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Temperature detection from electrical signals of induction system

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This article focuses on the development of a new method for detecting the temperature of workpieces heated by induction heating based on the analysis of electrical signals in the circuit of the induction system. The text compares commonly used temperature measurement methods, highlighting their technological advantages and shortcomings. The research also included the development of a special frequency converter optimized for the needs of the proposed temperature detection method. The properties of the new method were experimentally verified on four different types of ferromagnetic steels commonly used in industrial applications. The experimental results confirm the functionality and potential of this method for accurate and efficient temperature detection based on the analysis of electrical signals.

Keywords: induction systems, electrical signals, temperature measuring, frequency converter

1 Introduction

Induction heating is now a widely used technology that is used not only in households but also in industrial applications. This trend is becoming increasingly prominent, especially in the context of rising electricity prices, as induction heating gains importance due to its energy efficiency. Compared to traditional indirect heating methods, which exhibit higher energy losses, induction heating is not only more efficient but also more economical. The technology of induction heating allows energy to be concentrated directly into the material, minimizing heat losses to the surroundings. This gives induction systems a significant advantage in many sectors, from households to demanding industrial processes. For this reason, increasing emphasis is currently placed on improving these systems, both in terms of their energy efficiency and automation, which allows for easier and more precise control [1].

In the context of this trend, we focused on improving the control system of an induction device for surface hardening. Our goal was to detect the temperature from the electrical signals in the circuit of the frequency converter. The fundamental principle is the change in material properties of the inductively heated workpiece with temperature. In this case, the temperature affects both the electrical parameters, such as voltage or current due to the change in material impedance, and the magnetic parameters, such as the material's relative permeability. Of course, thermal parameters like thermal conductivity, specific heat capacity, and others are also influenced. The induction system is also influenced by the penetration depth of the electromagnetic field, which also affects the measured resistance and the temperature distribution within the material. The most detectable parameters with temperature changes, in this case, are the electrical parameters. In our case, we selected the impedance of the circuit or its individual parts, such as the resistance or inductance of the entire system, which better correlate with temperature changes and are also a physical consequence of these changes. The development of these two parameters was monitored during experimental measurements.

One commonly used contactless method for measuring material temperature is infrared radiation detection. A major advantage of infrared spectrometry is the ease of measuring rotating or moving objects, the negligible impact of the measuring technique on the measured object, and the quick response to temperature changes. In the case of infrared radiation, every object emits electromagnetic waves from its surface into the surroundings and simultaneously absorbs energy from other objects in a transparent environment. The electromagnetic waves are eventually absorbed by non-transparent objects and converted into thermal energy. Depending on the current state, the object either heats up or cools down if its emission of infrared radiation prevails. The measurement can be influenced by changes in physical parameters depending on the temperature, specifically the material's emissivity or the wavelength of the emitted radiation. Therefore, it is challenging to accurately measure the temperature of metallic materials at high temperatures. According to Wien's law, the wavelength of emitted radiation shortens with increasing temperature. Problems with changing emissivity can be partially eliminated in specific applications, for example, by using special coatings with constant emissivity. However, in the case of induction surface hardening, further complications arise, such as surface oxidation of the material and reflection of infrared radiation from the quenching medium. In specific cases, the so-called vapor cushions form when the heated material comes into contact with the quenching medium,

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causing it to evaporate, which prevents direct contact of the liquid with the surface. Vapor cushions reduce heat dissipation in these areas, affect temperature measurement, and lead to misinterpretation of the material's surface temperature [2].

Another widely used method for temperature measurement is the detection of thermoelectric voltage, which is utilized by thermocouples. This method is based on the Seebeck effect, where the junction of two different metals generates a thermoelectric voltage, the value of which depends on the temperature difference between the measured point, known as the hot junction, and the reference point, referred to as the cold junction. The advantage of this method is its wide temperature range, covering very low as well as extremely high temperatures, typically from -200 °C to 2000 °C, depending on the type of thermocouple used. Thermocouples are also simple, robust, and durable, ensuring their easy integration into measurement systems. The disadvantage is that thermocouples are sensitive to external influences, particularly electrical interference, which can negatively affect measurement accuracy, especially when using long cables or in demanding industrial environments. Additionally, the accuracy of thermocouples is typically ±1–2 °C, which may not be sufficient for applications requiring high precision. Unlike infrared measurement, which is contactless, thermocouples require direct contact with the measured material. This can be a disadvantage in the case of moving inductively heated workpieces, whether in rotational or translational motion, and it also disrupts the surface structure of the material by attaching the thermocouple through welding or drilling [3].

In the introduction of this article, we aimed to outline the issues and physical principles of various temperature measurement methods in induction processes. We anticipate increased automation of induction systems and the elimination of some technological challenges mentioned in this chapter through the use of the proposed method for temperature detection from electrical signals during induction heating.

2 Development of a frequency converter with a material temperature detection algorithm

Figure 1 shows the circuit of a frequency converter with the so-called full-bridge configuration of large IGBT modules with a rated continuous collector current of up to 200 A. The frequency range of the converter is 0-50 kHz. The figure also shows a three-phase bridge rectifier, damping coils in the DC link together with electrolytic capacitors with a capacitance of 2200 μF. A system for pre-charging the capacitors and regulating the voltage in the DC link is also installed. The power elements are mounted on a water cooler to ensure sufficient dissipation of heat losses.

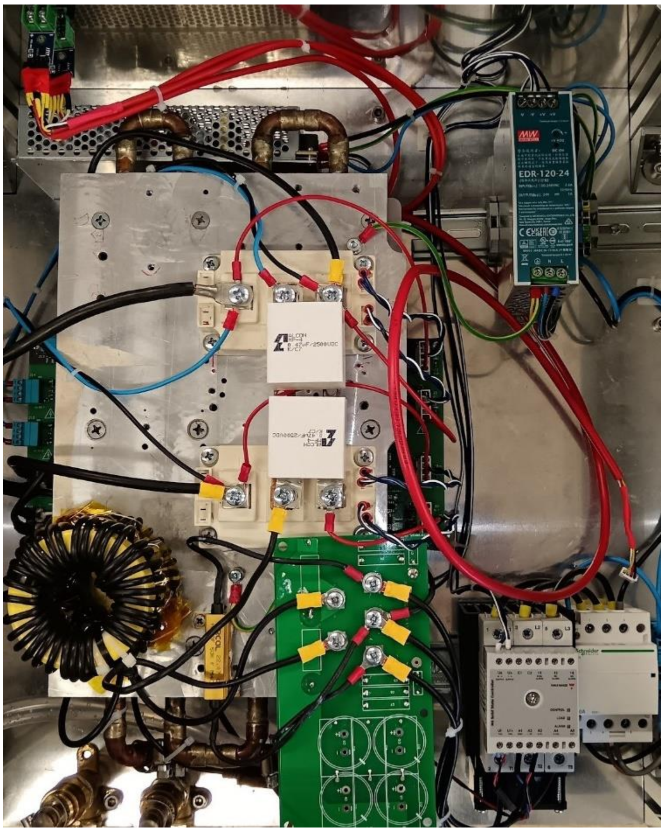


Fig. 1. Power elements of the frequency converter

For specific control needs, a new control board was designed with an integrated measurement system. The board shown in Fig. 2 is equipped with sensors for measuring currents operating based on the principle of the Hall effect, as well as voltage sensors at the converter's output and in its intermediate circuit. The measurement circuits evaluate the effective values of the signals and simultaneously ensure sufficient galvanic isolation between the control part and the power section. From the measured voltages and currents, the effective values of the signals are evaluated for the temperature detection algorithm.

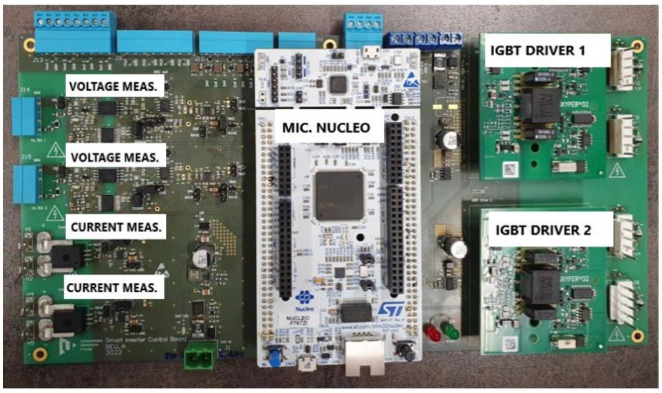


Fig. 2. Power elements of the frequency converter

For the transfer of PWM (Pulse Width Modulation) control signals from the microcontroller to the IGBT modules, Skyper 32R drivers were used. These drivers convert the rectangular control signal into the required voltage levels for switching on +15 V and for switching off IGBT –7 V. The drivers also ensure sufficient galvanic isolation between the control and power sections of the converter. This driver was selected with respect to the operating frequency of the converter and extensive fault detection capabilities. The driver is equipped with the detection of overvoltage pulses, circuit shorts, and other fault conditions. Its short-circuit protection mechanism, known as desaturation protection, continuously monitors the voltage between the collector and emitter during transistor switching. When this voltage exceeds the saturation limit, significant thermal losses occur in the transistor due to high collector current. After the preset time interval, the transistors are automatically switched off to prevent damage. At the same time, a signal indicating a fault is sent to the control microcontroller, allowing for quick diagnosis and appropriate measures to be taken.

For the control of the converter, evaluation, and storage of data, the Nucleo-F767ZI microcontroller was used. This microcontroller was chosen due to its extensive number of input-output pins, high-quality ADC converters, and a large number of high-speed timers, which are ideal for generating control signals with variable pulse width. The converter control algorithm is programmed in MicroPython, which is a reduced version of the Python language specifically designed for microcontrollers and small computing devices with a limited memory size [4].

The frequency converter is controlled from a 4.3” Nextion touchscreen display. This display, see Fig. 3, was chosen due to the integration of the user interface into the display's memory, thus avoiding an increase in performance requirements for the microcontroller.

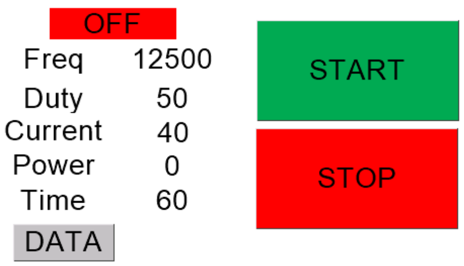


Fig. 3. User interface of the induction system

An advantage is also the ease of editing the user interface in the Nextion Editor software. Communication between the microcontroller and the display takes place via the UART interface. Defined heating parameters such as the desired frequency, heating time, and required current are transmitted. The display also shows the values that have been measured

Control with a constant duty cycle is the most primitive method of controlling a frequency converter, which is suitable only for some applications. During heating, it is necessary to regulate the voltage level externally using an autotransformer or, more sophisticatedly, using a controlled rectifier for the testing purposes of the temperature detection algorithm. Another option is to use semiconductor relays with proportional control.

Control for the desired power or current are a similar method. In the case of power, it is derived from the measured voltage and current values in the DC circuit is calculated the current power, which is compared to the desired value. After multiplying the difference by the correction coefficient, the opening of the IGBT module is proportionally decreased or, conversely, increased.

The same control principle applies to the desired output current. In this case, the measured RMS value of the current at the converter's output is compared with the desired value, and proportionally in each iteration, the duty cycle value for the PWM signal generated by timers is adjusted.

The temperature detection algorithm works on the principle of comparing the measured values of impedance or resistance with a database of the given material stored in the microprocessor's memory.

First, the system needs to be 'calibrated' for the given material and geometry. In this case, the material is heated to the chosen temperature with thermocouples attached to the surface of the material. All available measured data are then stored in the microcontroller's memory. Specifically, the voltage and current at the converter's output and their ratio, i.e., the circuit impedance, as well as the voltage and current in the DC intermediate circuit and their ratio, i.e., resistance, are recorded. Furthermore, the supplied apparent and active power calculated from these values are also stored.

Then, the algorithm created in the MicroPython language is capable of responding to changes in the induction system circuit, detecting the material's temperature during heating, or possibly regulating the system's settings to maintain this temperature. In Fig. 4, we can see a flowchart with a simplified representation of the induction system control and a description of the temperature detection algorithm.

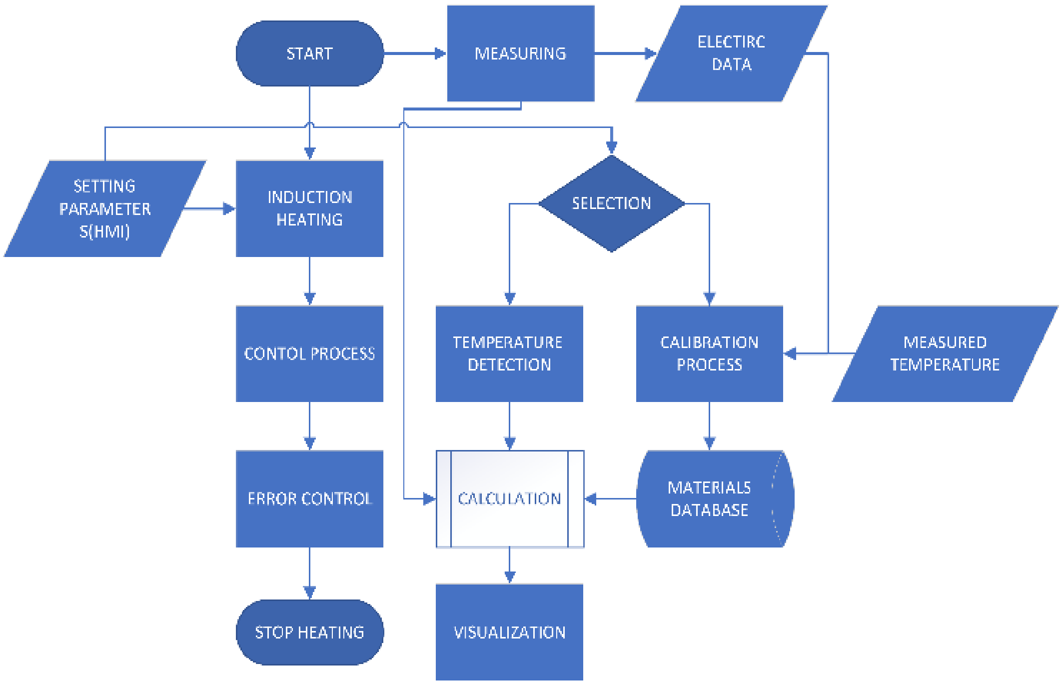


Fig. 4. Flowchart of the temperature detection algorithm

The part of the temperature detection algorithm named 'calculation' is designed for real-time data analysis and comparison with historical values stored in the microcontroller. The basis of the algorithm is the use of a lookup table, which contains historical records of resistance, impedance, and temperature. These values are loaded when the system starts. The lookup table serves as a deterministic foundation upon which the system builds temperature predictions based on the currently measured values of resistance and impedance. The data from the lookup table stored in the micro-controller's memory for steel can be seen in Fig. 5. In this case, the impedance and resistance of the induction system during heating to the Curie point are shown as a function of the material's temperature.

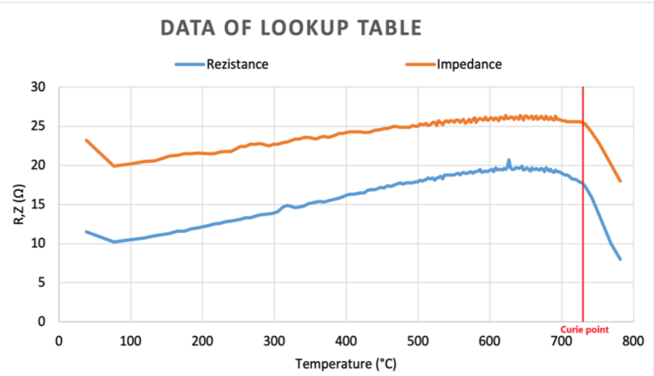


Fig. 5. Dependence of resistance and impedance on the temperature of steel

In real time, the algorithm processes the current measurements of resistance and impedance, which it then compares with the data stored in the lookup table. Based on the calculation of distances between the current measurement and historical values, the algorithm finds the closest matching points in the table and calculates the average predicted temperature.

This prediction is deterministic because it is based solely on fixed historical data and current measurements.

The resulting impedance is calculated from the measured current and voltage at the output of the frequency converter. The dependence of the RMS values of these quantities on temperature can be seen in Fig. 6. From the measured data, it is also apparent that the most significant change occurs in the Curie point area. This data is precisely processed and recalculated into the required impedance and resistance in the circuit of the frequency converter [5].

To make the temperature prediction more stable and accurate, the algorithm uses a Kalman filter, which corrects the temperature estimate and combines data from the lookup table with current measurements. The Kalman filter operates based on two key steps: prediction and update.

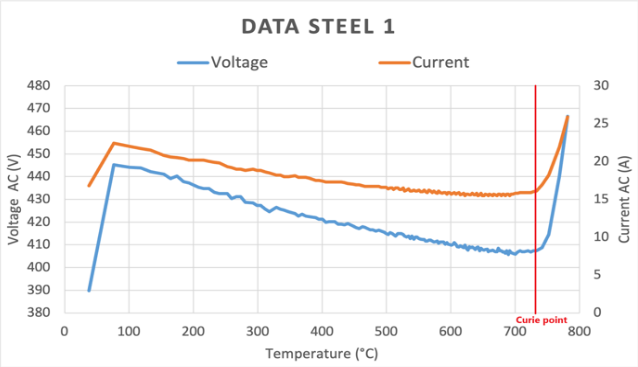


Fig. 6. Dependence of the RMS value of the measured voltage and current on temperature

2.1 Prediction phase

The prediction phase updates the error estimate:

$$P_k^- = P_{k-1} + Q \quad (1)$$

This equation predicts the estimation error for the next step.

P_{k-1}: Estimation error from the previous step.

Q: Process noise that models the uncertainty in the system dynamics.

2.2 Calculation of the Kalman gain

$$K_k = \frac{P_k^-}{P_k^- + R} \quad (2)$$

The Kalman gain determines how much weight is assigned to the new measurement.

R: Measurement noise that models the uncertainty of the measurements.

2.3 Update phase (state estimate)

Update of the state estimate based on innovation:

$$X_k = X_{k-1} + K_k \cdot (Z_k - X_{k-1}) \quad (3)$$

X_k: New state estimate (temperature)

Z_k: Estimated temperature from the lookup table.

$(Z_k - X_{k-1})$: Innovation error, the difference between measurement and prediction.

2.4 Clipping (limitation of change)

Clipping limits the maximum change in the estimate:

$$X_k = clip(X_k, X_{k-1} - \Delta T_{max}, X_{k-1} + \Delta T_{\max}) \quad (4)$$

ΔT_{max}: Maximum allowed temperature change in one step.

2.5. Error update

Update of the error estimate:

$$P_k = (1 - K_k) \cdot P_k^- \quad (5)$$

The update reduces the uncertainty of the estimate based on the Kalman gain.

2.6 Kalman filter parameters

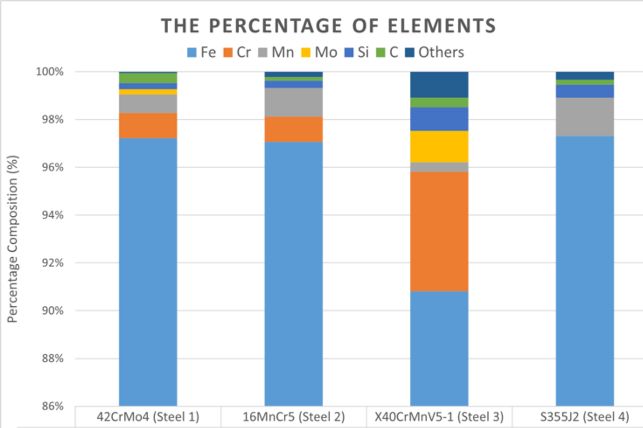
1. Process noise (Q): Influences how much the filter trusts the system dynamics model.
2. Measurement noise (R): Models the inaccuracy of measurements.
3. Error estimate (P): Initial value determining the confidence in the first estimate [6,7].

Within the algorithm, these equations are applied in such a way that the Kalman filter combines the predicted temperature from the lookup table, which is selected based on the current measurement of resistance and impedance. The lookup table provides a deterministic basis for calculating the predicted temperature, while the Kalman filter corrects this value and ensures a smooth transition between individual measurements, minimizing the influence of noise and outliers.

The final output of the algorithm includes the resulting temperature provided by the Standard Kalman filter. This value is stable and accurate because the system efficiently combines historical data from the table with current measurements. The integration of a deterministic approach (lookup table) and a stochastic approach (Kalman filter) allows the creation of a robust system that operates reliably even in resource-constrained environments, such as microcontrollers. This approach is key for applications where high measurement accuracy and efficient real-time data processing are essential.

3 Testing the temperature detection system for inductively heated materials

Next, an experiment was carried out in which four different types of steel were tested. On the induction system described above with integrated material temperature detection from electrical signals. In Fig. there is the percentage of alloys for the steels investigated.



	42CrMo4 (Steel 1)	16MnCr5 (Steel 2)	X40CrMnV5-1 (Steel 3)	S355J2 (Steel 4)
Others	0,06	0,22	1,09	0,34
C	0,42	0,16	0,39	0,20
Si	0,25	0,30	1,00	0,55
Mo	0,22	0,00	1,30	0,00
Mn	0,78	1,20	0,40	1,60
Cr	1,05	1,05	5,00	0,00
Fe	97,22	97,07	90,81	97,30

Steel samples

Fig. 7. Material composition of tested steels

In the experiment carried out, the induction system contained all the key components necessary for operation and measurement. The system contains a high-frequency transformer ensuring energy transfer to the load, a resonant capacitor optimizing the efficiency of the induction process, a frequency converter with a control board enabling precise adjustment of operating parameters, and a control display providing a user interface for managing the entire system.

During the experiment, the temperature of the workpiece was measured using three different methods, which allowed for the comparison of results and verification of the proposed method's accuracy. The experiment was conducted up to the Curie point, which is significant for ferromagnetic steels. The induction heating was without movement and any forced cooling of workpieces.

The first method involved contact measurement using a type K thermocouple, which was directly placed on the surface of the workpiece. The recorded temperature was stored synchronously alongside other data in the microcontroller's memory.

The second method was non-contact measurement using the InfraTec VarioCAM HD research 980 thermal camera, with two measurement points from the thermal camera connected to the data acquisition system for continuous temperature monitoring and precise synchronization of the measured data. The final method of temperature measurement was temperature detection through the analysis of electrical signals from the induction system. As previously mentioned, this method utilizes changes in electrical parameters related to the thermal properties of the heated material.

The following images show a comparison of the measurement results for the different types of steel that were analyzed. In Fig. 8, the temperature development for steel 1 is shown.

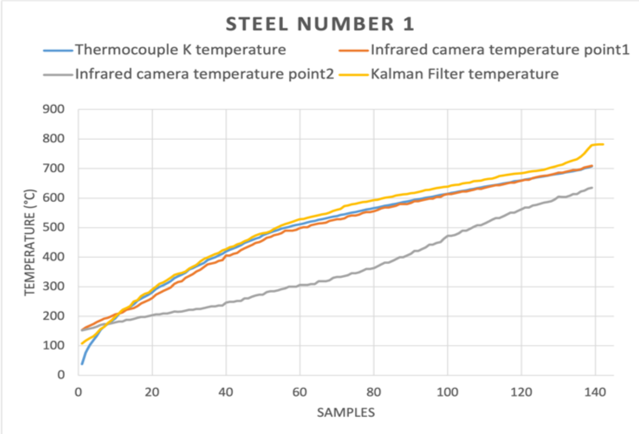


Fig. 8. Measured temperatures for steel 1

The graph includes the following measured quantities:

- Temperature measured by a thermocouple on the surface of the steel (Thermocouple K temperature)
- Temperatures from two measurement points obtained using a thermal camera (Infrared camera temperature point1 and point2)
- Temperature calculated by the temperature detection algorithm derived from the electrical signals of the induction system (Kalman Filter temperature)

Temperatures were measured at one-second intervals throughout the entire heating process. When utilizing the thermal camera, the emissivity was uniformly set to 0.8 for all workpieces. From the graph it can be observed that even though the measurement points on the thermal camera were placed close to each other, the resulting temperatures can vary due to uneven oxidation of the material's surface during heating.

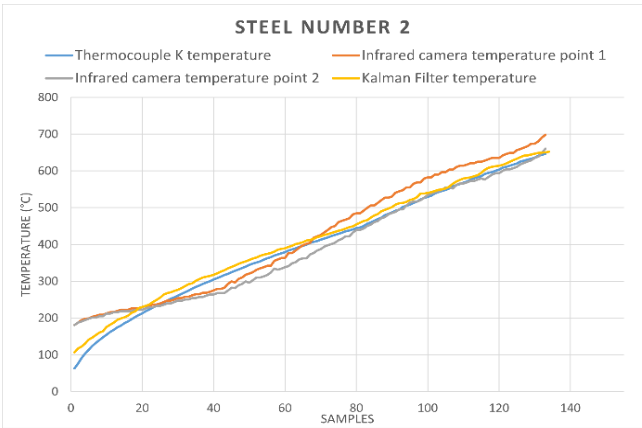


Fig. 9. Measured temperatures for steel 2

In Fig. 9, we see the results of temperature development for steel number 2. The conditions in this case were again the same.

We can observe that the temperature detection from electrical signals was, in this case, very close to the temperature obtained from the thermocouple, with a relative average error of approximately 7.61%. In the case of thermal camera measurement, it achieved a relative average error of 16.11%.

Similar results to those in Fig. 9 can be observed for the other tested steels, whose results are shown in Figs. 10 and 11. In all cases, the settings of the induction heating parameters were consistent. The source frequency was set to 10 kHz, while a constant voltage of 230 V was maintained in the DC intermediate circuit of the frequency converter. This unified approach ensured the repeatability of the experiment and allowed for direct comparison of results across different types of materials.

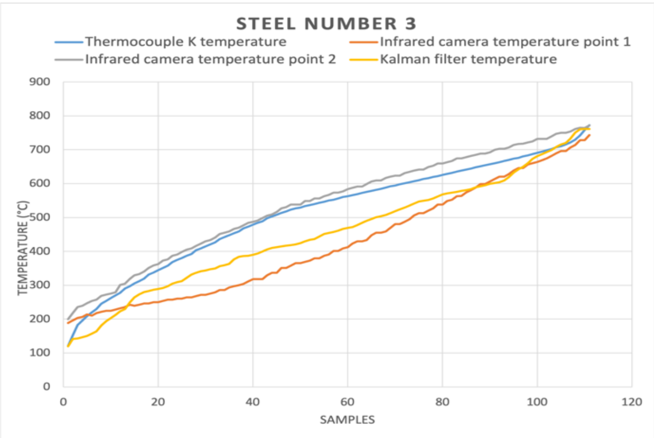


Fig. 10. Measured temperatures for steel 3

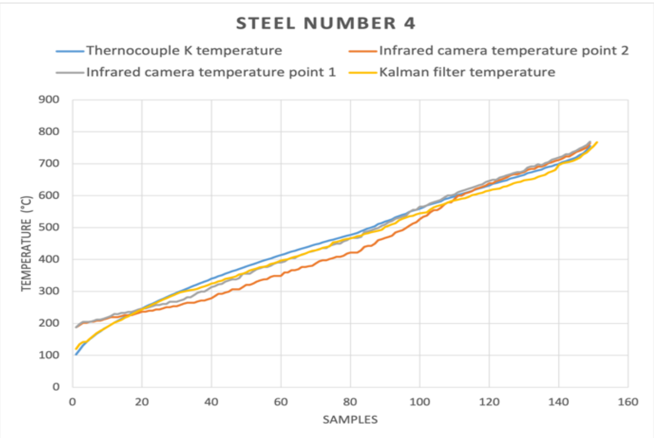


Fig. 11. Measured temperatures for steel 4

For each tested steel, it was necessary to store the corresponding dataset in the microcontroller's memory in the form of a lookup table. These tables were created based on the calibration function, the principle and implementation of which were described in detail in the previous chapter.

For a more detailed understanding of the accuracy of individual measurements, an analysis of relative errors was performed, summarized in Tab. 1. The table presents the average relative errors and medians of relative errors for each type of steel in a range of all samples from measured data. The temperatures measured by the thermocouple placed on the surface of the tested steels were used as reference values.

The results show that the average relative error of the temperature estimation from electrical signals was approximately 7.3% for all four tested materials. This value reflects the high accuracy of the method in estimating temperature. On the other hand, the average relative error of measurement using the thermal camera was significantly higher, reaching approximately 19,5% over the entire experiment. This difference may be due to differences in surface oxidation of the tested steel samples.

Moreover, the analysis of relative errors during induction heating revealed that the temperature detection method demonstrates the highest error rates at the onset of the heating process and, to a lesser extent, towards its conclusion. The initial error spike is likely attributed to inaccuracies in the initial temperature estimate and the calibration of the Kalman filter parameters. On the other hand, the error observed at the end of the heating

When examining the error analysis of the thermal camera measurements, a comparable trend emerges, similar to the method of detecting temperature through electrical signals. However, in the case of the thermal camera, the error spans a broader range of the heating process, particularly during its early stages. This discrepancy can be explained by the infrared camera's limited measurement range, which is optimized to provide accurate readings only within specific temperature intervals, such as 250°C to 2000°C. Outside these ranges, the camera's performance diminishes, leading to increased measurement errors.

Table 1. Error comparison

	42CrMo4 (Steel 1)		16MnCr5 (Steel 2)		X40CrMnV5-1 (Steel 3)		S355J2 (Steel 4)	
Relative error	average	median	average	median	average	median	average	median
Infrared camera 1	14.2%	7.3%	17.3%	8.1%	36.4%	31.0%	11.2%	10.0%
Infrared camera 2	36.9%	38.2%	14.9%	3.7%	18.4%	3.5%	7.1%	3.0%
Temperature detection	5.4%	3.7%	7.6%	3.4%	13.5%	15.4%	3.1%	2.2%

4 Conclusion

This article provided a detailed description of the issue of measuring the temperature of inductively heated materials, covering three different approaches: contact measurement using thermocouples, non-contact infrared measurement, and the proposed method of temperature detection based on the electrical parameters of the induction system. The article highlighted the advantages and technological drawbacks of each method and provided a detailed presentation of the algorithm development and specialised frequency converter.

The developed frequency converter with integrated temperature detection functionality operates on the principle of comparing measured electrical signals with stored data in a lookup table. Obtained data are calibrated for each tested material. Subsequent value correction using the Kalman filter ensures stable and accurate real-time temperature determination. The combination of deterministic and stochastic approaches resulted in a robust solution suitable for industrial applications.

Experimental testing was carried out on four commonly used ferromagnetic steels. Values were obtained through contact measurement with thermoscouples, infrared thermal imaging, and the newly proposed temperature detection method from electrical signals. Data analysis showed that the proposed method provides relatively accurate results, with an overall relative error for all samples of 7.3%, without cooling effect or movement of workpieces. These results confirm the high potential of the method based on electrical signals as an effective alternative to existing approaches. The infrared camera measurement achieved an overall average relative error of 19.5% for all samples.

The proposed method represents an important step towards higher automation of induction processes. It eliminates the need for physical sensors on the material surface, which is particularly significant in dynamic industrial applications, such as rotational or translational movement of the workpiece. This method can also minimise frequent complications related to surface oxidation, changes in emissivity, or the influence of vapor cushions.

The proposed temperature detection method from electrical signals also revealed some technological challenges during experiments. These include maintaining consistent settings of the induction system and geometry for data correlation with reality, as well as high memory demands for the material database. Additionally, for industrial applications, it is necessary to further develop and test the algorithm's behavior under active cooling conditions. All these issues can certainly be addressed through further development and testing of this methodology.

This method also offers significant benefits:

- Precise temperature attainment under the specific conditions tested during induction heating.
- Possible incasement of product quality due to precise control of the material surface temperature.
- Elimination of adverse effects associated with the movement of the heated material.

In the future, further improvements to the proposed temperature detection algorithm are possible, such as the integration of artificial intelligence for predictive data analysis or the implementation of advanced adaptive filters to further enhance measurement accuracy in real environments. Another potential avenue for future research involves extending the method to other material types and more complex workpiece geometries. Additionally, efforts could focus on broadening the measured temperature range and investigating the method's behavior during active material cooling to enhance the the versatility and robustness of the proposed system.

In conclusion, the proposed temperature detection method based on the electrical parameters of the induction system represents a promising solution for industrial applications of induction heating. Its implementation can not only enhance efficiency and measurement accuracy but also contribute to the overall automation and optimization of induction processes.

Acknowledgement

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