Single Tx-Rx circuit is shown in Fig. 2. The input voltage can be assumed purely sinusoidal having the fundamental frequency. This approach gives accurate results in circuit simulations where the quality factor is high. The simplified circuit is in Fig. 3. [4]

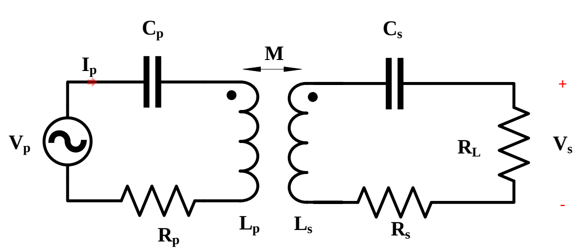


Fig. 3: First Harmonic Method Series-Series Resonance Circuit

Quality factor is a dimensionless parameter to show sharpness of the filter. There are some ways to calculate the quality factor in literature. The ratio of voltage of capacitor and resistor in (1) is commonly used. [5]

$$\mathrm{Q} = \frac{\mathrm{V_{cap}}}{\mathrm{V_{res}}} \tag{1}$$

Another definition of quality factor can be made as in (2) where the quality factor Q is defined as the ratio of center frequency $\mathrm{f_c}$ to the bandwidth $\Delta\mathrm{f}$.

$$\mathrm{Q} = \frac{\mathrm{f_c}}{\Delta\mathrm{f}} \tag{2}$$

Although higher Q factor is usually desired in filter design, choosing high Q would result in poor voltage regulation since any change in the loading or coupling would result in significant change in the output voltage. Moreover, having higher Q would also mean higher voltage stress on the compensation capacitors. As an example, $\mathrm{Q} = 10$ would result in $\mathrm{V_c} = 1000$ V for an output voltage of $\mathrm{V_{out}} = 100$ V. In the literature Q is usually chosen between 2 and 10.

In SS-RIPT systems zero voltage switching(ZVS) is achieved when the Tx current lags the Tx voltage. Hence operation above resonance frequency should ensure ZVS under normal operation. However, in doubly compensated systems the phenomenon called "Bifurcation" occurs when the coupling factor is bigger than a specific value for the rated loading. During bifurcation free operation there exist only a single zero crossing between the Tx voltage and current which is at resonant frequency whereas with bifurcation there exists three separate zero crossings. [6] The problem with bifurcation is that even if the operation above resonance frequency is guarenteed the Tx current may still lead the voltage and hard switching may occur. Different control methods were presented however they are complex and bifurcation is best avoided in the design process.

Circuit and system parameters are calculated with one Tx and one Rx coil. Table I shows the system requirements. Table III shows the calculation of parameters for the proposed design.

TABLE III: Calculation of Circuit and System Parameters

Parameter	**Calculation**	**Value**
$\mathrm{Q_s}$	Selected	4.5
$\mathrm{f_0}$	Selected	150 kHz
Coupling Factor	Selected	0.2
$\mathrm{R_L}$	$\frac{\mathrm{V_{srms}^2}}{\mathrm{P_o}}$	10 Ω
L_s	$\frac{\mathrm{Q_s R_L}}{\omega_o}$	47 μH
$\mathrm{I_{srms}}$	$\frac{\mathrm{V_{srms}}}{\mathrm{R_L}}$	10 A
$\mathrm{I_{prms}}$	$\frac{\mathrm{P_o}}{\mathrm{V_{prms}}}$	10 A
M	$\frac{\mathrm{I_{srms} R_L}}{\mathrm{I_{prms}}\omega_0}$	10.61 μH
$\mathrm{k_c}$	$\frac{1}{\mathrm{Q_s}}\sqrt{1 - \frac{1}{4\mathrm{Q_s^2}}}$	0.22
$\mathrm{L_p}$	$\frac{\mathrm{M^2}}{\mathrm{L_s k^2}}$	48.7 μH

TABLE IV: 2Tx-4Rx Voltages and Power Outputs for Different Cases.

	$V_{p1,rms}$	$I_{p1,rms}$	$V_{p2,rms}$	$I_{p2,rms}$	$V_{s1,rms}$	$V_{s2,rms}$	$V_{s3,rms}$	$V_{s4,rms}$	P_1	P_2	P_3	P_4	P_{out}
$Case_1$	90V	5.65A	90V	5.65A	90V	90V	90V	90V	240W	240W	240W	240W	960W
$Case_2$	90V	5.65A	90V	5.65A	90V	90V	90V	90V	240W	240W	240W	240W	960W
$Case_3$	100V	6.54A	56.5V	6.8A	100V	100V	0V	100V	333W	333W	0W	333W	999W

III. Modularity and Fault Tolerance Concept in SS RIPT Systems

Since the proposed system aims to replace slip rings and field exciters in synchronous machines reliability, i.e. fault tolerance is a key factor in design. Well designed modular structures are often employed to increase the fault tolerance. Similarly, in the design multi transmitter and multi receiver structures are used to allow proper operation in case of a short circuit or open circuit fault. Due to the nature of SS-RIPT systems, open circuited receiver fault case requires special attention since open circuited secondary results in short circuited transmitter.

As the presented example in Fig. 1, in case of open circuited receiver, the transmitter side will not be short circuited due to presence of another receiver during any time. Therefore, proposed modular design in Fig. 1, clearly increases the fault tolerance. Moreover, modular design also allows the change of the faulty module without the disassembly of the whole system.

IV. 2Tx-4Rx Design

The design is first done with a single Tx and single Rx. In order to increase the fault tolerance using modular design two Tx and four Rx structure will be under our investigation where single fault condition can be tolerated by slight increase in the power delivered by other modules. The proposed system can be visualized as in Fig. 1 and the circuit representation can be found in Fig. 4.

In order to keep the power delivered to the receivers constant, a second winding is used. However, in order to keep the power delivered constant and to keep the secondary inductance the same the load resistance should be doubled. The coupling factor was kept the same and since we have two transmitter the power delivered to each receiver is set to be 250 W where each transmitter has a power of 500W. Here it is important to note that initially selected Q is also halfed.

V. 3Tx-3Rx Design

In this paper special attention will be given to 3Tx-3Rx since it allows 3 phase operation which reduces the number of semiconductors used in the system. Moreover, it allows Wye and Δ connections which can be further utilized to increase the secondary line voltages or line currents. However, during normal operation special attention has to be given when two Tx phase coils have mutual coupling with a single Rx coil. Moreover, system behaviour during open circuit faults in the Rx coils need further investigation. In the literature, first harmonic approximation (FHA) method is often employed during RIPT system analysis. Similarly, FHA is also employed in this study. The proposed connections are $\Delta-\Delta$, Wye-Wye, Wye- Δ, Δ-Wye. The Tx coils are fed from 3phase inverter and the Rx coils are connected to 3 phase diode rectifier to supply 1kW power at the output.

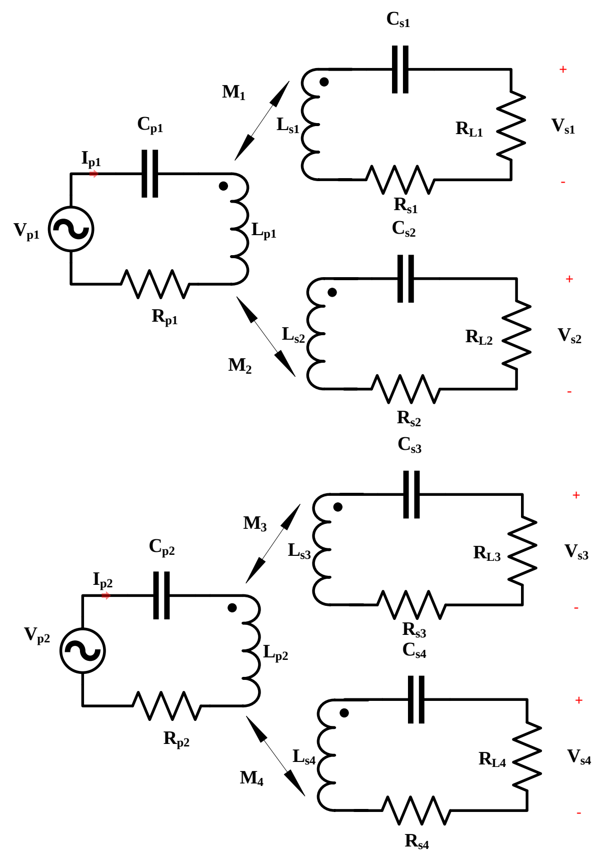


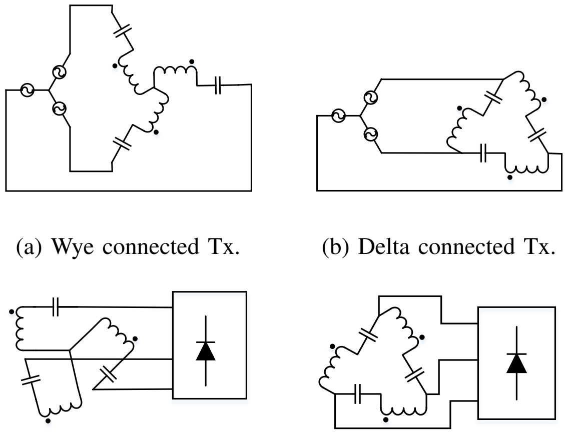
Fig. 4: 2Tx and 4Rx Series-Series Resonance Circuit

A. 3 Phase Operation

In this section four different connection types will be investigated as stated in Fig. 5. Special attention will be given to cases where the same Rx coil is excited by two phases. Moreover, open circuit fault condition will be modeled. In the final paper, the connection types will be analyzed and compared in terms of post fault operation, normal operation current and voltage ratings, overall efficiency, semiconductor ratings and compensation capacitor ratings.

B. Synchronous Operation

Clearly, 2Tx-4Rx configuration should operate in synchronous mode of operation meaning that each Tx coil is fed by separate H-bridges where the voltages are in phase.



(a) Wye connected Tx. (b) Delta connected Tx.

(c) Wye connected Rx. (d) Delta connected Rx.

Fig. 5: Four different connections which will be under investigation.

Similarly each Rx coil has its own full-bridge diode rectifier. In 3Tx-3Rx configuration if each Rx module have their own rectifier module, synchronous operation is also possible. In the full paper a comparison will be made with 3 phase operation.

VI. Comparison

VII. Conclusion

References

[1] C. C. Mi, G. Buja, S. Y. Choi, and C. T. Rim, "Modern advances in wireless power transfer systems for roadway powered electric vehicles," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 10, pp. 6533–6545, Oct 2016.

[2] D. Patil, M. K. McDonough, J. M. Miller, B. Fahimi, and P. T. Balsara, "Wireless power transfer for vehicular applications: Overview and challenges," *IEEE Transactions on Transportation Electrification*, vol. 4, no. 1, pp. 3–37, March 2018.

[3] M. Al-Saadi, A. Ibrahim, A. Al-Omari, A. Al-Gizi, and A. Craciunescu, "Analysis and comparison of resonance topologies in 6.6kw inductive wireless charging for electric vehicles batteries," *Procedia Manufacturing*, vol. 32, pp. 426 – 433, 2019, 12th International Conference Interdisciplinarity in Engineering, INTER-ENG 2018, 4–5 October 2018, Tirgu Mures, Romania. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2351978919302719

[4] A. Safaee and K. Woronowicz, "Time-domain analysis of voltage-driven series–series compensated inductive power transfer topology," *IEEE Transactions on Power Electronics*, vol. 32, no. 7, pp. 4981–5003, July 2017.

[5] E. Waffenschmidt and T. Staring, "Limitation of inductive power transfer for consumer applications," in *2009 13th European Conference on Power Electronics and Applications*, Sep. 2009, pp. 1–10.

[6] R. C. Fernandes and A. A. de Oliveira, "Theoretical bifurcation boundaries for wireless power transfer converters," in *2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC)*, Nov 2015, pp. 1–4.