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A brief history

The publication "**Electrotehnica, Electronica, Automatica**"* [Electrical Engineering, Electronics and Automation] is founded in **1950** under the name *Electricitatea* (ISSN 1220-2533; vol. 1-3) that, in **1953**, changed its title in *Electrotehnica* (ISSN 0013-5321; vol. 1-22).

In 1957, the publication "Electronica si Automatica" (ISSN 1220-2584; vol. 1-18; monthly issues until December 1974; publisher: ASIT) is founded.

In 1975, the publication "Electrotehnica, Electronica, Automatica" is the continuation of "Electrotehnica" after including "Electronica si Automatica"; it was published in 2 sections until December 1996:

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Section 2. "Electrotehnica, Electronica, Automatica. Automatica si Electronica": ISSN 0254-2242, vol. 19-39; 6 issues/year and keeping its own numbering and ISSN until 1995; publisher: OID al MICMUE). In 1996, it is published under ISSN 0376-4745 of the above Section 1.

In 1997, "Electrotehnica, Electronica, Automatica" receives the print ISSN 1582-5175 after merging the above 2 (two) sections and continuing the series numbering of "Electrotehnica" (vol.45-); monthly issues; publisher: Oficiul de informare documentara pentru electrotehnica al Icpe SA [Documentary Information Office for Electrical Engineering of Icpe SA].

Starting 2002, "Electrotehnica, Electronica, Automatica" has quarterly issues; publisher: Editura "Electra".

In 2014, "Electrotehnica, Electronica, Automatica" (EEA) also receives the online ISSN: 2392-828X (www.eea-journal.ro).

*For connections and continuations, see "Genealogy".

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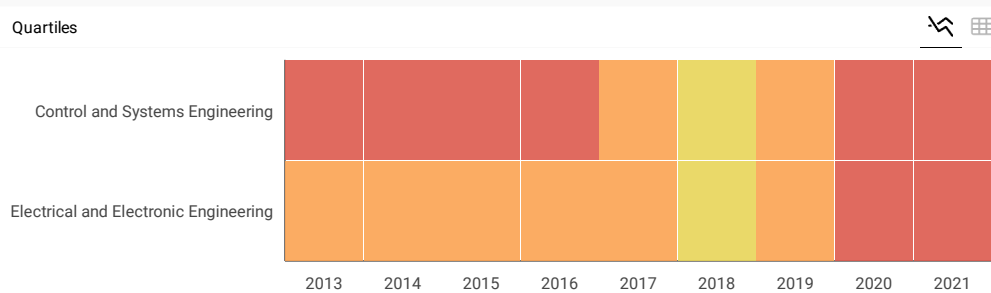
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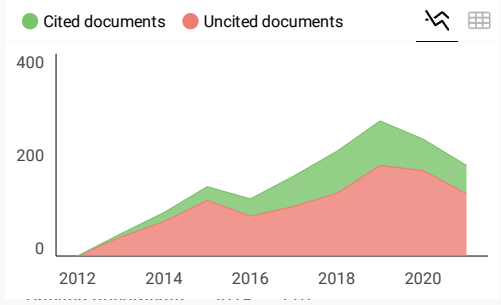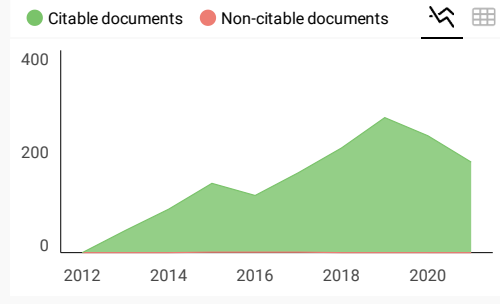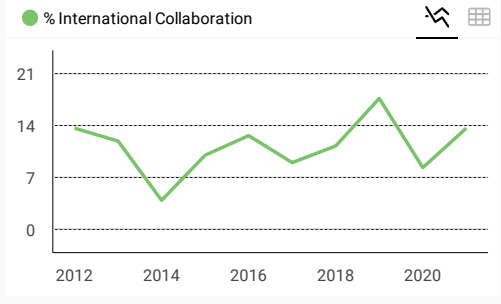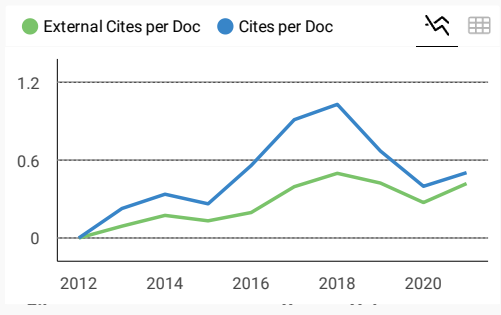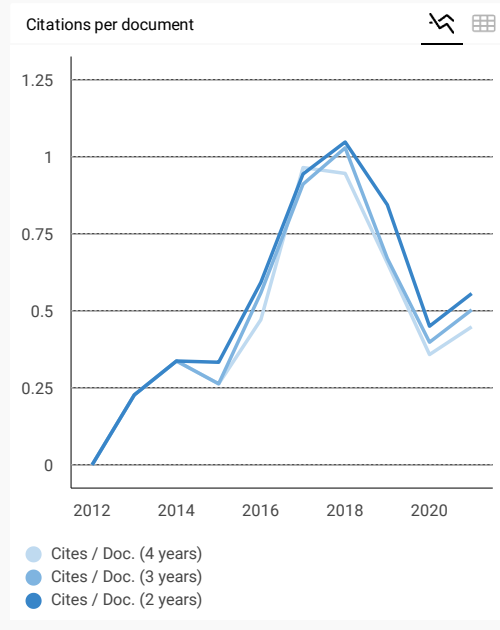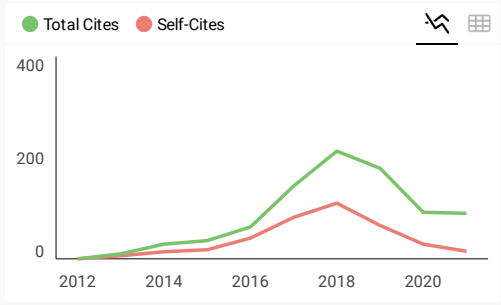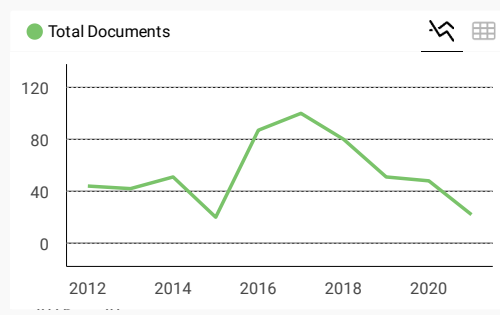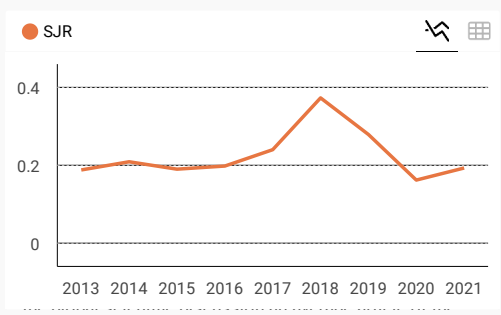
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Induction Heating Stove Prototype of 130 kHz using Arduino Uno

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Abstract

Induction electric heating utilizes the momentum of skin effect resulting from eddy current. In this study, the eddy currents exist in coils that have been induced from the heating and skin effect occurs on the skin of coil sheath that induces heat on the workpiece. This study also discussed the design of one induction electric heating method that is rarely used in cooker's coils that using resonant circuit of zero-voltage switching (ZVS). Typically, ZVS circuits are used on heater coils such as solenoid-shaped coils, so, in this study, there is an opportunity to utilize ZVS resonant circuit for heating on cooker coils in the form of pancake coils. The ZVS assisted the induction process in the heating control circuit. It used an Arduino Uno-based control circuit due to complete parts and compact. The microcontroller was played as the keypad and push-button input control. The sensor and display were played as the output. From the test results to determine the size of toroid transformers obtained toroid black type with a cable size about 1.5 mm solid with 10 turns. To determine the size of the coil pancake obtained air gap copper wire with a diameter of 4.7 mm (≈5 mm) with 12 turns. The average temperature rise reached 0.0815°C/s and 0.0889°C/s for the thermocouple and thermometer readings, respectively. The average heating rates were 21.4 cal/s and 81.6 cal/s, respectively for collector 1 and collector 2. The higher the temperature want to achieve, the lower the value of heat transfer efficiency. The yielded induction heating operational frequency on both channel was almost balanced at a frequency of 130-131 kHz, before shunt resistor installation. This small variation was probably cause by the choke position which was influenced by the pancake coil that was not exactly in the middle of the overall length of the coil. While, after shunt resistor installation, the yielded induction heating operational frequency was 125 kHz, which was for measurement purposes.

Keywords: heating rate, pancake coil, temperature rise, workpiece, zero-voltage switching (ZVS)

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1. Introduction

Melting, coating, shrink fitting, soldering, brazing, heating before deformation, and other metal heating treatments commonly used induction heating [1].

It is a faster, cleaner, and more efficient alternative to a conventional heating systems [2]. It is chosen in many industrial, domestic, and medical applications [3], [4] and uses a generated high-frequency magnetic field induction, due to arise eddy current on the object [5]. The development of a high-frequency power supply paved the way for induction heating [6]. The simultaneous solution of the eddy current and heat transfer equation was simulated [7]. It was a good agreement between the experiment and simulation [8]. Moreover, a saturation of magnetic steel allowed increasing penetration depth [9].

There are two types of induction heating methods, heater, and cooker coils. The former is the coil-wrapped solenoid so that the heating area is inside the coil. The latter is usually a pancake coil so that the heating area is only on the top of the coil. The

increase in working frequency was followed by a temperature rise [10], 11]. The frequency variation could be used as an estimation of the litz coil equivalent impedance and the delivered power [12], 13]. Both hysteresis and eddy current phenomena generated heat on the work piece. The latter was generated within the work piece, mainly concentrated on a strip surface coil projection and not uniform, which in turn led to a non-uniform temperature profile [5], [14], [15], and a shield of the stray magnetic field increased considerably [16].

The active and passive shields mitigated the stray field of an induction heater, and the combination yielded a field reduction [17]. The matching inductance was for maximizing the power transfer [18]. The induction heating can use a low-pass, high-pass, or band-stop filter [19]. The resonant converters were applied and compared to the existing topology [20]-[23]. The control system based on infrared (IR) thermometry has adequately worked to stabilize the temperature [24].

The required energy on the duration of induction heating is as equation (1) [25].

$$W = P_{eddy} \cdot t \tag{1}$$

While the required energy on an induction heating from temperatures T_1 to T_2 is as equation (2).

$$Q = m.c.(T_2 - T_1) \tag{2}$$

The efficiency is as equation (3) [10].

$$\eta = \frac{Q}{W} \cdot 100\% \tag{3}$$

The heating process efficiency also depends upon the power losses in the work piece, heating coil, and coil turns [26]. There are three heating coil types, namely the helical solenoid, with the part that be heated located inside the coil, the most considerable magnetic flux; the pancake coil where the coil is with flux from only one surface and the internal coils with bore heating, where there is only flux contained outside coil. Generally, the helical solenoid has the highest efficiency [5]. The heating process for above 200 watts usually uses an induction stove, and there was the prototype limited to the control circuit testing [10], [11], [27].

The design of the induction heating stove prototype has some advantages as a new idea on an induction stove, mainly on the part of the control circuit, heating circuit, and heating coil. The control circuit utilized the open-source technology of a microcontroller to simplify the program adjustment. The heating circuit utilized the switching method to improve the performance efficiency and minimize the loss in the components. Consequently, it maximized heat on the work piece. The heating coil was made of copper wire, where the size was generally applied to the heating coil. The induced voltage generation at the coil used the ZVS resonant circuit to generate the oscillating frequency of the sinusoidal waveform. A ferrite transformer was not necessary and replaced by using an integrated circuit (IC) and a toroidal ferrite choke to be a small space. The IC for 130 kHz operational frequency was easy to get in the market. Specifically, the arise heating in the components is low and lightweight.

The research objectives were to design and implement an Arduino Uno microcontroller-based induction heating stove prototype, to investigate the effect of the ZVS circuit and some influenced factors on the induction heating stove performance, and to obtain some parameter correlations, such as voltage, power, temperature, heat, and efficiency against time and temperature, and reading error. It also investigated some waveforms on some points of measurements.

2. Materials and Methods

At the early stage, the design was for a working frequency of 75 kHz. However, it used an IC and a ferrite transformer.

Consequently, it would ceaselessly trip and take ample space. Based on this reason, it did not use the ferrite transformer. However, it was replaced by using another IC and a toroidal ferrite choke to be a smaller space. Consequently, in the market, the last IC was 130 kHz operational frequency, and the arise heating in the components would be lower, and it would be hot quickly on the work piece.

Thus, the operational frequency of 130 kHz had some advantages, such as not necessarily a ferrite transformer, small space of choke, easy to get the ICs, low arise heating in the components, lightweight, and compact.

The designed induction stove used a trigger or control circuit as the input data. The circuit required the hardware, as the input data, and the display, as the output data. The driver circuit was a switching circuit to generate the induction voltage and centre-tap regulated-inductance on the heating coil as the pancake coil. The heating coil was used for magnetic induction and eddy current utilization. Both factors were for the heating generation on the work piece. A thermocouple was installed for the temperature measuring sensor. The ac voltage should be converted to dc voltage to supply the control circuit.

Nevertheless, the output voltage on the heating coil was turned to ac back. It had some specifications based on temperature and time. Both parameters were adjusted and displayed on the display to meet the system specifications. The required hardware and the connections among the components or sub-systems are shown by the block diagram in Figure 1.
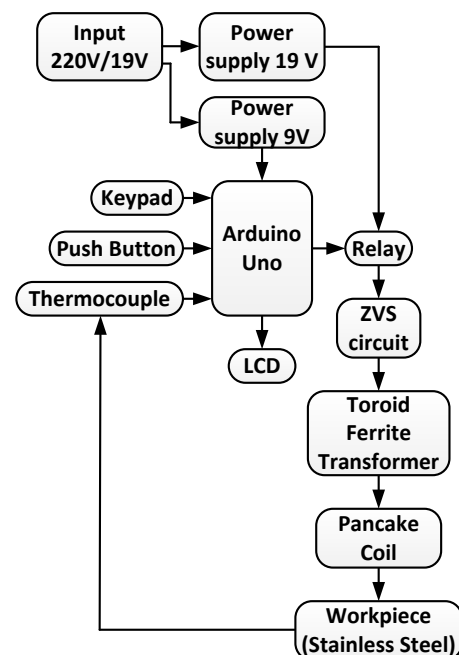
Figure 1. Components and operational flows of induction stove

The operational system was divided into four induction heating modes, based on temperature, time, manual combination, and automatic combination.

The first was conducted by the desired temperature input value, using the keypad, and executed or validated by the push button.

The circuit in the conduction to the heating conditions reached the previously entered temperature value, and it was measured by using the thermocouple sensor. While, the time-based induction heating mode was conducted by entering the desired input time value, using the keypad and executed or validated by the push button.

The third was done by entering the desired temperature and time input values, using the keypad and executed or validated by the push button. The circuit in the conduction to the heating condition reached the previously entered temperature and time values. When operating, the thermocouple measured and kept the temperature value to be constant according to the input value even if the time remained in running condition. Finally, it was conducted simply by the automatic menu button pressing on the keypad and executed or validated by using the push button. The circuit in the conduction to heating condition reached the previously programmed temperature and time values in the Arduino Uno. When operating, the thermocouple measured and kept the temperature to be constant according to the input even if the time remained in running condition. The working frequency was set at its maximum value, and it set the relay regulated circuit condition. After the parameters were achieved according to the entered values, where the temperature was measured by the sensor and the time was measured by the microcontroller count pin, the system would break the voltage to the circuit, and the display would reveal the reached parameter data. For the next, the system would restart, back to the start menu selection of heating modes.

The ac supply was converted to the dc voltage as 19 V and 9 V. It used the 19 V, 2.8 A adapter as the induction stove input, and for triggering the ZVS circuit using the half-wave MOSFET inverter. The used adapter, in addition, was for space and circuit component savings so that the latter was to minimize possible errors. Through Schottky diodes, it used the dc voltage to open the MOSFET gates alternately, and in turn, converted them to ac back for magnetic induction generation on the pancake coil and to be induced to the work piece. The thermocouple sensor was embedded in the centre of the work piece due to effective heat distribution, and a voltmeter was installed in the adapter for the input voltage measurement. For conduction conditions, the control circuit was for a high switching frequency. Therefore, it required the MOSFETs, which were being controlled by the Schottky diodes and resistors, capable to hold the component heat losses during MOSFET operation time. The ZVS circuit, which consisted of two MOSFETs, in the half-bridge arrangement, was for maximizing the generated inductance in the heating coil. Therefore, it became the maximum heating rate. The ability to hold the component heat losses should also be owned by the capacitor, as a parallel installation [28].

The generating inductance used a pulse ferrite transformer, to meet a working frequency, higher than 10 kHz. This research used a toroidal ferrite transformer as the generation of induction in the heating coil. The coil section, as the pancake coil, used a hollow copper wire with a diameter of 3 mm, commonly used as a melting heating type (heater) rather than a cooking heating type. The temperature measurement required an instrument that had high working frequency characteristics, more than 20 kHz, and a high-range working temperature.

Therefore, it required a thermocouple sensor, installed on the work piece. The 19 V power supply relay was for the triggering on the control circuit and transformer, through a conduction control relay. While, the 9 V power supply relay served the control of the microcontroller, which adjusted to the safe voltage range. The microcontroller board had its automatic voltage regulation to connect to the components with the voltage requirements of 3 V and 5 V. The simulation of the heating circuit used a ZVS, to emphasize a prediction of the output waveform. The control circuit simulation proved and compared the output signal to the reference.

The components were IRFS 4010 MOSFETs, Schottky 1N5819 diodes, 330 nF capacitor, resistors, and the pancake coil indicated by L_1 and L_{1b} as primary and secondary inductances. While, L_2 illustrated a toroidal inductance, connected to the heating coil. The inductance of the heating coil was assumed based on the temporary value and used as the comparator between the simulated and the oscilloscope output signal forms.

Moreover, Figure 2 shows the equivalent heating circuit, using the ZVS based on the simulation circuit.
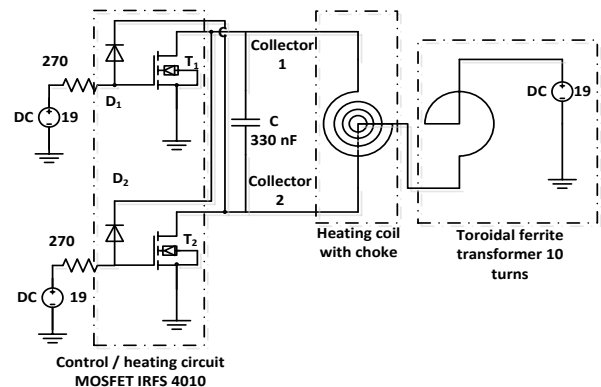
Figure 2. Equivalent ZVS circuit

For the hardware assembling, the components were installed separately on printed circuit boards (PCBs), among Arduino Uno, ZVS, relays, and display circuit boards. The induction heating coil should be in the pancake coil shape. The pancake coil was assumed as 8-13 turns, by fulfilling the prerequisite of simulated induction heating. Insulation was for covering the copper, to avoid heat and electric contacts to the work piece. The pancake coil arrangement was on the frame.

The work piece is a subsystem induced by the high-frequency magnetic field from the pancake coil, made of stainless steel, due to high magnetic permeability. Thus, it is useful in magnetic flux delivering and potentially generating considerable

heat. The stainless steel was 0.5 mm thick and square-shaped adjusted to the conventional casing stove.

The simulation program of the microcontroller was compiled by using a USB line. The stove prototype was created by assembling prepared components on the boards, including the pancake coil, sensors, and an Arduino Uno microcontroller. The system was tested by the program to investigate a probable error existence. If both the board and program did not experience a technical problem, it was preceded by the hardware testing, using measuring instruments. The finalization was stove insulating box covering and stainless-steel pedestal installations. IRFS 4010 MOSFETs, one of the main components, are for high-frequency power switching. As the control circuit, they were installed in series as a half-wave alternating inverter. The dc input voltage was for the MOSFET trigger, while the dc to ac voltage conversion supplied the coil, due to dc voltage on the choke for the coil inductance generation, and the 270 Ω resistors were selected based on the MOSFET datasheet. The working principle of MOSFETs is based on the relay conduction condition embedded in the Arduino Uno control program. The 1N5819 Schottky diodes were chosen based on the output characteristics, for the MOSFET gate triggering. Their characteristics have a high trigger speed and low voltage drop, in the range of 0.55 V. They operated alternately, at the time of operation with other diodes. They operated so that the output voltage changed to ac back, and transmitted to the toroid transformer, for the coil induction generation.

The push-button switches served whether to connect or separate the installation parts from each other. They consisted of pressed start-stop, reset, and switches for an emergency condition. The first push-button was the on/off button, so it was physically different from the two other pushbuttons, which were a boxy red colour, and placed on a separate bar and installed an indicator light. The second pushbutton was the start button, to execute the keypad entered data. This was required verification of whether the entered data was valid or not before taking the place of the heating process, on the microcontroller D13 board pin. It was around and green in colour. The third push-button was stop/reset, in case of user intervention, to stop the process urgently. It was red in colour, connected to the microcontroller board reset pin.

The 4x4 keypad was for communication between the user and the microcontroller, for human interaction. It used D2-D7 and D11-D12 digital pins. The button numbers for the inputs and letter keys were for setting temperature (A), time (B), and automatic mode (C and D). The asterisk (*) and punctuation (#) buttons were for the precise and enter functions, respectively. The program showed that the entered data were whether corrected or continued by pressing 2 or 3 buttons, respectively. The LCD provided several advantages, including energy-saving, lightweight, design comfort, ASCII code-based, and desired character displaying

capabilities. It used a 20x4 character display, with 20 connector pins.

The Arduino Uno microcontroller has digital input and output pins, used as PWM output. It was supplied by a universal serial bus (USB) cable connection, or via a power supply. This option was operated automatically. On one hand, if the given voltage was less than 7 V, the 5 V pin did not give the real 5 V, which might make the circuit worked imperfectly. On other hand, if the voltage was higher than 12 V, the voltage regulator might be overheating, which could ultimately damage.

As a consequence, the recommended voltage was between 7 volts and 12 volts. The microcontroller board connections among the remaining components consisted of several input/output (I/O) components. The reset and GND pins were connected to the external push button as reset operation/cancellation, operation/stop, and component board grounding respectively. The 5 V pin was used as the output regulator for the board-to-component connections. While the pin A4 (SDA) and A5 (SCL) pins were connected to I2C components, also support TWI communication, as a further connection to LCD pins. The D13 pin was for the external push button that served as the data verification for the next operation. Finally, D8, D9, and D10 pins were for output requirements, connected to the thermocouple, and D1-D7 and D11-D12 pins were the output requirements to the keypad, as digital logic connections.

The five pins of a K-type thermocouple were wired to the microcontroller board pins. Pin 1 was connected to the ground, pin 2 was connected to the regulator output 5 V pin, and pins 3, 4, and 5 were connected to the digital D8-10 pins of the microcontroller, respectively. The air-brass hardened copper wires were selected to maximize the skin effect, chosen as 2 mm, 5 mm and 8 mm diameters. Nevertheless, the final circuit used the 5 mm wire. The turn number was adjusted to the work piece dimension. The conducting wire, or the heating coil, was for heating transfer on the conduction method, or the eddy current accumulating place, which ultimately caused the skin effect and the magnetic field distribution in the ferromagnetic work piece.

In the induction stove mode, the pancake-shaped heating coil did not change the temperature, even though the temperature in the work piece experienced a massive change. Nevertheless, the heating coil was the place of eddy current and skin effect among the conductors, so that some touching sides of the conductors were insulated to prevent a probable short-circuit occurrence. The heating coil also induced the magnetic field, so that it inflicted heat on the work piece, in line with the circuit operating interval time of conduction. The induction heating coil operation depended upon the heating circuit relay condition and the generation of toroidal induction.

Notably, in the automatic heating mode, the temperature condition was kept being constant, according to the input value.

While the time was kept in running condition, and the circuit was in off condition. The circuit was in conduction to keep the temperature back. Although the circuit was in conduction or turned off, it did not influence the heating coil temperature.

One advantage of the toroid-shaped inductor is its large inductance and relatively small dimension compared to a cylindrical inductor. This small physical dimension provides high efficiency and low weight properties for assembling. Due to the circular-core toroid, the magnetic field induction was closed and relatively did not induce the adjacent components, within the PCB.

Another advantage of the toroid is turn number saving due to a strong magnetic field. The toroid was the black ring with ten-wire loops, T-50 type. The coil had experimented from 8 to 12 turns, where it was ten turns for the sufficient heating rate without MOSFET overheating. In the simulation, the toroid was placed as the choke on the heating coil, illustrated by the L2 inductor, used to maintain a high-frequency oscillation and to limit the current, avoiding a short circuit. The toroid was used as the choke for the inductance enhancement on the heating coil. The toroidal operation followed the conducting condition of the microcontroller-regulated relay. In the absence of the IC component, the generated inductance from the toroid was the maximum, to compensate for the maximum working frequency of MOSFETs.

Based on the hardware components, the outline overall wiring diagram of the induction stove prototype circuit is illustrated in Figure 3. Based on the system specifications, software is needed for simulation, design, programming, and for printing the Arduino shield. Arduino provides open-source software, namely (IDE) Arduino 1.0.6. In addition, software for the control circuit simulation is also required. In this study using the Ltspice IV program, which is free software. The Eagle software is used for the Arduino shield printing needs that have been assembled previously.

Arduino board programming is done using Arduino Software (IDE). The ATmega328 chip contained in the Arduino UNO R3 has been filled with an initial program which is often called the bootloader. The bootloader is in charge of making programming easier using Arduino Software, without having to use additional hardware. IDE (Integrated Development Environment) is an integrated environment used for development. This case is an environment due to through this software, an Arduino is programmed to perform the functions embedded using programming syntax. Arduino, resembles the C language, uses its own programming language.

Arduino IDE is equipped with a C/C++ library, called commonly Wiring, which makes easier input and output operations. It is made from the JAVA programming language. It was developed from the processing software which was, specifically for programming with Arduino, remodelled into an Arduino IDE.

Verify serves to check the code that has been made whether it is in accordance with existing programming rules or not. Upload

serves to compile programs or code that has been made into a language that can be understood by the machine. New function to create a new Sketch. Open functions to open a sketch that has been made and reopen it for editing or just re-uploading it to Arduino. Save function to save the Sketch that has been made. Serial Monitor is used to open the serial monitor. The serial monitor here is a window that displays any data that is sent or exchanged between the Arduino and the sketch on the serial port. This Serial Monitor is very useful when creating programs or debugging without using the LCD on the Arduino. This serial monitor can be used to display process values, reading values, and even error messages.

LTspice IV is a SPICE program (Simulation Program with Integrated Circuit Emphasis) which is used for simulating analogue/digital electronic circuits. LTspice is very powerful for checking designs and for predicting the characteristics of electronic circuits such as ICs, op-amps, transistors, resistors, capacitors and so on.

Compared to other SPICE programs, LTspice is available for free so it can be used without any time limit and is legal to use. In designing the simulation of this research tool, LTspice IV is used with consideration of its light and capable specifications with research support tools, it is also considered sufficient for the purposes of simulating a series of research tools.

EAGLE (Easily Applicable Graphical Layout Editor) is a program for designing electronics and PCB schematics, although it has limited functionality, but it is sufficient to be able to design, modify, and print layout drawings for later printing into PCB form.

The schematic editor is used to draw and edit electronic schematic circuits. Here you can use the components in the "Add" Library.

Eagle Board serves to transfer the schematic circuit to the PCB circuit. Here the components are arranged in the way they want and are required to use this feature for the routing function on the PCB.

In this study, using the EAGLE software for the printing needs of the Arduino shield and in general they use this software which is also free software. Based on the system specifications, software is needed for simulation, design, programming, and for printing the Arduino shield. Arduino provides open-source software, namely (IDE) Arduino 1.0.6. In addition, software for the control circuit simulation is also required. In this study using the Ltspice IV program, which is free software. The Eagle software is used for the Arduino shield printing needs that have been assembled previously.

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In this study, using the EAGLE software for the printing needs of the Arduino shield and in general they use this software which is also free software.

Therefore, the software for simulation, designing, programming, and printing was the Arduino shield, as open-source software, while LTSpice and Eagle software were for control circuit simulation and assembled Arduino shield printing respectively.
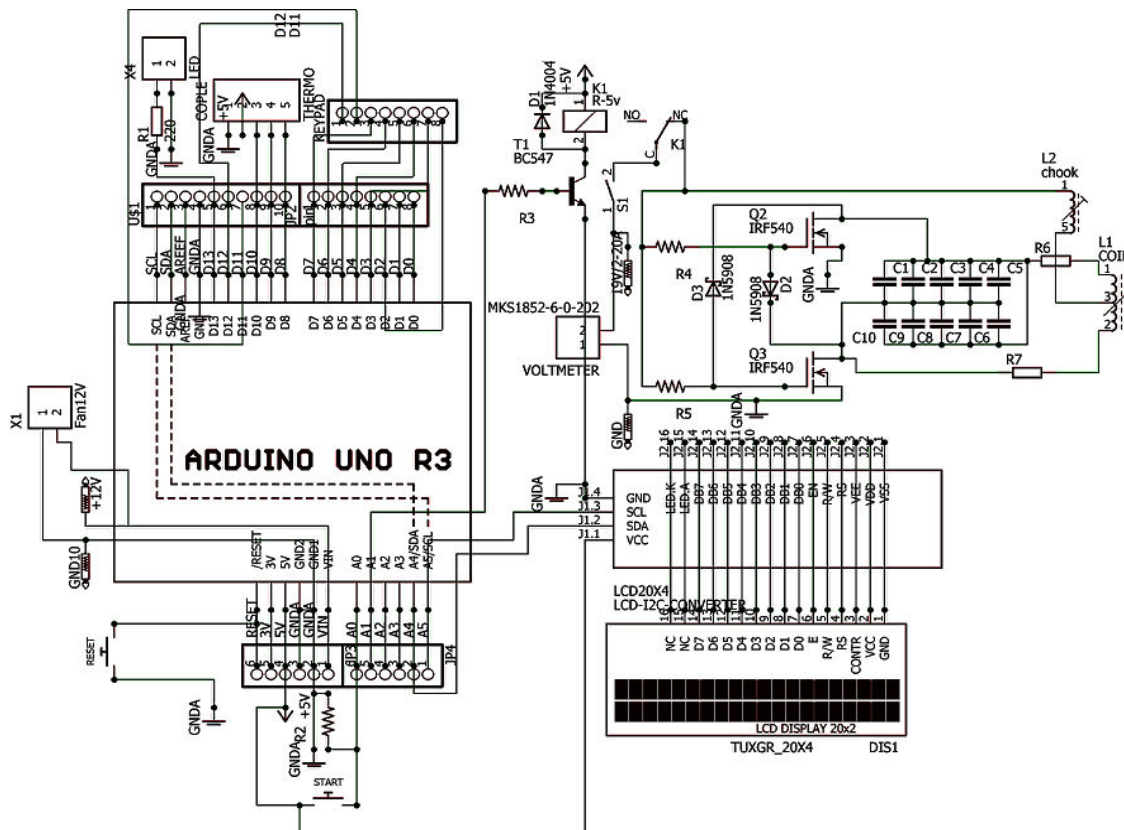
Figure 3. Overall hardware wiring diagram

The outline programming algorithm revealed the starting and initial display of the program, greeting message and the developer identity, display function set, program setting options, and entering data on the display input setting.

The data were in the form of numbers as well as automatic mode selection. If the verification process was approved or continued, the program continued to the temperature and time measurement displays.

However, if the verification process was corrected or cancelled, the program returned to the set function display. If the measurement of temperature and running time reached the entered parameters, it processed the display to reach the temperature and time parameters. If there was an interruption /correction /cancel /not reach the entered parameters, by pressing the reset /cancel button, when the temperature and running time measurements, it returned to set display function and to the display setting, as an option of program setting.

3. Results and Discussion

The research yielded the prototype and the testing data in the chart forms and output voltage waveforms. The measurements were for ensuring that the induction heating parameters under the design and correlations among parameters, especially the temperature and time. The V_i, V_{DD}, $I_{D(on)}$, $V_{GD(on)}$, and $V_{GS(th)}$ of the E-MOSFET type feedback configuration were 10 V, 10 V, 1.5 A, 10 V, and 3.8 V respectively. Based on the I_{DQ} data, the operational point of MOSFET [V_{GSQ}; I_{DQ}] was equal to [7.3; 0.41]. As a prediction, the capacitance was chosen as 330 nF, so that the installed capacitors were 10 x 33 nF, to reduce the inflicted heat in the MOSFET.

The planned toroid used a coil program, taking into consideration of the toroidal datasheet of T94-10 type of 0.58 µH inductance. The coil turns of the toroid should make an optimum inductance on the heating coil. The 1.5 mm diameter wire, including the insulating sheath, was selected for the wiring assembling on the toroid. While, the ferrite toroid of 10, 11, and 12 turns have been tested. It was black in color, 7.9 mm in height, 14.2 mm inner diameter, and 23.9 mm in outer diameter. The ten turns were the highest heating rate, with the input of 19 V, 2.8 A.

Figure 4 shows the heating coil circuit, connected to the choke. Its side was in contact with the rubber insulating coating.
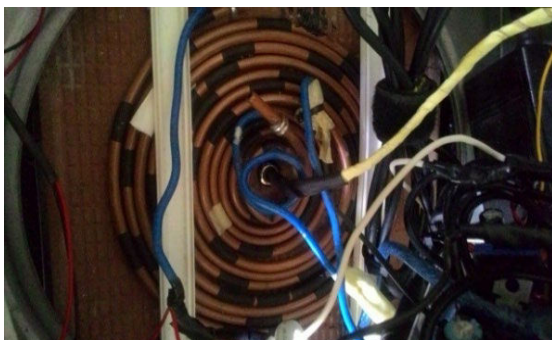
Figure 4. Heating coil

The measurements were conducted once in 5 days of consecutive testing, by using a digital storage oscilloscope as well as the work piece temperature by using a thermocouple, as shown in Figure 5.
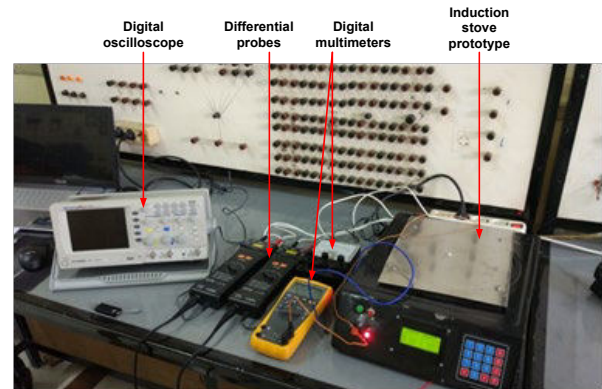
Figure 5. Research testing

There were two types of tests, based on time and temperature. The time-based testing observed the temperature rise and achievement over-limited time constraints. While the temperature-based testing observed the temperature rise and achievement with the regulated temperature limits. The time-limited test of 10 minutes reached 80°C. The temperature-based test was limited to 100°C, and the required time was 1800 seconds. The time-based test aimed to measure the electrical parameters based on the operating time, as well as the temperature that could be achieved within the specified time range. The initial temperature was 32°C, on both thermocouple and thermometer, with a room temperature of 25°C.

The output voltages were measured in the output circuit to the ground, and the peak-to-peak voltages were obtained by using the oscilloscope. The unbalanced voltages occurred, predictably caused by the toroid placement on the heating coil. In every minute, the occurred temperature rises of 2-8°C were measured by the thermocouple sensor. While the 4-7°C ones were measured by the thermometer. The influence of thermocouple sensitivity probably caused slight differences in the temperature measurements.

Table 1 lists the temperature and maximum voltage testing as the time function.

Table 1. Quantity testing function of time

Time (s)	T_1 (°C)	T_2 (°C)	Max. Voltage (V) 1 (L1)	Max. Voltage (V) 2 (L1b)	W (kkal) 1 (L1)	W (kkal) 2 (L1b)	η (%) Q/W_{in}	η (%) P_{out}/P_{in}
60	32	32	21.2	40.4	1.3	4.9	13.85	41.49
120	38	39	21.2	40.4	2.7	9.8	27.70	41.49
180	44	46	21.2	40.4	4.0	14.7	32.32	41.49
240	50	53	21.2	40.4	5.4	19.6	34.63	41.49
300	56	60	21.2	40.4	6.7	24.5	36.01	41.49
360	62	64	21.2	40.4	8.1	29.4	36.93	41.49
420	66	68	21.2	40.4	9.4	34.3	35.62	41.49
480	70	72	21.2	40.4	10.8	39.2	34.63	41.49
540	74	76	21.2	40.4	12.1	44.1	33.86	41.49
600	76	80	20.75	40.4	12.9	49.0	31.86	39.74

The temperature increased as time gradually rose. Nevertheless, the temperature was slightly saturated, not continually linear, mainly in high values of the time.

The average temperature rates were 0.0815°C/s and 0.0889°C/s for the conducted thermocouple and thermometer measurements, respectively. While, the voltages were fairly constant, in which the maximum averages were 42.31 V and 80.80 V for collector 1 and collector 2, respectively.

Table 1 also lists the yielded heating test in collector 1 and collector 2. The heat rose as time increased linearly. Nevertheless, the increments were different. The collector 2 increment was significantly higher than that on collector 1, with the average rates of 81.6 cal/s and 21.4 cal/s, respectively.

Table 1 lists the operational time-based efficiency too. The efficiency 1 meant the ratio of the output to input heat (Q/W_{in}). In this case, the output was the heat in the stainless-steel workpiece using the computation. The stainless-steel work piece was 0.25 kg so that the determined heat was at 500 J/kg°C. There were two inputs of heat, in collector 1 and collector 2. The initial values rose toward the peak, and they would further down slightly. On another condition, efficiency 2, i.e., the ratio of the output to input powers (P_{out}/P_{in}), tended to be constant, and it finally decreased very slightly. The output powers were collector 1 and collector 2. While the input power was the input voltage and current multiplication. Based on the heat, the maximum efficiency was obtained at a specific time, for 360 s, as 36.93 %, in this case. As time further increased, the heat was probably wasted. The efficiency slightly further reduced, as the temperature increased, although, in the early time, the efficiency of heat rose. Generally, this was evidenced at the testing time, which was required a long-time range to reach a high temperature. It indicated that the induction heat occurred on the work piece. The obtained power efficiency was majority constant, indicated, that, in the control circuit, the working voltage was constant, because the MOSFET worked at the maximum frequency. The sufficient output currents were measured in the MOSFET drain pin after installing the shunt resistor. The output powers were yielded by the sufficient current and voltage multiplications. The input powers were obtained by the adapter specification. The current did not change significantly on every measurement so that the input current was fixed as 2.85 A. The temperature changes were the difference in the measurements to the initial temperature of 30°C.

The heat as the temperature function of the thermocouple, on both terminals, L_1 and L_{1b} is also listed in Table 1. The heat rose, tended to be a parabolic pattern as the temperature increased. Nevertheless, both magnitudes of heat were different. On the terminal L_{1b}, it was higher significantly than that on the terminal L_1. The heating rates to the temperature had a variation between 0.09 and 1.8 kcal/°C on the collector 1, and 0.31 up to 6.53 kcal/°C, on the collector 2, with the averages of 0.58 kcal/°C and 2.10 kcal/°C respectively.

Finally, the efficiency as the thermocouple temperature function is also listed in Table 1. The efficiency 1 was the energy ratio representation, Q/W_{in}, while efficiency 2 was the power ratio representation, P_{out}/P_{in}. Based on the powers, the efficiency tended to be constant, with an average of 41.26 %. While the energy-based efficiency reduced significantly as the thermocouple temperature increased, with the average rate of reduction of -0.75 %/°C.

Table 2 lists the time as the function of the thermocouple temperature.

Table 2. Time and voltages versus temperatures

T_1 (°C)	T_2 (°C)	Time (s)	V_m (V)	
			1 (L1)	2 (L1b)
30	32	1	21.2	40.4
35	39	20	21.2	40.4
40	46	100	21.2	40.4
45	53	160	21.2	40.4
50	60	230	21.2	40.4
55	64	300	21.2	40.4
60	68	370	21.2	40.4
65	72	450	20.75	40.4
70	76	550	21.2	40.4
75	80	700	20.75	40.4
80	85	800	21.2	40.4
85	89	900	21.2	40.4
90	94	1000	21.2	40.4
95	98	1400	21.2	40.4
100	103	1800	21.2	40.4

The necessary time rose significantly, to follow a parabolic pattern, as the need for the temperature on the thermocouple increased. In other words, the temperature on the thermocouple increased linearly, and be continuously saturated if the time was continually raised. The temperature testing on the thermocouple was up to 100°C. The average required time for raising every Celsius degree was 25.7 s/°C.

Furthermore, Table 2 also lists the time as the thermometer temperature function. The necessary time rose significantly, followed a parabolic pattern, if it is plotted, as the need for the temperature increment on the thermometer, similar to the thermocouple. The temperature testing on the thermometer was up to 100 °C. The average required time to raise every Celsius degree was 28.2 s/°C. The voltages tended to be constant, with the averages of maximum values were 21.14 V and 40.4 V for collector 1 and collector 2, respectively.

Moreover, Table 3 lists the absolute and relative errors of the time-based testing measurements on the thermocouple temperature.

Table 3. Errors versus temperatures

Thermoc. temp. (°C)	Meter temp. (°C)	Abs. Err. (°C)	Rel. Error (%)
32	32	0	0
38	39	1	2.56
44	46	2	4.35
50	53	3	5.66
56	60	4	6.67
62	64	2	3.13
66	68	2	2.94
70	72	2	2.78
74	76	2	2.63
76	80	4	5.00

Generally, the errors rose, reached the peaks, and go down as the temperature increased. Nevertheless, the absolute and relative average errors were 2.2 °C and 3.57 % respectively. The peak errors were 4 °C or 6.67 % at 56 °C of the thermocouple temperature. The temperature slope on the thermometer to that one thermocouple was 1.148, as slightly closed to unity, which meant that both temperature values were still very close.

Another test lists the thermocouple temperature-based absolute and relative temperature errors. Both errors increased, reached the peaks, and decreased as the temperature increased. The average error was 5.6 °C or 8.77 %. While, in these measurements, the maximum error was 10 °C or 16.67 %. The slope of the thermometer to thermocouple temperatures was 1.0143, as closed to unity, which meant that both temperature values were still very close. Based on tests, the highest errors occur in the 50-55 °C range. The errors were probably caused by the sensitivity of the thermocouple, which was not the same as the thermometer one.

The voltage waveforms consist of three types, i.e., the coil output, the MOSFET gate, and the MOSFET drain voltage signals. The measurement of the output signal was conducted on the node of the capacitor connected to the heating coil. The gate voltage measurement was conducted on the gate pin of the MOSFET input, and the drain voltage measurement was conducted on the drain pin of the MOSFET output.

Figure 6 shows the coil output voltage signal forms.
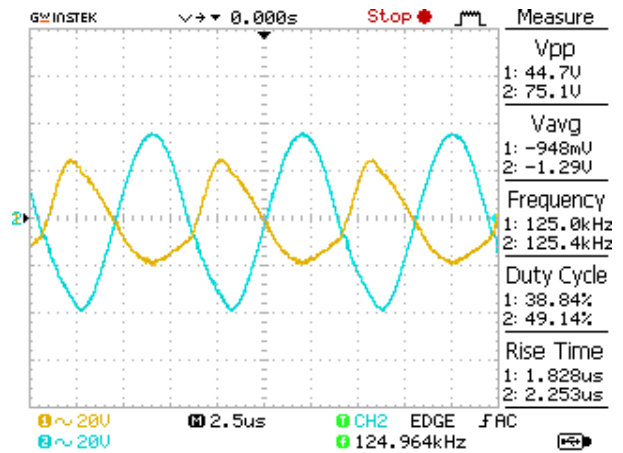
Figure 6. Coil output voltage wave signals (V_{out})

The placement of the toroid was not precisely at the mid-length of the entire heating coil.

It shows that the large toroid-generated voltages were unbalanced on the heating coils.

The operational frequency of the gate voltage, depicted in Figure 7, was after the shunt resistor installation.
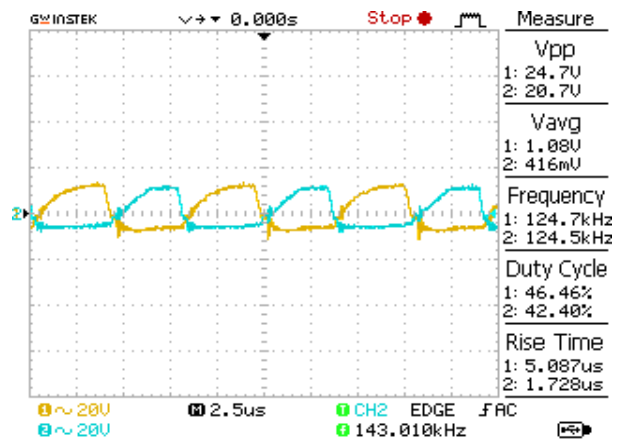
Figure 7. Input wave signals to MOSFET gate (V_G)

The signal waveforms show the required voltages to conduct the MOSFETs within the safe voltage limits. It shows that the ZVS circuit application was the utilization of the shift phase signal to maximize the generated induction heat from the heating coil to the work piece plate.

The MOSFET drain signal waveform, as illustrated in Figure 8 shows the pure output voltage before connecting to the capacitor C_1.
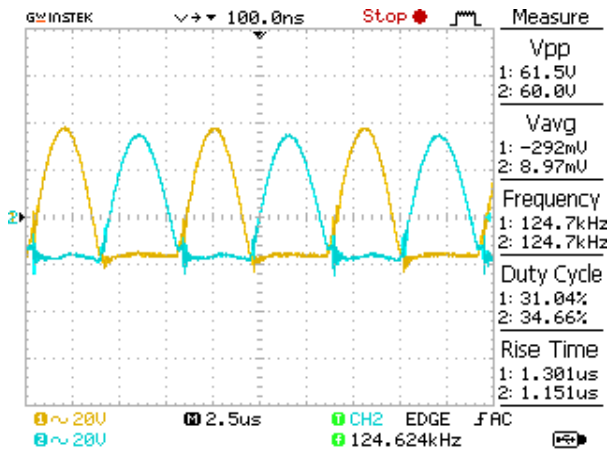
Figure 8. Output MOSFET drain signals (V_D)

Refer to the equivalent circuit, the MOSFET drain was connected to a different capacitor or gate pin so that the MOSFET operated alternately. The induction heating transfer was occurred in the ferromagnetic work piece, as evidenced by the temperature of the heating coil remained constant at room temperature even though the temperature on the work piece plate increased significantly.

Generally, the tests concerning the control system indicated to operate correctly. A circuit using ZVS was investigated, for the heater size, around 80 W, due to small power consumption.

The typical ZVS used solenoid coil(s) for melting (heater or boiler) and rarely used heating material (cooker). The simulation of the ZVS circuit used IRFS 4010 MOSFETS, identical to the parallel LC inverter circuit. The inductance (L) and capacitance (C) have been obtained by using the simulation in parallel with the pancake coil and toroidal ferrite.

The signal shows that the ZVS mode in the control circuit was conduction when the voltage was not zero. The coil had a wire airgap of 4.7 mm (be rounded 5 mm) diameter, brass copper made. This wire type was identical to the heat utilization in a melting form, whereas the coil type was a solenoid. This wire was chosen to be different from other cooker coils, as well as an experiment that the heater coil could also be used as a cooker coil. The ferrite toroid using 10 turns, 11 turns and 12 turns was tested. It was black, 7.9 mm high, 14.2 mm inner diameter, 23.9 mm outer diameter, and 1.5 mm solid wire size. It was yielded the best heating rate by using 19 V input voltage. The heating temperature rates on 11 coil and 12 coil turns quickly reached the specified temperature.

However, the read temperatures became to be very imprecise. At a temperature lower than 50 °C, it became a short circuit condition. Therefore, the coil turn was chosen to be ten turns.

The most impact implication of 80 W power was the slow heating rate for induction cooker size, as 10-30 seconds to raise every 0.75 °C. It reached a maximum temperature of 100 °C for an air-circulated enough ventilated room, 105 °C for the well-ventilated room, and 108 °C for the poorly ventilated room. The measurements of temperature were up to 101-108 °C and only intended to measure the maximum ability of induction heating.

Although using K-type thermocouple, due to being suitable for high frequency and high-temperature capability, the temperature measurements experienced considerable margin errors, around 5 °C lower than the actual temperature. Nevertheless, the initial temperature readings and the initial temperature rise were found as the same values.

During several tests, the operational frequency of MOSFETs was around 130 kHz. A shunt resistor was required, less than 10 Ω, for measurement purposes. After its installation, the operational frequency slightly decreased to around 125 kHz. Nevertheless, it did not influence the overall output signal or MOSFET output waveforms considerably. In the temperature and time-based testing, the oscilloscope-measured parameters were so not different. At the 10-minute-time-limited test, the temperature reached 80 °C. On the temperatures-based tests, limited to 100 °C, the required time was around 1800 seconds.

4. Conclusions

The prototype was according to the design, with a rather long heating time to reach 100°C.

The ZVS assisted the induction process in the heating control circuit, so minimized the heating component and enhanced the induction heating work piece.

The pancake coil size followed the heating area on the work piece plate. The influenced temperature efficiency indicated that the occurred induction heating in the work piece plate was inversely proportional to the temperature rise. The higher the temperature or the longer the heating time, the heating efficiency decreased. While the electrical output power showed a stable efficiency due to not any temperature change influence, the working frequency and output voltage tended to be constant.

The average temperature rate reached 0.0815 °C/s and 0.0889 °C/s for the thermocouple and thermometer readings, respectively. The average heating rates were 21.4 and 81.6 cal/s for collector 1 and collector 2, respectively.

The operational frequencies of the induction heating were 130 kHz and 125 kHz before and after the shunt resistor installation, for measurement purposes.

Nomenclature

ac	: alternating current
dc	: direct current
E-MOSFET	: Enhancement- MOSFET
GND	: Grounding
I2C	: Inter-Integrated Circuit
IC	: integrated circuit
LC	: inductor, capacitor
LCD	: liquid-crystal display
LTSpice	: high-performance SPICE
m	: mass [kg]
MOSFET	: Metal Oxide Semiconductor Field

PCB	:	printed circuit board
		Effect Transistor
P_{eddy}	:	power due to eddy current (watt, W)
PWM	:	Pulse Width Modulation
Q	:	required energy due to temperature change (joule, J)
RLC	:	resistor, inductor, capacitor
SCL	:	clock line
SDA	:	Serial Data
SPICE	:	Simulator Program with Integrated Circuit Emphasis
t	:	time (second, s)
T_1	:	initial temperature (°C)
T_2	:	final temperature (°C)
TWI	:	Two-wire Serial Interface
USB	:	Universal Serial Bus
W	:	required energy due to duration (joule, J)
ZVS	:	zero-voltage switching
η	:	Efficiency (%)
µH	:	Micro Henry

5. Bibliographic References

[1] BORAGE M., TIWARI S., "A 25 kW, 25 kHz Induction Heating Power Supply for MOVPE System using L-LC Resonant Inverter," *Advances in Power Electronics*, 2013, Vol. 2013, Article ID 584129, Hindawi Publishing Corporation, 10 pages.

[2] LUCIA O., MAUSSION P., DEDE E.J., BURDIO J.M. "Introduction to the Special Section on Induction Heating Systems," *IEEE Transaction on Industrial Electronics*, 2014, Vol. 61, No. 5, pp. 2504-2508.

[3] LUCIA O., MAUSSION P., DEDE E.J., BURDIO J.M. "Induction Heating Technology and Its Application: Past Developments, Current Technology, and Future Challenges," *IEEE Transactions on Industrial Electronics*, 2014, Vol. 61, Iss. 5, pp. 2509-2520.

[4] SELVI S.P., KUMAR P.S., VISHWANATHAN N., "Design and Control of Two-Inverter Dual Frequency Induction Hardening," *Eighteenth National Power Systems Conference (NPSC)*, 18-20 Dec. 2014.

[5] ZINN S., SEMIATIN, L., "Elements of Induction Heating - Design, Control, and Applications," *ASM International*, Ohio, USA. 1988.

[6] CYRIAC J.T.K., SREEKALA P., "Induction Heating Topology with Asymmetrical Switching Scheme," *International Journal of Research in Engineering and Technology (IJRET)*, 2015, Vol. 4, Iss. 5, pp. 35-40.

[7] TER MATEN E.J.W., MELISSEN J.B.M., "Simulation of Inductive Heating," *IEEE Transactions on Magnetics*, 1992, Vol. 28, No. 2, pp. 1287-1290.

[8] CHABOUDEZ C., CLAIN S., GLARDON R., MARI D., RAPPAZ J., SWIERKOSZ M., "Numerical Modelling in Induction Heating for Axisymmetric Geometries," *IEEE Transaction on Magnetics*, 1997, Vol. 33, No. 1, pp. 739-745.

[9] MORANDI A., FABBRI M., "In-depth Induction Heating of Large Steel Slabs by Means of DC Saturating Field Produced by SC Coils," *IEEE/CSC & ESAS Superconductivity News Forum*, 2016, pp. 1-7.

[10] BUDIMAN R.A., WARSITO A., KARNOTO, "Half-Bridge Inverter Design for Power Supply of Heating Induction in Plastic Extruder Tools," *Department of Electrical Engineering*, 2012, Universitas Diponegoro, Semarang, Indonesia.

[11] ZHULKARNAEN Y., WIJONO, DHOFIR M., "Design and Implementation of Induction Heating with Pancake Coil Method Based on Microcontroller Atmega 8535," *Jurnal Mahasiswa TEUB*, 2014, Vol. 2, No. 2.

[12] PATIDAR B., HUSSAIN MD. M., JHA S., DIKSHIT K.B., SHARMA A., "Modelling and experimental demonstration of a litz coil-based high-temperature induction heating system for melting application," *IET Electric Power Applications*, 2018, Vol. 12, Iss. 2, pp. 161-168.

[13] DOMINGO N., BARRAGÁN L.A., MONTIEL J.M.M., DOMÍNGUEZ A., ARTIGAS J.I., "Fast power–frequency function estimation for induction heating appliances," *Electronics Letters*, 2017, Vol. 53, No. 7, pp. 498-500.

[14] TAVAKOLI M.H., KARBASCHI H., SAMAVAT F., "Computational Study of Electromagnetic Fields, Eddy Currents and Induction Heating in Thin and Thick Workpieces," *Communications in Computational Physics*, 2010, Vol. 8, No. 1, pp. 211-225.

[15] SUN Y., WANG W., YANG X., PANG L., "A Novel Coil Distribution for Transverse Flux Induction Heating," *International Federation for Heat Treatment and Surface Engineering 20th Congress*, 2012, Beijing, China, pp. 32-37.

[16] SERGEANT P., HECTORS D., DUPRE L., VAN REUSEL K., "Thermal analysis of magnetic shields for induction heating," *IET Electric Power Applications*, 2009, Vol. 3, Iss. 6, pp. 543-550.

[17] SERGEANT P., ADRIANO U., DUPRE L., BOTTAUSCIO O., DE WULF M., ZUCCA M., MELKEBEEK J.A.A., "Passive and Active Electromagnetic Shielding of Induction Heaters," *IEEE Transactions on Magnetics*, 2004, Vol. 40, No. 2, pp. 675-678.

[18] BITOLEANU A., POPESCU M., SURU V., "Maximizing Power Transfer in Induction Heating System with Voltage Source Inverter," *International Conference on Nonlinear Dynamics of Electronic Systems (NDES), Communications in Computer and Information Science*, 2014, Vol. 438, Springer, Cham, pp. 134-141.

[19] GYÖRÖK G., "A Special Case of Electronic Power Control of Induction Heating Equipment," *Acta Polytechnica Hungarica*, 2014, Vol. 11, No. 5, pp. 235-246.

[20] ANJANA M.P., GOPINATHAN S., ELDHOSE K.A., "Improved AC-AC Converter for Induction Heating Applications," *International Journal of Electrical, Electronics and Data Communication*, 2013, Vol. 1, Iss. 2, pp. 55-59.

[21] SARNAGO H., MEDIANO A., LUCIA Ó., "High-Efficiency AC-AC Power Electronics Converter Applied to Domestic Induction Heating," *IEEE Transactions on Power Electronics*, 2012, Vol. 27, No. 8, pp. 3676-3684.

[22] MEESRISUK W., JANGWANITLERT A., SUWAN-NGAM W., "Implementation of two-output three-level series-resonant inverter for induction melting application," *IET Power Electronics*, 2018, Vol. 11, Iss. 1, pp. 129-139.

[23] RUBAVATHY S.J., MURUGESAN P., "Class D Series Resonant Inverter with PDM Scheme for Induction Heating Application," *International Journal of Applied Engineering Research*, 2016, Vol. 11, No. 6, pp. 3819-3827.

[24] Lasobras J., Alonso R., Carretero C., Carretero E., Imaz E., "Infrared Sensor-Based Temperature

Control for Domestic Induction Cooktops," *Sensors*, 2014, 14, pp. 5278-5295.

[25]   SAWHNEY A.K., *A Course in Electrical Machine Design*, Dhanpat Rai & Sons, New Delhi, 2019.

[26]   MAGNUSSON N., RUNDE M., "Efficiency analysis of a high-temperature superconducting induction heater," *IEEE Transactions on Applied Superconductivity*, 2003, Vol. 13, Iss. 2, pp. 1616-1619.

[27]   LIU Z., LAI J., MEEHAN K., YU W., *High-Frequency Inverter Power Stage Design Considerations for Non-Magnetic Materials Induction Cooking*, Thesis, 2011, Electrical Engineering, Virginia Polytechnic Institute, and State University.

[28]   ANDREYCAK B., "Zero Voltage Switching Resonant Power Conversion," *Unitrode, Application Note*, 1999, Texas Instruments Incorporated, U-138, pp. 3-329-3-355.

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