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Hyeong-Seok Oh, Chan-Bae Park, Seung-Hwan Lee, Jae-Bum Lee, Tae-Hyung Kim, and Hyung-Woo Lee
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Hyeong-Seok Oh,1 Chan-Bae Park,2 Seung-Hwan Lee,3 Jae-Bum Lee,2 Tae-Hyung Kim,4 and Hyung-Woo Lee1,a)

AFFILIATIONS
1Department of Railway Vehicle System Engineering, Korea National University of Transportation, Uiwang-si 16106, Korea
2School of Railroad Engineering, Korea National University of Transportation, Uiwang-si 16106, Korea
3School of Electrical and Computer Engineering, University of Seoul, Seoul 02504, Korea
4Department of Electrical and Computer Engineering, University of Michigan-Dearborn, Dearborn, Michigan 48128, USA

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ABSTRACT

In this paper, to complement the capability of the existing heating system using an electric-heating wire for melting snow and ice in railway turnouts, 250kHz-200W-class Induction Heating (IH) system was designed. The IH system consists of the resonant inverter and the IH device. In order to perform the electric circuit, the electromagnetic field, and the thermal analysis, the Multi-Physics analysis for IH system was derived. In addition, IH system was compared with the existing heating system.

I. INTRODUCTION

This paper is a study on de-icing for railway turnouts using 250kHz-200W-class induction heating system. Railway transportation is transportation that has robust characteristics for the external environment compared to air transportation and road transportation and has excellent on-time and safety, however, even in the case of railway transportation, extreme weather conditions such as snowfall cause damages due to disability and accidents. The winter damage prevention application areas of railway transportation can be broadly categorized into railway vehicles, overhead lines, and railroad tracks. Railroad tracks of these areas include obstacle prevention of railway switches. A railway switch is a device that switches the direction of a branch installed to railway turnouts from one railroad track to another, which is one of the most important devices of the railway infrastructure, which determines the direction of the vehicle. Since the railway switch of railway turnouts in winter may cause railway vehicle delays and accidents due to snow and ice, they are currently being melted with electric-heating wires. The heating device typed electric-heating is simple in structure and making it easy to install, but this heating device is the old technology that is not good electrical and thermal efficiency. The heat generated by the heating device is immediately transferred to the rails. The rail is bigger than the heating device, and the larger the volume, the faster the radiant heat into the air. As a result, the heating device heats the entire rail, and a lot of power is consumed to heat the long rail. Currently, the heating device typed electric-heating which is a lot of power consumption due to the system has been used in the Republic of Korea. In addition, A low-efficiency heating system may cause difficulties in railway operation if it fails to properly perform the role of snow removal and deicing. Therefore, there is a need for research on the efficient and reliable new heating system to replace the existing heating system.

The Induction Heating (IH) proposed in this paper is highly reliable because it is very widely used throughout the industry.
The fundamental principles of IH technology are Ampère’s circuital law and Faraday’s law of electromagnetic induction. An alternating magnetic field is formed by flowing alternating current in the coil, and the alternating magnetic field formed induces an eddy current in the heated object, and the induced eddy current causes the heated object to generate heat due to Joule’s law. Unlike conduction and convection, which require a medium, IH is a technology with high heating efficiency because energy is transferred without a medium and is a very efficient way to locally heat a specific part of a heating element.

In addition, the use of high-frequency alternating current reduces the depth of penetration due to the skin effect, allowing the heating element to be heated in a short time.

For this purpose, an additional resonant inverter was applied to enable high-efficiency operation of the heating system power unit. Therefore, when the high-frequency IH method and the resonant inverter are used in the heating system, the electrical and thermal efficiency can be improved compared to the heating wire electric-heating wires. Fig. 1 shows the concept of applying the IH system in the turnout.

II. DERIVATION OF MULTI-PHYSICS ANALYSIS FOR IH SYSTEM

The IH system proposed in this study consists of the power source for power supply and the IH devices for melting. To supply the power required by the IH devices of the IH system, the electrical circuit design of the power department was carried out, converting 1Φ/220V/60Hz of commercial power into high-frequency power. The parameters required for electromagnetic field analysis were also derived through the formula and simulation. The parameters were adjusted by the number of layers and turns for the primary coil through (1) and simulation. (1) is a design formula derived to confirm the required inductance of the primary, and matched with (1) by changing the number and layers of the primary coil in the electromagnetic modeling. The coupling coefficient and the parameter of the secondary were the value measured in the simulation, current and frequency were 2A and 250kHz.

\[
L_{1_{\text{need}}} = \left( \frac{|I_2| \cdot Z_2}{(I_{\text{act}, \text{rms}} \cdot \omega) \cdot k^{-1} \cdot (\sqrt{L_2})^{-1}} \right)^2
\]

Based on the derived parameters, electromagnetic design and analysis were conducted for heating. Since temperature verification

| Symbol | Specification | Value |
|--------|---------------|-------|
| V\text{in} | Input voltage | 180 ∼ 240 V\text{rms} 60Hz |
| I\text{ripple} | Inductor current ripple | 25% |
| V\text{out} | Output voltage | 350 V |
| I\text{out} | Output current | 2 A |
| P\text{max} | Maximum power steady state | 700 W |
| f | Frequency | 250 kHz |
| V\text{ripple} | Output voltage ripple | 10 V\text{p-p} |
| L\text{coil} | CCM coil inductance | Min. 504 μH |
| C | CCM capacitance | Min. 530.5 μF |
of the heating system is important for melting, thermal analysis was performed by interlocking the results of the electromagnetic field analysis performed earlier with thermal analysis conditions. Based on these results, a Multi-Physics analysis that can be integrated with electric circuit analysis, electromagnetic field analysis, and thermal analysis of the IH system was derived. Fig. 2 shows the Multi-Physics analysis for the IH system. The designed circuit is analyzed and interlocked as the source of the electromagnetic field. The red area in electromagnetic analysis of Fig. 2 is shown the eddy current loss which will be transformed into the heat source. The heat source is evenly distributed in the center of the heating plate, and in Fig. 2, it can be seen that the heating plate is heated. The temperature with time was shown as a graph, and it can be confirmed that the heating time from -40 °C to about 40 °C is about 30 seconds.

III. DESIGN AND ANALYSIS

A. Electric circuit in IH system

The melting point of the snow and ice is about 0 °C, so they can be sufficiently removed at room temperature. Therefore, excessive heat is not needed to melt the snow loaded on the railway turnout, and it is necessary to maintain the proper temperature to the extent that the snow is removed. To generate the appropriate temperature, a suitable heat source needs to be generated. The alternating magnetic field generated by the coil generates eddy currents induced on the surface of the heating element. Next, the heat source generated by Joule’s law heats the heated object. Therefore, by adjusting the induced eddy current, the heat source can be properly distributed to the heating element, and the adjustment of the eddy current can be realized by adjusting the current applied to the coil of the IH device.

The basic design of resonant inverter for the IH system has been performed. The resonant inverter consists of a filter, a Boost PFC, and an inverter. To prevent Electromagnetic Interference (EMI), a filter has been added to the input side, which consists of a parallel capacitor, a resistance, and a common mode choke. Power Factor Correction (PFC) is necessary to achieve high efficiency. To realize this, the Boost PFC was designed. Diode and MOSFET were designed considering the rated voltage and loss. The inverter was determined to be MOSFET, considering the loss while satisfying parameters. Parameters for the power supply unit of the IH system are selected based on formulas and simulation, as shown in Table I.
**B. Design and analysis in electromagnetic field**

The existing heating system of the railway turnout is operated by electric-heating wires. The electric-heating wire is to apply the positive and negative currents to the nichrome lines so that their heat is generated. In this study, the IH device was designed to be similar to an existing heating wire for compatibility with the existing system. The heating device is located between the rail and the switch rail and is attached to the boundary of the bottom and the abdomen of the rail and does not interfere with the bolts and nuts fastened to the switch rail. In consideration of this situation, the IH device was designed to be within 20 mm wide and 6 mm thick. Fig. 6 shows the modeling for the electromagnetic field. Since there is a narrow space for design specifications, it is difficult to use relatively thick Litz wire as the primary coil. Therefore, the primary coil was designed as a PCB to satisfy the limited size. The secondary heating plate is made of stainless steel SUS430, which is also used as a heat sink.

**TABLE II. Material data for electromagnetic field analysis condition.**

| Symbol | SUS430 | Ferrite sheet | UIC 60 | Copper |
|--------|--------|---------------|--------|--------|
| $\mu$  | 409    | 100           | 400    | 0.99991|
| $\rho$ [kg/m$^3$] | 7,750  | 4,600         | 7,850  | 8,933  |
| $\sigma$ [S/m]    | 1,666,667 | 0.01          | 1,100,000 | 58,000,000 |

**FIG. 5.** The simulation results of the power supply for IH system.

**FIG. 6.** The modeling of IH device for electromagnetic field analysis.

**FIG. 7.** The results of electromagnetic field analysis ((a) The line current density of the heating plate, (b) The surface loss of the heating plate).
material for cookware for an induction range. It was designed with an E-type ferrite to concentrate magnetic flux made from the primary coil and was later replaced with a ferrite sheet considering its manufacture. Table II shows material data used for electromagnetic field analysis conditions. These design and analysis conditions were used to perform electromagnetic field analysis and the analytical program used a FEM-based commercial program (ANSYS HFSS) suitable for high-frequency analysis. Fig. 7(a) shows the line current density in the heating plate, it can be confirmed the flow of the eddy current. As shown in Fig. 7(b), the loss of eddy current, which is the source of heat source, was confirmed from the electromagnetic field analysis. Figure 8(a) and (b) show the comparison of the analysis results with the target value for the resistance and the loss of heating plate. From this, it can be seen that the current can be reduced to meet the loss of 200W. Therefore, when the current of 2A was converted to about 1.67A, the load loss of 200W was confirmed from the analysis.

C. Thermal analysis

The thermal analysis based on the electromagnetic field analysis result was performed. The thermal analysis requires additional material data such as specific heat and thermal conductivity. Table III shows the material data used in the IH system. The initial and ambient temperature were selected at -40 °C to reflect extreme conditions. Also, because the Finite Element Method (FEM) based analysis tool was used, the mesh of the IH device and the rail were set to 0.5 mm and 1 mm, respectively. Fig. 9 shows the analysis conditions of the thermal analysis. To compare the existing heating system with an IH system, the Multi-Physics analysis was performed by modeling electric-heating wire. For comparison, the input power was adjusted so that the loss of the heating wire 200W. The reason is there is no publicly available data on the efficiency that is the ratio of input and output of the existing system in the Republic of Korea. The modeling consists of two nichrome wires and a stainless-steel case. Therefore, the temperature change over time of each of the two systems was confirmed, which is shown in Fig. 10. In the heating system, heat is conducted to the rails and local heating is impossible. On the contrary, the IH system intensively transfers heat to the heating plate and reached a temperature of room temperature in a relatively fast time. The temperature rise compared to the same time is represented by the slope. The slope of the IH system is 0.0266, and the slope of the electric-heating wire is 0.0296. Since the difference in the slope was insignificant, the temperature difference at the same time was compared. At 120 seconds, the IH system is about 19.4 °C and the electric-heating wire is about -4.3 °C. Therefore, unlike electric-heating wire, the IH system can melt snow that builds up in the rail base in 120 seconds.

| Item                     | SUS430 | Ferrite sheet | UIC 60 | Copper |
|--------------------------|--------|---------------|--------|--------|
| Specific heat [J/kg·°C]  | 460    | 750           | 461    | 385    |
| Thermal conductivity [W/m·°C] | 26    | 4             | 53     | 400    |

FIG. 8. The comparison of the analysis results with the target value ((a) The resistance, (b) The loss of heating plate).

FIG. 9. The analysis conditions of the thermal analysis.
IV. CONCLUSION

In this paper, the 250kHz-200W-class IH system, which is a high-efficiency heating technology, is proposed to replace the existing heating system. As a previous study for the application of the new heating system in the railway turnout, the electric-heating wire was investigated to compensate for the shortcomings of the existing heating system in the railway turnout. The electric circuit for the power supply of the IH device was designed and analyzed to derive the required parameters of the IH device. The modeling for the electromagnetic field design and analysis was performed, and the thermal analysis was performed by linking the electromagnetic field analysis results. The Multi-Physics analysis was derived to link the circuit/electromagnetic field/thermal analysis for the IH system in the railway turnout. As a result, the IH system that can be locally melted in a shorter time than the existing system has been proposed. In the future, multi-physics analysis and IH system through this study can be used to study the heating device applications for a large-scale heating systems in railway turnout.

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