AUTOMATIZACIJA PROCESA PROIZVODNJE BAKARNE ŽICE METODOM LIVENJA U VIS – PODSISTEM ZA INDUKCIONO ZAGREVANJE

AUTOMATION OF A COPPER WIRE MANUFACTURING PROCESS USING UP-CASTING METHOD – SUBSYSTEM FOR INDUCTION HEATING

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Cilj ovde predstavljenog istraživanja je da se projektuje i implementira sistem za automatsku proizvodnju bakarne žice, metodom livenja u vis (eng. up-casting). Podsistem indukcionog zagrevanja obuhvata automatsku kontrolu temperature bakra, topljenog kao i žarenog, automatsko regulisanje snage indukcionog zagrevanja, kako bi se omogućilo pravilno grejanje bakarne žice, tako da se može dostići potrebna temperatura, i postiglo žarenje ili topljenje. Zavojnica je izrađena od bakarne cevi i njena temperatura se reguliše pomoću prisilnog proticanja ulja kroz cev. Sistem se može lako prilagoditi za automatsko žarenje čelične žice ili žice od železa, imajući u vidu električna i magnetska svojstva železa i čelika. Sistem je proizveden, testiran i stavljen u funkciju.

Ključne reči: *automatizacija; indukciono zagrevanje; mehatronika; žarenje*

The aim of the research presented here is to design and implement a system for automatic production of copper wire, by the method of up-casting. The subsystem for induction heating includes automatic control of the temperature of the melted as well as annealed copper, automatic regulation of the induction heating power. The induction coil was designed and made to provide proper heating of the copper wire that is produced, so that the necessary temperature can be reached and its annealing or melting obtained. The coil is made of copper tube and its temperature is regulated using forced oil flow through the tube. The system can be easily adapted to be used in automation of the process of steel wire or iron wire annealing, having in mind the electrical and magnetic properties of the steel and iron. The system was produced, tested and put to work.

Key words: *annealing; automation; induction heating; mechatronics*

1 Introduction

Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction, through heat generated in the object by eddy currents [1]. Induction heating is based on conversion of electro-magnetic field energy into heat [2]. This conversion is obtained through electromagnetic induction which is performed in systems for induction heating. The systems for induction heating can be with or without magnetic core [2].

An induction heater consists of an electromagnet and an electronic oscillator that passes a high-frequency alternating current (AC) through the electromagnet [1]. The rapidly alternating magnetic field penetrates the object, generating electric currents inside the conductor, called eddy currents. These currents flowing through the material cause the metal to be heated by Joule heating, because

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of materials electric resistance [1]. Joule heating is exploited here for melting copper to produce copper wire, and is applied afterwards on the copper wire produced to obtain its annealing.

In ferromagnetic (and ferrimagnetic) materials such as iron, heat may also be generated by magnetic hysteresis losses. Since the generated alternating magnetic field is of high frequency, eddy currents are also having high frequency, which causes another effect to take place – the skin effect. The frequency of current used depends on the object size, material type, coupling (between the work coil and the object to be heated) and the penetration depth [1] - [4].

Both heating causes, eddy currents and hysteresis, occur in electric machines, however these are there referred to as energy losses, i. e. the losses in copper and losses in iron, whereas losses in iron could be due to hysteresis and eddy currents [5] - [7]. In contrast to that, both are intentionally induced heating effects in systems for induction heating.

In case of steel, its properties could be with or without significant ferromagnetic characteristics, depending of its composition and intended application.

Induction heating of copper is done with induction coil made out of copper as well. Since the frequency of the AC supply used in the copper coil is very high, skin effect occurs in the coil. This allowed that the coil is made out of helicoidally twisted copper tube rather than a copper rod or wire. Since the material of the inductive coil is hollow, the flow of oil through the copper tube is used to provide regulation of the coils temperature.

Skin effect is the tendency of an alternating electric current (AC) to become distributed within a conductor in such a way that the current density is largest near the surface of the conductor and decreases exponentially with increase in depths in the conductor [3], [4]. The electric current flows mainly at the "skin" of the conductor, between the outer surface and a level called the skin depth. Skin depth depends on the frequency of the alternating current; as frequency increases, current flow moves to the surface, resulting in thinner skin depth. Skin effect reduces the effective cross-section of the conductor and thus increases its effective resistance. Skin effect can be caused by opposing eddy currents induced by the changing magnetic field resulting from the alternating current. At 60 Hz in copper, the skin depth is about 8.5 mm [4]. At high frequencies the skin depth becomes much smaller [3], [4].

The upward continuous casting method, better known as the UPCAST® system, was originally developed within the Finnish Outokumpu Group in the late ’60s [8]. According to [8], the outcome resulted from a synthesis of innovative thinking and long production experience. The first UPCAST® production line was installed in 1971 at the facilities owned by the Group, located in Pori, Finland, and is still in operation and up to date, thanks to a number of modernizations. This first production line has been followed by a continuous string of others delivered worldwide, establishing UPCAST® as the undisputed market leader in its field [8].

As a result of Outokumpu Group’s decision to divest its copper business, a new, independent company UPCAST OY was established in 2006 to carry the UPCAST® legacy into the future. UPCAST OY is the exclusive supplier of the original UPCAST® process, as stated in [8].

2 Half Bridge with IGBT and Low Pass Filtering

The Insulated Gate Bipolar Transistor, (IGBT) is semiconductor switching device that has the output characteristics of a bipolar junction transistor, (BJT), but is controlled like a metal oxide field effect transistor, (MOSFET) [9]. IGBT combines the insulated gate (hence the first part of its name) technology of the MOSFET with the output performance characteristics of a conventional bipolar transistor, (hence the second part of its name).The result of this hybrid combination is that the “IGBT Transistor” has the output switching and conduction characteristics of a bipolar transistor but is voltage-controlled like a MOSFET [9].

IGBTs are mainly used in power electronics applications [9], such as: inverters, converters and power supplies, were the demands of the solid state switching device are not fully met by power BJTs and power MOSFETs. High-current and high-voltage BJTs are available, but their switching speeds are slow, while power MOSFETs may have higher switching speeds, but high-voltage and high-current devices are expensive and hard to achieve, as stated in [9].

Because the IGBT is a voltage-controlled device, it only requires a small voltage on the Gate to maintain conduction through the device, unlike BJT's which require that the Base current is continuously supplied in a sufficient enough quantity to maintain saturation [9]. One of the main advantages of the IGBT transistor is the simplicity by which it can be driven "ON" by applying a positive gate voltage, or switched "OFF" by making the gate signal zero or slightly negative allowing it to be used in a variety of switching applications. It can also be driven in its linear active region for use in power amplifiers. Also the IGBT is a unidirectional device, meaning it can only switch current in the "forward direction", that is from Collector to Emitter, unlike MOSFET is which have bi-directional current switching capabilities (controlled in the forward direction and uncontrolled in the reverse direction) [9].

In figure 1 is given simplified equivalent circuit of a IGBT (on the left), and IGBT symbol (on the right), taken from [9].

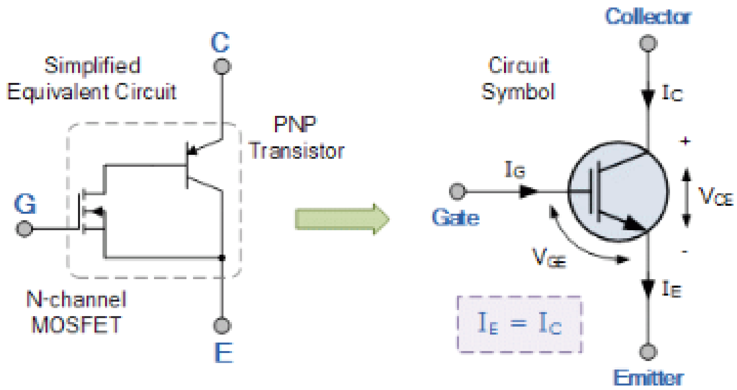

Figure 1 IGBT: simplified equivalent circuit (on the left), and IGBT symbol (on the right) [9]

A general comparison between BJT's, MOSFET's and IGBT's is given in the table 1, as taken from [9].

Table 1 Comparison between BJTs, MOSFETs and IGBTs [9]

Device Characteristic	Power BJT	Power MOSFET	IGBT
Voltage Rating	High <1kV	High <1kV	Very High >1kV
Current Rating	High <500A	Low <200A	High >500A
Input Drive	Current, $h_{FE} = 20 – 200$	Voltage, $V_{GS} = 3 – 10V$	Voltage, $V_{GE} = 4 – 8V$
Input Impedance	Low	High	High
Output Impedance	Low	Medium	Low
Switching Speed	Slow (μs)	Fast (ns)	Medium
Cost	Low	Medium	High

The principal of operation and Gate drive circuits for the IGBT are very similar to that of the N-channel power MOSFET. The basic difference is that the resistance offered by the main conducting channel when current flows through the device in its "ON" state is very much smaller in the IGBT. Because of this, the current ratings are much higher when compared with an equivalent power MOSFET, as described in [9].

The main advantages of using the **IGBT** over other types of transistor devices are its high voltage capability, low ON-resistance, ease of drive, relatively fast switching speeds and, combined with zero gate drive current, these make it a good choice for moderate speed, high voltage applications such as in pulse-width modulated (PWM), variable speed control, switch-mode power supplies or solar powered DC-AC inverter and frequency converter applications operating in the hundreds of kilohertz range. With its lower on-state resistance and conduction losses as well as its ability to switch high voltages at high frequencies without damage, makes the **IGBT** ideal for driving inductive loads such as coil windings, electromagnets and DC motors [9].

Here a half-bridge with a pair of IGBTs is used to supply inductive load, used for inductive heating of a wire. The half-bridge, depicted in schematics in figure 2, is implemented to provide current to supply to an induction coil – an output load (not in figure 2). The current waveform is sinusoidal approximate. A coil is to be connected as output inductive load of the half-bridge in figure 2. When the coil is connected, it forms an oscillatory circuit with conducting capacitors - during one half period with C_4, or during other half period with C_5.C_2 and C_3 also contribute to this behavior. According to [10], both IGBTs and diodes have capacitances that have to be taken into account.

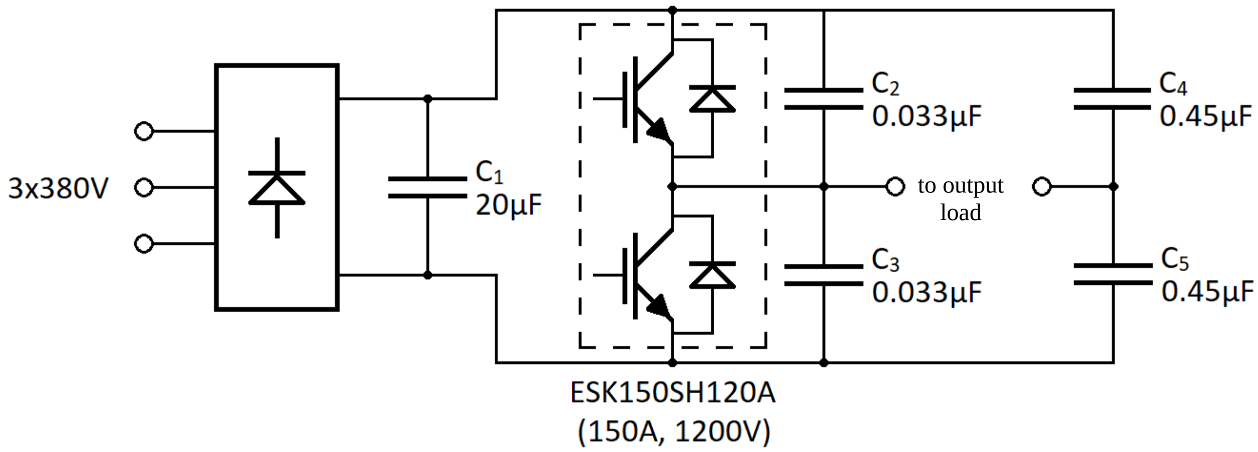

Figure 2 Half Bridge with IGBT Transistors and Low Pass Filtering

Diodes in figure 2 between Emitter and Collector of either IGBTs are freewheeling diodes or fly-back diodes [11]. These diodes are used to protect switches from arcs or sparks of current when inductive load is powered, during IGBT transition from its forward state to its blocking state, while another IGBT is at the same time to be in transition from its blocking state to forward state. When the current of inductive load is switched off, a transient response occurs, preventing the immediate drop to zero of the inductance current. This transient current could damage IGBT that is in its blocking state, if there would not be the diode between IGBTs Emitter and Collector that will turn on when is in its forward state and protect the IGBT. It is of utmost importance to prevent that both IGBTs are in their forward state at the same time, since it would make the shortcut of the power supply unit and almost certainly cause its failure. According to [10] capacitive effects of diodes during reverse recovery process should be modeled as well. In [10] extensive research work is derived and presented, analysis is performed and calculation of power switching losses in IGBTs of a half-bridge two level converter is performed.

3 Automated System for a copper wire manufacturing process using up-casting method

In building systems such as this one, where expert knowledge in several areas is required, it is wise to implement mechatronic approach to design. Concise description of the mechatronics is given in [12] whereas in [11] it is presented in more detail. Mechatronic approach to design has several stages, and is often referred to as the V-Model or V scheme [13], [14].

The V-Modell is a guideline for the planning and execution of development projects, which takes into account the whole life cycle of the system. In this process the V-Modell defines the results that have to be prepared in a project and describes the concrete approaches that are used to achieve these results. It also defines the responsibilities of the individual participants in the project, as stated in [15]. In the V-Model every stage in the designing and planning process has its counterpart in the timeline of testing and verification (and this outline even resembles the form of letter V, so it is named after this letter).

Suggestions on how to increase reliability in mechatronics systems are given in [16].

Some good advices and best practice recommendations for the implementation of mechatronics systems and computer-controlled systems can be found in [11] and [17].

The system designed and described here has electronics and electrical subsystem, mechanical subsystem, and it is used in a metallurgy process for heat treating (sometimes referred to as thermal treatments) [18], [19]. Mechanical part is twofold: hydraulic is one and moving and storing the wire is another. Hydraulic part has to provide oil circulation through the inductive coil, in order to obtain the temperature regulation. Drive of the wire is implemented using step motor, for a step-by-step moving of the processed wire and storing is done in wrapped turns of the annealed wire.

The inductive coil is part of the electrical subsystem as well as part of the hydraulic system, for cooling of the coil with the flow of oil through its interior. Along the axis of inductive coil a wire is drawn that is heated using inductive heating, until it is being annealed. Knowledge in signals and systems and automatic control is necessary to design and produce automated regulation of several variables: frequency of the input converter, temperature of the core wire, temperature of the induction coil (or the flow of the oil, which is cooling it), speed of the pulling of the wire, etc.

Furthermore, the plants specialized and used for this kind of manufacturing and processing usually are huge factories with lots of machinery and spacious halls (as can be seen in a video in [8]), while this system is of size small enough to be placed on the desktop (figures 3 and 4).

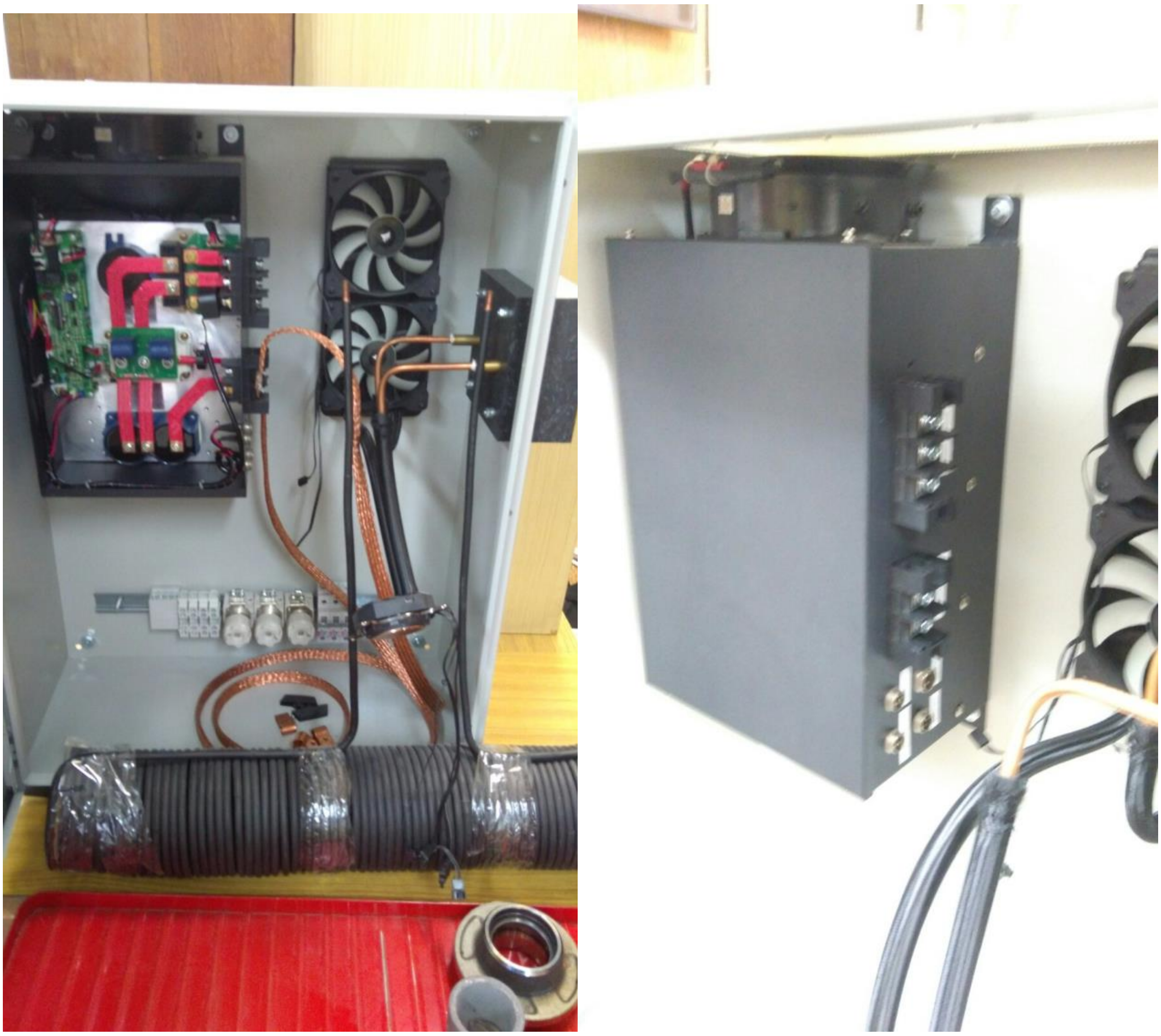

Figure 3 a) On the left, the finished device, with control unit having half bridge with IGBT transistors visible in the upper left corner and induction coil in front of the cabinet.
b) On the right, the Control unit enclosed in casing, with visible connectors.

Figure 3 a) and b) are the photos of the finished device. Photo on the left, figure 3.a) is the interior of the electrical cabinet, with control unit visible in the upper left corner, two fans on the upper right side, and induction coil in front of the cabinet. The control unit has half-bridge with two IGBT transistors. Photo on the right, figure 3.b) depicts the control unit enclosed in casing, with connectors visible on its right side.

The whole device for automated annealing completed is shown in the figure 4. The inductive coil in the figure 4 is being connected both to its electrical wiring as well as to the hydraulic installation providing oil flow for the regulation of the coils temperature.

The system was successfully put in operation on 22. 07. 2020. which can be seen in figure 4.

Figure 4 Finished system for induction heating: the electrical cabinet is situated on the left, and induction coil is placed on the wooden holder (on the right) while being connected to both electrical and hydraulic installation.

4 Conclusion

The aim of the research presented here was also the object of a project mentioned in Acknowledgements - it is to design and implement a system for automatic production of copper wire, by the method of up-casting. The goal of the project was completely fulfilled. The system was produced and tested and put to work. The system can be easily adapted to be used in automation of the process of steel wire or iron wire annealing, having in mind the electrical and magnetic properties of the steel and iron.

5 Acknowledgments

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6 Nomenclature

AC/DC - Alternating Current/ Direct Current,
BJT - Bipolar Junction Transistor,
DC - Direct Current,
IGBT - the **Insulated Gate Bipolar Transistor,**
MOSFET - Metal oxide semiconductor Field Effect Transistor,
NDT - Nondestructive testing,

PWM - pulse-width modulation (noun), pulse-width modulated (adverb),
UCT Company - Up Cast Technologies Company.

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