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Temperature Influence on Electrical Signals in Induction Systems

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Abstract **-** This paper examines the impact of temperature on electrical signals in induction system with heated workpiece. Induction systems stand out as highly efficient methods of heating, primarily due to their ability to precisely concentrate energy into the material being heated, thus selectively heating specific parts. The paper presents a numerical model developed using ANSYS APDL software, which elucidates the basic aspects of how temperature affects the material parameters of the heated workpiece and the induction system, particularly the frequency converter circuit. The influence of temperature on electrical signals was further substantiated through experiments with steel typically used for induction surface hardening. The insights gained are especially valuable in the context of induction systems, where understanding the material's temperature impact is critical for processes like induction surface hardening, tempering, or induction soldering.

Keywords**:** induction systems, steel, workpiece, Curie temperature, impedance

1. Introduction

The induction system employed in our configuration comprises several key components, including a frequency converter, resonant capacitors, a high-frequency transformer, an inductor, and a workpiece. Typically, for surface hardening purposes, the workpiece is made of ferromagnetic materials, such as specific steel alloys. Ideally, the induction system operates in series resonance, where the source draws only active power from the grid. This power is then converted into the desired Joule heat in the workpiece. In a resonant state, when the circuit is finely tuned, a nearly sinusoidal current flows through it at a frequency determined by Thomson's relation (1). This state allows for the most efficient induction heating, up until the material is heated above the so-called Curie temperature. Beyond this point, the material's changing properties significantly impact the heating process. Ideally, this change should be countered by adjusting the frequency, for instance, by using a Phase-Locked Loop (PLL) or by initially setting the source to a state above resonance at the onset of heating.[1]

$$f_r = \frac{1}{2\pi\sqrt{LC}} \ \text{(Hz)} \tag{1}$$

It is well understood that in the field of induction surface hardening, the material must be rapidly heated to the austenitizing temperature to enable the formation of a pure martensitic structure upon rapid cooling by quenching, which is indicated by high hardness. Therefore, during this process, it is essential to pass through the so-called Curie temperature region. For steels, depending on their alloy composition, this is typically around 760°C. [4] Throughout the heating process, the workpiece affects the circuit of the induction system by altering its material properties with temperature. Changes occur in the material's electrical conductivity, relative permeability, thermal conductivity, specific heat, and density. Of these, the electrical conductivity and relative permeability are the most influential on the induction system's circuit. These effects are further discussed in the paper and substantiated through both numerical simulation and experimental verification.

2. Numerical simulation of temperature influence

The induction heating model was developed using ANSYS APDL software. The objective was to simulate the induction heating of steel, taking into account the material's temperature-dependent changes, and to evaluate the inductor's impedance during heating, as it influences the entire induction system. The problem is modelled as 2D axisymmetric and involves solving a strongly coupled transient problem with temperature-dependent material parameters updated at each simulation step. As mentioned, this process is nonlinear and characterized by temperature-dependent properties such as resistivity, thermal conductivity, specific heat capacity, and other material parameters. Additionally, the material's relative permeability is temperature-dependent. The simulation mirrors the experimental setup, which is described in the following section of the paper. The model includes half of a cylindrical workpiece and three circular inductor turns with a specified current magnitude. The environment is also defined in the model. A constant current of 750 A at 25,000 Hz was set through the inductor.

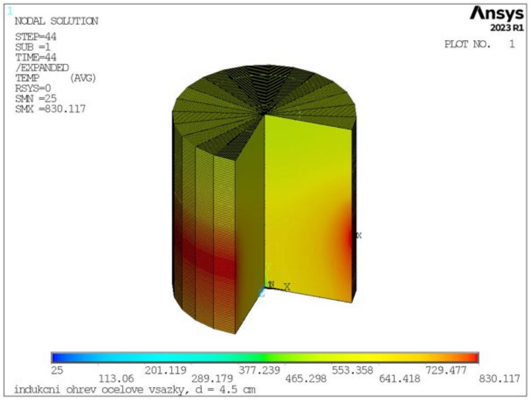

Fig. 1: Temperature distribution at 44s

The material properties used in the numerical model correspond to steel S355J2, which comprises C = 0.24%, Mn = 1.7%, Si = 0.6%, P = 0.035%, and S = 0.035%. The results of the simulation are presented below. In Figure 2, we can observe the temperature profile and compare the numerical simulation with the experimental results. As shown, the curves are remarkably similar. The workpiece is heated for 90 seconds and then allowed to cool through natural convection. In the numerical simulation, cooling by radiation is also considered. Notably, on the blue curve, we can see the temperature decrease at around 25 seconds, which is due to the change in relative permeability at the Curie point. A similar observation is made on the green curve, which represents the experimental measurement.

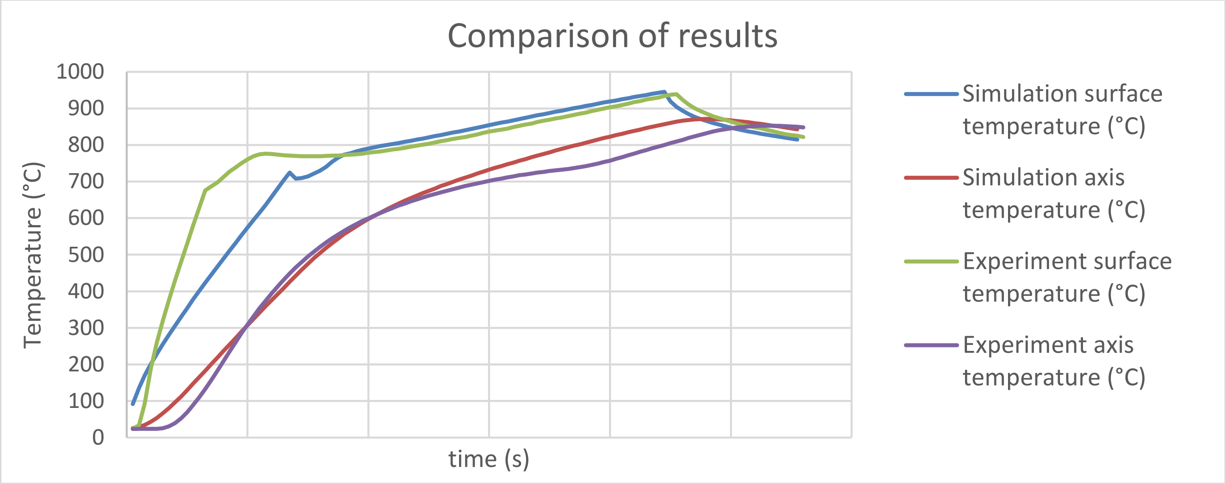

Fig. 2: Comparison of temperature profiles

In the numerical simulation, the voltage at the inductor was calculated, which was then used to determine the impedance during the induction heating of the workpiece. It is evident that changes in impedance significantly affect the entire induction system, including the resonant circuit. A comparison between the experimental data and the numerical simulation is presented in Fig. 3. There, we can see the decrease in the inductor's impedance upon reaching the Curie temperature, which occurs at approximately 25 seconds. The discrepancy between the impedance values from the numerical simulation and the experiment can be attributed to the simulation focusing solely on the inductor, rather than considering the transformer and the entire circuit. Similar patterns are also observed for the individual impedance components, such as resistance and inductance, as shown in Fig. 4.

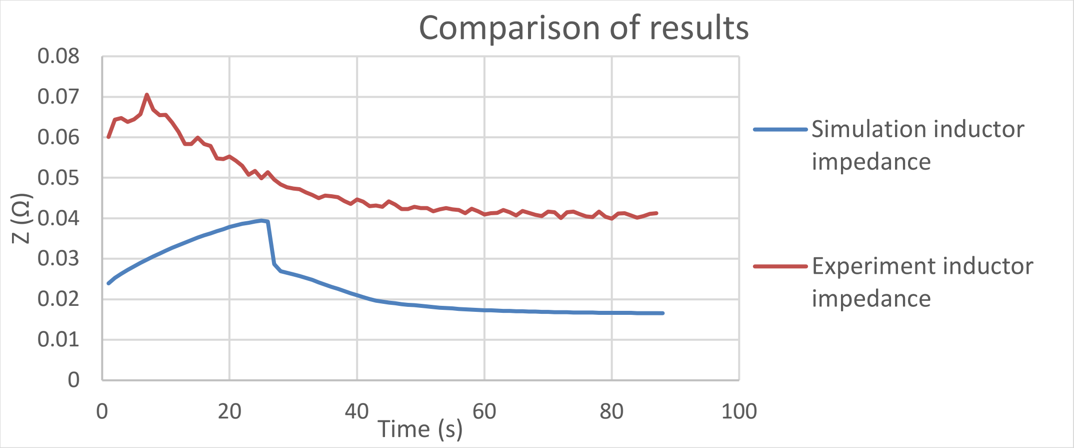

Fig. 3: Comparison of impedances

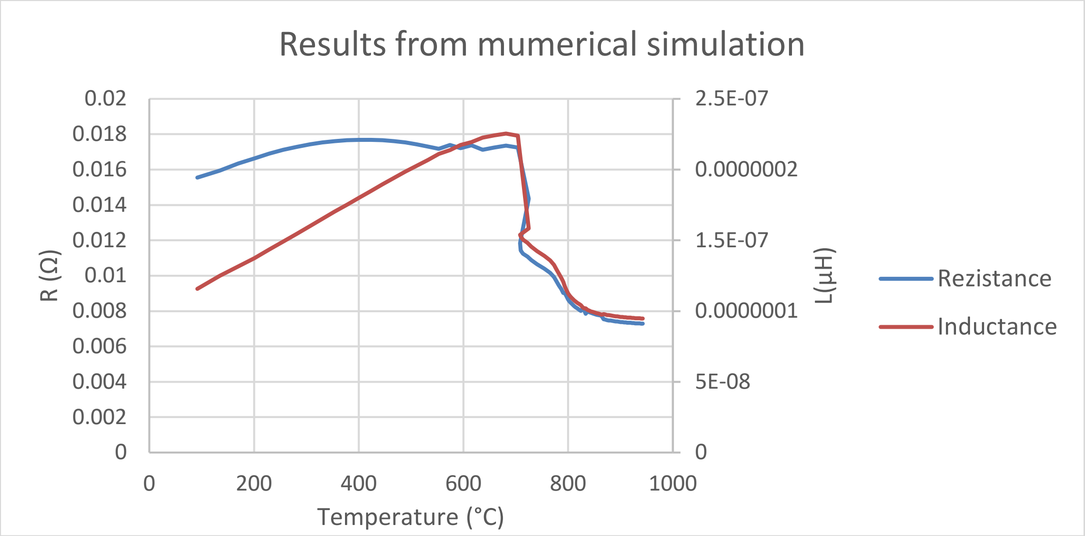

Fig. 4: Evolution of impedance parts with temperature

3. Experimental measurement of temperature influence on electrical signals

The experiment focused on verifying the simulation results in reality, primarily to examine the behaviour of currents and voltages in the induction system's circuit. Based on the numerical simulation results, it is evident that changes in impedance significantly affect the current in the circuit of the induction system. However, this behaviour varies among different materials and steel alloys, depending on their specific composition.[5]

In Fig. 5, we observe the current profiles as they relate to temperature changes. The current measured at the output of the frequency converter, denoted as Iac, decreases until reaching the Curie point, after which it rapidly increases. This is attributed to the impedance changes during the heating process. A similar profile is observed in the intermediate DC circuit, with the current, labeled Idc, of the frequency converter in the induction system. These changes were observable due to a special type of frequency converter control. It was operated with a constant duty cycle, but in actual processes, the current is typically controlled to a constant value, with changes being observable only in the voltages. The voltage variations during the heating process are depicted in Fig. 6.

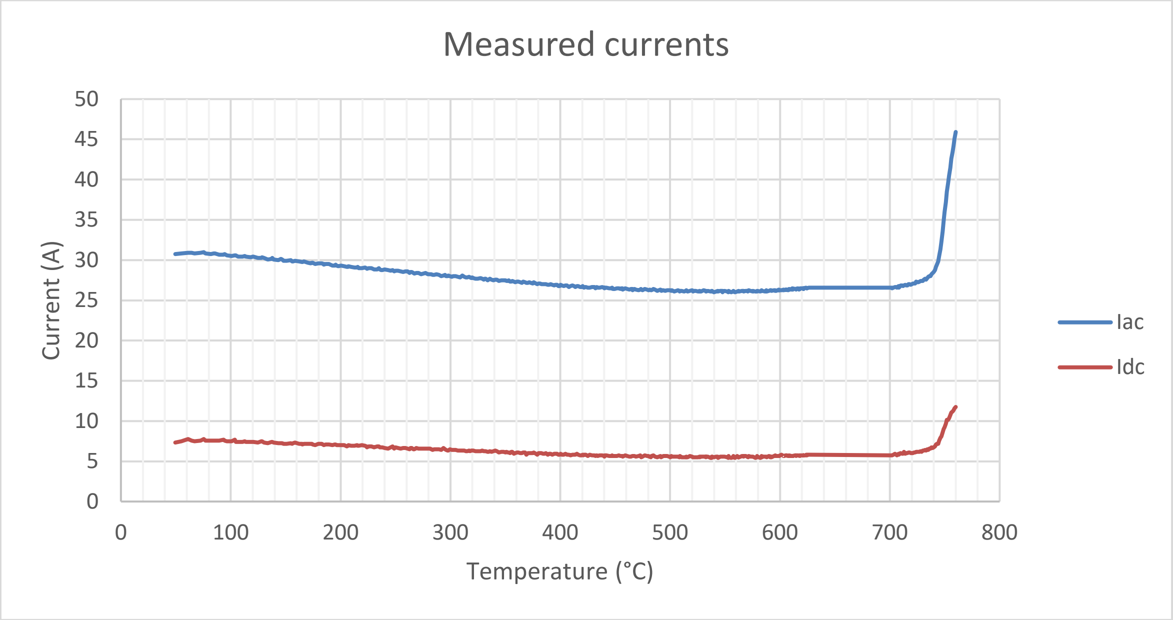

Fig. 5: Current profiles with temperature of workpiece

In the picture Fig. 6, we observe the voltage profile during the heating process. The voltage at the output of the frequency converter decreases until reaching the Curie point, at which it increases due to the rapidly decreasing impedance of the workpiece. A similar behaviour is observed in the intermediate DC circuit. However, after reaching the Curie point, the voltage rapidly decreases, attributable to the stiffness of the electrical grid.

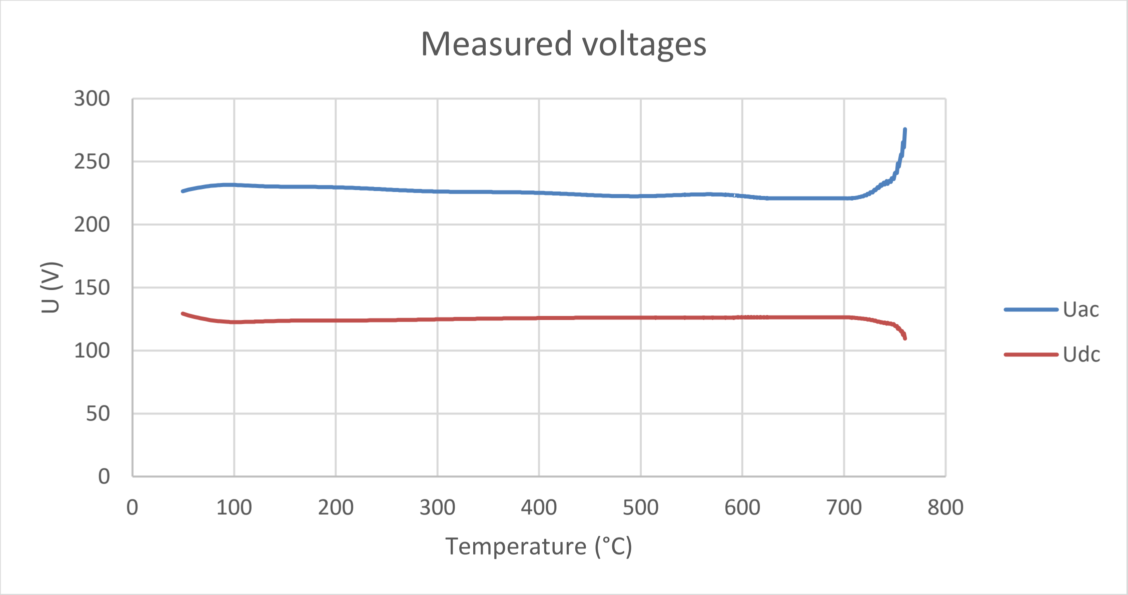

Fig. 6: Voltages profiles with temperature of workpiece

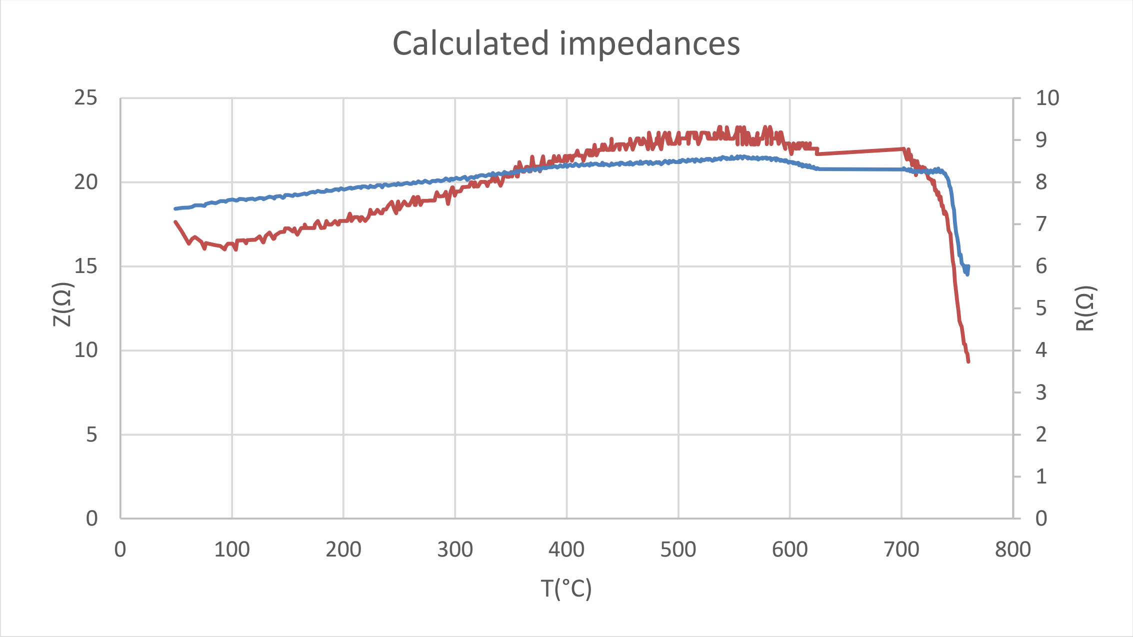

Fig.7: Calculated impedances from measured signals

In Figure 7, we can observe the impedance change as a temperature function. There is calculated impedance at the frequency converter's output marked with blue colour, and the red curve is for calculated resistance at the intermediate DC circuit. The significant decrease in impedance is primarily caused by the change in the relative permeability of the steel workpiece. As the temperature rises, the material properties of the steel alter, leading to a reduction in permeability at the Curie point. This, in turn, affects the impedance.

Moreover, the variations in impedance are mainly attributed to changes in the penetration depth of the magnetic field. As the temperature increases, the skin depth of the magnetic field changes, impacting how the field interacts with the steel workpiece and the disbalance of the serial resonant circuit.

4. Conclusion

The article describes the problem of changing material parameters during the heating process. It includes a description of the induction system and its components. Notably, the article addresses the issue of impedance variation with the temperature of the workpiece. This phenomenon is clearly described and verified through numerical simulations prepared using ANSYS Mechanical APDL software. Furthermore, we compared results from these numerical simulations with experimental measurements. The impact of these changes on the electrical signals in the frequency converter circuit is also detailed. From our perspective, these findings are significant for induction systems in terms of adjusting the source and enhancing the heating efficiency. Additionally, this feature is potentially valuable for detecting the temperature of the workpiece from electrical signals in the frequency converter circuit without the installation of any additional probes for temperature measurement. This finding is beneficial for the field of induction heating, as these processes require precise temperature knowledge. The temperature detection system will probably contribute to higher automation of these processes.

Acknowledgements

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