Five-phase travelling wave induction heater for continuous heating of flat material

Ali K. Al-Shaikhli1, Abdul-Rahim T. Humod2, Fadhil A. Hasan2

1Dijlah University College, Baghdad, Iraq
2Electrical Engineering Department, University of Technology, Baghdad, Iraq
E-mail: fadhil.a.hassan@gmail.com

Published in The Journal of Engineering; Received on 2nd September 2015; Accepted on 4th January 2016

Abstract: This study proposed a novel travelling wave induction heating system with five-phase exciting current. The proposed system used special exciting current to obtain a homogeneous eddy current density, which affects the temperature pattern over the material surface. Five-phase system has been attracted from many industrial applications due to its inherent features compared to the three-phase system. An even number of phases is not preferred because the poles exchange with each other. A comparison investigation with other traditional methods is represented to realise the features of the proposed method. A finite-element method simulation is represented by using ANSYS 15®; the simulation results show that the proposed system gives superior performance of energy transferred, uniform heat distribution and higher power factor over that of the traditional three-phase system. Moreover, it performs identical eddy current, power densities, temperature and efficiency to that of the six-phase system with profits of reduction in size, weight, cost and winding copper losses.

1 Introduction

Single phase induction heating systems have wide industrial applications of heating and melting process, which has known as transverse flux induction heating (TFIH). Unfortunately, the TFIH systems have many practical drawbacks such as: non-uniform heat distribution, relative movement between inductor and work-piece is essential, high electromagnetic forces which cause vibration between heater and strip, and represent an unbalanced load of the power network.

Conventional longitudinal system is insufficient to obtain high performance and uniform temperature pattern on the work strips, especially on flat materials [1]. Poly-phase induction heating systems have many advantages, which present a good solution of the most disadvantages of the TFIH systems and made very suitable for many heating processes [2]. The main attractive characteristics of TFIH and longitudinal induction heating (LIH) are: (i) a high electrical efficiency, including the heating of strips of low resistivity materials; (ii) the possibility of using low frequencies (in particular 50 Hz); and (iii) more useful ‘open’ inductor geometry. All these characteristics are exhibited by TWIH which, however, have other advantages, such as (i) the possibility to heat quite uniformly, thin strips or regions of a body without moving the inductor above its surface; (ii) reduce the vibrations of inductor and load due to the electro-dynamic forces and also the noise provoked by them; (iii) obtain nearly balanced distributions of power and temperature; and (iv) represents balance load to the power utility [3, 4].

These features may be achieved in the best manner by the so-called travelling wave induction heating, which has concerned from many industrial applications in the field of heating flat materials [5, 6].

Usually increasing the number of phases lead to enhance the performance of the poly-phase induction heating system to obtain more uniform heat distribution and reduce the mechanical vibration and noise. Recently, multiphase (more than three-phase) systems have been concerned by researchers because of their features compared to three-phase systems [7, 8]. It is to be mentioned here that the multiphase induction heaters are usually supplied by six-phase AC supply. Thus, the focus of the researches on the multiphase TWIH are limited to the configuration of the heater, such as yoke, slots or pole-shoe and so on. In the literature, there are no efforts to investigate the effect of changing phase number. They choose the six-phase system because of the simplicity of designing of this type of systems. Certainly increasing phase number could enhance the performance of the system, but it’s uneconomical and lead to increase system’s weight and size. Moreover, selection of odd number is practically preferred more than even number of phases because the performance of the even number is degraded as the poles exchange with each other. Therefore, a five-phase may be preferred [8].

This paper proposed a novel five-phase TWIH to overcome the drawbacks of both three- and six-phase heaters. A three-dimensional (3D) numerical simulation and analysis of the traditional TWIH and the proposed heater is represented in this work by using FEM program code. System Efficiency, output power, eddy current, power factor and temperature are investigated. Also a comparison between the traditional three-phase, six-phase and the proposed five-phase performance is presented for different strip thickness.

2 Configuration of TWIH

The concept of the TWIH profits the phase shift between the multiphase excitation currents fed the heater coils to produce resultant electromagnetic field travels through the material at a velocity proportional to the line frequency. In conjunction with a transverse flux heater, in which the resultant magnetic field neutralise itself at the centre and become zero, the root mean square value of the magnetic field is almost uniform over the area faces the heater [9]. Winding arrangement could affect the heat distribution on the workpiece surface and the choice of a suitable power supply. Researchers proved that the in short pitch coil the obtained temperature range is wider and better than the full pitch coil. Also, the heat uniformity is more than the full pitch coil and the time rise time is shorter than of full pitch [10, 11]. Moreover, researchers find out that the arrangement of coil windings could affect the heat distribution. For the up–down mode coil arrangement gives particularly uniform power distribution on load’s surface. However, in the left–right mode arrangement the heat distribution is non-uniform on the load’s surface [2, 12].

In this work, the short-pitch and up–down mode coil arrangements are used to obtain more uniform power distribution on the strip surface. Fig. 1 shows the configuration of a traditional three-phase heater, which has double inductors on the opposite sides of the load; slots are perpendicular to the direction of movement.
The heater yoke has six slots and six coils fed by three-phase exciting current of 120° phase shift as shown in Fig. 1.

Fig. 1 Double side three-phase TWIH system

[1 – yoke, 2 – windings, 3 – load, (t) load thickness, (g) air-gap between heater yoke and strip, (g1) air-gap between winding and strip and (v) direction of movement]

Fig. 2 Double side six-phase TWIH system

[1 – yoke, 2 – windings, 3 – load, (t) load thickness, (g) air-gap between heater yoke and strip, (g1) air-gap between winding and strip and (v) direction of movement]

Fig. 3 Double side five-phase TWIH system

[1 – yoke, 2 – windings, 3 – load, (t) load thickness, (g) air-gap between heater yoke and strip, (g1) air-gap between winding and strip and (v) direction of movement]

The excited current is combination of typical three-phase of 120° phase shift (A, B and C) and other three-phase of 120° between each (AA, BB and CC), but with phase shift of 30° apart the first three-phase as shown in Fig. 2.

Whereas, the proposed five-phase TWIH is shown in Fig. 3, which consists of double side magnetic yoke having ten slots and coils, which are fed with balanced five-phase excitation current (A, B, C, D and E) of electrically phase shift of 72° apart as shown in Fig. 3.

3 System analysis

TWIH system performance can be investigated by examine the energy transferred efficiency, input power factor, output power density, eddy current, copper losses and workpiece temperature. Analytical and numerical techniques can be used for this analysis. Analytical methods are more suitable for the integral parameters calculation and analysis. Also, this method is more convenient for simple geometries calculations and some assumptions or sometimes reduction of dimension may be essential [2, 6]. Whereas, the finite-element methods (FEMs) are more universal and it’s very useful for analysing the induced eddy currents and power distribution if a high accuracy is demand, such as consideration of the both edge-effects and slots effects of the induction end workpiece. Therefore, 2D or 3D FEM is a universal choice for simulation and analysis multiphase systems. Both methods need a relatively long calculation time, which includes large quantities of work to input data and a previous knowledge of the poly-phase exciting current (amplitude, frequency and phase) [1, 2]. The variation of the strip thickness has been analysed in this work to investigate different heating conditions. The FEM numerical analysis is used to investigate the electrical and thermal performance.

4 Simulation performance

To represent the features of different types of the TWI heater (three-phase, six-phase and the proposed five-phase), a comparison analysis is done to investigate different system’s parameters variation as a function of strip thickness from 1 to 10 mm by step 1 mm. For the reason of high accuracy and consideration of edge and slot effect a numerical 3D-FEM analysis is implemented by using...
Table 1 System parameters

| Parameter                        | Value                          |
|----------------------------------|--------------------------------|
| heater                           |                                |
| length                           | 0.65 m (3-ϕ), 1.05 m (5-ϕ), 1.25 m (6-ϕ) |
| height                           | 0.15 m                         |
| width                            | 0.25 m                         |
| relative permeability            | steel $B-H$ curve              |
| no. of phases                    | 3, 5 and 6                     |
| excited phase voltage            | 70 V                           |
| frequency                        | 50 Hz                          |
| air-gap                          | 5 mm                           |
| strip (aluminium)                |                                |
| length                           | 1.5 m                          |
| width                            | 0.5 m                          |
| thickness                        | 1–10 mm step 1 mm              |
| resistivity ($\rho$)             | $2.82 \times 10^{-8} \Omega \text{ m}$ |
| relative permeability            | 1 (dimensionless)              |
| movement velocity                | 1 m/min                        |
| thermal conditions               |                                |
| ambient temperature              | 25°C                           |
| convection coefficient           | 100 W/(m² C)                   |
| thermal conductivity             | 211 W/(m C)                    |

Fig. 4 Input phase current

ANSYS® program code. The non-linearity $B-H$ curve of the steel magnetic yoke is taken into account. Table 1 shows the main parameters of the three-phase, five-phase and six-phase TWIH systems which are simulated and examined in this work.

Fig. 5 Input power factor

Fig. 6 Total winding copper losses

Fig. 7 Eddy current density

Fig. 8 Strip time averaged power density

Since the movement velocity of the strip is slow and does not highly affect the heat distribution, therefore a transient analysis at a specific time is done for the different types of TWIH. The same values of input phase voltage, line frequency and coil turns are used to determine the input phase current, input power factor,
total winding copper losses, strip eddy current density, strip time averaged power density, system efficiency, strip temperature and the rate of energy transfer (output temperature/input power) which are illustrated in Figs. 4–11.

Fig. 9 Efficiency

Fig. 10 Strip temperature

Fig. 11 Rate of energy transfer (output temperature/input power)

Fig. 12 Temperature distribution
   a Three-phase
   b Proposed five-phase
   c Six-phase

5 Discussions

Clearly, from the results it can be seen that at the same value of input voltage and frequency the three-phase heater drawing much line current than of five- and six-phase heaters, while the last two types drawing approximately the same current for different load
thickness as shown in Fig. 4. Also, the power factor is improved with increasing thickness in three-phase heater, while in five- and six-phases improved until 8 mm thickness and then degraded. The better power factor appears with five-phase heater as depicted in Fig. 5. Therefore, the total windings copper losses in the five-phase heater is lower than that of both three- and six-phases as illustrated in Fig. 6. The induced eddy current density and the produced power density within the load for five- and six-phases are almost equal and greater than that of three-phase system. By sequence the electrical power efficiency and the obtained strip temperature are closed in the five- and six-phases, and greater than that of three-phase system as shown in Figs. 7–10. The duty efficiency of the system can be investigated by the ratio of the output temperature to input power which refers to the overall electrical to thermal energy transferred efficiency. It can be seen clearly that the proposed method has the greater energy transferred efficiency as illustrated in Fig. 11. Furthermore, five- and six-phases have more uniform temperature distribution as shown in Figs. 12a–c.

6 Conclusion

Obviously, the analysis shows that the five- and six-phase TWHs give a superior performance with respect to the three-phase TWH for most load thickness at same excited voltage and frequency. Which show lower drawing current, highest eddy current and power densities, higher efficiency and temperature and more uniform temperature distribution. On the other hand, the proposed five-phase TWH gives an identical output performance to that of the six-phase heater with profit. In other words, the same output performance and temperature of six-phase heater can be obtained by five-phase heater, which gives many gains in operation and design. The most features of the proposed five-phase over the six-phase heater can be summarised as follows:

(a) Lower winding copper losses, and hence lower cooling required.
(b) Higher input power factor.
(c) Higher electric to thermal energy transferred.
(d) Smaller size and weight.
(e) Lower cost.
(f) Represent a balance load to the utility.

7 References

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