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Wireless power supply of mobile inductors for inductive heating of a rotating cylinder

***Abstract**. In this article, a project and method of realization of wireless powering of system of inductors used to heat the rotating steel cylinder being an element of a paper machine has been described. The proposed solution gives an opportunity of supplying the heating power in a flexible and selective way to the surface of the cylinder, which enables attaining high quality control of the temperature of the cylinder surface for an arbitrary given temperature distribution.*

***Streszczenie.** W artykule przedstawiono projekt i wykonanie bezprzewodowego zasilania wzbudników do nagrzewania obracającego się walca stalowego będącego elementem maszyny papierniczej. Proponowane rozwiązanie daje możliwość dostarczania do powierzchni walca mocy czynnej w sposób elastyczny i selektywny, co umożliwia osiągnięcie wysokiej jakości regulacji dla zadanego rozkładu temperatury. (**Bezprzewodowy system zasilania ruchomych wzbudników w nagrzewanym indukcyjnie obracającym się walcu**).*

Keywords: Wireless power supply, induction heating, moving inductors.
Słowa kluczowe: Zasilanie bezprzewodowe, nagrzewanie indukcyjne, ruchome wzbudniki

Introduction

Inductive heating is one of modern, efficient and ecological solutions of heating rotating steel cylinders used among others in paper industry to drying and calendaring paper. Assuring a sufficient quality of these processes is connected with the necessity of maintenance of the given profile of the temperature on the surface of the cylinder regardless of changing process conditions (e.g. different conditions of heat exchange dependent on the construction of the cylinder, local decrease of the temperature of the cylinder due to different humidity of the paper, etc.) [1]. It requires not only use of temperature control systems, but also ensuring a specific freedom and selectivity of heating power supplying to different areas of the surface of the cylinder, what can be derived by using mobile power sources (inductors)[2,3]. A significant impediment on the way to realize this kind of problem is the huge necessary velocity of the inductor along the cylinder and the sustainability of technological processes. In particular, this problem concerns sufficiently durable connection between the inductor and the supplying high frequency generator. From the set of possible solutions, such as use of cables prepared for bending or supplying the inductors by moving contact, it seems that the best one is to use electromagnetic wireless transmission of energy to the inductors. This solution enables to eliminate most of the disadvantages of the remaining, such as damage of cables or noises caused by sparkling contact. Moreover wireless supplying ensures galvanic separation of the circuits, which can be a important advantage in technological application.

Project assumptions and overall idea of the system of wireless supplying of the inductors.

The general aim of the system is to supply the inductors heating inductively the surface of rotating steel cylinder, using energy from high frequency generator, with simultaneous ability of the inductor to move along the axis of the cylinder. The chosen parameters of the system are given in Table 1.

Table 1. Required parameters of heating system

Parameter	Value
Inductor power	≥1 kW
Working frequency	≈20 kHz
Inductor mass	≤7 kg
Inductor velocity	≥1m/s
Inductor acceleration	≈7 g
Number of inductors	6
Galvanical isolation	≥2,5 kV

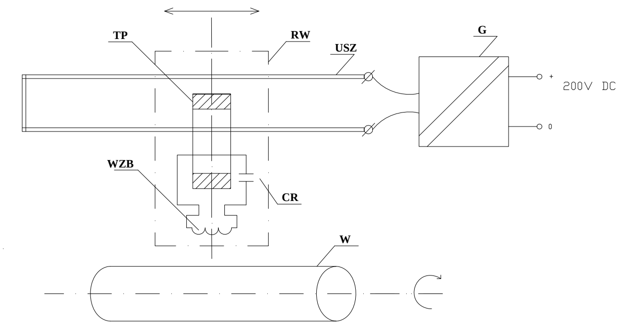

Fig 1. General idea of moving inductor supply system

Problem defined this way requires solving two connected problems: mechanical-drive and electric. While in mechanical layer it is possible to apply usually used solutions, in the electric problem solution is not so unambiguous. Taking into account basic assumptions and limitations of the supplying system, the general idea of the proposed solution is shown in figure 1.

Wireless providing of the electric energy to the mobile inductor (WZB) heating the surface of rotating steel cylinder (W) can be attained by using the intermediate transformer (TP) with “stretched” primary winding (USZ), connected to stationary inverter (G). Such winding, placed along the axis of the cylinder, would stay at rest, while the core of the transformer TP, connected mechanically and electrically to the inductor, would move on a specially constructed trolley (RW) in a rectilinear motion above the surface of the cylinder. In such a system, in arbitrary position of the core the energy would be transferred via transformer TP from the inverter G to the inductor WZB.

Project and realization of the system

Mechanical-drive layer

In the abovementioned system of inductive heating of the surface of the rotating steel cylinder, it has been planned to use six inductors, each of power of about 1kW, which ensures satisfying all the technological requirements concerning the working temperature of the surface of the cylinder. The inductors with their drive systems have been located in the area surrounding the cylinder in a way to derive a wide set of possible configurations of the relative position and motion of the inductors. An illustration of a part of the construction is shown in Fig. 2.

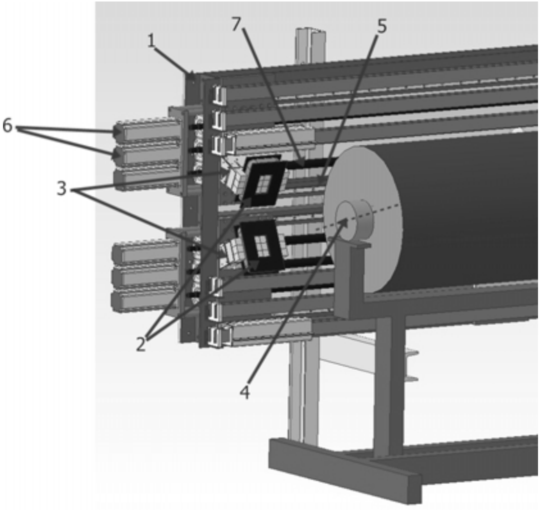

Fig 2. Mechanical-drive part of the heating system

The base of the construction is a vertically located support frame (1), to which remaining parts of the system are connected. The inductors (2) are placed on individual trolleys (3), arranged in two sections, ensuring the symmetry about the horizontal axis of the system, collinear with the axis of the cylinder (4). These trolleys are mechnically connected by the guides (5) stabilizing their motion along the form of the cylinder. In order to lower the mass of the system and limit the side effects of magnetic action on the elements of the system, the trolleys are made of aluminium. The linear motion of the trolley along the generatix of the cylinder has been attained by use of a pull-ball screw (7) and a nut fixed to each trolley. The screws are individually driven by servo drives (6). Such solution enables an independent motion of the inductors in the borders of their working area. When projecting the method of fixing the inductors to trolleys, it has been ensured that the distance between the inductor and the surface of the cylinder is constant regardless of the position of the inductor. Apart from that, the considered system enables placing all trolleys out of the contour of the cylinder, which widens the configuration possibilities of the system during experiments.

Types and parameters of the elements of the driving system have been chosen on the basis of catalogue data, taking into account the requirements of typical technological processes ran with the use of such cylinders (comp. Table 1).

The major concern was to ensure the required velocity of linear motion of trolleys with consideration of the estimated mass of the trolley and the assumed length of the construction. Taking into account the length of the cylinder (1200 mm) and the planned possibility of placing the trolleys out of the contour of the cylinder, the decided length of the screws is equal to 2000 mm. The diameter of the screw, the pitch and the type of nut have been decided on the basis of strength calculations using following relationships:

(1) $$N_C = 2{,}71 \cdot 10^8 \cdot \left(\frac{f_M \cdot d_r}{L_t^2} \right), \ N_p = 0{,}8 \cdot N_C$$

where: N_c – critical angular velocity [rpm], f_M – coefficient for a given type of bearing (f_M=0,692), d_r – diameter of screw core (d_r=21,8 mm), L_t – distance between the bearings (L_t=1990 mm), N_p – maximal load [rpm]

When projecting the driving system, apart from required technical parameters, the accessibility of the elements, their cost and strength have to be also taken into account. Achieving the sufficient strength of the system requires using a screw working with possibly low angular velocity, which can be attained by using a screw with sufficiently high pitch and small diameter (the decided screw diameter is 25 mm). Taking all the abovementioned requirements and limitations, the choice of the elements is as follows: KGSR 2525-2000 type ball screw of diameter 23,5 mm and thread step of 25 mm, KGMR 2525 FSC type ball nut.

In turn, attaining the assumed acceleration of the motion of the trolley in face of the total trolley mass with inductor attached (about 5 kg) requires using driving moment of 1,4 Nm. This means the necessity to use a servo-drives of power not lower than 176 W, which comes from the following relationship:

(2) $$P = 2\pi \frac{n}{60} M_n$$

where: rotating velocity of the screw n=1200 rpm, M_n=1,4 Nm.

Regarding the series of available components, the AC 60 SQA 13030 type servo-drive of nominal power 200 W has been chosen.

Electrical layer

According to the conception, each of the moving inductors is supplied by a high frequency generator via intermediate transformer fixed mechanically to the trolley, whose "stretched" primary winding creates a resting system of fences parallel to the generatix of the cylinder. In order to analyze the working conditions of such an electric system, its equivalent scheme has been sketched in figure 3.

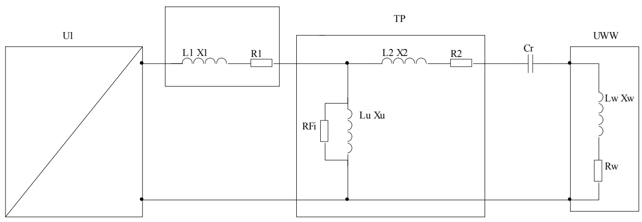

Fig. 3. Equivalent electrical circuit of wireless supplying of moving inductors

Because of presence of a considerable air gap in the inductor-cylinder system, it is necessary to ensure work of the electric system in the conditions of resonance, which guarantees sufficiently high efficiency of the device. This resonance, because of complexity of the system seen from the ports of the high frequency generator may be derived in many ways. In considered system, a resonance capacitor (CR) has been attached directly to the inductor in a way to create a resonance system with the coil of the inductor. It enables lowering the values of voltage and current in stationary elements of the system, by loading them only with active power used to heating the cylinder. This solution is also important for reducing the unfavorable thermal phenomena, as it lowers the level of heating the primary winding of the transformer TP.

The tracks creating the primary winding of the transformer have been made of insulating material, on which the winding was made by putting several layers of a copper tape of thickness of 0,089 mm separated by layers of insulating tape. It enabled limiting the total thickness of the winding, with preserving its strength and galvanic isolation. During the motion of the trolley, a part of the tracks system USZ that creates the primary winding of the transformer and are connected to the secondary winding is changing. However, the construction of the transformer TP ensures constant inductive coupling between the windings.

Parameters of elements of electrical circuit have been calculated using formulae given in [4,5,6].

- Self inductance of the tracks system LUSZ :

$$L_{USZ} = \frac{\mu_0}{\pi} z^2 (b+c) \cdot \left[\ln\frac{2bc}{a+r} - \frac{c}{b+c} \ln\left(c + \sqrt{b^2+c^2} \right) - ... \right.$$

(3)

$$\left. ... - \frac{b}{b+c} \ln\left(b + \sqrt{b^2+c^2} \right) + \frac{2\sqrt{b^2+c^2}}{b+c} - \frac{1}{2} + 0{,}447 \frac{a+r}{b+c} \right]$$

where: winding dimensions (Fig.4a): a=0,03 m, b=2,05 m, c=0,03 m, r=0,001 m, number of turns - z=3

- Resistance of the tracks system RUSZ :

(4) $$R_{USZ} = \frac{lz}{rS}$$

where: turn length l=4,4 m, number of turns z=3, r – specific resistance copper, the field of winding cross-section S=2,136 mm^2.

- Dissipation inductance of transformer TP LTP :

(5) $$L_{TP} = \mu_0 z^2 \frac{L_{sr}}{L_u} \left(\frac{a_1}{3} + \delta + \frac{a_2}{3} \right)$$

where (Fig.4b): average length of turn $L_{śr}$= 0,42 m, winding heigth L_u= 0,03 m, windings thickness a_1=a_2=0,7 mm, air gap thickness δ=5 mm, number of turns **z**=3.

- Secondary winding resistance RTP :

(6) $$R_{TP} = \frac{lz}{rS}$$

where: turn length l=0,5m, number of turns z=3, r – specific resistance of copper, field of winding cross-section S=2,136 mm^2.

- Magnetization induction of the transformer core LμTP (assessed basing on catalogue data for the E55/28/21 type ferromagnetic core):

(7) $$L_{\mu TP} = AL \cdot z^2 \cdot n$$

where: core induction coefficient AL=6100 nH, number of turns z=3, number of cores n=10.

- Power losses in the transformer core have been estimated basing on catalogue data for the E55/28/21 type ferromagnetic core as 8,4 W. Hence taking into account output voltage of the generator 100 V, it yields R_{FeTP}~1200Ω.

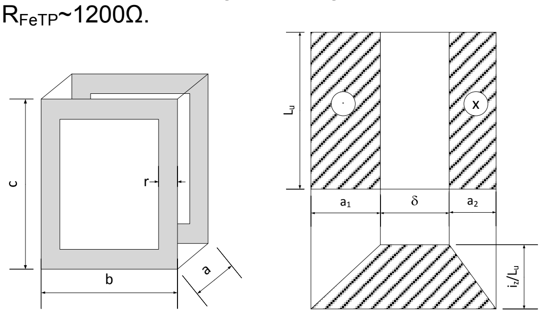

Fig. 4. Supplementary drawings for calculation of electrical parameters of the system.; a) primary winding of the transformer TP (a-turn's high, b-track length, c-distance between tracks, r-thickness of the copper layer), b) part of the transformer TP.

The parameters of the inductor-cylinder circuit, because of the complexity of the occurring phenomena, have been estimated empirically. To do so, the system has been led to resonance by choosing the adequate capacity of resonance capacitor C_R (C_R =0,25 μF). Then, for the resonance frequency f_R≈20 kHz, the equivalent inductance of the inductor-load system has been calculated as L_W≈250 μH. Similarly the equivalent resistance Rw was computed, where during the work of the device, the power generated inside the cylinder and the current of the system of tracks have been measured. Hence, for the power of about 1 kW and current 12 A the resistance is of about R_W≈6,94 Ω.

The values of the parameters calculated above have been collected in table 2.

Table 2. Parameters of the equivalent electrical circuit

Parametr	Value
Self inductance of the tracks system LUSZ	10,85μH
Resistance of the tracks system RUSZ	0,11 Ω
Dissipation inductance of the transformer TP LTP	0,87 μH
Secondary winding resistance RTP	0,013 Ω
Magnetization induction of the core LμTP	540μH
Power losses in the transformer core RFeTP	1200Ω
Equivalent inductance of the inductor-load system LW	250 μH
Equivalent resistance of the inductor-load system Rw	6,94Ω

The determined parameters of the equivalent electrical system enabled computing the voltage and power loss in each element of the system.

Voltages on reactances of the tracks system and on a dissipation reactance of the intermediate transformer show that the drop of the efficiency of the system should not exceed 16% (comparing to the system with static inductors), which enables assuring the required heating power supplied to the cylinder. In turn, the power loses derived from calculations should not lead to overheating of the construction.

Technical and operational parameters of the system

Experimental verification of the system of drive and wireless supply of the inductors built according to the abovementioned requirements has shown that it satisfies the assumed technical parameters collected in table 1. In particular, the heating powers and motion velocities achieved correspond with the requirements of carried out research. Examples of realization of the temperature control system of the cylinder surface with the use of mobile inductors have been presented in [3].

During the research, the electric parameters of the elements of the system have been measured, and high accuracy with the theoretical assumptions given in sec. 2.2 has been attained. An important parameter of the system, deciding of its durability and confirming the correctness of assumed solutions is the working temperature of each element of the system. Example measurements of temperature in arbitrary points of the system have been shown in table 3.

Table 3. Working temperature of chosen elements of the system

Ambient temperature	25°C
Tracks temperature	35°C
Temperature od secondary winding of transformer TP	33°C
Inductor winding temperature	42°C
Temperature of cylinder surface	67°C

Summary

The carried research has proven that the chosen conception of the system was right, and so was the elaborated construction. The system has satisfied the assumed requirements both in the mechanical and in the electric layer. The device is of prototype nature, thus the solutions and experience derived from it may be the base of building such devices on industrial scale in the future. For instance, the observed low temperature increases of several elements indicate the possibility of increasing the power transferred through the system and of decreasing its dimensions and mass. It may give a measurable effects e.g.

decrease of production costs with maintaining or improving the exploitation parameters of the device.

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REFERENCES

[1] Zgraja J., Uproszczony model do symulacji chłodzenia mokrą wstęgą papieru nagrzewanych indukcyjnie walców kalandrujących, *Przegląd Elektrotechniczny* (2011), nr 11, ss. 85-88

[2] Frączyk A., Urbanek P., Kucharski J., Modelling and optimal temperature control of in-duction heated rotating steel cylinder,. *13th IEEE IFAC International Conference on Methods and Models in Automation and Robotics*. Szczecin, (2007), s.351-355

[3] Frączyk A., Urbanek P., Kucharski J.: Algorytmy sterowania nagrzewaniem indukcyjnym wirującego walca stalowego za pomocą ruchomych wzbudników. *Przegląd Elektrotechniczny* 86 (2010), nr 2, s. 42-46

[4] Kalantarov P.L., Ceitlin L.A.: Rascziot induktivnosti. Leningrad ENERGOATOM, IZDAT, 1986

[5] Jegierski, E.: Transformatory. *WNT*, (1975), Warszawa

[6] Karty katalogowe rdzeni ferrytowych EE 55/28/21

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