Electrodynamic Forces in Steel Strip during Induction Heating

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Abstract

The forces, which act on current and/or field-conducting components of induction heating installation are the result of the reciprocal effect of the electromagnetic (EM) field with the current flowing in the system as well as with field-conducting elements [1]. These forces can cause oscillations of parts of the plant or even movement of the workpiece. If the heating installation is designed asymmetrically, developing forces can also lead to deformations of the strip (see fig. 1). Moreover a large problem could be the noise during the transverse flux heating. This noise results mainly from vibrations of the strip.

It is differentiated between temporally constant and periodically variable forces, which arise either individually or together. The temporally constant component can lead particularly with thin strip to static deformations and cause in non-symmetrical systems uncontrolled movements of the volume. The periodically variable force components however cause vibrations of the system elements as well as noise.

1. Models to calculate the electrodynamic forces

Generally there are three possibilities to calculate the electrodynamic forces in transverse flux heating systems [2].

The first model is based on the reciprocal effect of current with magnetic field. The magnetic field is produced by currents in the inductor and in the other elements of the system. The force density \( f_A \) is a vector product of current density \( \mathbf{S}_A \) and flux density \( \mathbf{B} \). The force density \( f_A \) corresponds to the integral of the volume force density over the strip thickness.

The total force, which affects the body, is an integral \( f_A \) over the volume \( V \):

\[
f = \int_V f_A \, dV = \int_V \mathbf{S}_A \times \mathbf{B} \, dV .
\]  

This model can be used for calculation of electrodynamic forces in non-magnetic elements of the induction systems.

The second method is based on Maxwell’s stress tensors. This model can be formally used for all kind of workpiece. Current conducting and magnetic bodies cause a deformation...
of the field, which leads to a resulting strength. In this case, the force is determined by over a stress tensor expressed field at the surface.

The third model makes over energy calculations for the total force, which affects on the body or a part of the body. This model can be used for all kind of workpiece also. The principle comes from the energy equilibrium in electromagnetic field, where the electromagnetic strength, which affects a body, produces an elementary work and an appropriate elementary change of electromagnetic energy of the system. Here the rule is used that the sum of all forces is in a closed system equal to zero.

The described methods make possible to calculate the forces, which affect the body if the distributions of the current and the field over the volume are determined.

2. Electrodynamic forces in non-magnetic materials

Many numerical investigations are made by an example of simple arrangement. The won realizations can be transferred however qualitatively to more complicated systems.

Because of an asymmetry of the metal strip position, tangential field components are trained (in the sheet metal), which usual result in working components to the sheet metal surface. The normal component of the force lining arises among the inductor leaders. This force rises with larger shift from the symmetrical position of the strip and is arranged in y-direction for the centre position of the sheet metal. Therefore it can be stated that with non-magnetic sheet metals electrodynamic forces work stabilizing, i.e. these forces try to centre the strip between the inductors.

3. Electrodynamic forces in ferromagnetic materials

The electrodynamic forces, which affect a ferromagnetic strip within the air gap, consist of two parts: the Laplace force and the magnetization force. A method to determine this force, exists in the integration of the electrodynamic forces over the volume force density [3]:

\[ F = \int \left( S_A \times B \right) dV - \int \left( \frac{1}{2} \cdot H^2 \cdot \text{grad} \mu \right) dV = \int \left( S_A \times B - \frac{1}{2} \cdot H^2 \cdot \text{grad} \mu \right) dV = \int f \, dV. \]  \hspace{1cm} (2)

The volume density of the force \( f \) is a sum of the Laplace component \( f_L = S_A \times B \) and magnetization component \( f_m = -\frac{1}{2} \cdot H^2 \cdot \text{grad} \mu \). These two forces act to opposite directions. That means that the Laplace force works tightening and the magnetization force repulsively to the inductor. Then the total force for ferromagnetic materials is calculated by integrating the volume force density or by integrating the Maxwell stress tensor.

Electrodynamic forces in transverse flux induction system affect the metal strip within the air gap between two inductors. The Laplace-component of the force tries to centre vertically the strip within the air gap. The magnetization component works against it (at the same time the magnetization component centres the sheet metal in horizontal direction).

4. Electromagnetic model for calculation of the forces

To analyse the electrodynamic forces in transverse flux heating systems, numerical computations were accomplished using the software-package ANSYS. In principle, the forces occur in all three spatial directions. But their representation is then extremely extensive. Normal to the strip surface time-independent component of electrodynamic forces is a subject investigated in the paper. In practice these forces are of significant importance. It was
specified for the calculations, that the inductor current $I_0$ contained only one real component ($\text{Im}(I_0) = 0$). 2D approach is used for the calculations. The model consists of inductors, strip, magnetic core if needed and free space. Because the represented model is symmetrical along the y-axis, it can be reduced to one half of the plant. In the other part of the process the forces look reflected alike.

The strip has a thickness of $d=1 \text{ mm}$. The dimensions of the strip are alike in all calculations. The calculations are accomplished for two different materials: non-magnetic with $\mu_r = 1$ and ferromagnetic with a constant $\mu_r = 30$. Electrical resistivity of the strip material corresponds to the steel C45. Different configurations of induction system with and without magnetic core of different shape were investigated.

5. Parametric examinations

The calculations were conducted for three configurations of the induction system (see fig. 2). For each type of the system the frequency, the pole pitch and the permeability of the workpiece were varied. In order to receive comparable results, power in the strip was kept constant on the level of $P = 500 \text{ kW}$ during all calculations.

Normal to the strip surface forces are equal to zero only with accurate centering of the sheet metal between upper and lower inductor, since in this case no tangential force component arises and therefore also the component normally arranged to the surface is equal to zero. In practice an accurate centering of the strip in the operating gap is impossible due to inaccurate guidance of the strip or its thermal deformation. Therefore an asymmetrical deviation of the strip from the middle position within the air gap is accepted in the calculations.

For the chosen geometry the optimal frequency should be selected, at which the maximum efficiency and the maximum power factor are reached. With rising frequency first the electrical efficiency of the transverse flux system increases strongly until reaching a maximum value. Afterwards it drops again easily, since the heat losses in the inductor become higher. The power factor has a distinctive maximum. The maximum electrical efficiency and the maximum power factor appear at easily different frequencies. To choose of the optimal frequency therefore it is necessary to find a compromise between maximum efficiency and maximum power factor. To determine the optimal frequency, efficiency and power factor were calculated for a broad spectrum of frequencies. These calculations were accomplished using the program package HIHTEC 2D, which was developed at the University of Hanover.
In the following the test results for non-magnetic and ferromagnetic strip materials are compared to each other. Therefore the curves corresponding to the relative magnetic permeability of $\mu_r = 1$ and $\mu_r = 30$ are represented in figures. The influence of pole pitch, frequency, air gap and type of the system on the size of the total force is examined.

In fig. 3a the dependence of the resulting force on the shift of the strip from its central position for different values of the pole pitch and the permeability is represented. The calculations were accomplished for optimal frequency and for the system without magnetic core. It is to be taken from the picture that the larger pole pitch provides more homogeneous field and thus smaller forces, which work stabilizing. At ferromagnetic materials the forces are smaller compared with non-magnetic materials, since the magnetization portion reduces the total force. In this example all forces are negative and thus stabilizing.

Fig. 3. Influence of pole pitch and $\mu_r$ for system a) without MC and b) with MC with pole.

At the system with magnetic core with poles the forces, which affect the ferromagnetic sheet metal, can become positive (see fig. 3b). In this case, the magnetization component is greater than the Laplace portion and the resulting force becomes positive. The magnetic core has influence on both force components. For example, also the Laplace component is reduced because of the concentration of the magnetic field.

The fig. 4a and 4b show the distribution of the force over the length of non-magnetic strip for different shifts $dh$ of the strip from central position. It can be distinguished at the system without magnetic core (fig. 4a) that with approximation of the sheet metal to the inductor the total force becomes larger and remains always negative.

Fig. 4. Distribution of normal forces density in the strip for the system a) without MC and b) with MC with pole.
Forces that affect the sheet metal are concentrated under the inductors. The force in non-ferrous strip has also positive portions, although the resulting force remains always negative. For the system with magnetic core with poles (fig. 4b) the total force is equal to zero in the central position and also becomes greater and works more stabilizing with approximation of the strip to the inductor. But it is also shown in the picture that the total force becomes smaller compared with the distributions in the strip without magnetic core. There are more positive force components present, which lead in case of addition to a smaller magnitude of the total force, which remains nevertheless negative.

Fig. 5a, 5b and 6a represent the dependence of the total force on the shift of the strip from the central position for different frequency, when it is low or higher its optimum value. In fig. 5a frequency \( f \) and permeability were varied. It was calculated with the pole pitch of \( t=400 \text{ mm} \), the air gap of \( h=100 \text{ mm} \) and without magnetic core. It is to be taken from the picture that without magnetic core the resulting force remains always negative and thus stabilizing. The forces in ferromagnetic strip are smaller compared with non-magnetic one, because of the magnetization component.

![Graph](image1.png)

Fig. 5. Influence of frequency and \( \mu_r \) for system a) without MC and b) with MC with pole.

Fig. 5b shows the same dependence for the system with magnetic core with poles. Similarly to the previous picture, the negative total force is smaller at rising frequency. At non-magnetic materials the forces for both frequencies are stabilizing. In contrast to that, the resulting forces, which affect the ferromagnetic strip, become positive, since the magnetic component outweighs the Laplace-portion. At optimal frequency the forces can go into the positive range as well.

![Graph](image2.png)

Fig. 6. Influence a) \( f \) on system without MC, b) \( h \) on system with MC with pole.
The results, which are represented in fig. 6a, were calculated for the system without magnetic core and pole pitch of \( t=200 \text{ mm} \). As shown in the picture, the negative total force becomes larger and thus more strongly stabilizing, at rising frequency. It is confirmed again, that negative forces are smaller with ferromagnetic materials than with non-magnetic ones. All the time the magnetization component works against the Laplace force. Comparing fig. 5a and 6a it can be shown the influence of the pole pitch on non-magnetic and ferromagnetic materials. The smaller the pole pitch is the more strongly stabilizing are the resulting forces. During the calculations for non-magnetic materials it was shown that with enlargement of the pole pitch the magnetic field becomes more homogeneous and the force, which remains always negative, becomes smaller. The enlargement of the pole pitch, during the usage of ferromagnetic materials, can lead to positive forces, which attract the strip to the one of inductors.

The dependence of the force on the shift of the strip from its central position for different air gaps \( h \) is represented in fig. 6b. The calculations were accomplished with magnetic core with poles, at a pole pitch of \( t=400 \text{ mm} \) and at the optimal frequency. As shown in the picture the larger the air gap is the more stabilizing the forces become. As before, the total force in ferromagnetic material is smaller than in non-magnetic one. With smaller operating air gap the forces in ferromagnetic materials become positive and thus no more stabilizing, although with reduction of the gap the magnetic field becomes more homogeneous. It goes without saying that the effort of the field homogenization and reduction of the forces in ferromagnetic materials can lead to positive forces.

**Conclusions**

The electrodynamic forces in non-magnetic metal strip during transverse flux induction heating are always negative and thus stabilizing. These forces have only the Laplace-component, which tries to bring the strip into the central position. The resulting forces in ferromagnetic materials can become both negative and positive. That depends on which from both portions outweighs. If the Laplace portion is larger, the forces are negative. With larger magnetization component, which always works against the Laplace portion, the forces become positive. But with exactly analyzed geometry of the system and operating conditions (e.g. adjusted frequency) the heating of ferromagnetic strip is possible, without any sticking of the workpiece to the inductors.

**References**


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