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Design and control strategy applying the novel highly effective magnetic flux coupling (HEMFC) scheme for a non-contact power transfer system

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Abstract

In this paper, the novel design concept for highly effective magnetic flux coupling (HEMFC) schemes, based on enhancement of path guiding effect for leakage flux transmitting, is proposed for a non-contact power transfer system. Two implementation techniques are presented herein utilizing simple structure opinions of specific slant air gap as well as adding of metal bushing components. Both simulation and experimental results demonstrate that the improvement of magnetic coupling ratio and overall system efficiency are achieved by applying the two HEMFC schemes as the power transmitting devices.

Keywords: High effective magnetic flux coupling scheme; Non-contact power transfer system

1. Introduction

Nowadays, convenience and safety considerations for operation of products and devices apparently become one of the primary requirements in applications of daily life, described in Refs. [1,2]. Power transferring issue can be sorted out as one of the critical concerns in such a development trend and need more efforts to be involved in design of applicable schemes, especially for hazardous environment utilization.

Contact power transfer systems may be dangerous due to contact spark and are not suitable for several applications, for example: operation with water, oil extraction, high power transfer and so on, introduced in Refs. [2–4]. Non-contact power transfer systems, hereafter, provide the effective schemes for solving the above problems and conform to the trend.

The key design element for the non-contact power transfer system is the magnetic-power coupling transformer, also named the detachable transformer, and high coupling ratio can be concluded as its ultimate development goal [4,5]. Research opinions on special shape design for composing the main part of the detachable transformer have been presented in Refs. [1–3,6,7], such as the applying magnetic core with combination shapes of flat, disk, pot, and pillar. Nevertheless, the shapes of cores may lead to a special-made requirement to the manufacturing [6,8]. By the above description, the design with simply modified appearances of commercial core legs, which can limit the cost for production, as well as owning enhancement for the coupling effect have motivated this research work.

Hence, two novel designs of the highly effective magnetic flux coupling (HEMFC) scheme taken as the bridge-like device for power transfer, utilize the tendency of path of magnetic flux transmitting by means of magnetism concept, are proposed. Besides, a novel non-contact power transfer system is also implemented with criterion of

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collocation of topologies and energy processing control strategies in counterparts.

2. Overall system design concept

Among all the design goals of this system, the overall efficiency is the ultimate design concern.

2.1. Modelling strategy of system control

A developed non-contact system with novel HEMFC schemes illustrated as Fig. 1, is designed to be with power rating of 1 kW, input AC voltage of 110 V of 50/60 Hz, and output DC voltage of 100 V. The presented non-contact power transfer system includes three main parts of the input energy-processing unit, output energy-regulation unit, and the intermediate magnetic transmitting unit. The magnetic flux transmitting component, defined as HEMFC scheme herein, is the most crucial device related to effectiveness evaluation of the applicability for this developed system.

According to the simple relations of power values expressed in Eq. (1), the energy-processing requirements can be conformed and computed by the deployed control strategies and the related circuit operation, which can keep the desired transferring power eventually.

$$E_{\mathrm{ff}} = \left(P_{\mathrm{f}} \Big/ P_{\mathrm{i}}\right) e_{\mathrm{c}}(C_{\mathrm{pl}}, F_{\mathrm{lx}}) \left(P_{\mathrm{o}} \Big/ P_{\mathrm{s}}\right), \tag{1}$$

where E_{ff} means system efficiency. P_{i}, P_{f}, P_{s}, and P_{o} express system input power, primary-side input power, secondary-side input power, and system output power, respectively. e_{c}, C_{pl}, and F_{lx} denote the pre-measured efficiency mapping function, magnetic coupling ratio, and magnetic flux in the primary side.

The control strategy can be derived further based on the system model, shown as Fig. 2.

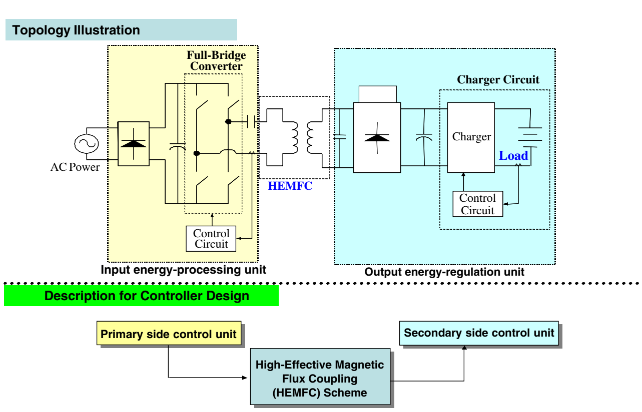


Fig. 1. Overall scheme of the non-contact power transfer system.

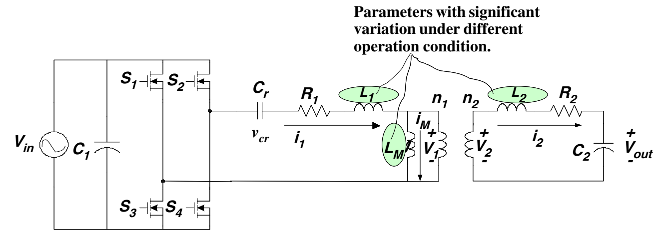


Fig. 2. Circuit model of the non-contact power transfer system.

Then, the control model can be realized by the state expression of the system in the form of

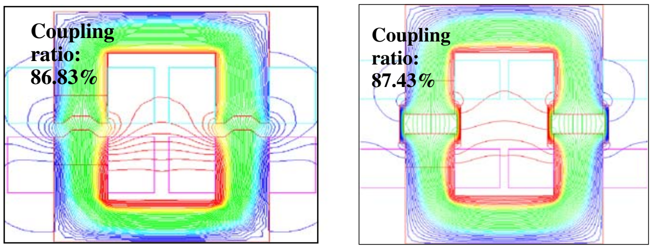
$$\begin{bmatrix} \frac{\mathrm{d}i_1}{\mathrm{d}t} \\ \frac{\mathrm{d}i_2}{\mathrm{d}t} \\ \frac{\mathrm{d}v_{cr}}{\mathrm{d}t} \\ \frac{\mathrm{d}v_{out}}{\mathrm{d}t} \end{bmatrix} = - \begin{bmatrix} \frac{(L_2+a^2L_{\mathrm{M}})\cdot R_1}{\Delta} & \frac{aL_{\mathrm{M}}R_2}{\Delta} & \frac{L_2+a^2L_{\mathrm{M}}}{\Delta} & \frac{aL_{\mathrm{M}}}{\Delta} \\ \frac{(aL_{\mathrm{M}})\cdot R_1}{\Delta} & \frac{(L_1+L_{\mathrm{M}})R_2}{\Delta} & \frac{aL_{\mathrm{M}}}{\Delta} & \frac{L_1+L_{\mathrm{M}}}{\Delta} \\ -\frac{1}{C_{\mathrm{r}}} & 0 & 0 & 0 \\ 0 & -\frac{1}{C_2} & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} i_1 \\ i_2 \\ v_{\mathrm{cr}} \\ v_{\mathrm{out}} \end{bmatrix} + \begin{bmatrix} \frac{(1-2D)\cdot(L_2+a^2L_{\mathrm{M}})}{\Delta} \\ \frac{(1-2D)\cdot aL_{\mathrm{M}}}{\Delta} \\ 0 \\ 0 \end{bmatrix} \cdot [v_{\mathrm{in}}], \tag{2}$$

where C_{r} and C_2 mean the serial resonant capacitor and loading capacitor. Suffix 1 and 2 denote the indexes for indicating the parameters of primary and secondary side, respectively. R and L are winding resistance and leakage inductance of the transformer. L_{M} is the magnetizing inductance. n_1, n_2 are winding turn numbers with the ratio $n_1/n_2 = a$. i_1, i_2, i_{M}, v_{cr} and v_{out} are primary-side current, secondary-side current, magnetizing current, voltage crossed the resonant capacitor, and output voltage, respectively. D denotes the control parameter of signal duty cycle. Besides, define $L_1L_2 + L_2L_{\mathrm{M}} + a^2 L_1 L_{\mathrm{M}} = \Delta$. And, the regulation of inputting electric energy can be achieved based on the above-described model.

2.2. Design of HEMFC scheme

Two HEMFC schemes, using material of 3C90 of U-type cores based on the flux leakage reduction for increasing of magnetic flux coupling effect, are proposed by specific slant shape and applying metal bushing coverage. The bushings in the legs of wound cores can significantly decrease leakage magnetic flux, as well as the effect of surpassing magnetic flux coupling by slant shape design of legs with protruding and concaving, shown in Fig. 3.

The software of Ansoft Maxwell EM is applied to perform the preliminary analysis and verification of the magnetic coupling effect of the proposed HEMFC schemes. As shown in Fig. 3, the two designs both with higher flux densities in air gap, improve the magnetic flux



(a) (b)

Fig. 3. The proposed novel HEMFC schemes and effect analysis. (a) Specific slant shape design and (b) Added bushing design.

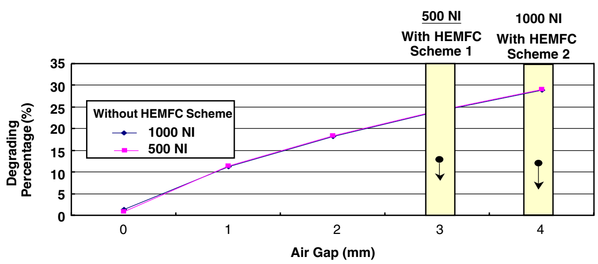
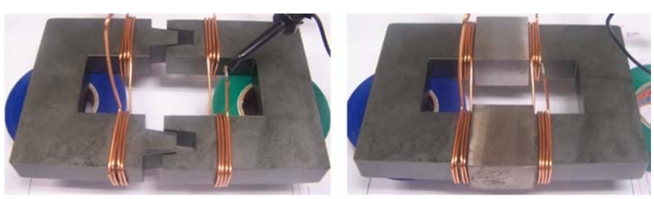


Fig. 4. Results of reduction of magnetic flux coupling degrading.



(a) (b)

Fig. 5. The implementation structures of the HEMFC schemes. (a) Specific slant shape design and (b) Added bushing design.

coupling ratio to be more than 86% under air gap length of 10 mm.

The overall system efficiencies integrating the two new HEMFC schemes are both higher than 85% and with improvement of 11% compared to the contactless power transfer system applying ordinary 3C90 material of U-type core without specific magnetic coupling design, shown as Fig. 4.

3. Experimental setup and results

In general, coupling effect of transformers can be evaluated by equivalent parameters. By following Eqs. (3) and (4), the magnetic coupling coefficient k can be obtained:

$$L_t = L_{1p} + L_{2s} + 2M, \tag{3}$$

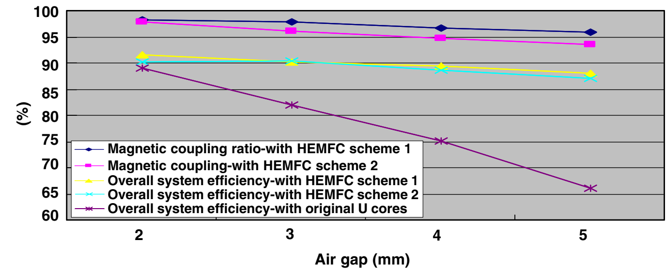


Fig. 6. Experimental results for system verification.

$$k = M/\sqrt{L_{1p} \cdot L_{2s}}, \tag{4}$$

where L_t, M, L_{1p} and L_{2s} mean total serial inductance, mutual inductance, primary-side self inductance, and secondary-side self-inductance of the transformer, respectively. By impedance analyser (HP 4194), the above parameters can be measured. The transformers based on the two novel HEMFC schemes are made by the commercial core with detail type number of FERROXCUBE U93/76/16, photoed as Fig. 5.

The performance evaluation results for the developed prototype non-contact power transfer system, with the setting operation value of switching frequency of input energy-processing unit chosen to be 70 kHz, are illustrated as Fig. 6. It is clear that both the coupling effect and overall system efficiency is upgraded by the proposed HEMFC schemes.

4. Conclusion

Two novel HEMFC schemes are proposed to improve the magnetic coupling ratio for upgrading the efficiency of a non-contact power transfer system. The structure designs of the magnetic core based on the concept of lowering the leakage flux demonstrate the significant improvement of magnetic coupling effect and their applicability.

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