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Contactless Field Excitation System of Wound-Rotor Synchronous Motor

Ali AĞÇAL*

[1]Electrical and Electronics Engineering Department/ Engineering Faculty, Suleyman Demirel University, Turkey

*(aliagcal@sdu.edu.tr) Email of the corresponding author

Abstract – Transferring energy to the rotating parts of electrical machines through brush or slip ring has always been a problem due to maintenance, friction loss and arcing. All of these problems are eliminated with contactless energy transfer systems. In this study, a magnetic resonance coupling (MRC) based wireless power transfer (WPT) system was used in the excitation of a synchronous motor. Single-layer circular planar spiral coils were used in the transmitting and receiving coil design, thus achieving high coupling factor and low thickness. The WPT system successfully transfers energy in low air gaps between the rotating and stationary parts of the electrical machine. Simulations of the WPT model were made with MATLAB and Maxwell 3D. According to the simulation results, the system can operate with over 98% efficiency in a wide frequency band. The system was operated at 100 khz resonance frequency and 50 W power was transferred to the output with 98.22% efficiency. This design is not affected by the rotation of the rotor and does not create an imbalance in the rotor, since the receiver and transmitter coils are positioned parallel and symmetrically. This WPT system offers a reliable, low-cost and low-complexity solution to excite a synchronous motor.

Keywords –Wireless Power Transfer, Contactless Fıeld Excıtatıon, Contactless Energy Transfer, Electric Machinery, Wound-Rotor Synchronous Motor

I. INTRODUCTION

Rotary electrical machines have been essential in our lives for over 100 years. Conventional rotating electrical machines such as synchronous and DC machines use brush or ring structures to transfer energy to the armature or excitation windings. Friction loss, maintenance and repair cost, inability to be used in explosive areas, and arc risk are the most important disadvantages of ring or brush rotary electric machines. WPT provides efficient, reliable and stable solutions for transferring energy to the excitation windings of rotating electrical machines. It eliminates many of the disadvantages of the ring and brush.

Various methods are used in the literature for contactless energy transfer to rotating parts of electrical machines. Since the most suitable techniques for WPT from the near field are capacitive [1] and inductive coupling [2], these two methods are generally emphasised. On the other hand, inductive-coupled energy transmission is preferred more than capacitive-coupled transmission due to less loss, lower operating frequency range and higher power density.

In applying the inductively coupled WPT system to the rotating parts of the electrical machine, many different coil designs, circuit topologies and hybrid circuit setups have been studied. U-type transmitter and spiral circular receiver coils are designed for the excitation of rotor windings of electrical machines [3]. However, in this design, it was observed that severe eddy losses occurred in the shaft, passing through the middle of the circular coil in the receiver. For this reason, the efficiency did not exceed 51.19%. WPT system is designed for an in-wheel outer rotor switched reluctance motor drive using receivers with different resonance frequencies [4]. A brushless excitation mechanism is designed with WPT based on MRC [5]. A WPT system was designed that determines the rotor's position and excitates the rotor wirelessly. The varying inductances of the WPT system and the resulting variable frequencies in the power electronics circuit were used to evaluate the rotor position [6]. A primary side controller is designed for brushless excitation of the excitation windings of the synchronous motor [7]. The WPT system based on resonant inductive power transmission was designed to supply field power to brushless alternating current (BLAC) or brushless direct current (BLDC) motors without permanent magnets in the rotor. A single-layer helix coil is used in the receiver, and a multilayer coil structure is used in the transmitter [8]. A coaxial nested rotary WPT system was proposed for energising the excitation windings of rotating electrical machines. The effect of the offsets formed due to the vibration of the rotor on the WPT system was investigated. The case was protected and losses were reduced with a ferrite core design [9]. Various coil designs were investigated for contactless excitation of synchronous motor excitation windings. A prototype for high-speed synchronous machines with a WPT system instead of rings was made [10]. A rotary WPT system with serial parallel topology was implemented for the excitation of rotating electrical machines [11]. An inductive power transmission system with a rotating transformer was proposed as an alternative solution to slip-ring systems. A prototype system was built with a sensor mounted on the ball-bearing shaft. It was also examined in terms of coupling factors and losses [2]. With the radial-flux rotational WPT system, the rotor's position and speed were determined and the excitation windings were energized [12]. Stability analysis and control of the synchronous motor field excitation system with rotary transformer was made. A dynamic model of the system based on variables was investigated using the harmonic balance technique [13]. A low-cost and less complex contactless field excitation system was implemented that uses existing motor drivers and does not require extra converters in the receiver and transmitter [14]. Planar circular spiral coil sizes with PCB for contactless electrical excitation of synchronous motors were discussed. PCB was chosen because of its simple manufacturing process, compactness, power density, low AC resistance to proximity and skin effect [15].

In this study, the MRC-based WPT system is designed for contactless excitation of synchronous machines. 50 watts of power was transferred from 2 mm air gap with 98.22% efficiency. It was operated at a frequency of 100 kHz. Eddy losses on the shaft were investigated. The subsequent sections of the paper is outlined below. In Section II, the contactless field excitation system for the excitation windings of the synchronous motor is explained. The features of the WPT design and the simulation results are given in Section III. Results and discussion are presented in Section IV.

II. ROTARY WPT DESIGN

Inductive coupling is the most suitable method for brushless or ringless energy transfer to the excitation windings of rotating electrical machines. In the inductively coupled WPT system, coils transfer energy between the transmitter and receiver. For WPT, a magnetic coupling must be between the receiver and transmitter coils. In the WPT system, coil designs are about increasing the coupling between the receiver and the transmitter or obtaining the optimum coupling with a smaller size. Although increasing the connection between the receiver and the transmitter increases the efficiency, more is needed. A compensation system that balances the inductive reactive power of the coils and increases the power transmission capacity and efficiency is required. The basic four compensation topologies are series-series, series-parallel, parallel-serial, and parallel-parallel. In the literature, there are combined topologies such as LCC-S, S-LCC, and LCC-LCC, which are a combination of these basic topologies. An overview of a rotary WPT system for the excitation of a synchronous motor is shown in Figure 1.

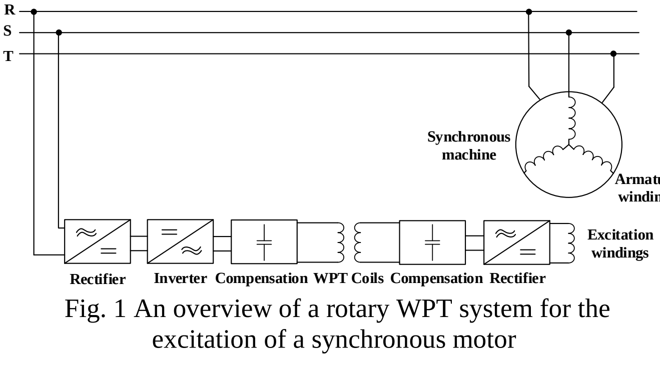

Fig. 1 An overview of a rotary WPT system for the excitation of a synchronous motor

This study used SS topology due to its simplicity and ease of control. The basic WPT circuit for the SS topology is shown in Figure 2.

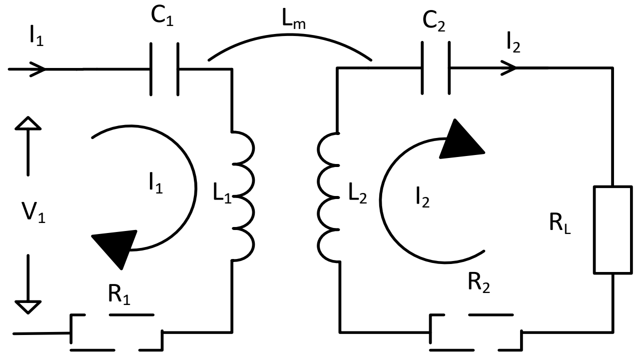

Fig. 2 WPT system with SS topology

Where, V_1 and I_1 are the input voltage and current, respectively. I_2 is the output current. L_1, C_1, and R_1 are the transmitter's inductor, capacitor and internal resistance, respectively. R_L is the load resistance and L_m is the mutual inductance. L_2, C_2, and R_2 are the receiver's inductor, capacitor and internal resistance, respectively. When determining the SS topology's inductance, capacitance and resonant frequency, the basic LC circuit is used first. The resonance frequency is the frequency at which inductive and capacitive reactive power is balanced in compensation topologies. The natural resonance frequency is calculated by Equation (1).

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

Where, f_r is the natural resonant frequency, L is the inductance and C is the capacitor. The optimum working frequency in WPT differs according to the application areas. High frequencies are used in low-power application areas, while low frequencies are used in high-power applications. It is also available in frequency bands recommended for some application areas or determined by standards. In contactless excitation of rotating electrical machines, WPT applications are generally made in the low-frequency band. After the frequency is determined, the inductance and capacitance values are selected. While determining the inductance and capacitance values, the resonator's quality factor is desired to be high. The quality factor is given in Equation (2).

$$Q = \sqrt{\frac{L}{C}}R \qquad (2)$$

Where, Q is the quality factor. WPT can be achieved from higher air gaps with high quality factor resonators. However, high quality factor creates voltage stress in capacitors and increases capacitor sizes. In contactless excitation of a synchronous motor, designs with lower quality factors are preferred to ensure energy transfer from the near field and keep the capacitor size in the receiver to a minimum. Equivalent impedance and efficiency equations for the WPT system with SS topology are given in equations (3) and (4), respectively.

$$Z_{Eq} = R_1 + j\omega L_1 + \left(\frac{1}{j\omega C_1}\right) + \left(\frac{{L_m}^2\omega^2}{R_2 + j\omega L_2 + \left(\frac{1}{j\omega C_2}\right) + R_L}\right) \qquad (3)$$

$$\eta = \left(\frac{jL_m\omega}{R_2 + j\omega L_2 + \left(\frac{1}{j\omega C_2}\right) + R_L}\right)^2 * \frac{R_L}{Z_{Eq}} \qquad (4)$$

Z_{Eq} is the equivalent impedance, η is efficiency, and ω is the angular frequency. The resonant frequency is not always one and constant in magnetically coupled systems. The resonance frequency may change and bifurcate depending on the change in circuit parameters. The resonance frequencies are found by Equation (5).

$$\frac{\partial \eta(\omega)}{\partial \omega} = 0 \qquad (5)$$

At the resonant frequency, the derivative of the efficiency with respect to the frequency is zero. The extreme points found with the derivative are the resonance frequencies. While one or three resonant frequencies occur in basic topologies, the number of resonant frequencies can be increased with combined topologies.

Coil design is one of the main issues of the WPT system. In coil design, it is necessary to keep the coupling between the receiver and transmitter high, reduce eddy losses, reach higher air gaps, or pay attention to special restrictions depending on its application area. Square, rectangular or polygonal coils are not preferred in rotating electrical machines as they create an imbalance in the shaft. Circular coil designs are generally used. Spiral, helical or multi-layer coils are often used in the rotating WPT literature. The coupling factor between the receiver and transmitter of helical coil designs is lower than that of spiral coil designs. Therefore, a single-layer planar spiral coil is generally preferred. In low-frequency applications where the inductance of the single-layer planar spiral coil is insufficient, the multilayer coil is preferred. In this study, a single-layer circular planar spiral coil was used due to its high coupling factor, low thickness and suitability for rotating WPT. The single-layer circular planar spiral coil is shown in Figure 3.

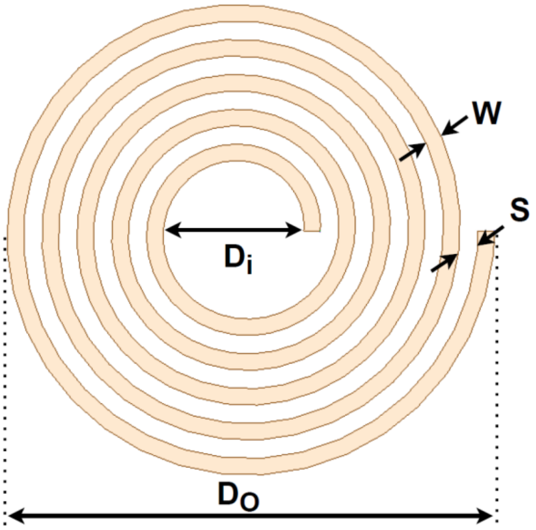

Fig. 3 Single-layer circular planar spiral coil [16]

A Single-layer circular planar spiral coil was designed by using (6) and (7).

$$L = \frac{N^2A^2}{30A-11D_i} \tag{6}$$

$$A = \frac{D_i + N(W+S)}{2} \tag{7}$$

Where, W is diameter of the wire, N is the number of turns, and S is the space between wires. D_0 and D_i are the coil's outer and internal diameters, respectively.

III. WPT DESIGN FEATURES AND SIMULATION RESULTS

The dimensions of the rotary coil were determined so that the coil would be placed between the stator and the shaft. According to a synchronous machine with a stator inner diameter of 95 mm, the transmitter and receiver coils were designed in Maxwell 3D. The parameters of the coils are given in Table 1.

Table 1. Parameters of the coils

Number of turns	9
Distance between wires	0.2 mm
Wire width	1 mm
Outer diameter of the coil	90 mm
Inner diameter of the coil	68.8mm
Self-inductance	11.3 uH
Mutual inductance (2mm air gap)	8.96 uH
Length of wire	2.25 m
Coupling factor (2mm air gap)	0.79
Inner resistance of wire	49 mΩ

Rotary WPT design in Maxwell 3D is shown in Figure 4.

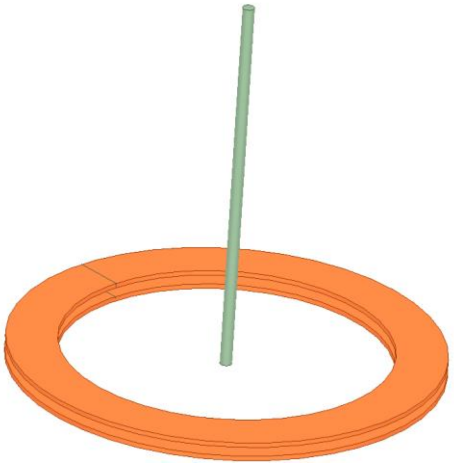

Fig. 4 Rotary WPT design in Maxwell 3D

Resonance capacitance was determined 224 nF for 100 kHz resonance frequency. the load resistance was selected 5 Ω. Efficiency and equivalent impedance according to frequency for 5 Ω load was shown in Figure 5.

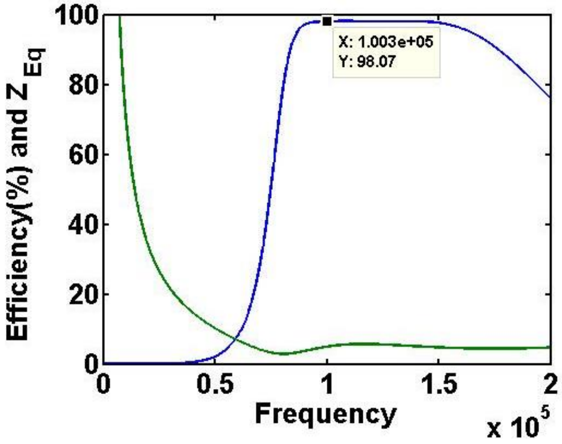

Fig. 5 Efficiency and equivalent impedance according to frequency

As can seen in Figure 5, WPT system efficiency is higher than 98 % at the wide frequency band.

The magnetic field distribution of the coils is shown in Figure 6.

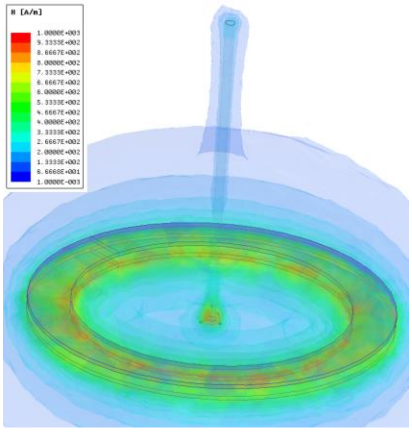

Fig. 6 Magnetic field distributions of the rotary WPT design

The circuit of the rotary WPT system for excitation of synchronous motors is set up in Simplorer and shown in Figure 7.

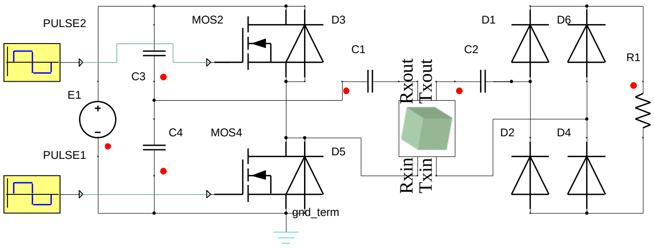

Fig. 7 The circuit of the rotary WPT system for excitation of synchronous motors

The transmitter circuit was fed with a half-bridge inverter. Since the excitation windings of synchronous motors work with DC, the output of the WPT system is rectified with a full bridge rectifier. The voltages, currents and powers of the receiver and transmitter were measured. They are shown in Table 2.

Table 2. Parameters of the coils

f_r = 100 kHz	
V_{DC} = 38.39 V	V_L = 14.47 V
I_1 = 2.91 A	I_L = 2.83 A
P_i = 50.91 W	P_L = 50 W
V_{C1} = 30.77 V	V_{C2} = 32.3 V
ŋ = 98.22 %	

As can seen in Figure 5 and Table 2, WPT system efficiency is higher than 98% The rotating WPT system can be easily provided with a simple resonance and rectifier circuit using passive elements in the receiver. This coil design is not affected by the turn of the receiver coils. In this design, since the receiver and transmitter are parallel and symmetrical to each other, there is no change in the mutual inductance due to the rotation of the rotor.

IV. CONCLUSION

Excitation of synchronous machines with the help of brushes and rings has always been a problem due to maintenance, friction loss and arcing. It has limited the application areas of synchronous machines. This paper provides an effective alternative for the field excitation of synchronous motors with an MRC-based WPT system design. The designed WPT system achieved operation in low air gaps, high frequency and high efficiency. Using single-layer planar spiral coils in contactless excitation of rotating electric machines provided a high coupling factor and low thickness. 50 W power was transferred to the excitation windings on the rotor of the synchronous machine with 98.22% efficiency.

The simulation results show that the designed WPT system is a suitable solution for the excitation of synchronous motors. The system offers a low-cost, reliable, maintenance-free and low-complexity alternative for the field excitation of synchronous motors. It eliminates the problems associated with contact energy transfer to the excitation windings of rotating electrical machines. This design can be developed and further optimised for use in industrial applications. This paper highlights the potential of MRC-based WPT systems to provide excitation to synchronous motors and may inspire future research in this area.

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