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LABORATORY TESTING OF THE ENERGY EFFICIENCY OF THE RAIL INDUCTION HEATING

Abstract

Results of energy efficiency of rail induction heating testing are presented in this paper. Methods of snow and ice removal from turnouts currently in application are not economical in terms of energy consumption. Ways of saving energy must be explored, therefore. Induction heating described in this paper is one of those. The U type of heater was employed in laboratory testing of rail induction heating. Application of an inductor in the form of a coil wound around a ferrite core showed maximum energy efficiency. A DC/AC converter including a current inverter and a parallel resonant circuit supplied power to the inductor was applied. The temperature of the rail during induction heating and natural cooling was presented. The results support the method of rail induction heating in railroad turnouts.

INTRODUCTION

Electric heating of turnouts eor is the dominant method of melting snow and ice on turnouts in Poland [1]. This system works on more than 18 000 turnouts with a total power of about 110MW. The average heating time of eor is 300h in the season. It is assumed that the power of 330W of heating of the rail per meter in the eor method gives good efficiency of melting resulting in the proper functioning of railway turnouts during winter. It is also assumed that the efficiency is sufficient for the average weather conditions corresponding to the temperature to -20 ° C and the average (not catastrophic) snowfall.

In the heating system flexible to changing weather conditions it is difficult to determine the efficiency of heating turnouts. It is assumed that sufficient heating efficiency contributes to the elimination of snow and ice of all critical components in an accordingly short time, enabling the continuous functioning of the vehicles. At the same time the energy consumed for this purpose should be minimized. Heating efficiency mainly depends on:

- ambient temperature,
- intensity of the snowfall,
- intensity of blowing snow by wind and passing trains,
- speed, number and length of trains,
- wind speed,
- humidity,
- installed heating power per 1 meter of a rail,
- cross-sectional shape of the heater and its positioning on a rail,
- quantity and quality of mounting brackets heaters,
- efficiency of isolating transformers,
- rails weight,
- turnouts design,
- turnouts drainage.

Turnout is effectively heated when the space between switch and the proper part of a rail is free of snow (Fig. 1) and saddles under the switch, on which the switch slides are deiced. At the state of contact of switch and the rail (Fig. 1.a) heating efficiency is higher than in the case when the switch is moved away from the rail (rys.1.b) when energy can easily escape out of the turnout. These conditions make it difficult to determine the conditions for the control system of the heating system. Based on years of experience it is assumed that effective turnouts heating occurs when the temperature of the rail changes from 1-6^{o}C while heating to 20-30 minutes depending on ambient conditions. Figure 2 illustrates the cycle of automatic heating cycle of the eor for the case of heating without heat insulation and with the use of heat insulation of the rail. Presented heating cycle may provide basis for determining working conditions for induction heating analyzed in the article.

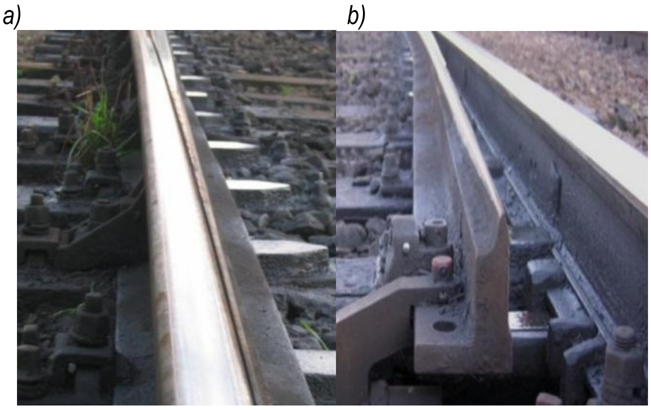


Fig. 1. *Part of the turnout: a) switch adjacent to the rail, b) switch pulled away from the rail*

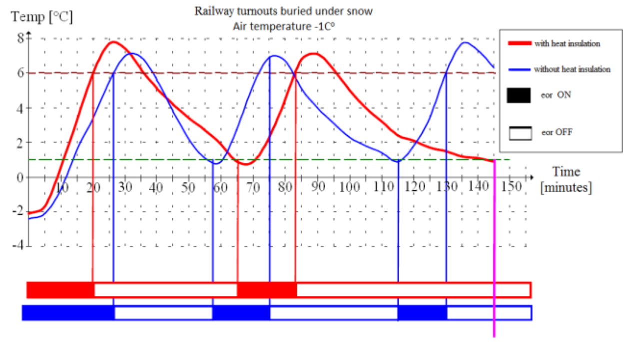


Fig. 2. *Automatic heating cycle for rail UIC-49 with heat insulation and without heat insulation [1]*

Heating of railroad turnouts with a variable magnetic field at a frequency of 50 Hz was applied to the Polish railroads by the Railway Institute of Warsaw in 1978/1979 [1, 2]. Heating rods inside an insulation coating, without direct contact with rails, were employed. A rail was heated by eddy currents induced inside it. The heating rods were made of copper wound with tarflon tape and placed inside steel covering. 3V÷3.3V at 50Hz and approximately 350A current were supplied to the rods. 2800VA transformers powered the rod regardless of the types of heaters. Given the mains frequency of 50Hz, the heating rods vibrated and produced acoustic waves audible to the human ear with a frequency twice greater than of the supply voltage. The inductive loading of the power mains required application of shunt capacitors to improve the power factor $\cos\varphi$ from circa 0.5 to 0.85÷0.9. Shunt capacitors adjusting powers of 4kVA were used in a single turnout.

The induction heating of railroad turnouts exhibited an energy efficiency higher by about 30%, lower costs of operation and maintenance, more effective and faster snow and ice removal, a safe low voltage and lower heater temperature (approx. 65^0C) compared to the classic electrical turnout heating (eor). Life of an induction heater (coil) was longer, lubricants were slower to dry. Unfortunately, the then state of the engineering art could not guarantee an adequate reliability of the system and further application trials were discontinued.

This paper is an attempt at verifying the possibility of rail induction heating at turnouts for frequencies of the supply voltage other than 50Hz. The purpose of this article is to present the results of laboratory tests on rails induction heating for low frequency voltage up to 1kHz. The results were compared by the use of thermographic method for selected shapes inductors. The topology of current inverter with the parallel resonant circuit was used.

1. EFFECTIVENESS OF RAIL HEATING FOR DIFFERENT FREQUENCIES OF THE SUPPLY VOLTAGE

A cycle of laboratory testing was run to verify effectiveness of rail induction heating. Selected shapes of inductor supplied with sinusoidal voltage at variable frequencies were used. The testing stand is shown in Figure 3 [9, 12, 13].

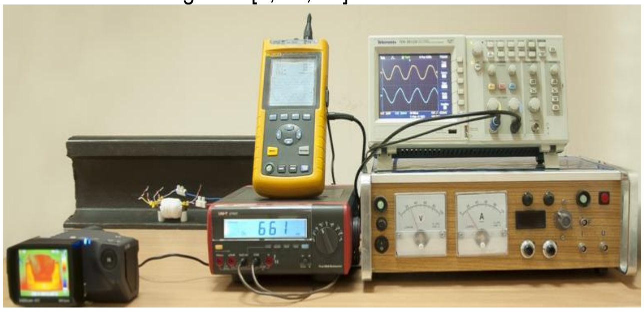


Fig. 3. *Laboratory stand for rail induction heating*

The laboratory stand consists of the following elements:

- Inductor in the rail foot [9],
- Thermographic camera VIGO cam v50,
- Functional generator G 432,
- Power amplifier AVT 2153 of rated power 100W [6],
- Analyser of energy quality Fluke 43.

The magnetic circuit of the inductor and the rail was constituted by heating coil wound around a U-shaped ferrite core. The closed magnetic loop comprised a piece of the heated rail foot and the coil around it with a variable number of windings z [9]. The heater, that is a coil wound round a U-shaped ferrite core, achieved a closed magnetic loop consisting of a piece of the heated rail foot and the coil around it with a variable number of windings z. Figure 4 shows a closed magnetic loop consisting of a coil and a piece of the heated rail foot in its design and laboratory versions.

The thermographic camera recorded temperature rises in the heated fragment of the rail foot at selected moments in time. After 30 minutes of heating rails, followed by the thermodynamic equilibrium of the object and the temperature underwent stability.

The analyser of energy quality Fluke 43, equipped with a current and a voltage measurement probe, tracked current and voltage waveforms in the circuit and the angle shift between the waveforms tracked, thus the active power [5, 11] lost across the heating element. The functional generator G 432 was designed to generate a voltage input sinusoidal waveform of the power amplifier AVT 2153. Generator parameters allowed to perform the test to the power supply frequency equal to 1kHz.

A series of experiments were conducted as a function of supply voltage frequency f in the range of (50 – 1000) Hz at a constant power of 60W supplied to the heaters.

a)

b)

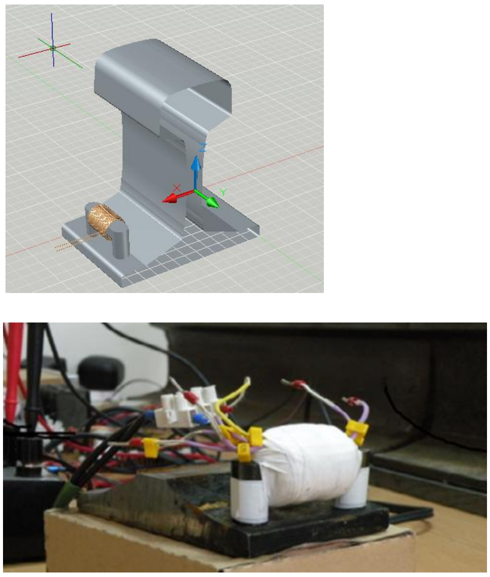


Fig. 4. *Fragment of a rail and inductor in the form of a coil wound around a U-shaped ferrite core: a) autocad version, b) laboratory version [9]*

Figure 5 presents temperature increments ΔT in the process of rail induction heating for t=30min, frequency range f (0 – 1000)Hz and coil windings z =150, recorded by the thermographic camera.

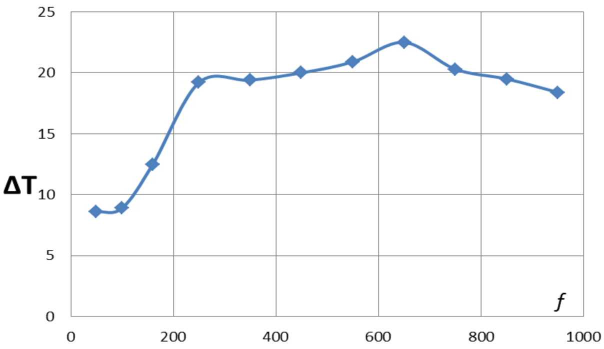
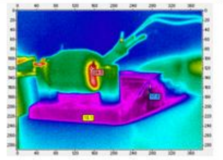
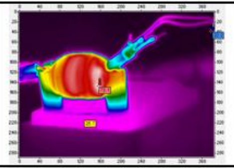
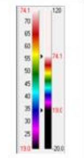
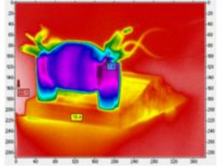
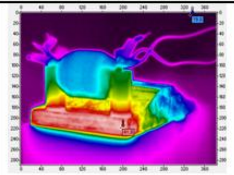
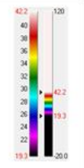
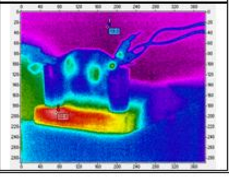
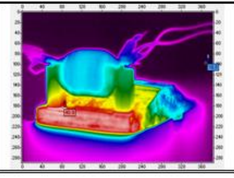
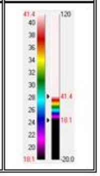


Fig. 5. *Temperature increments ΔT in the process of rail induction heating for t=30min*

Table 1 shows the image captured by the thermographic camera in the process of rail heating for selected frequencies of the inductor supply voltage and coil windings z =150. The image implies a dependence of the temperature of inductor windings and rail foot after 30 minutes of heating for the selected frequencies f and a constant power supply of 10W

These results of laboratory testing helped to develop design assumptions for a DC/AC converter including a resonant circuit in its load system.

Tab. 1. *Thermal images of heating at selected frequencies f for a coil wound around a ferrite core with z = 150 winding: a) start of heating, b) heating after t=30min [9]*

f [Hz]	Start of heating t=0min.	Heating after t=30 min.	Colour range of temp.
50			
650			
950			

2. CONFIGURATION OF DC/AC CONVERTER

Application of any equipment to rail systems requires reliable operation and electromagnetic compatibility EMC, particularly in respect of safe working with the rail control system SRK. Regulations of design and construction of rail control systems are set out in the standards PN-EN 50126; 50128; 50129, which define rail applications, systems of communication, data processing and traffic control, as well as software of rail control and security systems.

Given the rigorous operating conditions of equipment dedicated to railroads, the following assumptions have been adopted for the purposes of DC/AC converter:

- Sinusoidal waveforms of the inductor's voltage and current,
- Low sensitivity of the converter's input parameters to variations of the inductor's parameters,
- Control of the inductor's active power,
- Absence of impact on communication, data processing and rail traffic control systems.

Diverse structures and properties of converter systems enabled selection and verification of applicability of a parallel current converter to induction heating of a rail (Fig. 6) [3, 4, 7, 8]. The initial resonant circuit is constituted by a capacitor C_r inductance L_r and resistance R_o, which are the equivalent inductance and resistance of the inductor and rail, in parallel. Capacity C_r is selected appropriate to the assumed voltage supplied to the inductor. Additional capacities C_s in parallel to each transistor are designed to relieve transistors operating in states of transition, which results in sinusoidal voltage and current waveforms of the inductor. The testing led to the recommended capacity C_s=1μF.

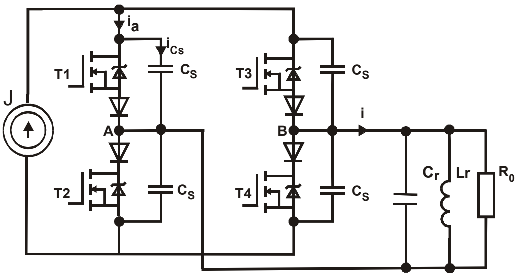


Fig. 6. *Diagram of DC/AC resonant converter system [8]*

A current inverter integrated into the converter includes four MOSFET IRFP460 transistors (T1-T4) and cut-off diodes HFA25TB60 in series. The diodes prevent shorting of the resonant circuit, thereby reducing losses of the energy they store. This topology is highly efficient as the transistors are switched at zero voltage (ZVS) or zero current (ZCS) [4]. The classic method of controlling operation of the transistors is applied, where transistor pairs, T1,T4 or T2,T3, are controlled for half a period. The converter system is supplied from a current source *J* which comprises a variable rectified voltage DC in series with a high inductance, L_d=30.5mH. For these parameters of the power source and inductor load, the current waveform is virtually a straight line. Active power of a receiver R_o is controlled by variations of the supply voltage DC, which substantially translates into power of heating lost inside the rail.

3. EXPERIMENTAL TESTING OF DC/AC CONVERTER

A required heating power of approximately 300W/rm is adopted for the purposes of electrical heating systems (eor) currently in application. Active length of a turnout to be heated varies depending on the radius of turnout curve and permissible speed of rolling stock. Assuming 10rm of a turnout is heated, the converter's power should be around 4kW. The converter's power of up to 300W per one metre of a rail has been assumed for the testing. Operation of the inductor at a frequency of f=650Hz (Table 1), good for the temperature increment in a unit of time, requires high capacities of costly pulse capacitors. By way of a compromise, the bottom value of f_d=1500Hz and the maximum: f_g=10kHz have been assumed. Since the load, i.e. the rail, is non-linear, the inductance L_r and resistance R_o are variable. This means the resonant frequency of the resonant circuit changes. Operation beyond the resonant point adversely affects consumption of power from the source and increases current in the resonant circuit C_r, L_r, which reduces efficiency of the whole system as a result. A control system should match its frequency of transistor keying to the resonant frequency. The input power P_{we} is then minimum and equivalent to the sum total of power lost across the resistance R_o and to power losses of the semi-conductor system. The laboratory testing demonstrated power losses of the semi-conductor system are virtually negligible. The laboratory test stand for the system is shown in Figure 7.

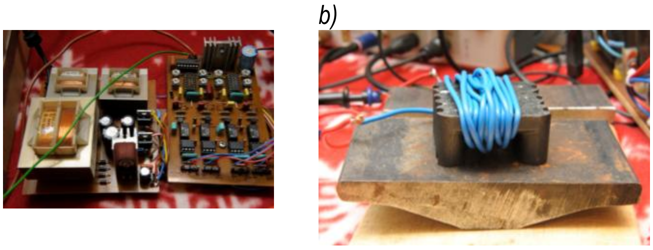

a) *b)*

Fig. 7. *Laboratory stand for the: a) DC/AC converter, b) ferrite core including three parallel cores*

The testing implies insufficient surface of the inductor core fosters its saturation as current rises, reduces its reactance and deforms the waveform of its current. A ferrite core including three parallel cores was adopted ultimately (Fig. 7b).

Examples of laboratory results are discussed below, including sample oscillograms of current and voltage waveforms at selected points of the converter circuit at the time of current resonance in the load circuit. Current of the inductor (sum total of L_r and R_o currents) and voltages across the inductor are sinusoidal without exhibiting any additional harmonics (Fig. 8).

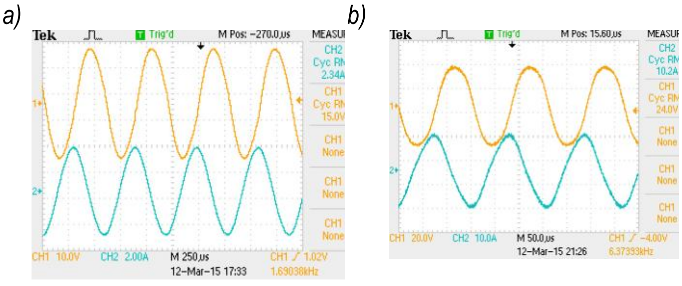

a) *b)*

Fig. 8. *Waveforms: (CH1) voltage across the inductor U_{wzb}, (CH2) current of the inductor I_{wzb}. Rms values: a) U_{wzb}=15V, I_{wzb}=2.34, f=1.69kHz; b) U_{wzb}=24V, I_{wzb}=10.2A, f=6.38kHz*

Induction of the input choke, L_d=30.5mH easily smoothes ripples of the input current *J*, which has considerable impact on the sinusoidal form of the inductor's current. Figure 9 illustrates a flat waveform of a supply current *J*=2.8A for a voltage supplied to the inductor U_{wzb}=15V.

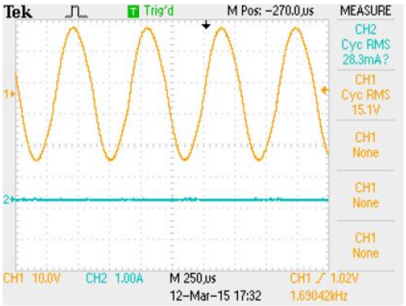


Fig. 9. *Waveforms: (CH1) voltage across the inductor U_{wzb}, (CH2) current supplied to the converter J*

The efficiency of induction heating analyzed for the four T1-T4, selected points of the rail (fig. 10). For heating power 240W changes in temperature at points T1-T4 is illustrated in Figure 11. Foot rails - T3, has warmed about 25°C within 15 minutes which proves highly dynamic temperature rise and allow preliminary assessment of high efficiency induction heating crossover railway in the field.

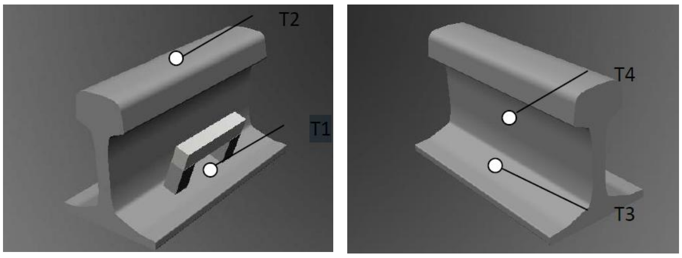


Fig. 10. *Points T1-T4 measurement of rail temperature during induction heating*

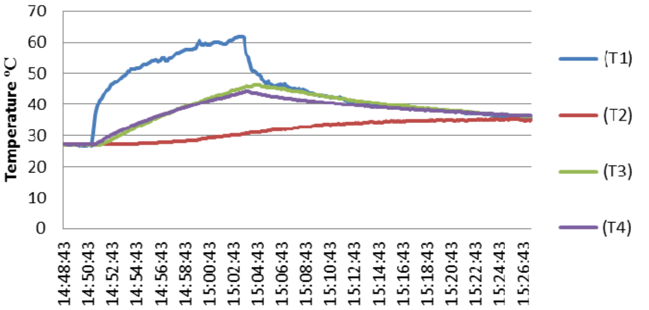


Fig. 11. *The points T1-T4 temperature during induction heating and natural cooling*

CONCLUSION

Application of a DC/AC converter including a parallel resonant circuit fulfils requirement of railway systems at the time of induction heating. Voltage and current waveforms become sinusoidal, which provides opportunities for safe cooperation with other rail track equipment. Input frequency of a voltage supplied to the inductor is dependent on variable parameters of the inductor to a minor extent. Losses across the converter's power circuit are negligible. The induction heating efficiency is high in the laboratory testing. The efficiency comparison must be made to the conventional heating method eor for the real turnouts.

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BADANIA LABORATORYJNE EFEKTYWNOŚCI ENERGETYCZNEJ GRZANIA INDUKCYJNEGO SZYNY

Streszczenie

Artykuł przedstawia wyniki badań grzania indukcyjnego szyny kolejowej. Stosowane obecnie metody służące do usuwania śniegu i oblodzeń z rozjazdów kolejowych nie są energooszczędne. Metoda elektryczna jest łatwa w montażu i wygodna w eksploatacji, natomiast pociąga za sobą ogromne koszty zużycia energii. W związku z tym zachodzi potrzeba poszukiwania sposobów oszczędzania energii. Jedną z nich, opisaną w artykule, jest metoda grzania indukcyjnego. Przedstawiono temperatury szyny podczas ogrzewania indukcyjnego i naturalnego chłodzenia. Największą efektywność energetyczną w obrębie stopki szyny uzyskano przy zastosowaniu wzbudnika w kształcie cewki nawiniętej na rdzeniu ferrytowym. Do zasilania wzbudnika użyto przekształtnika rezonansowego DC/AC z falownikiem prądu i równoległym obwodem rezonansowym. Uzyskane wyniki badań wykazują przydatność metody grzania indukcyjnego szyny w rozjazdach kolejowych.

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