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An advanced double-layer combined windings transverse flux system for thin strip induction heating

Youhua Wang,[2] Junhua Wang,[1,a)] Lingling Pang,[2] S. L. Ho,[1] and W. N. Fu[1]
[1]*Department of Electrical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong*
[2]*Province-Ministry Joint Key Lab. of Electromagnetic Field and Electrical Apparatus Reliability, Hebei University of Technology, Tianjin 300130, China*

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A novel double-layer (DL) combined windings transverse flux induction heating (TFIH) system is used to address the inhomogeneous eddy current density problem which dominates the thermal distribution on the surface of work strips. The single-phase winding of a typical TFIH system is replaced by a double-layer combined one, which enables the magnetic fluxes generated by each phase to interact and complement each other to compensate for the weak magnetic areas that otherwise would generate more uniform and concentrated eddy current density and temperature distribution. In order to attain the performance of the proposed DL-TFIH system, an interpolative finite element analysis modeling method is introduced in this paper. Simulation results of the proposed systems are compared with a typical TFIH device. © *2011 American Institute of Physics*. [doi:10.1063/1.3536469]

Despite the wealth of potential industrial applications of the transverse flux induction heating (TFIH), there are few reports in the literatures on this important technology when compared to longitudinal induction heating systems, even though there are some dedicated analytical studies and numerical methods on TFIH systems.[1,2] In fact, prior studies only introduce some unrealistically oversimplified and impractical assumptions using, for example, a current sheet on the yoke without slots as the model. In this paper, an advanced novel double-layer (DL) combined windings -TFIH system is proposed.

For transient performance, such as the eddy current and temperature field distributions, the results from traditional methods are not as accurate as expected due to skin effects on the solid pole surface and serious magnetic nonlinearities. With the advent of powerful computing workstations, two-dimensional (2-D) and 3-D finite element analyses (FEAs) have now become feasible in practical applications, not only for steady-state field analysis but also for transient performance study of induction heaters.[3–5] But for complicated TFIHs, a transient 3-D FEA study to include the eddy current and temperature field distributions is computationally expensive and very often infeasible for industrial applications due to its complex 3-D meshing process and the excessively long solution time required.

In order to attain the performance of the proposed DL-TFIH system, an interpolative FEA modeling method is introduced in this paper. With the proposed novel 3-D models and due consideration to their operational physics, an effective core length is proposed and the end-turn parameters are reevaluated and incorporated into a 2-D FEA model.

Figure 1 shows the 3-D schematic of the proposed novel configuration of the DL-TFIH heater with two linear inductors on opposite sides of the strip, slots perpendicular to the direction of the movement and a relatively large air-gap due to the thickness of the refractory material interposed between the inductor and the strip.

For the transient analysis, the time step needs to be sufficiently fine, such as 0.1 ms in this study, so as to simulate the eddy current distribution correctly. Based on the observations, it is estimated that it takes more than a few days in order to obtain the complete solution with 3-D FEA. Two main causes for inaccuracy in the simulation results when using 2-D models to replace 3-D ones are the end-turn leakage inductance and the equivalent effective core length.

The end-turn winding is included by coupling the electric circuit of end-turn winding with the end-turn leakage inductance. The total inductance in the phase winding can be obtained by

$$L_\sigma = q \cdot n_c \cdot k_w \cdot L, \tag{1}$$

where q is the slot number per pole per phase, n_c is the turn number per coil, k_w is the winding factor, and L is the end turn inductance for the measured coil.

Effective core length is another issue to be considered for a large induction heater with axial cooling ducts.

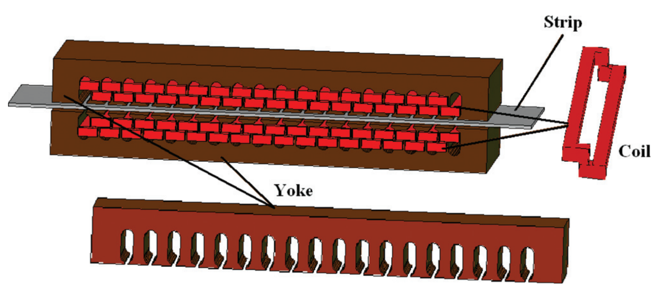
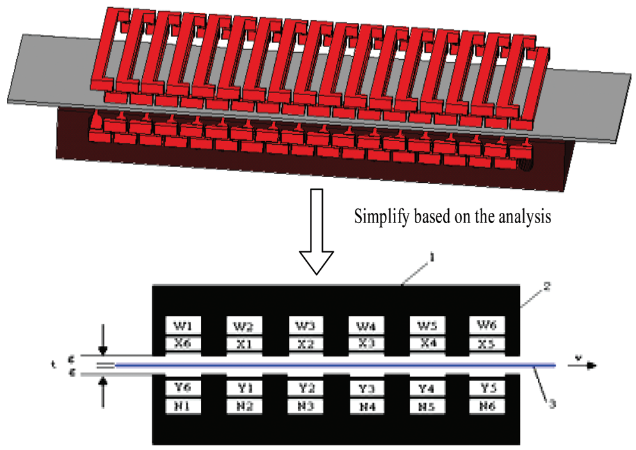
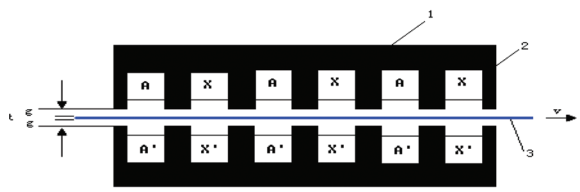


FIG. 1. (Color online) The 3-D schematic of the proposed novel configuration of the TFIH heater.

a)Author to whom correspondence should be addressed. Electronic mail: junhua.wong@polyu.edu.hk.



(a) DL-TFIH



(b) Typical TFIH

FIG. 2. (Color online) Schematic of the 2-D DL-TFIH and typical TFIH transient FEA model (1: magnetic yoke; 2: exciting windings; 3: load metal sheet; *t*: strip thickness; *g*: airgap between inductor and load; *v*: strip movement velocity).

Typically, the net core length is used as the model depth in a 2-D model, and the net core length l_{net} is defined as

$$l_{net} = l_t - n_{duct} \cdot l_{duct}, \tag{2}$$

where l_t is the nominal stack length, l_{duct} is the width of each air-duct, and l_{duct} is the number of cooling ducts.

The use of net core length cannot give sufficiently high accuracy in the 2-D FEA simulation. However, these differences can be compensated with a modified effective core length, i.e., the core length in the 2-D model should be interpolated based on the 3-D flux value.

Based on the analysis, a 2-D transient FEA model with the above modified parameters is proposed which is shown in Fig. 2(a). The procedure is computing the end-turn leakage inductance and the effective core length according to the method described above. For comparison, the structure of the typical TFIH system is also displayed in Fig. 2(b).

The operation of the proposed induction heating devices, namely, the DL-TFIH systems, are investigated using FEM analysis. Particular attention is paid to the analysis of the magnetic flux density, the eddy current distribution, and the power density.

Because ac current through every winding generates a magnetic field, which induces eddy currents to produce the thermal field, the total magnetic field is the additive contribution of six pairs of upper-and-lower windings. The result of the airgap flux density calculation of the DL-TFIH system is shown at different positions in Fig. 3. The average trend of the airgap flux density B has a symmetrical waveform having similarly triangle-topped amplitude. Flux densities in the

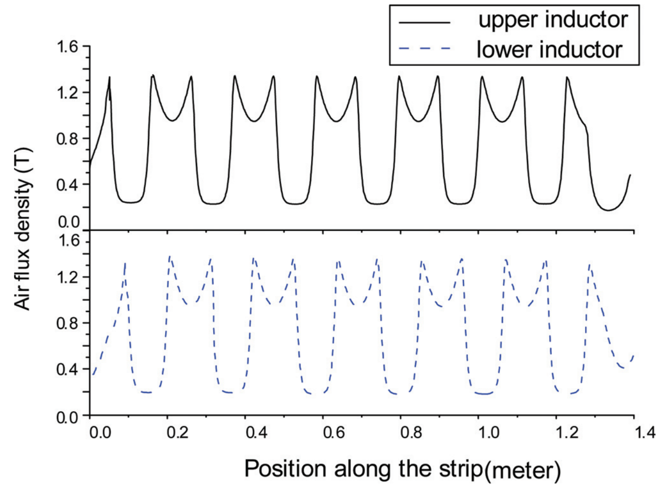


FIG. 3. (Color online) The airgap flux density distribution in the work strip from the upper and lower inductors.

upper and lower inductors make up for the weak areas of each other.

In order to study the efficiency of the DL-TFIH system, the flux density distributions along the direction of the strip movement are also shown in Fig. 3. It can be seen that a typical TFIH system's magnetic flux is distributed symmetrically along both sides of the axis and reaches the maximum above the magnetic yokes, while the magnetic flux intensity is relatively weak above the windings. Near the center of axis the intensity decreases to the minimum. The curve of the DL-TFIH system's magnetic flux density is relatively more homogeneous than that of a typical TFIH heater, which shows low density only in several limited regions. Thus the eddy current field and the temperature field distributions on the work strip should be more uniform in the proposed DL-TFIH system than that in typical TFIH systems as confirmed.

For the induced eddy current field, the basic equations are established using $\vec{A} - \phi$ formulation. The magnetic vector potential $\vec{A}$ is defined as $\vec{B} = \nabla \times \vec{A}$ and the current density is

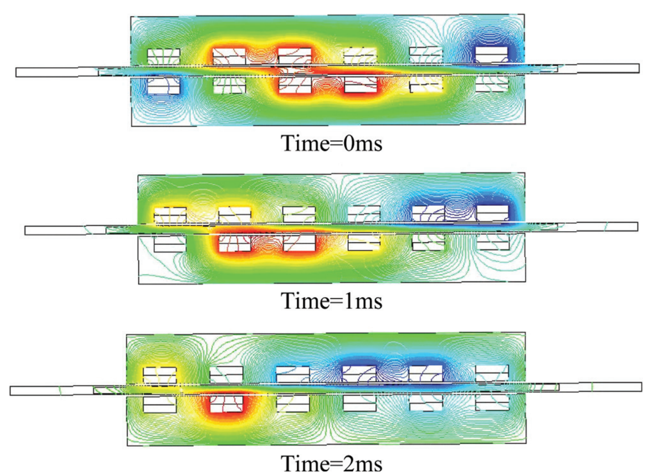
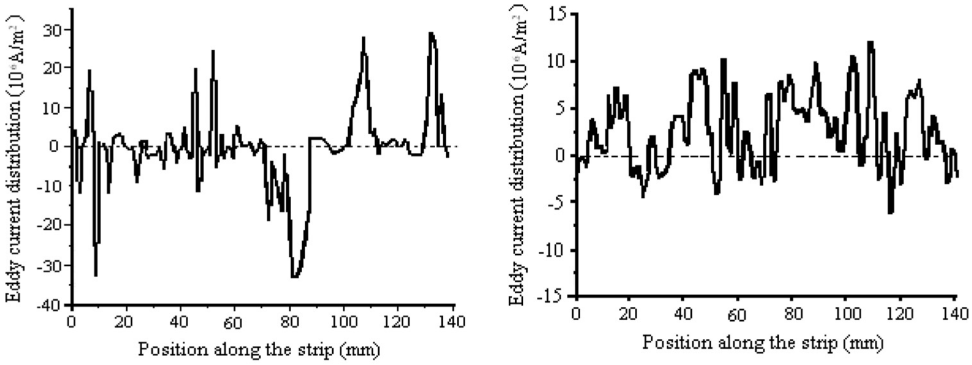


FIG. 4. (Color online) Magnetic flux distributions of the DL-TFIH system in the strip along the direction of its movement (yoke size: 1300 × 30 mm; slot size: 150 × 50 mm; airgap: 1 mm; strip thickness: 2 mm; currents supply *I*: 1300A; *f*: 500 Hz).



(a) Typical TFIH (b) DL-TFIH

FIG. 5. The eddy current density distribution in the strip of typical TFIH and DL-TFIH systems.

$$\vec{J} = -\sigma\left(\frac{\partial \vec{A}}{\partial t} + \nabla\varphi\right) + \vec{J}_s, \tag{3}$$

where σ is the electric conductivity, $\vec{J}_s$ is the impressed exciting current density, $\vec{E}$ is the electric field intensity, and

$$\nabla\varphi = -\vec{E}. \tag{4}$$

The induced current density in the strip is generated by variations in the magnetic flux. The vortex effects in the strip are attributed to the magnetic fields produced by different structures of typical TFIHs or other types of heaters like TWIH.

The magnetic flux distributions in the strip of typical TFIH and DL-TFIH systems are shown, respectively, in Fig. 4 at the times 0, 1, and 2 ms. It can be seen that the novel DL-TFIH system has a relatively more uniform magnetic flux density distribution. This is accomplished mainly because of the application of crossed ac excitations to create uniform magnetic fields that govern the eddy current density distribution. On the other hand, the combination of double-layer windings serves to widen the directions of the induced magnetic field which is distributed along the magnetic yokes. These inductors interact with each other and compensate for the weak magnetic areas existing between the gap districts.

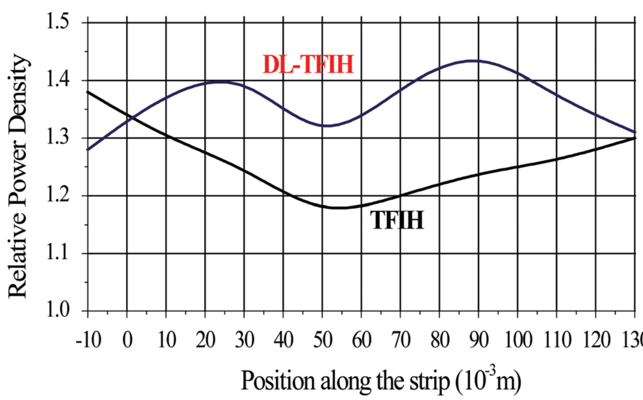


FIG. 6. (Color online) Relative power density (P/P_0) distribution of DL-TFIH and TFIH.

Figure 5 shows the eddy current density distributions in typical TFIH and DL-TFIH systems. As DL-TFIH uses crossed induction heaters, the upper and lower induction heaters are installed properly to compensate for the low-fields so as to realize uniform heating results. It can be seen that the eddy current distributions are more uniform in DL-TFIH when compared to those in typical TFIH.

Another characteristic of TFIH systems that needs to be considered is the presence of many high eddy current peaks on the edges of the sheet, which can give rise to, in some cases, dangerous strip deformations. In the proposed DL-TFIH system this problem is reduced since sharp peaks of eddy currents are much fewer than those in typical TFIH systems.

The best cases among both typical TFIH and DL-TFIH systems, which has a similar geometry, are compared in Fig. 6, where the irregularities due to the use of a relatively small number of mesh elements have been smoothed. It can be seen that from 0 to 130 mm, the DL-TFIH system induces higher power than any other systems being studied. It is shown that with this approach, the simulation time is substantially reduced, yet the high accuracy of the eddy current and temperature field distributions is retained.

For the further study, the electromagnetic problem solution must be coupled with the thermal and mechanical ones in order to have a better understanding of the different temperature distributions, mechanical deformations, and noises. Moreover, an economic evaluation of the different power supply systems must be carried out.

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