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Hardware Structure of an Efficient and Optimal Circuit for Induction Cap Sealing

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ABSTRACT

This paper presents the design and hardware implementation of an efficient and optimal induction heating circuit for induction sealing. The circuit has a low implementation cost, so the proposed system with a simple and efficient structure can cover the needs of this technology field. Here, the focus is on the implementation process and practical tips in this field. The proposed induction sealing circuit uses zero-voltage switching technology with parallel MOSFETs. In this structure, by using inductors and capacitors with appropriate tolerable current and voltage, it can provide the power and frequency of the output signal applied to the induction coil for various applications. The use of transistors with suitable current capability makes the circuit appropriate for applications that require stronger magnetic fields. In addition, the induction coil has an elliptical structure, which makes it efficient for sealing a wide range of bottles. It is constructed using Litz wire to reduce power loss in the coil. In the presented structure, the frequency of the output signal is equal to 31 kHz, which is suitable for creating an eddy current in the aluminum foil in the bottle caps. The circuit has been tested and investigated and has acceptable sealing for various industries.

I. Introduction

In the food, health, chemical, and pharmaceutical industries, induction sealing is a good method for sealing bottle caps and is very effective in the shelf life of products. Keeping products fresh and preventing contamination from entering the product during the handling and selling stages is one of the advantages of sealing products. Preventing contamination of pharmaceutical products, food (dairy products, beverages, etc.), cosmetics-hygiene, petroleum products, etc. is very important [1]. Induction sealing of products is one of the methods used for this purpose. The induction cap seal restricts the product from coming into contact with oxygen to prevent it from fermenting or spoiling. The method used by induction sealing equipment to heat metals is called induction heating. Induction heating is a process for heating metals. High-frequency sealing is a process of joining thermoplastic materials by induction heating [2]-[3]. Thermoplastics are materials that become soft and elastic when heated. During induction heating, when the metal absorbs current and a short circuit occurs, electrical losses occur in the metal. This electrical loss manifests itself as heat in the metal. Induction sealing is typically used for packaging food and pharmaceutical products. This process involves the controlled heating of a conductive metal such as aluminum foil by electromagnetic induction. Eddy currents are the reason for the generation of heat [4]-[5]. The most common application of induction sealing is the sealing bottle caps containing pharmaceutical or food substances. In this method, the cap is contactlessly attached to the lid of plastic or glass containers. This sealing process is done after filling and tightening the container lid. The lids are packed with a layer of aluminum foil that is already placed inside the bottle cap. Common induction seals are multi-layered. The top layer is paper that is usually attached to the cap in a dotted fashion. The next layer is wax, which functions to adhere the aluminum foil layer onto the paper. The bottom layer is a thin layer of polymer placed on the foil [6]. The lid is placed inside the door,

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then the lid is automatically or manually wound onto the container and the container passes under the induction coil. As the vessel passes under the induction coil, the eddy currents begin to heat the aluminum foil. The heat will melt the wax and release the foil from the cap. The thin polymer layer also heats up and flows to the edge of the container. After cooling, the polymer adheres to the container, resulting in a closed product [7]. The heat in this process does not affect the container or its contents. The foil can overheat and damage the sealing layer and the bottle cap. Therefore, proper induction sealing is necessary to produce a specific product.

In this paper, the design and implementation of a circuit for induction sealing based on an optimal and low-cost circuit is discussed. The proposed circuit has been tested and investigated. It has acceptable sealing for the various bottles. The most important features of the proposed structure are as follows:

- Here, the focus is on the implementation process of this circuit. The proposed circuit for induction sealing is very low cost.
- The induction sealing circuit is implemented based on zero voltage switching technology. This technology is simple and very efficient.
- The proposed circuit is based on paralleled Metal Oxide Silicon Field Effect Transistors (MOSFETs), for operating in a wide range of output powers. This feature reduces the heat of MOSFETs and their better cooling. Using transistors with high current capability for applications that require high power and stronger magnetic fields can be effective.
- In this structure, by changing the oscillator capacitors' capacity and the power supply's current, the frequency and strength of the applied signal to the induction coil can be controlled according to different applications.
- To reduce power loss significantly in the coil, it is constructed based on Litz wire. The induction coil has an elliptical structure that makes it suitable for sealing a wide range of bottles. This coil generates a uniform magnetic field along the length of the coil.

The rest of the paper is organized as follows. The related works are presented in Section 2. An introduction to the induction sealing method is presented in Section 3. In Section 4 the structure of the designed induction sealing circuit is discussed. The implementation considerations are presented in Section 5. The results of the circuit are described in Section 6. The conclusion of the work is presented in Section 7.

II. Related Works

In recent years, different works have discussed the design and implementation of induction heating circuits. For example, the work [2] summarizes the main milestones in the development of induction heating technology and analyzes the current state of induction heating technology in industrial, domestic, and medical applications. In [7] the authors investigate a method to show the allowable current density of various types of Litz wire-based coils used in induction heating applications. In [8], the heating of water using electromagnetic induction is demonstrated in the laboratory through an experimental approach. In [9], the second-order sliding mode control properties of the qualitative characteristics of an oscillator circuit in an air-cooled inductive seal were investigated. The paper [10] focuses on the role of inverter topology in the design of a 1.5kW, 50kHz induction heating system for induction sealing. In [11], an optimization method is proposed for the design of chokes on the PCB for use in domestic induction cookers. The cables of classic chokes are made of multi-strand round Litz wire for increased efficiency. A planar Litz structure in the PCB was used to achieve performance similar to traditional designs (in terms of maximum output power, inductive efficiency, and thermal behavior). In work [12], a three-phase, three-switch PWM rectifier with simple configuration and control is designed to achieve a high input power factor for industrial heating applications. A controlled multi-zone induction heating system was effectively implemented in [13] through a suitable spiral design. The coil is powered by a single-resonant converter. In [14], a low-frequency induction heating circuit for sealing plastic microfluidic systems is proposed. The work [15] presents the design and experimental analysis of a self-resonant inverter for induction heating of melting furnaces based on parallel IGBTs. An analytical calculation of the inductance of a flat air-core coil for induction heating applications is given in [16]. In [17], a study of design guidelines for flat induction heating systems whose coil is located significantly further from the load is discussed. In [18], the finite element method is used to perform an electromagnetic-thermal analysis for the proposed coil and to study its performance during the heating period. One of the important features of the proposed work is implementation based on a few numbers of elements, which are much less than the existing works. The use of two MOSFET transistors in parallel increases the current flow of the circuit and ultimately increases the output power. Another feature of the proposed circuit is using the Litz wires in an elliptical shape. In this case, we create a uniform magnetic field, which causes better sealing of the bottles. The proposed method has a simple structure, and all circuit parts (oscillator and capacitor bank) are implemented on a single board for a better and simpler assembly. This reduces the cost of circuit construction. In previous works, the authors used high hardware resources [10] and utilized more coils [13] and [19]. In the proposed work, the maximum diameter of the bottle that can be sealed is 13cm, while it is 12cm and 12.5cm in the works [10] and [13], respectively.

III. Induction sealing

Sealing the lid of containers using the induction method helps to create credibility for a product and its durability. Sealing methods can generally be divided into vacuum sealing, thermal sealing, thermoforming sealing, and induction sealing. The main difference between the induction method and other sealing methods is that the heat is delivered to the container through a magnetic field. Inductive cover lids (inductive wads) common for all kinds of containers such as polyethylene, polypropylene, PET, and glass are multi-layered. Fig. 1 shows the constructive layers of bottle caps in the food, health, and pharmaceutical industries. The upper layer is paper, which is usually attached to the cap. The next layer is wax, which is used to stick the aluminum foil layer to the paper. The bottom layer is a thin layer of polymer placed on the foil. When the inductive wads pass through the magnetic field which is created by the coil, the aluminum layer acts as a conductor of electric current. The electric current inside the aluminum foil causes the aluminum layer to be heated, and it is transferred to the polymer layer. When the polymer layer is heated, it is attached to the container lid and sealed.

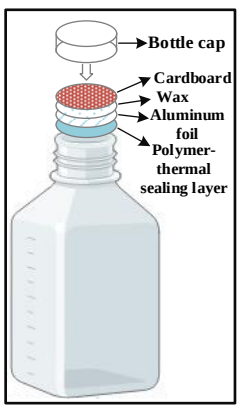


Fig. 1. Constructive layers bottle caps in the food, health, and pharmaceutical industries.

IV. The structure of induction sealing circuit

The implemented induction sealing circuit works based on zero-voltage switching technology. Each pair of MOSFETs is turned off as the opposite-phase pair of MOSFETs turns on, and this continues until the primary voltage reverses phase. This phase reverse happens when the primary voltage crosses zero, so switching occurs when there is zero voltage across the pair of MOSFETs. The MOSFETs in this technology are turned on when they have the minimum voltage and current to turn on. In this circuit, to create a magnetic field in the coil, we pass a large current through the coil with an oscillator. Fig. 2 shows the proposed circuit for the implementation of induction sealing. The induction heating circuit converts the DC input voltage, which must have a high current, into a high-frequency AC sinusoidal signal. This AC signal is generated in the coil. When current flows through the coil, a magnetic flux is created around it. This type of flux has the property of increasing heat in metals. One of the most important advantages of this process is that the heat is generated and induced in the metal itself instead of being provided through another external heat source. Therefore, metal can be heated much faster. When the bottle cap with aluminum foil is placed under the coil, the created magnetic field induces eddy currents in the foil. This process heats the polymer layer of the aluminum foil.

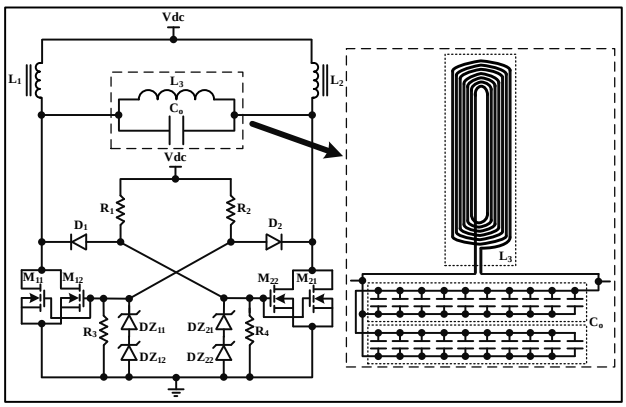


Fig. 2. The proposed circuit to implementation of the induction sealing.

In the circuit of Fig. 2 we use the four MOSFETs (M_{11}, M_{12}, M_{21}, M_{22}). In this circuit, the cathode of the Zener diode DZ_{11}, the anode of the diode D_2, the resistor R_3, and the resistor R_2 are connected to the gate pins of the MOSFETs M_{11} and M_{12}. For the MOSFETs M_{21} and M_{22} we have a similar case. Then the other pin of resistors (R_1 and L_2) and the pins of thyroid inductors (L_1 and L_2) are connected. On the other hand, the positive end of the power supply is connected to this node. The anode pin of the Zener diode DZ_{12}, the other end of the resistor R_3, the source pins MOSFETs (M_{11}, M_{12}), the anode pin of the Zener diode DZ_{22}, the resistor R_4, the source pins MOSFETs (M_{21}, M_{22}) are connected to each other. This node of the connections is connected to the negative pin (ground) of the power supply. In this circuit, 20 capacitors are connected in parallel to the drains of the MOSFETs. The cathode of the diode D_1 is connected to the drain pins of the MOSFETs M_{11}, M_{12} and the cathode of the diode D_2 is connected to the drain pins of the MOSFETs M_{21}, M_{22}. The main coil of the induction sealing circuit is connected to both ends of the capacitors.

The operation of the circuit can be presented as follows: At first, the supply voltage turns on the MOSFETs. But considering that no two MOSFETs can have the same conductivity characteristics, the four MOSFETs are not turned on together, but only one side ((M_{11}, M_{12}) or (M_{21}, M_{22})) of them is turned on. In other words, oscillation is kicked on by differences in the circuit components. Suppose M_{11} and M_{12} are turned on first. When this happens, due to the current

flowing through these MOSFETs, the drain-source voltage drops to zero. In this case, diode D_1 is turned on, and the gate voltage of the MOSFETs M_{21} and M_{22} is reduced. However, the equivalent capacitor C_o, L_3 and inductor L_2 play an important role. The sudden conduction of M_{11} and M_{12} causes a sinusoidal pulse to be generated at the Drain pins M_{21} and M_{22}. When the amplitude of the sinusoidal pulse decreases, the gate voltage of M_{11} and M_{12} decrease and turn them off. This leads to an increase in the Drain voltage of M_{11} and M_{12} (in this case diode D_1 is turned off), which allows the gate voltage for M_{21} and M_{22} be increased (based on the voltage divider of the R_1 and R_4). Now, the MOSFETs M_{21} and M_{22} are turned on, and we have a similar process such as M_{11} and M_{12}.

Figure 3 shows the equivalent circuit of Fig. 2. Here, K_1 and K_2 keys are used instead of the MOSFETs. Suppose the MOSFETs M_{11} and M_{12} are turning on (in other words, the K_1 key is connected), in this case, the gate voltage at the MOSFETs M_{11} and M_{12} is almost zero. This voltage causes the diode D_1 to turn on. In this case, the gate-source voltage of MOSFETs M_{21} and M_{22} is reduced, and these transistors are turned off (in other words, the K_2 key is off). When these transistors are turned off, the drain current in them is practically zero. At this moment, the capacitors are charged through the inductor L_2. This process is shown in Fig. 4 (a). When the capacitors are charged, the drain voltage in the MOSFETs M_{11} and M_{12} increases and this causes the D_1 diode to turn off. Therefore, the gate-source voltage of the MOSFETs M_{21} and M_{22} is increased and these transistors are turned on (in other words, the K_2 key is connected). When these MOSFETs are turned on, the drain voltage in them becomes almost zero and the D_2 diode is turned on. In this case, the gate-source voltage of MOSFETs M_{11} and M_{12} decreases, and these transistors turn off (in other words, the K_1 key is turned off). When these transistors are turned off, the drain current in them becomes zero and the capacitors are charged through the inductor L_1 (Fig. 4 (b)). When the capacitors are charged, the drain voltage in the MOSFETs M_{21} and M_{22} increases and this causes the D_2 diode to turn off. Therefore, the gate-source voltage of the MOSFETs M_{11} and M_{12} is increased and these transistors are turned on (in other words, the K_1 key is connected). In this way, this cycle continues ((M_{11}, M_{12}) are on and (M_{21}, M_{22}) are off and (M_{11}, M_{12}) are off and (M_{21}, M_{22}) are on). Therefore, this cycle causes an oscillation and creates an AC voltage at the output. The oscillating happens when the drain voltage is close to zero. Therefore, it leads to the minimization of switching losses. This cycle continues and causes the circuit to oscillate at the resonant frequency of the L_3-C_o circuit.

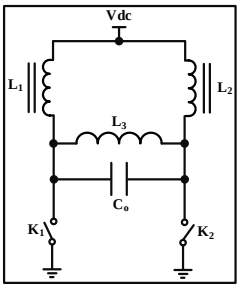


Fig. 3. Equivalent circuit of Fig.2.

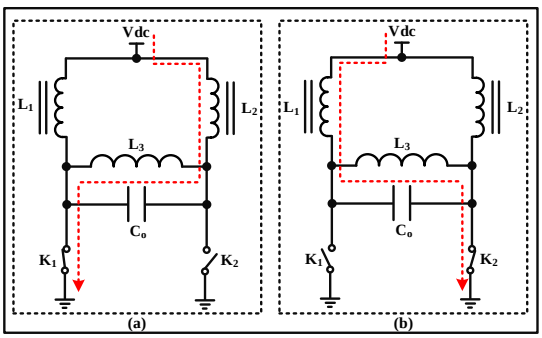


Fig. 4. The turning off and on process of the MOSFETs.

Figure 5 shows the waveforms of drain voltages and waveform across the main coil L_3. As seen from the figure, the waveforms of drain voltages have no overlap and the final output is a high-frequency sinusoidal waveform. Resonance is adjusted to an optimal point depending on the L_3-C_o values. The fast-switching ZVS has low dissipation and can normally be resolved with relatively small heatsinks. Due to this feature, the MOSFETs in ZVS self-amplification circuits need much smaller heatsinks. The frequency of the circuit depends directly on the inductance of the coil L_3 and the capacitor C_o. Oscillation frequency can be calculated using the following formula:

$$F = \frac{1}{2\pi\sqrt{L_3 C_o}}$$

The L_3 is the inductance of the main heating coil and C_o is the capacitor equivalent of all parallel capacitors. The total impedance of the parallel L_3-C_o is given by

$$Z = \frac{Z_{L_3} Z_{C_o}}{Z_{L_3} + Z_{C_o}}$$

after substitution of $Z_{L_3} = jwL_3$ and $Z_{C_o} = \frac{1}{jwC_o}$ and simplification, gives

$$Z(w) = -j\frac{wL_3}{w^2 L_3 C_o - 1}$$

Using $w_0 = \frac{1}{\sqrt{L_3 C_o}}$ it further simplifies to

$$Z(w) = -j(\frac{1}{C_o})(\frac{w}{w^2 - w_0^2}) = j\frac{1}{w_0 C_0(\frac{w_0}{w} - \frac{w}{w_0})}$$
$$= j\frac{w_0 L_3}{(\frac{w_0}{w} - \frac{w}{w_0})}$$

Note that $(\lim Z(w))_{w \to w_0} = \infty$ but for all other values of ω the impedance is finite. In the following, we analyze time domain solution of the circuit. By Kirchhoff's voltage law, the voltage V_{C_o} across the capacitor plus the voltage V_{L_3} across the inductor must equal zero:

$$V_{L_3} + V_{C_o} = 0$$

From the constitutive relations for the circuit elements, we also know that:

$$V_{L_3}(t) = L_3 \frac{dI_{L_3}}{dt}, I_{C_o}(t) = C_o \frac{dV_{C_o}}{dt},$$

Rearranging and substituting gives the second order differential equation:

$$\frac{d^2}{dt^2} I(t) + \frac{1}{L_3 C_o} I(t) = 0,$$

Using the resonant angular frequency $w_0 = \frac{1}{\sqrt{L_3 C_o}}$ we can simplify the differential equation:

$$\frac{d^2}{dt^2} I(t) + w_0^2 I(t) = 0,$$

The associated Laplace transform is

$$s^2 + w_0^2 = 0,$$

Thus $s = \pm j w_0$, where j is the imaginary unit. The complete solution to the differential equation is

$$I(t) = Ae^{+jw_0 t} + Be^{-jw_0 t},$$

It can be solved for A and B by considering the initial conditions. Since the exponential is complex, the solution represents a sinusoidal alternating current. Since the electric current I is a physical quantity, it must be real-valued. As a result, it can be shown that the constants A and B must be complex conjugates $A = B^*$, Now let:

$$A = \frac{I_0}{2} e^{+j\phi}, B = \frac{I_0}{2} e^{-j\phi},$$

Next, we can use Euler's formula to obtain a real sinusoid with amplitude I_0, angular frequency $w_0 = \frac{1}{\sqrt{L_3 C_o}}$, and phase angle ϕ. Thus, the resulting solution becomes

$$I(t) = I_0 cos(w_0 t + \phi),$$

$$V_{L_3}(t) = L_3 \frac{dI}{dt} = -w_0 L_3 I_0 sin(w_0 t + \phi),$$

The initial conditions that would satisfy this result are

$$I(0) = I_0 cos(\phi),$$

$$V_{L_3}(0) = -w_0 L_3 I_0 sin(\phi),$$

The higher the frequency of the induction heating circuit the heating operation of the circuit is increased. Also, the metal gets more heat. The output frequency of the induction heating circuit is usually between 20 kHz and 100 kHz [7]. In the output of the circuit, the capacitors are connected to the coil, and the coil creates an electromagnetic field. Fig. 6 shows how to create a magnetic field around the used coil in the circuit. This coil generates a uniform magnetic field along the length of the coil. The generated field covers around the coil for a wide range of cap sizes. Fig.7 shows the general structure of the induction sealing device and the bottle that is placed in the magnetic field around the coil. Using this device, containers can be sealed one after the other without stopping. This increases the speed of packaging. When the induction coil is placed next to or around the induction seal wads, the lines of the field are concentrated in the air gap between the coil and the induction seal wads. The magnetic field that surrounds the induction coil induces an equal and opposite current in the induction seal wad. The induction seal wad heats up due to the resistance to the induction current. The heating speed of the induction seal wad depends on the frequency of the induction current, the intensity of the induction current, the specific heat of the material, the magnetic permeability of the material, and the resistance of the material against the current. Induced currents have the highest intensity near the magnetic field. In this way, the aluminum foil in the bottle cap is heated and sticks to the container cap.

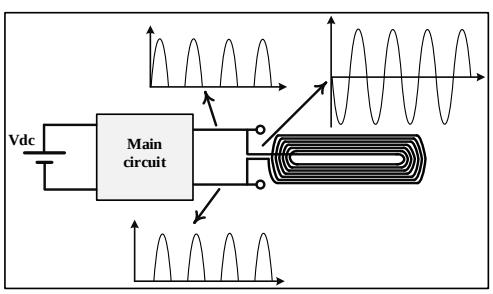


Fig. 5. The waveforms of drain voltages and across the main coils.

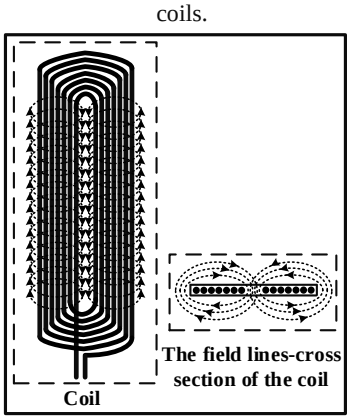


Fig. 6. Created unified magnetic field around the coil.

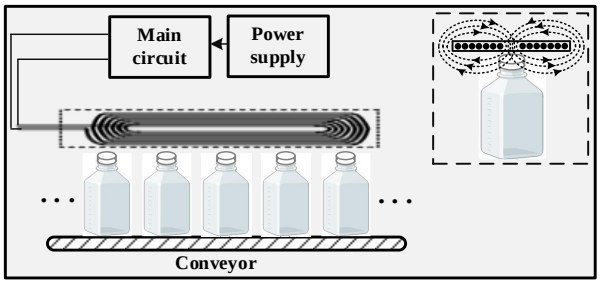


Fig. 7. The general structure of the induction sealing device and the bottle that is placed in the magnetic field around the coil.

In the following, the role of the components of the circuit is described. The role of Zener diodes in this circuit is to limit the gate voltage of the MOSFETs, which prevents the MOSFETs from being damaged. In case of high supply voltage, these diodes prevent gate voltage from going too high. Considering that to increase the power of the circuit, the number of parallel transistors is equal to 2, one of the parts that need to increase the power dissipation is the Zener diodes. For this purpose, we use two Zener diodes. The diodes are connected in series. Two fast recovery diodes D_1 and D_2 with resistors R_1 - R_2 provide gate drive. These fast diodes provide a fast turn-off of the MOSFET gates when they are driven toward the ground as the opposite-phase MOSFET saturates. When two MOSFETs M_{11} and $M_{12}$are turned on, it pulls the gate of the opposite MOSFETs M_{21} and M_{22} down. Therefore, 4 MOSFETs can't be on at the same moment. The inductors L_1 and L_2 provide almost constant current to the resonant circuit.

V. Implementation considerations

One of the most important parts of this paper is the implementation considerations. Because inappropriate elements and no consideration of the implementation points in the circuit lead to no desired answer in practice. In this circuit, we can use any N-channel MOSFET transistor with high power, voltage, and current in different ranges. It depends on the application and the expected power from the circuit. In addition, because of the resonant voltage rise in the drains about 2 times the power supply voltage. Therefore, the maximum drain-source voltage recommended is in the rating of 3 to 4 times the supply voltage. To receive high power, we can use MOSFETs that have a maximum drain-source voltage between 150v to 600v and a drain current between 20A to 100A. The heatsinks can be used to cool them. Here, in the circuit, we use four IRFP260N MOSFETs with the minimum $V_{gs(th)}$ equal to 2v. The use of the Zener voltage higher than the minimum gate-to-source turn-on voltage ensures that the MOSFETs are conducting at a high level. On the other hand, the maximum V_{GS} is equal to 20V. Therefore, we use two series Zener diodes with a Zener voltage equal to 6v. Inductors L_1 and L_2 are a type of choke that helps eliminate any possible high-frequency content from the power supply and also limits the current to a safe level. These inductors have a ferrite core. The amount of these inductors should be much higher (about 10 times) compared to the induction coil. To prevent heating of the circuit, capacitors, and inductors L_1 and L_2 should be selected based on considerations. For this purpose, the inductors must have a high-tolerable current (more than 15 amps).

The inductors L_1 and L_2 must be able to handle the current drawn from the power supply and power losses in the core. Typically, the choke is wound on a powdered iron (Material 26 and Material 52). The relative permeability of these materials is equal to 75; the core will not saturate at the maximum power supply current. The wire used in the choke must be able to handle the maximum current demanded by the power supply without significant core losses. In this work, a 108 μH inductor with a current of about 40A is constructed and used in the circuit. The inductors L_1 and L_2 are made based on six 0.75mm lacquered wires twisted together. Fig. 8 shows the constructed inductor for L_1 and L_2. The core is based on material 52 with an inner diameter of 24mm, outer diameter of 47mm, and height of 18.2mm. Here, the two meters of 0.75mm Lacquered wire is used for the wiring of inductors. For the output capacitor, several capacitors should be used in parallel. The total capacity of parallel capacitors should be equal to the capacity of the equivalent capacitor (C_o). If the number of capacitors is low, for example, one or two capacitors equal to 20 capacitors are used the internal resistance increases and the possibility of their damage increases. By increasing the number of capacitors, the current value is increased and it is divided between parallel capacitors. In this case, the capacitors heat up less, and their useful life in the circuit increases. For example, if the output equivalent capacitor has a capacity of 3uF, it is better to use 20 capacitors of 150nF in parallel. The capacitors must have a high current and voltage. The best option for this work is MKT capacitors with a maximum voltage more than of 100V so that the circuit works better and does not heat up. In this work, we have used 20 capacitors of 150nF with a maximum voltage of 630V. If the equivalent capacity value of the capacitors decreases, the frequency of the circuit increases and the circuit becomes stronger, but capacitors with a lower capacity must be paralleled. So that the number of paralleled capacitors is not reduced. At the input of the induction sealing circuit, the electric current of the power supply has a higher priority. Because the higher the current provides, the higher the power of the induction sealing circuit. However, the higher input voltage affects the heating speed instead of the heating power. The voltage of the power supply can be between 5 to 48 volts, and the current from 5 to 50 amps, depending on the load. Fig.9

shows the used coil in the induction heating circuit. For the construction of the coil, we use Litz wire to increase the power transfer efficiency and reduce the heat losses. Because in many high-frequency heating applications, the induction coil is often based on Litz wire [7]. The coil is constructed based on a Litz wire with 24 strands of 0.5mm lacquered wires twisted together. As mentioned before, one of the characteristics of this coil is the creation of a uniform magnetic field. This feature is due to the winding of the wire in an elliptical shape. In the elliptical coils, due to their long length, it produces more field. So we have a field with a larger area. This kind of coil has a very good heating rate for this aluminum foil. When the bottles pass under it, there is enough time for sealing (due to the length of the coil). In this case, the sealing is done using only one coil and there is no need to use an additional coil. The creation of a uniform magnetic field along the length of the coil causes uniform heating of the aluminum foil on the bottle cap. By increasing the length of the wire, the coil can have larger dimensions and number of turns. In this case, it can seal a wide range of bottles with different sizes of lids. On the other hand, with the increase in dimensions and the number of turns of the coil, the power supply current must be increased. Also, cooling of the coil and the circuit should be considered. The amount of induced heat can be controlled based on changing the dimensions and number of turns of the coil, the diameter of the wire, and the current of the power supply. One of the points of implementation in this circuit is the cooling of the induction coil. In samples with powers more than 3kW, cooling is done by oil for easier cooling. On the other hand, in many cases, the cooling system is air-cooled, and cooling is done with fans that are placed on top of the induction coil. In the present work, a fan is used for cooling. One of the most important challenges of the circuit during the design process is to make a precise and symmetrical coil based on Litz wire. Because according to the output power of the circuit, the diameter of the wire and the number of turns should be considered. In addition, to have a uniform magnetic field, the symmetry of the coil (in terms of size and number of turns) is essential. Using high-voltage MKT capacitors is another limitation that should be considered in the design. Because of the working conditions (continuous work in industrial environments and increasing the temperature of the capacitors) and the high current of the circuit, the MKT capacitors must be used. Constructing the L_1 and L_2 inductors is another circuit challenge. These inductors must have a high current capability, in the process of designing them, the diameter of the wire and the size of the ferrite core must be considered.



Fig. 8. The constructed inductor for L_1 and L_2.

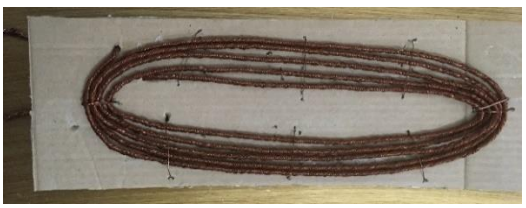


Fig. 9. The shape of the used coil in the induction heating circuit.

The printed circuit board (PCB) of the layer induction heating circuit is shown in Fig. 7. Interconnection traces on the PCB are wide and as short as possible. The dimensions of the board are 15×30cm^2. As can be seen from the figure, the paths with more current have a wider width (20mm). In addition, after making the printed circuit, the sensitive and high-current paths should be tin-plated. In order not to damage the MOSFETs, capacitors, and inductors, as well as heat them up, a suitable fan and heatsink must be used to prevent overheating during operation.

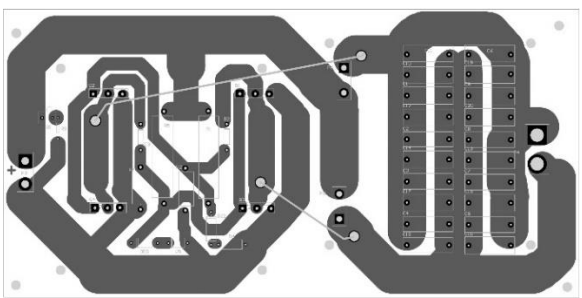


Fig. 10. One layer printed circuit board of the induction heating circuit.

VI. The Results of the Implementation

In this section, some results of the proposed circuit are presented. In the implementation of the circuit, we use a 24-volt switching power supply with a maximum current of 15 amps. The induction coil is wrapped by a Litz wire with an outer diameter of 12mm. The coil is constructed based on a Litz wire with a 24-strand of 0.5mm lacquered wires twisted together. The amount of the induction coil measured by the LCR meter is equal to 8.5uH. The desired oscillation frequency in the output is achieved by using the 20 capacitors 150nF-630v in parallel. The hardware parameters of the circuit are shown in Table 1. The components' tolerances and variability (variations in quality) impact the circuit's performance (efficiency and reliability). Therefore, we must consider some points in the design to reduce these effects as much as possible. For example, Litz wire reduces losses if

there are many strands with a smaller diameter in the wire structure [7]. On the other hand, the MOSFETs must be of suitable quality and be connected to the heat sink to reduce electrical variations. The used capacitors in the output must be MKT type, which does not change their capacity due to temperature changes. The MKT capacitors are popular and normally used for large pulse handling such as dc-link for high-frequency inverters [20], etc.

TABLE 1: HARDWARE PARAMETERS OF THE CIRCUIT.

Elements	Specification
R_1-R_2	470Ω, 10W
R_3-R_4	10kΩ, 5W
D_1-D_2	Fast recovery diode UF4007
DZ_{11}-DZ_{22}	6V, 5W
M_{11}-M_{22}	IRFP260N
L_1-L_2	108uH, 40A
Coil L_3	8.5uH, 24-strand Litz wire
C_o	# 20 (150nF-600V)

Figure 11 shows the real circuit of the proposed induction heating. Here, we have designed a single board for the circuit and the capacitor part, which reduces the assembling work and its cost. The gate voltage of the MOSFETs in the oscilloscope is shown in Fig. 12. Fig. 12 (a), (b), and (c) shows the gate voltage of the MOSFETs (M_{11} and M_{12}), (M_{21} and M_{22}), and both voltages, respectively. Also, Fig. 13 shows an example of the drain voltage signals (V_{d1} and V_{d2}) of the MOSFETs in the oscilloscope. Fig. 13 (a) shows the sample of the drain voltage signal of the MOSFETs M_{11} and M_{12} the middle figure (Fig. 13 (b)) shows the sample of the drain voltage signal of the MOSFETs M_{21} and M_{22}, and both voltage of the drains of the MOSFETs (M_{11} and M_{12}, yellow diagram) and (M_{21} and M_{22}, blue diagram) in the oscilloscope are shown in Fig. 13 (c). The horizontal axis is in terms of time (second) and the horizontal axis is in terms of voltage (V). We can see the order of turning off and turning on the MOSFETs in these diagrams. The gate of the MOSFETs was switched alternately at a frequency of 34 kHz. Fig. 14 shows an example of the signal produced at the output (two ends of the induction coil) by the oscilloscope. As can be seen, this waveform is completely sinusoidal. Here, the peak-to-peak output voltage is approximately equal to 85v and the oscillation frequency is approximately equal to 31kHz. The amplitude and frequency of the output are quite suitable for inducing a magnetic field in the induction coil. Changing the number of turns of the L_3 coil is one of the most important ways to scalability the proposed work. In this case, the capacity of C_o and the number of capacitors must also be changed to achieve the desired output frequency. Therefore, by changing the number of turns of the coil, increasing (or decreasing) the diameter of the Litz wire, and increasing the power supply's current and the output capacitor's capacity, the circuit can be adapted for different applications. In addition, for high-volume production environments, as the circuit is constantly under load, cooling of the output coil should be considered. In this case, a water or oil cooling system should be used to cool the output coil.

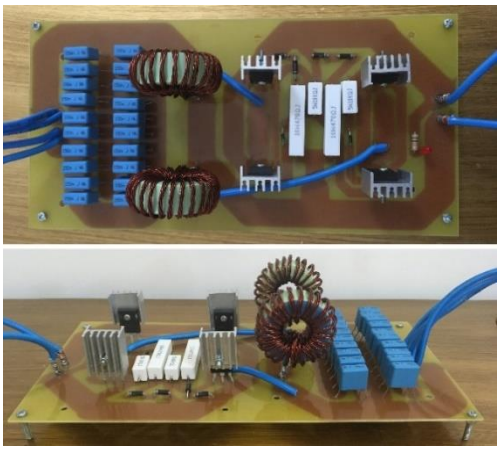
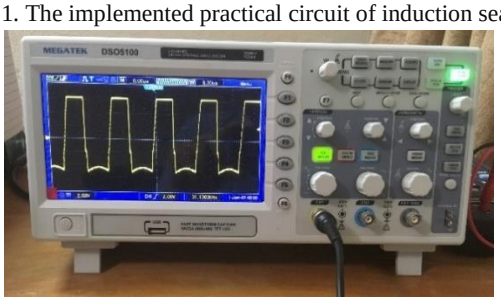
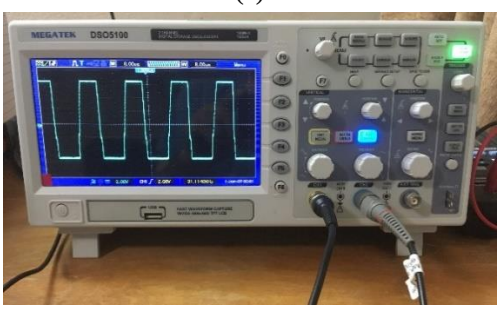


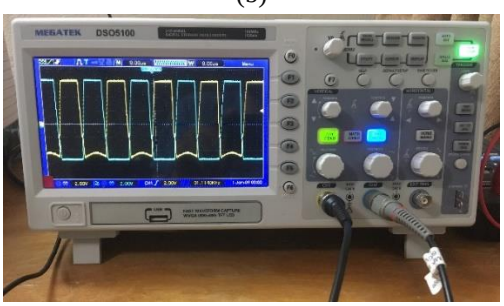
Fig. 11. The implemented practical circuit of induction sealing.



(a)

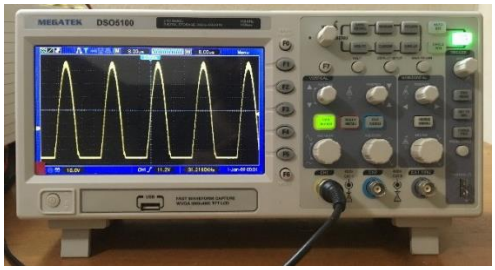


(b)

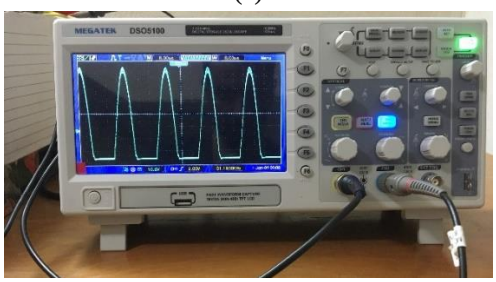


(c)

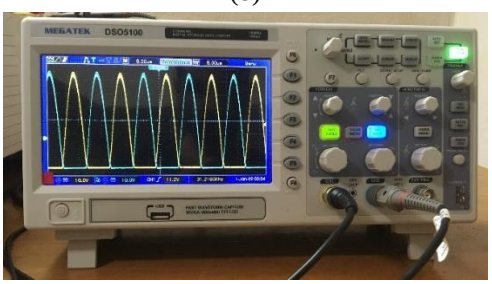
Fig. 12. The sample of the gate voltage signal of the MOSFETs M_{11} and M_{12} (a), the sample of the gate voltage signal of the MOSFETs M_{21} and M_{22} (b), and both voltage of the gates of the MOSFETs (M_{11} and M_{12}, yellow diagram) and (M_{21} and M_{22}, blue diagram) in the oscilloscope (c).



(a)



(b)



(c)

Fig. 13. The sample of the drain voltage signal of the MOSFETs M_{11} and M_{12} (a), the sample of the drain voltage signal of the MOSFETs M_{21} and M_{22} (b), and both voltage of the drains of the MOSFETs (M_{11} and M_{12}, yellow diagram) and (M_{21} and M_{22}, blue diagram) in the oscilloscope (c).



Fig. 14. An example of the output signal (two ends of the induction coil) produced in the oscilloscope.

In the presented work, the diameter range of the bottles that can be sealed is equal to 1cm to 13cm. This range is completely required by the food and pharmaceutical industries. In Fig. 15, two examples of bottles used in the pharmaceutical industry are sealed with the implemented circuit. The diameter of the bottle in Fig. 15 (a) is 4 cm and the diameter of the bottle in Fig. 15 (b) is 13 cm. This bottle (Fig. 15 (b)) is one of the largest bottles used in the pharmaceutical industry. As seen from the figure, the sealing has an acceptable result.





(a) (b)

Fig. 15. Two examples of bottles used in the pharmaceutical industry are sealed with the implemented circuit.

VII. Conclusions

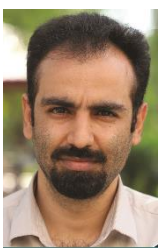
Induction heating enables the conversion of electrical energy into thermal energy with fast and high conversion efficiency in a wide range of industries. In this paper, an optimized hardware design and implementation of an effective and optimal induction heating circuit for induction sealing has been investigated. The implemented induction sealing circuit works based on zero voltage switching technology to generate the output signal. In this work, the focus is on the implementation process and practical tips for implementing this circuit. In this structure, by using inductors, transistors, and capacitors with suitable tolerable current and voltage, it can supply the power and frequency of the output signal applied to the induction coil for various applications. Also, the induction coil has an elliptical structure with a uniform magnetic field along the length of the coil, which makes it suitable for sealing a wide range of bottles. In the presented structure, the frequency of the signal created at both ends of the induction coil is around 31kHz, which is suitable for generating the eddy current in the aluminum foil in the bottle caps. The proposed circuit has been tested and investigated. It has acceptable induction sealing for various industries. Future research that can be done on the circuit includes using a power supply with variable voltage to control the output power according to different applications (different bottle sizes) can be effective in designing a flexible circuit. In addition, providing an oil-based cooling system for coil cooling is another work that improves circuit performance in industrial applications.

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