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A Sandwiched Magnetic Coupling Structure for Contactless Slipring Applications

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Abstract

This paper proposes a sandwiched winding structure used for contactless slipring systems. A contactless slipring is an alternative to current mechanical slipring systems. To minimize the losses and increase the power transfer capability, a new magnetic coupling structure with unique core geometry is proposed to transfer electrical power across an air gap allowing for free rotation. A Finite-Element-Boundary-Element (FEM-BEM) model is developed and FEM analysis conducted. The proposed contactless slipring system has been verified using simulation results. The rotating transformer output power, voltage gain and current gain plots are presented to assess the system performance. It has been found that the fringing flux on the windings, affects the conduction losses and the EMI, which can be reduced by placing the winding away from the air gap of the core. Practical design considerations as well as advantages of the proposed structure as compared to a typical coaxial design of rotating transformer have been discussed. It has been shown that the proposed coupling structure can deliver up to 4173 Watts of power at a 25 Ω resistive load. An excellent magnetic coupling factor of 0.92 is achieved as a result of the specific core geometry with a single air gap. The voltage gain for this system is 0.94, which indicates that the voltage drop across the leakage inductances and windings resistances is insignificant.

Key words: Contactless Power Transfer (CPT), Fringing flux, JMAG, Rotating Transformer.

I. INTRODUCTION

Contactless Power Transfer (CPT) is to transfer electrical power from one point to another through an air gap without any electrical contacts. CPT has been used for applications where either a direct amount or a continuous delivery of power is required, but where conventional wires are inconvenient, hazardous, unwanted or impossible [1], [2]. For instance, in applications such as electric plugs for battery charging, sliding contacts, supplies for trolley buses, etc, direct electric contacts may cause electric shock, short circuit, sparking, etc. This makes the system unsafe or unreliable with reduced lifespan. In rotating applications, mechanical sliprings are widely used to transfer power to a rotating part. However, despite all the developed technologies, their inherent high friction characteristics often cause too much wear and tear over time. Eventually, this is subjected to frequent maintenance and often the brushed of the sliprings need to be cleaned or replaced. The maintenance cost can be very high in applications such as wind turbines [3]. Therefore, there is a need to develop an alternative non-contact solution with low maintenance and long life cycle.

A new Contactless power transfer system based on inductive power transfer technology has been proposed [4], in which the primary and the secondary windings of a traditional transformer are wound on separate magnetic cores can overcome the above mentioned shortcomings. The benefits of transferring power to moving equipment without using electrical contacts have motivated many researchers in the past. Back in 1970s, the rotating transformer was proposed for the first time to transfer power from rotating photovoltaic panels to a satellite [5]. They have found that the core geometry and windings layout of the rotating transformer, the air gap between the two parts, the inductors misalignment and thermal resistances are some of the factors that affect the electrical behavior of the system. Different approaches, either improving the magnetic coupling structure; [6], [7], [8], [9] or leakage inductance compensation(resonant techniques); [10], [11] have been researched on to overcome the problem of low coupling coefficient and high leakage inductances in this field. Despite all the progress made so far in the field, there are still a lot of room in existing rotating transformer systems for improvements, such as low power transfer capability, high power losses and resultant temperature rise due to the fringing flux, low voltage gain, etc. Therefore, more research is needed in contactless slipring systems in order to replace the current mechanical slipring systems being used.

The aim of this research is to reduce the losses and increase the power transfer capability the contactless slipring systems by investing new magnetic coupling configuration. A new magnetic coupling structure with unique core geometry proposed for a rotating transformer to transfer electrical power between the two parts. The simulation results are presented for the system assessment. The impact of fringing flux on the windings conduction losses is analysed, and a solution to reduce the EMI is presented. Finally, practical design considerations are discussed, and the proposed system is compared with the typical existing coupling design [12], drawing the final conclusion.

II. Description of the Proposed System

There are two basic aspects that characterize the behaviour of the magnetic coupling structure used for contactless slipring systems: the magnetic core geometry and the windings layout. A detailed geometry of the proposed magnetic coupling structure is shown in Fig. 1. As a good magnetic coupling is important in contactless sliprings systems, the windings are interlocked. It is observable from the Fig. 1(a) that the rotating winding is sandwiched between the two parts of the stationary winding. This is done by dividing the primary winding in two parts and connected in series, while the secondary winding is placed in between them as it is shown in Fig. 1(b).

(a) (b)

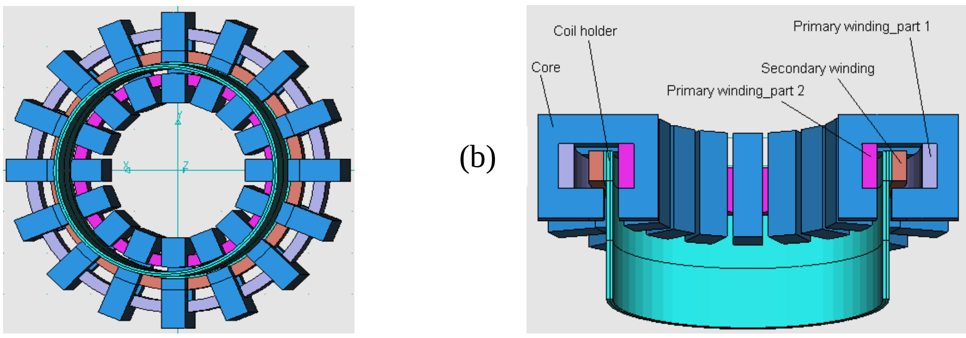

Fig 1: Proposed coupling structure: (a) Complete Geometry, (b) Cross-section view

Refer to Fig. 1; structure design of the proposed rotating transformer comprises a rotating winding wound on a non-magnetic and non-conductive holder, a ferrite core and two parts of stationary winding. Non-conducting and non-magnetic material is used to prevent any electrical or magnetic influences on the performance of the transformer. Ferrite core and stationary windings are fixed to the housing, while the rotating winding fixed on the shaft by the means of the coil holder and rotate with the shaft. The power supply is applied to

the stationary winding, whereas a 25 Ω resistive load is connected to the rotating winding. In this structure, there is no core used in the rotating part which simply the system. Therefore, only primary and non-rotating core is used in the stationary part of the proposed rotating transformer. This helps to eliminate the magnetic force interaction between permeable ferrite surfaces because all of the ferrite material remains fixed.
Only one air gap is used for the ferrite core in order to improve the magnetic coupling between the windings, reduce the changes in the reluctance as well as reduce the flux leakage. Therefore, undesired electromagnetic emissions are considerably can be reduced as a result of the single air-gap. However, the length of the air-gap is correlated to the thickness of the coil holder. In other words, it can be as small as possible if the coil holder is thin and strong enough to hold the rotating coil [see Fig. 2(a)], in turn, the associated losses and EMI would reduce.

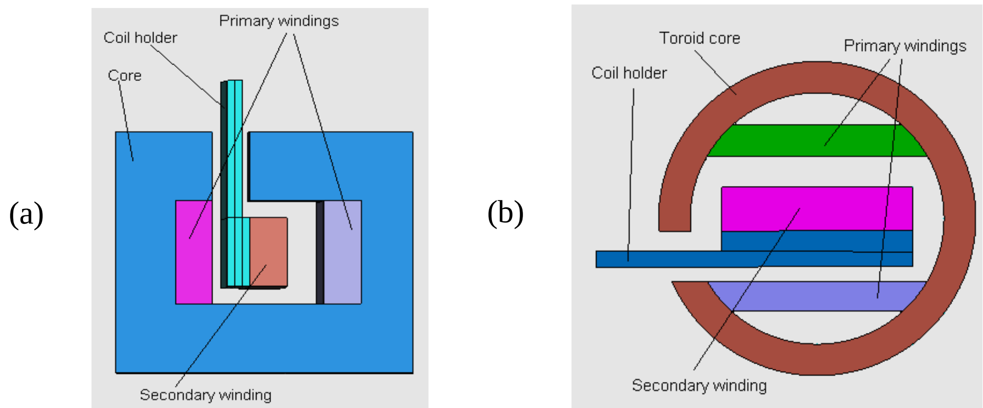

Fig 2: Core geometry and windings layout with: (a) U-shapes, (b) Toroid shape.

It can be seen from Fig. 2(a) the whole core shape can be made easily using two U-parts of the ferrite material. Besides, the alternative shape for the used core is the ring type of ferrite (Toroid) as it shown in Fig. 2(b). Number of cores used for this modeling was 16 which would be of assistance to achieve a good magnetic coupling and high power transfer capability as explained in details later in section-V (A). The axial symmetry of the proposed core geometry provides a fixed cross sectional area for any angle of rotation. This, in combination with the fixed air gap length, would result in the most important property of a rotating transformer; fixed electrical characteristics.

III. FINITE ELEMENTS MODELLING AND ANALYSIS

A. *Magnetic Coupling Structure Characterization*

To study the magnetic analysis and predict the electrical properties of the proposed system, a finite element 3D model of the coupling structure has been performed. The software used for this purpose is the JMAG package. The magnetic 3D model is developed to calculate the inductances, coupling factor as well as determine the efficiency and power transfer capability of the system. The procedure is comprised of four basic stages: drawing the 2-D model, defining material properties and boundary conditions, create the 3-D model and simulating/post processing the results. The simulation is performed at 38.4 KHz operating frequency, N1=N2=10, air gap of 5 mm, and $\Delta B_{max}(T)=0.3$. For the purpose of minimizing the winding losses, Litz wire has been assigned for the modelling.
Simulation procedure has been done in two steps; First step is the no-load analysis to calculate the inductances and coupling factor between the windings. Using the simulation

results of the first step is followed by load analysis the second step of the simulation to study the voltage, power and efficiency of the proposed system. Second step has been done for the various values of load and simulation results are demonstrated in Table 1. Due to the sandwiched winding layout with specific core geometry for the proposed system, the magnetic coupling factor is achieved about 0.92 which is quiet superior for the contactless power transfer system.

No load analysis		Load analysis					
		R_{load}(Ω)	5Ω	10Ω	15Ω	20Ω	25 Ω
		I_{in}(A)	18.7	18.7	18.7	18.7	18.7
		V_{in}(v)	102	182	250	302	342
		V_{out}(v)	89	169	234	285	323
L_{11}(H)	1.23E-04	I_{out}(A)	17.8	16.9	15.6	14.2	12.9
L_{22}(H)	1.03E-04	P_{in}(w)	1907	3403	4675	5647	6395
M_{12}(H)	1.03E-04	P_{out}(w)	1584	2856	3650	4061	4173
K	0.92	ΔB_{max}	0.04	0.07	0.1	0.14	0.17

Table 1. Simulation results for the proposed system.

B. *Validation of the Proposed Coupling Structure*

1. *Output Power*

From the Table 1, the flux density for the highest load value (25 Ω) was 0.17 which is much lower than the saturation limit with 0.3 Tesla. This indicates the unsaturated core as well as low core losses for this magnetic coupling structure. It can be seen from Table 1 that 4173 watts maximum power transferred to the load side. The input power for this case was 6395 watts. Therefore, the efficiency of the proposed structure is 65% for the worst condition (full load operation at 25 Ω). It's noticeable that these values are the uncompensated power values for the proposed system, which they would be greater in compensated conditions. More details about uncompensated/compensated inductive power transfer systems presented in [13].

2. *Voltage Gain*

The voltage gain of the transformer is useful in order to assess the transformer's capability to deliver the required power. A voltage gain that is lower than 1.0 implies a voltage drop across the leakage inductances and winding resistances. The voltage gain should be adequate to produce the desired output voltage under the worst case operation (minimum input voltage and maximum loading). The voltage gain curve of Fig. 3(a) indicates that the proposed system operates with a high voltage gain of 0.944 and it is quiet adequate for a rotating transformer. It can be observed that for this structure the voltage drop across the leakage inductances and winding resistances is insignificant.

3. *Current Gain*

The current gain of Fig. 3(b) is basically the ratio between the useful (load) current to the total current; it is, therefore, an indirect measure of the ability of the transformer to transfer power to the load. A poor current gain reveals a high magnetizing current in comparison with the reflected load current. The high primary current is likely to cause excessive conduction losses in the windings, and for this reason, it is not desired. It can be observed that the rotating transformer of the proposed coupling structure demonstrates an excellent current gain at highest load value. The minimum value for the current gain was 0.7 at 25 ohms connected load and output power of 4173 watts. This is obtained again at the uncompensated condition for the system.

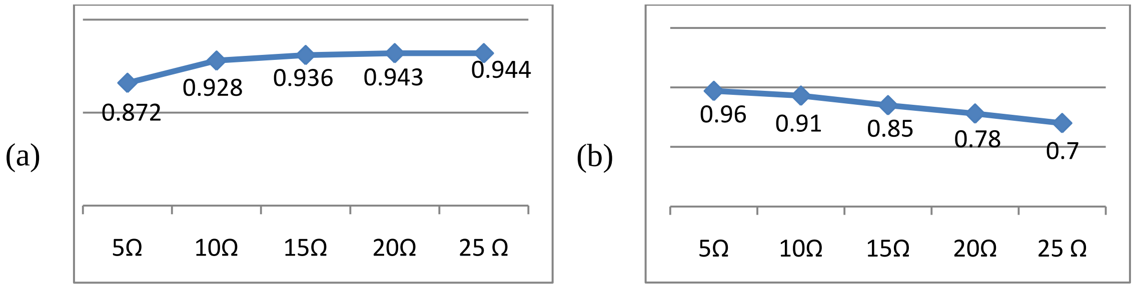

Fig 3: (a) Current gain and (b) Voltage gain: for various load values.

IV. Effect of Fringing Flux

The fringing magnetic flux around the rotating transformer air-gap is likely to cause two possible problems: 1) the development of eddy currents in the nearby turns and 2) the electromagnetic emissions of the transformer. The eddy currents are responsible for high temperatures in the winding turns that are next to the air-gap. The stray magnetic-field lines around the air gap as well, are associated with electromagnetic emissions. Due to varying the magnetic field, variable electric field would be created and the result is an electromagnetic emission around the air gap [14].

A. Winding Power Losses

To survey the effects of the fringing flux generated around the air gap, a cross-section view of the windings layout and the ferrite core is demonstrated in Fig. 4. The magnetic flux lines that cross any conductive material around the air gap generate eddy currents; these currents add to the winding current at certain points and subtract from it at others.

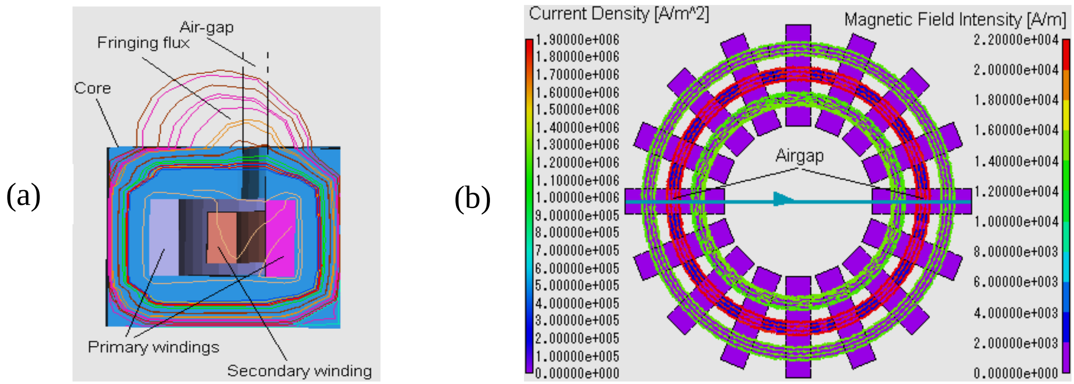

Fig 4: Effect of fringing flux: (a) on the neighbouring turns, (b) around the air gap.

In this paper, to avoid the interaction with the fringing magnetic field, the windings are placed away from the air gap in the core window area as it shown in Fig. 4(a). This resulted in reduction of the winding power losses as well as increases the voltage gain due to the lower voltage drops across the windings, in turn, increasing the overall efficiency.

B. Thermal Issues

Fig. 4(b) presents the field and current distribution of the proposed system at 25 Ω resistive load. The right side of the figure shows the increased magnetic field intensity with the maximum value of 2.2×10^4 A/m around the air gap and the nearby turns. This resulted in increased current density with the value of 1.9×10^6 A/m^2 close to the air gap. Referring to Fig. 4(b), it can be observed that the current density for this design structure is low and not even succeeded 2×10^6 A/m^2 at full load operation. This confirms the low operating temperature for the proposed magnetic structure. As a result, there will be no hot spot created in the windings to reduce the power capacity of the system; therefore, the transformer can operate in high power (full load) condition. Moreover, the air-gap of the core is not made toward the shaft of the system to prevent any excessive heating the shaft due to the above mentioned fringing flux generated around the air gap.

C. *EMI Concerns*

In case of the EMI associated with fringing flux, in this coupling structure, because of the particular core geometry with a single air-gap, the total generated fringing flux is less than a typical coaxial rotating transformer with two air-gaps. Besides, the interaction of fringing flux with windings is avoided by placing them away from the air-gap. This is shown in Fig 4(a). All these reasons are indicating that in this magnetic structure, undesired electromagnetic emissions are substantially reduced.

V. PRACTICAL DESIGN CONSIDERATIONS

A. *Number of Cores*

To study the magnetic core selection, its size and number of cores; initially the proposed coupling structure has been simulated with a single piece of core. Then, numbers of cores have been increased to 2, 4, 8 and 16 (full core) at a constant 25 Ω connected load. Simulation process has been repeated for the different number of cores and simulation results are given in Table 2 for the assorted cores number.

Core	1	2	4	8	16
P_{out}(w)	150	272	967	1413	4173
ΔB_{max}	0.38	0.37	0.32	0.24	0.17
K	0.75	0.8	0.86	0.89	0.92

Table 2. Simulation results for various numbers of cores.

Referring to Table 2, it can be observed that increasing the number of cores will increase the power transfer capability and minimize the core saturation losses. Saturated cores for the cases with 1, 2 and 4 cores demonstrated in Table 4, are exceeded the saturation limit with 0.3 Tesla. The values of ΔB for these cases are 0.38, 0.37 and 0.32 respectively. Accordingly, the maximum power values transferred to the load side are 150, 272 and 967 watts. Whereas, ΔB is 0.17 for the case of 16 cores which is much lower than the maximum saturation limit. Besides, a good magnetic coupling factor is achieved about 0.92 for this case. This is obtained at 4173 watts power transferred to the load side.

It can be seen that to design a contactless power transfer system based on rotating transformer; the first step is to choose an appropriate core (size and number). Likewise, required power supply will be designed later according to the chosen core, number of windings turns and the diameter of the wires as detailed in the following section.

B. *Number of Turns*

Second tentative selection for designing a rotating transformer is the number of windings turns. The number of turns determines the magnetic flux density within the core. Following this the diameters of the primary and secondary conductors can be calculated depending on the RMS-values of the currents. The minimum number of turns can be calculated to ensure that a certain change of flux density ΔB is not exceeded to avoid any unacceptable losses i.e. heat generation. Eq. 1 is derived from Faraday’s law and gives the minimum required number of primary winding turns $N_{p.min}$, for maximum flux density changes (ΔB_{max}) of a magnetic core with a minimum effective area A_{min}, when a voltage V_{in} applied across the winding [14].

$$N_{p.min} \geq \frac{V_{in}.T/2}{\Delta B.A_{min}} \quad (1)$$

Accordingly, diameter of the wire D, with the current density J, can be calculated from the Eq. 2 as following:

$$D = \sqrt{4.I_{rms}}/\pi.J \quad (2)$$

It's noticeable that number of turns should not be chosen significantly higher than $N_{p.min}$, otherwise the copper losses of the wire would increase unnecessarily due to the longer inductor. Moreover, for high frequencies and large diameter of the wire the skin effect should be considered. For operating frequencies more than 20 KHz and diameters of more than 1mm, Litz wire or copper foil should be used.

VI. EVALUATION OF THE PROPOSED COUPLING STRUCTURE

In this section, electrical as well as mechanical advantages of the proposed structure as compared with the typical coaxial rotating transformer [12] are discussed below:

A. *Electrical Attributes*

- *Sandwiched structure:* By this, the coils are magnetically interlocked to achieve a good magnetic coupling factor. (k=0.92)
- *Single core:* Using a single core, helps to eliminate the magnetic force interaction between permeable ferrite surfaces because all of the ferrite material remains fixed.
- *Single air gap:* As a result of single air-gap, the flux leakage as well as the changes in reluctance is reduced.
- *Reduced EMI:* Undesired electromagnetic emissions are reduced as a result of single air-gap and placing the windings away from the air-gap in the core window area.
- *Low Fringing Flux:* Because of the unique core shape with a single air gap, the generated fringing flux and flux leakage is less than a conventional rotating transformer with two air gaps. This had a great effect on increasing the power transfer capability of the system. The output power of the 25 Ω resistive load was 4173 watts.
- *Rotating coil holder:* Non-conductive and non-magnetic material is used to prevent any electrical or magnetic influences on the performance of the transformer.

B. *Mechanical Attributes*

- *Non-rotating core*: This is one the advantages of this design structure which avoids any possible breaking of ferrite material during rotation.
- *Air-gap positioning:* The air-gap of the core is not placed on the shaft side. The only connection between the transformer and shaft is the non-magnetic and non-conductive rotating coil holder [see Fig. 1]. This will significantly avoid any excessive heating the shaft due to the rotating transformer losses such as fringing flux, etc.
- *Easy to assemble:* Core shape is available and easy to assemble by using two U-parts of ferrite. An alternative to this is the available ring type of ferrite (Toroid).

VII. CONCLUSION

A new magnetic coupling structure with unique sandwiched core geometry is proposed for contactless slipring systems. The system modelling and analysing carried out based on the Finite Elements Analysis using the JMAG software. It has been found that positioning of windings and the air-gap has great influences on power loss and EMI reductions. Practical design issues are explained and the advantages of the proposed design structure are discussed. The proposed magnetic coupling structure has avoided the interaction between the windings and the fringing flux. Besides, proper positioning of the air gap can help to reduce excessive heating of the shaft due to the fringing flux generated around the air gap. Furthermore, undesired electromagnetic emissions are substantially reduced as a result of single air gap and placing the windings away from the air gap in the core window area. This results in reduction of the winding power losses while increasing the voltage gain due to the lower voltage drops across the winding. It has been found that the maximum power transferred to the load side is 4173 Watts. Moreover, a good magnetic coupling factor of 0.92 is achieved as a result of the specific core geometry with single air-gap. The voltage gain is 0.94, which shows that the voltage drop of the system is negligible.

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