Characteristic analysis of relatively high speed, loosely coupled rotating excitation transformers in HEV and EV drive motor excitation systems

Yong Yu and Xudong Wang
School of Electrical and Electronic Engineering, Harbin University of Science and Technology, Harbin 150080, China

Abstract: An inductively coupled power-transfer method is proposed using a new, brushless motor excitation method called contactless excitation system (CES). Uses a loosely coupled rotating excitation transformer (LCRET) and realize the transmission of excitation power, thereby proving to be safer and simpler than traditional excitation systems. The principles and two topologies are introduced. LCRET can achieve excitation-energy transmission when the primary and secondary sides rotate at a relatively high speed. The transient characteristics of the proposed topologies are compared using a finite element analysis to establish an optimal topology and verify the safety and high-efficiency energy transmission of LCRET by conducting tests.

Keywords: motor excitation, brushless excitation, inductive coupled power transfer, CES, loosely coupled rotating transformers

Classifcation: Power devices and circuits

References


1 Introduction

In HEV and EV drive motor excitation system, the electric brush produces contact resistance; with increasing excitation current, the electric brush and slip ring always generate extra heat because of the poor contact condition. As a result, the slip ring may easily burn, and the quality of the electric brush directly influences operational stability. Therefore, the failure rate of this type of motor is relatively high. In addition, unavoidable carbon dusts generated during electric brush abrasion can destroy the operational environment with potential dangers to operational safety [1, 2, 3]. Because of this obvious drawback, operating crews need to inspect components and often change the electric brush. The relatively high-frequency electromagnetic interference during electric brush operation can deteriorate the electromagnetic environment and cause severe electromagnetic interference. These effects prevent the motor’s reliable operation [4, 5].

The technology of inductive coupled power transfer system is developing rapidly. It is widely used in transportation, medical, communication, aviation and other fields. The technology will be the perfect combination of electricity and magnetism by means of power devices. It realizes that the supply side and the receiving side are not physically connected and is a good solution to the security problems of electrical equipment. A novel excitation method is developed based on the high-frequency power supply technology. This system does not require any electric contacts, and the excitation current is controllable. The overall system structure is simple, occupies limited motor space and does not require changes in the structure of the armature and excitation windings [6, 7, 8]. CES is theoretically based on inductively coupled power transfer, adopting the interior loosely coupled rotating excitation transformer as the core of energy transmission, the DC voltage
from stator side links the LCRET through the inverter, the excitation energy transmit to the excitation coil on the rotor side with the method of controllable excitation current without any electric contact by rectification. The designed motor excitation system is capable of successfully replacing the original electric brush and slip ring structure and is easier to manage. Meanwhile, the CES is highly reliable. Compared with the traditional brushless excitation method, the CES excludes an exciter and other additional complex devices; the simulation and experimental results verify the design feasibility and prove the proposed method to be a novel thinking for the motor excitation method [9, 10, 11, 12].

2 The contactless excitation system

A flowchart of the CES is shown in Fig. 1. Based on the ICPT high-frequency switch power supply mechanism, motor excitation windings have been connected to the output of the switching power supply. It can provide excitation current according to the need of the field current; at the same time, it can be easily controlled. The motor rotor and stator part is relative motion, but the traditional device for high frequency switching power supply is fixed. Therefore, a special device is needed for dynamic and static energy transfer; this device is called the LCRET. An inverter controls the switch tube power through a high-frequency signal. The power supply input DC is transformed into a high-frequency alternating current that is loaded to the primary windings of the LCRET; these primary windings are fixed at the end of a motor stator iron core, which mirrors to secondary windings. Under high-speed rotation, the secondary side produces high-frequency voltage that passes the rectifying filtering supply to field winding.

The secondary side iron core is coaxial with the rotor of the motor because of the adoption of cylindrical magnetic tank transformation; the magnetic circuit will hardly be affected, and the advantages of the CES compared with traditional brushless excitation motors are obvious. On the other hand, the secondary iron core is rotating with the rotor; it leaves the exciter part and rotating rectifier of AC excitation. It does not occupy extra motor space and can realize favourable and
controllable excitation. Using the same DC bus, which is arranged at the stator casing surface, the controller and inverter are in the stator shell cavity. A 1–3-mm air gap exists between the primary and secondary windings in the LCRET.

The CES assembly is presented in Fig. 2. The A–A plane shows a motor shaft section. The primary windings are fixed at the stator end, and the LCRET secondary windings are fixed at the rectifier circuit. The B–B and C–C planes are perpendicular to the direction of the motor’s rotation at different profile locations. Along the B–B direction, the secondary windings of the LCRET internal structure can be clearly observed. Along the C–C direction, the structure of the rectifier circuit board can be observed. The function of the rectifier is to transform AC into DC. To prevent the deflection of the rectifier circuit, it is fixed at the side of the rotor, and the circuit is designed to have a circular symmetric structure.

3 The loosely coupled rotating excitation transformer

Loosely coupled rotating excitation transformer (LCRET) is a rotatable, detachable and axisymmetric excitation system with a consistent cross-sectional area. When the primary side and the secondary side of the system are rotating relative to each other, they are not affected by each other’s state. LCRET maintains normal working conditions for energy transfer. Moreover, LCRET has good electromagnetic compatibility and interchangeability because of its structural characteristics and materials used for the transformer tank. It is suitable for use in hybrid electric vehicles (HEVs) and electric vehicles (EVs) because of its large magnetic effect, high permeability, reliable temperature characteristics, low attenuation and ease of installation. The vertical view and front view annotations of LCRET are shown in Fig. 3. As per the requirements of the contactless excitation system (CES) in the LCRET design, two types of winding topologies can be developed for the transformer structure, i.e. an adjacent topology structure and a coaxial topology structure.

3.1 Physical model of LCRET

First, an accurate magnetic resistance model and an electrical model can be developed from the physical layout of the winding topology. The view of adjacent topology is shown in Fig. 4. The view of coaxial topology is shown in Fig. 5.

Equation (1) is directly derived from Faraday’s law and gives the required number of primary winding turns $N_p$ for optimum utilization ($\Delta B_{\text{max}}$) of a magnetic
core with an effective area $A_e$ when a voltage pulse $V_i$ of a duration $D_{\text{max}}/f_{SW}$ is applied across the winding.

\[ N_p = \frac{V_i D_{\text{max}}}{A_e B_{\text{max}} f_{SW}} \quad (1) \]

\[ L_m = N_p^2 (R_e + R_s)^{-1} \quad (2) \]

\[ L_m = N_p^2 \left( \frac{l_e}{\mu_0 h_c A_c} + \frac{l_a}{\mu_0 h_c A_a} \right)^{-1} \quad (3) \]
In Equation (3), \( l_c \) and \( l_a \) represent the magnetic circuit length and air-gap length, respectively. \( A_c \) and \( A_a \) are the winding cross-sectional area and air-gap cross-sectional area, respectively. In an air gap, the high-speed rotating transformer \( R_a \) will be much larger than \( R_c \), and therefore, the latter can be ignored without compromising on accuracy:

\[
L_m = N_p^2 \left( \frac{l_a}{\mu_0 \mu_{rlk} A_a} \right)^{-1}
\]

(4)

Similarly, the leakage inductance can be approximated by

\[
L_{lk} = N_p^2 \left( \frac{l_{lk}}{\mu_0 \mu_{rlk} A_{lk}} \right)^{-1}
\]

(5)

Where \( \mu_{rlk} \), \( l_{lk} \) and \( A_{lk} \) are the permeability, effective length and air space area, respectively, where the leakage flux resides. The windings’ effective resistance is an important parameter for the CES that determines the LCRET efficiency and depends on several factors. According to the abovementioned analysis and Equations (1)–(5), the effective resistance of LCRET is given by:

\[
R_{eff} = R_{dc} + \frac{\Psi}{3} \Delta^4 R_{dc} \left( \frac{f'}{IoI} \right)^2
\]

(6)

\[
\Psi = \frac{5p^2 - 1}{15}
\]

(7)

\[
\Delta = \frac{d_{eff}}{\delta_0}
\]

(8)

\[
R_{dc} = 4 \rho \frac{n \times MLT}{\pi \times STR \times d_c^2}
\]

(9)

Where MLT is the mean length of a turn, SRT is the number of strands of the windings, \( d_{eff} \) is the effective winding thickness of a layer, \( p \) is the number of winding layers, \( I \) is the rms value of the current and \( f' \) is the rms value of the derivative of the current flowing through the windings.

### 3.2 Equivalent electrical model and electromagnetic theory

From the analysis in Section 3.1, the magnetic-flux coupling relation between each side of the transformer is quite complex and the value of the leakage inductance is high because of the air gap in LCRET relative to the motion of CES. Therefore, the electrical characteristics of the primary side are closely related to those of the secondary side in LCRET. The traditional equivalent circuit model for the leakage inductance of a transformer does not produce reliable results for the electrical characteristics of LCRET and the calculation process is found to be redundant for CES. A mutual inductance circuit model, wherein the magnetic flux is the sum of the mutual inductance magnetic chain and corresponds to the self-induction of the primary side, is more appropriate in this context. The hinge flux on the secondary side is a type of mutual inductance. Therefore, when the mutual inductance model is applied to the system, the leakage effect can be ignored, thereby simplifying the calculations for the inductance.

The reluctance model and the equivalent circuit of the two winding topologies are presented in Fig. 6. Because of axial symmetry of the LCRET, there is not any
influence when it rotating. Maxwell equations are still applied. Use the Maxwell equations to describe the basic principle of the electromagnetic field.

\[
\nabla \times \mathbf{H} = \sigma \mathbf{E} \\
\n\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \\
\n\n\nabla \cdot \mathbf{B} = 0 \\
\n\n\nabla \times \frac{1}{\sigma} \nabla \times \mathbf{H} + \frac{\partial \mathbf{B}}{\partial t} = 0
\]

4 Instantaneous characteristic analysis of the LCRET

In this study, a three-dimensional (3D) transient field is calculated using edge elements in a finite element model. Two types of 3D models for CESs are developed in this study. LCRET rotates in a relative manner in a state of transient field. The performance of these two models under the same operating conditions is analyzed using the Maxwell simulation software (Ansoft Corporation) and the triangle subdivision graph obtained is shown in Fig. 7.

4.1 Magnetic induction intensity of the LCRET

To determine the electrical characteristics of LCRET, it is necessary to compare the magnetic induction intensity under both relative resting and relatively high-speed rotation conditions for both adjacent winding and coaxial winding topology structures. The results of this comparative analysis are shown in Fig. 8. Comparing Figs. 8(a & c) and Figs. 8(b & d), it can be observed that there is a very small difference in the gap of LCRET when comparing its stationary state and relative-rotation state. Therefore, the state of LCRET has little impact on the distribution of the magnetic induction intensity of a transformer. Both winding topologies...
described in Section 2.1 have been verified as applicable to LCRET. The magnetic induction intensity of the secondary side is greater than that of the primary side irrespective of the type of topology structure selected.

When the secondary side is in the relative rotation state, the magnetic induction intensity of magnetic core on the primary side and secondary side is symmetrical. It is a closed loop similar to the shape of a water vortex and has a specific divergence, which is a direct cause of the low value of the transformer coupling coefficient. The magnetic flux leakage in LCRET has a close relationship with air as the magnetic circuit is not saturated. Magnetic induction intensity maintains a linear relationship with the winding current; therefore, it is strongly related to the size, shape and arrangement mode of the winding. Furthermore, the leakage inductance for the adjacent winding topology and coaxial winding topology, which directly affects the transmission efficiency, is different for the same operating conditions. These can be compared by observing Figs. 8(a) to Figs. 8(d). It can be seen that the average value of magnetic induction intensity for the adjacent winding topology is higher than that for the coaxial winding topology. From this viewpoint, the adjacent winding topology is preferred for CES. The coupling between the primary side and the secondary side is different for the LCRET area of each topology because of the axial distance of the magnetic tank being less than its diameter.

Fig. 7. Triangle subdivision graph.

Fig. 8. Magnetic induction intensity LCRET.
4.2 Current density distributions of LCRET

In addition, for the high-speed rotation, the mechanical processes of the secondary side place a higher demand on the coaxial winding topology. A slight jitter of the motor or the introduction of a human error in the configuration of the transformer can easily lead to a collision between the primary side and secondary side, causing serious safety issues. Therefore, the adjacent winding structure has been identified as the optimal topology for LCRET.

The waveform simulation of the current density is shown in Fig. 9. For the same power input, the current density in the adjacent winding topology is higher than that for the coaxial winding topology. When the external conditions are consistent, the influence of the air gap on the current density is relatively small. Therefore, the current density of the secondary side is relatively larger and the power-transfer capability is better owing to the advantages of the coupling area.

In addition, for the high-speed rotation, the mechanical processes of the secondary side place a higher demand on the coaxial winding topology. A slight jitter of the motor or the introduction of a human error in the configuration of the transformer can easily lead to a collision between the primary side and secondary side, causing serious safety issues. Therefore, the adjacent winding structure has been identified as the optimal topology for LCRET.

5 Experimental results and analysis

5.1 LCRET output characteristic tests for different topologies

To objectively represent the characteristics of the two winding topologies, experiments on the electrical output characteristics are conducted on both topologies. The turns ratio of LCRET was set at 1:1. With an identical input power, the output characteristics of each topology are shown in Fig. 10.

The output voltage and output current are different because of the structural differences of each topology. For the adjacent winding structure, the output voltage is relatively regular compared with a rectangular wave. There is a slight pulsation at both high and low levels. The input characteristics have no effect on the output characteristics in this case. For the coaxial winding structure, the output voltage is an arc and it introduces a serious waveform distortion. For the waveform of the output current for the adjacent winding topology, a small pulsation of current can be observed because of a small fluctuation in the voltage, whereas for the coaxial winding topology, the current presents a relatively smooth triangular wave shape.

The loosely coupling characteristics of LCRET require a resonant compensation because of the air gap. The detailed principles of resonant compensation for coupled winding topologies have not been elaborated on in this study; however, the
The efficiency of loosely coupled systems is shown to be lower than that for tightly coupling systems; however, the same for the adjacent winding topology is shown to be comparatively higher than that of the coaxial winding topology.

5.2 Excitation output performance test

On the basis of the experimental results, the accuracy of the finite element modelling is verified as the results agree well with the expected outcomes. To further verify the principles and optimal topology of CES, a testing prototype is established. The results of the output performance of this prototype are shown in Fig. 12. The measured primary side current waveform and excitation voltage are shown in Fig. 13.
Following a series resonance compensation strategy, the primary side presents a standard sine-wave current. A two-port network shows that the system can maintain pure resistance. At the same time, the winding voltage is 12 V, approximating the ideal excitation state. The excitation output phase voltage waveform is presented in Fig. 14. The phase voltage obtained from the picture standard sine amplitude is approximately 450 V. The CES function states were reasonably and accurately realized. The design is verified by the accuracy of the LCRET and CES is feasibility.

5.3 Efficiency of the CES at different air gaps in LCRET
The efficiency of the CES at different air gaps is shown in Fig. 15. When other conditions are unchanged, the air gap directly determines the efficiency. Mechanical processing is difficult when the motor with high speed that the air gap and can’t be too narrow at the same time. Based on the simulation analysis, at an air gap of approximately 1 mm, efficiency can reach more than 78% and can satisfy the requirements of excitation.

5.4 Voltage at different speeds
To validate the proposed excitation, the system was tested at different rotational speeds. The obtained output voltage values are shown in Fig. 16. It is clearly observed that the output voltage waveform is not ideal under low speed. In more than 1200 rpm, the voltage waveform is ideal, meaning that the CES is ideal under high-speed motor routine conditions.
6 Conclusion

Owing to the high cost and poor excitation performance of traditional motors in HEVs and EVs, a novel rotor excitation design for a motor called as CES is proposed in this study. Two topology types are proposed for LCRET. Furthermore, a finite element model is established based on these designs and the characteristics of the electromagnetic field conditions for LCRET within CES are selectively analyzed. The corresponding electrical output characteristics for both adjacent winding topology and coaxial winding topology are obtained from experimental data. The following conclusions regarding the corresponding output excitation results and transmission performances at different speeds and air gaps are obtained from the simulation and experimental results:

(1) The 3D finite element simulation for LCRET, which compares the magnetic induction intensity, current density and mechanical considerations of setting up LCRET, suggests that the efficient and stable characteristics of the adjacent winding topology satisfy the requirements of the CES design in a better manner than the coaxial winding topology.

(2) The prototype tests verify that the combination of an adjacent winding topology with resonant compensation enables good excitation performance. The measured excitation parameters and phase voltages at high-speed conditions demonstrate a transmission performance adequate for realising the CES design.

(3) The optimum working air gap for LCRET is determined as 1 mm. Furthermore, the efficiency–air gap curve shows that the efficiency of power transmission is 78% at the optimum air gap, which satisfies the excitation power requirements. In addition, the speed–voltage results demonstrate that the excitation performance of the CES design is optimal when the operating speed is greater than 1000 rpm.

These conclusions verify the feasibility and accuracy of the LCRET design. Therefore, the proposed CES provides a new method for the excitation of the synchronous motor.

Acknowledgments

The work was financially supported by the National Science Foundation of China (51177031).