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The results of the rail induction heating by the current inverter with the parallel resonant circuit

Abstract. Results of rail induction heating testing are presented in this article. Methods of snow and ice removal from turnouts currently in application are not economical in terms of energy consumption. The electrical method offers ease of assembly and convenience of operation yet generates enormous costs of energy. Ways of saving energy must be explored, therefore. Induction heating described in this paper is one of those. Various types of heaters were 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 resonant converter including a current inverter and a parallel resonant circuit supplied power to the inductor. The results support the method of rail induction heating in railroad turnouts.

*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. W badaniach laboratoryjnych grzania indukcyjnego szyny użyto różnych rodzajów grzałek. 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. (**Przekształtnik DC/AC z równoległym obwodem rezonansowym w systemie grzania indukcyjnego rozjazdu kolejowego**)*

Keywords: induction heating of railroad turnouts, DC/AC converter, resonant circuit
Słowa kluczowe: grzanie indukcyjne rozjazdów kolejowych, przekształtnik DC/AC, obwód rezonansowy

Introduction

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 cosφ 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.

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 1 [9, 12, 13].
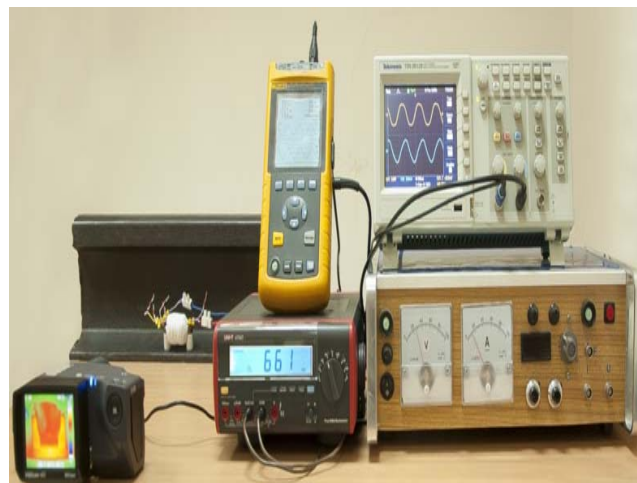

Fig.1. Laboratory stand for rail induction heating

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 [9]:
- Two oblong, 1.13m long heaters generating different shapes of magnetic fields (flat oblong heater, cup oblong heater)
- 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*.

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.

A series of experiments for the three types of the magnetic circuit used in the heaters 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. Results of the laboratory testing of rail heating at the selected f=650 Hz using a cup oblong heater are illustrated in Figure 2 and using a flat oblong heater in Figure 3.
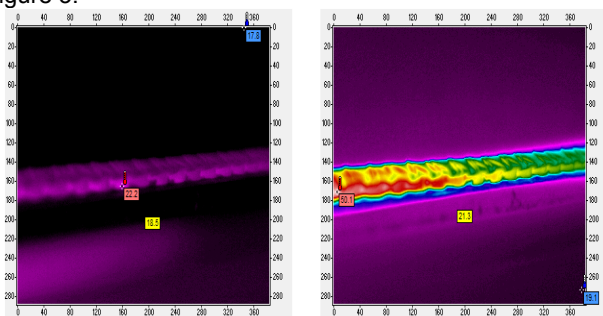

Fig.2. Image from the thermographic camera recording temperature increments ΔT in the rail foot after 30 min. of heating by the cup oblong heater [9]

The oblong heaters fulfilled design requirements for the method of electrical turnout heating [10] with regard to geometric dimensions. However, effectiveness of rail heating with the flat and cup oblong heaters was very low. The thermographs recorded with the camera indicated only the heaters themselves became hot, while ΔT noted for the rail foot was below 3°C during 30 minutes and comparable across the entire range of f. Inductors in the form of oblong heaters failed to constitute a closed magnetic loop that would penetrate the rail, therefore, the magnetic field they generated became dispersed [14]. The current flowing across the inductor winding caused heat to release primarily in the resistance of heaters.
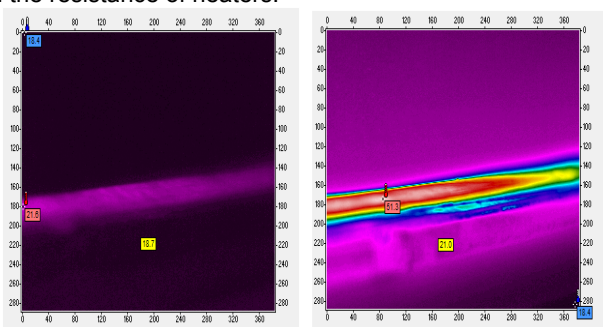

Fig.3. Image from the thermographic camera recording temperature increments ΔT in the rail foot after 30 min. of heating by the flat oblong heater [9]

The third type of 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

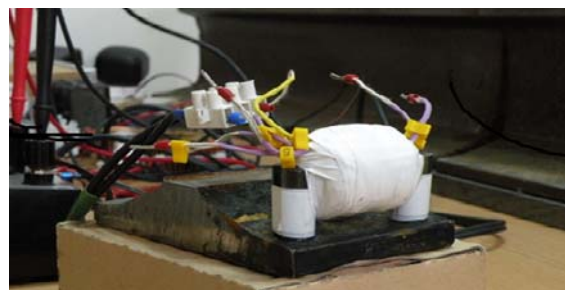piece of the heated rail foot in its design and laboratory versions.

a)
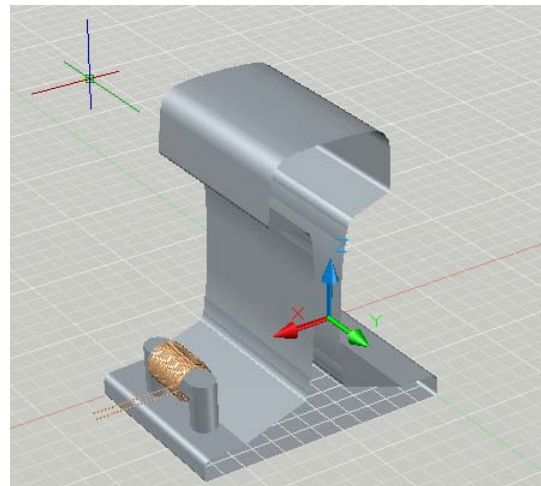
b)

Fig.4. Fragment of a rail and inductor in the form of a coil wound around a U-shaped ferrite core [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.
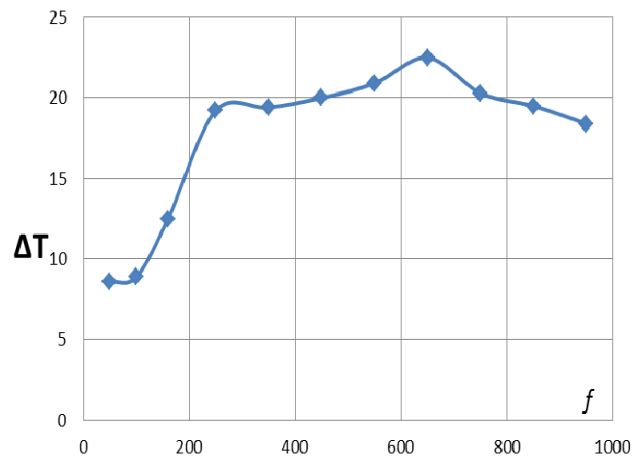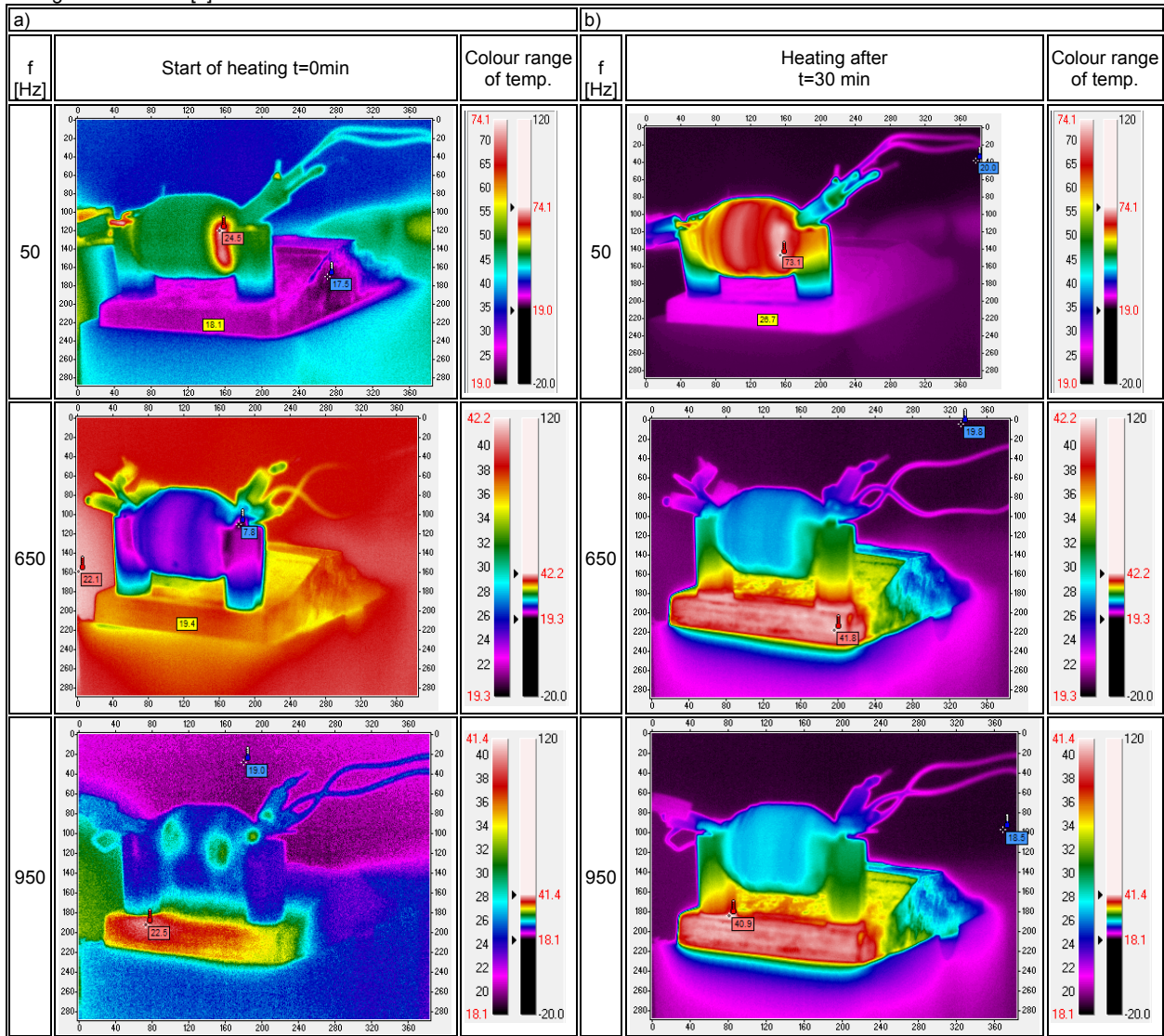

Fig.5. Temperature increments ΔT in the process of rail induction heating for t=30min

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

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

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

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.
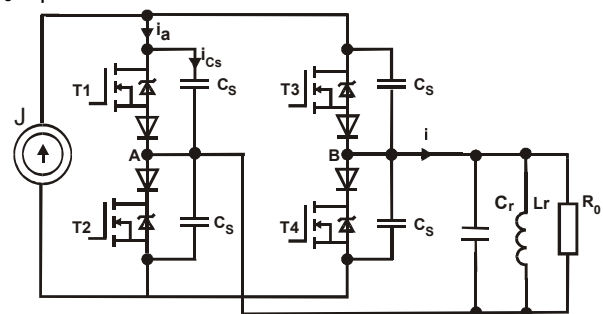

Fig.6. Diagram of DC/AC resonant converter system [8]

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.

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.
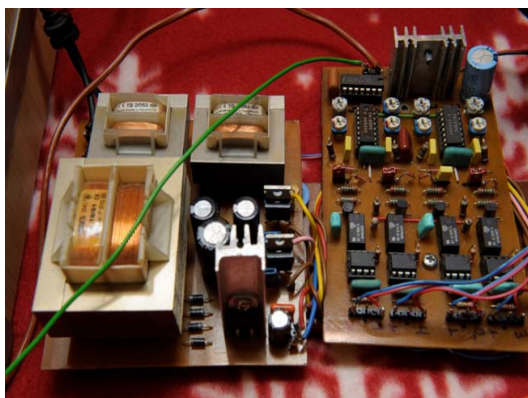

Fig.7. Laboratory stand for the DC/AC converter

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. 8).

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. 9).
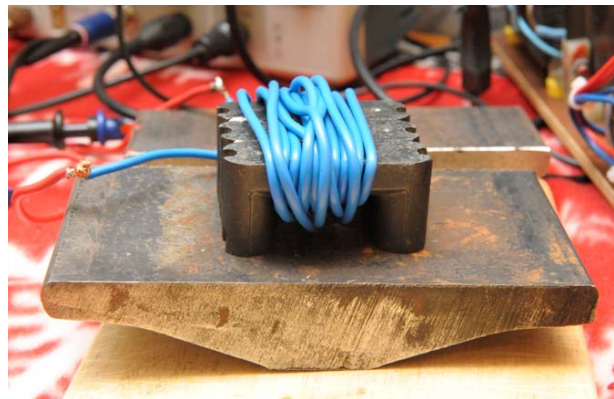

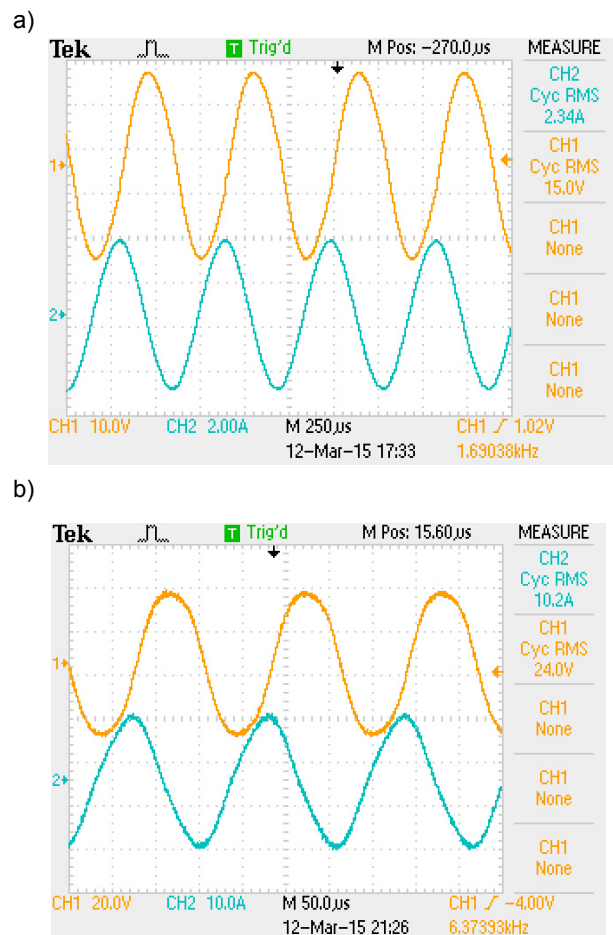Fig.8. Laboratory stand containing a ferrite core including three parallel cores

a)

b)

Fig.9. 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 10 illustrates a flat waveform of a supply current J=2.8A for a voltage supplied to the inductor U_{wzb}=15V.
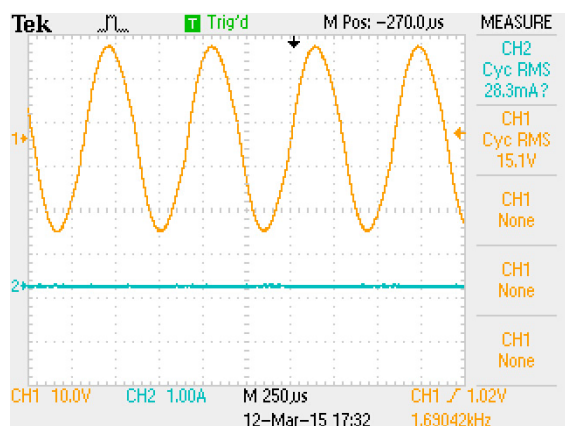
Fig.10. Waveforms: (CH1) voltage across the inductor U_{wzb}, (CH2) current supplied to the converter J

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. Power of heating is adjustable to weather conditions. The issues require continued research into a complex system of turnout induction heating working with rail automatic equipment in winter conditions or a climate chamber.

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