# Wireless power transfer for industrial applications (converter design)

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**Abstract**

This research is focused on the designing, analysis, and implementation of a parallel lc resonant converter which is set to function at its resonant frequency of 2.6868khz. This design has a capacitor of 60uf and an inductor of 58.48uh and also has 2 matching inductors to be able to match the impedances entering the resonant tank to avoid any losses or damage to the circuit while the circuit is operating. We first started by studying the design theoretically, covering the basis of how the components function and what is the role of each of them and how they will help us achieve a stable and efficient converter in the end. The calculations were done precisely to be able to be as accurate as possible in case of resonant frequency, the impendences within the circuit, the power losses throughout the circuit. This part was crucial because it sets the foundation of the whole design, and any miscalculation might set us further away from our goal. Moving on to the simulation phase, which helps us prove that our calculations are correct and are aligning with the data we extracted from the simulations made, in addition to giving us an opportunity to check if there is any room for improvement in terms of efficiency or functionality. Finally, laying out our design on a pcb to be able to have fully functional hardware and to test each aspect of this study. This paper provides a comprehensive study on the design and implementation of parallel lc resonant converter and covers the areas of choosing the components, doing all the necessary calculations and proving it using simulation. The results provided are a guide for designing and implementing a resonant converter to be used in various manufacturing sectors.

## Chapter 1

**Introduction:** with the increased demand of induction heating majorly due to its uses in forging and hardening metals in the manufacturing industry, heating and bonding components in the automotive industry, in addition to its uses in the sterilization process in the medical in- dustry, induction heating became A vital process in many of the industries that lead the world of production of our era. In general, induction heating is the process of heating an electrically conductive material without direct contact, this part was the game changer as the whole fundaments of heating

1- germany international university

objects changed Forever. This type of heating uses al- ternating magnetic fields to be able to heat the conductive material, in addition to giving us control over the amount of heating being generated through adjusting the frequency of the ac through the coil used. Having also precise control of the heating area of the workpiece was another advantage to this process.

Moreover, with it being non-contact and a more efficient process, induction heating became a vital process in many sectors and helped in decreasing the overall losses while operating which in turn leads to more heat being produced with less energy being con- sumed. The first concept of heating was introduced centuries ago, and it mostly being in a furnace which was introduced by edwin f. Northrup. Years later and with the technological advancement, the increased demand for war materials in the 90's marked a significant change in the equipment and techniques used in induction heating, which in turn led to drastically enhancing its efficiency and control. In addition, the advance- ments in power electronics led to it being more adapted throughout the world and easy to design and implement. Nikola tesla was the first to lay the foundation of operating with high-frequency currents and demonstrated how electromagnetic fields could generate heat in the conductors in the early 90's, which set the fundamentals for centuries to come. Coming to our modern day, induction heating became widely used in metalworking, au- tomotive, aerospace, and cooking application.

## Chapter 1. Introduction

**1-1- general description of parallel lc resonant con- verter:** the central function of the parallel resonant converter is to act as a power electronics device to utilize the resonance between an inductor and capacitor to achieve the highest efficiency possible while the system is in operation. The resonant tank mainly consists of these 2 components which are an inductor and a capacitor which can also change depending on the aim of this device, or what the desired outcome is. The resonant tank is also considered the core of the converter as all the energy conversion takes place there, and it also comes in different configuration as in series or parallel. In this study we fo- cused on the parallel lc resonant converter as shown in figure 1.1.

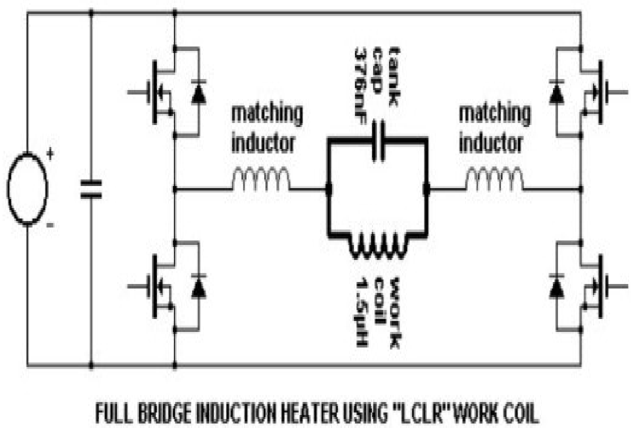


**Figure 1.1: connection diagram of parallel lc resonant converter**

The need to increase the efficiency of induction heating and decrease the overall losses throughout the circuit was the main aim of this study. Each component has its unique functionality and is configured in a way to help us achieve this goal. The success of induction heating relies on the amount of heat transferred to the workpiece with the least losses possible, or else it would be costly in terms of money and energy used. In addition, most of the energy used to supply the induction heating process negatively affects our planet through the non-renewable energy used to supply it, so having it working more efficiently doesn't necessarily solve this issue, but it at least gives a glimpse of hope for our future generations. This study has been also divided into different sections to be able to cover all the topics related to this study, as the background information is summarized in section 1. In addition to the literature review being in section 2, the methodology is in section 3 which summarizes how we designed and simulated this design. Finally, section 4 included the results we gathered from our simulation and the implementation of this prototype, section 5 included the results of the prototype, and the components used, sec- tion 6 is a short summary of this study and what has been achieved throughout its process.

**Chapter 2 literature review:** resonant converter system, especially ones used for induction heating has been a talking point for years due to the increased demand on it in several sectors and considered one of the best options for the induction heating process due to its numerous advantages.[1] in this literature review we will dive into the fundaments and principles of the parallel resonant converter, its advancements throughout the years, challenges, and future di- rections of resonant converters in the induction heating sector.[2]

**2-1- resonant converters:** recently resonant converters became the corner stone of the induction heating pro- cess, with emphasizing on its operation at or near the resonant frequency which helps us achieve higher efficiency and decreasing the overall efficiency as stated by[3]. While operating at the resonant frequency it allows for soft-switching techniques to reduce the stress on components, in addition to increasing the durability of said components. With adding a filter inductor, the current ripple inductor is minimized, which helps us achieve a more stable and smooth output at resonance, while its absence reduces the size of the tank and lowering costs, but according to the authors these were measures that had to be taken in order to increase the overall efficiency of this resonant tank. Using a full- bridge mosfet and configuring it to be optimized at the resonant frequency was one way to achieve our goal at the resonance frequency, and to ensure smooth switching in the mosfets.

**2-2- efficiency and performance optimization:** the importance of efficiency is crucial in this power electronic device, as it sets the stan- dard of operation throughout the process. With higher efficiency it will achieve higher

**4 chapter 2 literature review:** power transfer and also decrease the losses throughout the circuit. But with the chal- lenges faced due to the increased noise, and inefficient soft switching under large power variations, the authors [4] suggested an approach to fix this issue once and for all. With integrating a current-controlled variable inductor (vi) and a phase shift (ps) in order to optimize the efficiency of the power transfer. This control uses a configuration of two in- ductors and a capacitor in order to improve the overall efficiency of the induction heating system. The design maintains an optimal balance between the inductance and capaci- tance while in operation, leading to enhanced efficiency. The main objective of this study was to minimize the switching losses by reducing the rms current while maintaining consistent zvs operation, which is crucial for achieving high efficiencies. This study also discussed its application on series and parallel resonant circuits and the drastic change in the efficiency and optimization it resulted in.

**2-3- challenges and limitations:** despite the advancements and breakthroughs, the resonant converter has seen throughout the past decades, this device has faced several challenges throughout its implementation. The primary concerns were the challenges faced due to the impedance matching and volt- age instability [5]. With trying to stabilize the circuit in order to avoid any damages to the components being used and also using the matching impedance in order to achieve the highest efficiency possible, the main aim was to always to advance this design to make it more efficient, consume less, and most importantly being stable while in operation.

the authors suggested introducing a parallel inductor to the existing circuit, which in turn enhanced the efficiency and stability but it also affected the flexibility of this converter. Ongoing research is needed to address these issues to ensure the stability and efficiency of this converter with the ongoing demand of induction heating in industrial, medical, and technological applications.

**2-4- research gaps:** despite the extensive research that was done regarding our topic,
there were many gaps in the current literature review. Firstly, while many studies focused on the enhancement of efficiency, many ignored the concept of it being cost effective even though being cost effective was one of the main reasons that made the use resonant converters widely used in induction heating process, and this electronic device being expensive due to the extensive use of the components might drive users to seek other options instead. In addition, the reliability of the components was never discussed or studied throughout the literature re- view, as we are creating an electronic device for induction heating, heat is one of the main losses in power transfer, and that heat affects the functionality of the devices being used

**2-5- dvantages and disadvantages of parallel resonant converters5:** and it leads to degrading the lifetime of said devices. Finally, and most importantly, the impact on the environment was not included, which leaves a significant question mark, as this is one of the most important topics in our generation and it is yet to be explored.

**2-5- advantages and disadvantages of parallel reso - nant converters:** as for the advantages of using such converters, most importantly it helps us achieve the highest efficiency while operating at the resonant converters.[6] in addition, the circuit is simple to implement and more flexible while choosing the components depending on the application it's being used for.[7] also, by introducing the soft-switching technique, we can generally decrease the overall losses of this system while in operation. On the other hand, resonant converters are not strictly being used for parallel configuration only, many studies and research have been done on this topic, and many authors suggested different configuration which shows the flexibility of such device.[8, 9]

As for the disadvantages, for such a device to function perfectly, there are many factors to be considered. Firstly, each solution that is introduced to increase the overall losses or the amount of energy the device uses, it shows that another component is being affected, one such incident is when using matching impedances between the source and the tank, one of the factors that is affected is the current entering the tank, which leads to less energy being transferred.[10] another issue was the durability of the components, with the immense current being transferred through the circuit, many components function at levels higher than its capacity to handle them, which increases the wear and tear of said components.[2]

**2-6- future directions:** the study of parallel resonant converters has demonstrated significant potential for im- proving efficiency, stability, and performance in power conversion systems. However, several areas remain ripe for exploration to address existing challenges and unlock new opportunities.[11] future research could focus on advanced control strategies, such as adaptive frequency modulation and machine learning-based algorithms, to optimize the operation of parallel resonant converters under varying load conditions. Another promis- ing direction is the development of hybrid resonant topologies that combine the benefits of parallel and series resonant circuits, offering improved impedance matching and voltage regulation across a wider range of applications. In addition, the application of parallel resonant converters in sectors such as renewable energy systems, electric vehicle charging,

**6 chapter 2. Literature review:** and wireless power transfer presents another chance for the resonant converter to face new advancements and increase its testing and implementation. In conclusion, addressing practical challenges, such as power losses, and cost-effective design, will be critical for the widespread adoption of these systems. By pursuing these options, future research can create a way for more efficient, and more reliable power transfer.

**2-7- hypothesis:** the hypothesis for this study is implementing a parallel lc resonant converter with enhancing its efficiency, matching impedances, in addition to using soft-switching tech- niques, which will in return help us achieve a higher power transfer in the resonant tank, less switching losses, and more durable components.

## Chapter 3

**Methodology & simulation:** the resonant tank mainly consists of a capacitor and inductor, and they are either connected in series or parallel, in which they are called a “series resonant converter” or “parallel resonant converter. In addition, our project is named “parallel lc resonant converter” and the only thing we added is the “lc” which is named after our components in our resonant tank as shown in figure (3.1). The main functions of the resonant tank can be summarized in the following: energy storage and transfer, control and tunability. We will first start with the energy storage and transfer part, which is where the energy is stored which is mainly in the capacitor and transferred into the inductor, so the resonant tank is where this energy transfer takes part. Secondly, harmonic filtering which is the process where the tank circuit starts to filter out other frequencies to be able to perform at its peak capabilities which will lead to having a higher efficiency and a smoother power transfer in the circuit, in addition to decreasing the losses throughout the tank circuit. We will first start by assigning the correct values to the capacitor and the targeted resonant frequency that we will operate at and using the following formula:

$$f_0 = \frac{1}{2\pi\sqrt{L.C'}} \qquad (3.1)$$

We will be able to calculate the appropriate value for the inductor. In addition, we need to also choose the appropriate value for the resistance which will be connected in series with the inductor, to be able to simulate the amount of voltage passing through it and act as if it was the load itself, and in this case the value we have chosen for our resistance is 0.272 ohm, and for the capacitor we have chosen to work with 60uf and the resonant frequency of 2.6868khz which is suitable for small induction heating applications.

Below in table 3.1 is the full configuration of the resonant tank circuit, and as shown in the table below the exact values of the capacitor, inductor, and resistor that will be used in this simulation.

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**Table 3.1: components configuration**

| Components | Value | |
|---|---|---|
| Capacitor | 60e-6 f | |
| Inductor | 58.48e-6 h | |
| Resistor | 0.272 Ohms | 0.273 |

**3-1- open-loop simulation:** referring to matlab/simulink to build the circuit designing a full h-bridge includes the use of four mosfets and four pulse generators to con-vert dc voltage into high- frequency ac. The operation of the h-bridge is based on the alternating activation of the mosfets. Similarly to how the different connections of this circuit are arranged, the activation of the mosfets during the h-bridge keeps varying for each cycle, thus in one half-cycle t1 and t4 mosfets are open allowing current to flow in one direction through the load, whereas in the other half-cycle t2 and t3 are turned on. This con- figuration of the h-bridge ensures that the received voltage is perfectly inverted in the second half cycle and thus will allow the delivery of a complete alternating wave. This configuration provides a reliable and accurate solution to the need for high-frequency ac in applications like powering resonant circuits.

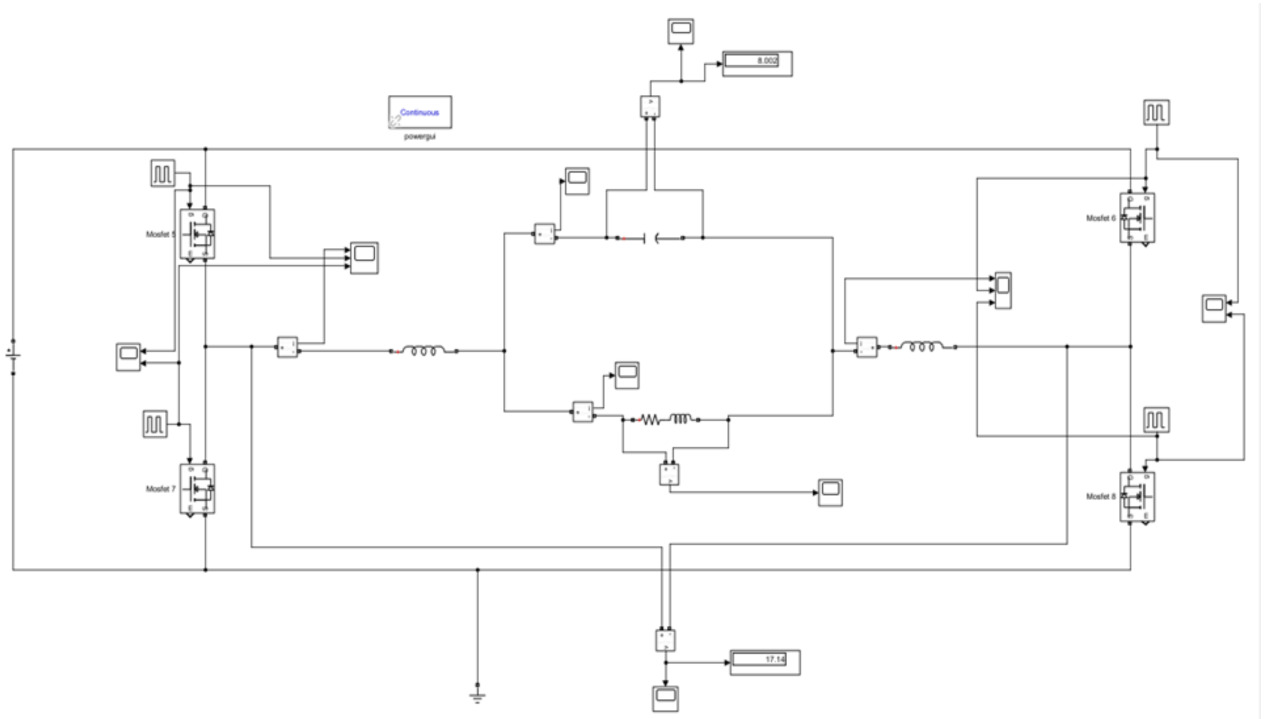


**Figure 3.1: open-loop circuit of parallel lc resonant converter**

## 3-2- configuration of pulse generators 9

**3-2- configuration of pulse generators:** as for the pulse generators, we have 4 of them as shown in figure (3.1) and each is connected to its own mosfet respectively. Its main functions are to control the signal generation to give us control of when the mosfet's turn on and off. Time and phase con- trol to be able to turn the mosfet's on in pairs and to avoid short circuiting the circuit. In addition, it gives us the option to adjust the duty cycle which is 50% in this case as m1&m4 are on 50% of the time, and m2&m3 are on the other 50%. To be able to make the mosfet's work in pairs we must set p1&p4 together and p2&p3. We will also adjust the amplitude in the pulse generators to 10v for pulse generators as they are mainly set between 10v-15v, in addition to setting the pulse width to 50%. After using the formula. We will be able to set the right value for the period, which is the same for all the pulse generators.

$$T = \frac{1}{f}, \qquad (3.2)$$

Finally, setting the phase delay differs in p1&p4 and p2&p4 as they are supposed to work in pairs. The phase delay in p1&p4 are set to 0 as shown in table 3.2 as they are supposed to be working in the first 50% of the duty cycle. To implement a phase delay in p2&p3 we use the formula in equation 3.3 to ensure that they don't function in the first 50% of the duty cycle but rather the second, and its configuration is shown in table 3.3.

As for the configurations of p1&p4 which is shown in table 3.2 and the configuration of p2&p3 which is shown in table 3.3, the only difference is in the phase delay. As we mentioned before, we should implement a phase delay for p2&p3 work in the second half cycle not in the first for the system to work efficiently and to avoid any collisions or errors while the circuit is functioning. To set the phase delay of p2&p3 we will use the following rule:

$$\Delta t = \frac{T}{2}, \qquad (3.3)$$

And once we calculate it then we are all set. For p1&p4 we will have the amplitude as 10v, the period we calculated at a frequency of 2.6868khz which will be 0.00006667, a pulse width of 50% and finally a phase delay of 0 secs as shown in table 3.2.

As for p2&p3 we will set the phase delay according to the formula we mentioned before, so we will have the amplitude as 10, the period as 0.0000667, the pulse width as 50%, and the new phase delay as 0.00003333 secs as shown in table 3.3.

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**Table 3.2: pulse generator 1 & 4 configuration**

| Block parameters | P1 & p4 |
|---|---|
| Pulse type | Time-based |
| Time (t) | Use simulation time |
| Amplitude | 10 |
| Period (secs) | 0.000006667 |
| Pulse width(% of period) | 50 |
| Phase delay (secs) | 0 |
| Interpret vector parameters | Checked |

**Table 3.3: pulse generator 2 & 3 configuration**

| Block parameters | P2 & p3 |
|---|---|
| Pulse type | Time-based |
| Time (t) | Use simulation time |
| Amplitude | 10 |
| Period (secs) | 0.000006667 |
| Pulse width(% of period) | 50 |
| Phase delay (secs) | 0.000003333 |
| Interpret vector parameters | Checked |

**3-3- configuration of mosfets:** in this application we have used a full-bridge rectifier, a "full-bridge" generally means that there are 4 mosfet's working together as pairs. The mosfet's job is mainly to switch the current flow in the circuit, in addition to voltage control, and most importantly fre- quency control. Firstly, the switching of the current flow which controls the direction and timing of the current flow which enters the resonant tank circuit. In general, the mosfets work in pairs as in m1&m4, m2&m3, so once m1&m4 turns on m2&m3 are switched off and vice versa, this technique help the capacitor in the resonant tank to continuously charge/discharge to get an alternating magnetic field in the resonant tank circuit, and with this alternating magnetic field we get eddy currents which helps us reach our goal which is to transfer the energy into heat. So, with the control on the current and the voltage we have full control on what enters and leaves the resonant tank circuit and with the period and amplitude that we choose or see appropriate. Finally, the control on fre- quency helps us operate the circuit at, or below, or higher than the resonance frequency to help us achieve zvs/zcs which in turn will help us decrease the switching losses throughout the circuit.

As for table 3.4 which is the configuration of the 4 mosfet's, but making them work in pairs is the function of another component which is the pulse generator block which we will discuss later on. The configuration is mainly a standard number that is always

**3-4- Configuration of matching inductors 11:** used and rarely changed for most applications.

Table 3.4: mosfet's configuration

| Component (mosfet) | Configuration |
|---|---|
| Ron (ohms) | 0.1 |
| Lon (h) | 0 |
| Rd (ohms) | 0.01 |
| Vf (v) | 0 |
| Ic (a) | 0 |
| Rs (ohms) | 1e5 |
| Cs (f) | Inf |

**3-4- configuration of matching inductors:** the main function of the matching inductors can be summarized in the following: impedance matching, filtering the waveforms, limiting current, and finally phase adjustment. Each has its own functionality and advantages, we will first start by the impedance matching, which is mainly about matching both impedances coming from the source and the load to be able to maximize the power transfer to the resonant tank circuit. Secondly, it acts as

A filter where it smooths out the current waveform from the block signal into a sinusoidal wave which is an important aspect when dealing with heating components or applica- tions. Moving on to limiting current, which is mainly to reduce the current stress on the components to be able to have a properly functioning device with the highest efficiency while in operation. Lastly, the phase adjustment which helps with a changing load or source and in turn it fixes the resonant conditions in order to fit this particular applica- tion. In addition, we use 2 matching inductors in this circuit to match any impedance entering the resonant tank circuit and also because the mosfet's are operating in pairs, so the direction of current and voltage differs throughout the duty cycle.

Now moving to the calculations part, one crucial point we must do before moving on with our circuit is to make sure that xl=xc, where x(l) is the reactance of the inductor, and the x(c) is the reactance of the capacitor. In a parallel resonant converter, both re- actance's cancel each other out as they are equal in magnitude but opposite in direction. So, we will first use the following formulas to get the reactance in the resonant tank circuit:

$$X_L = 2\pi f L, \qquad (3.4)$$

$$X_C = \frac{1}{2\pi f C}, \qquad (3.5)$$

**12 chapter 3. Methodology & simulation:** after substituting the value of each one we will finally get the xc=10.61 ohm and xl= 10.61 ohm which proves that the reactance's are equal. We then move on to the second part which is getting the impedance which is to find the impedance of the tank circuit which is z(tank) through the following rule:

$$Z_{\text{tank}} = R_{\text{Load}} + jX_{\text{parallel}}, \qquad (3.6)$$

$$X_{\text{parallel}} = \frac{X_L . X_C}{X_L + X_C}, \qquad (3.7)$$

And after doing the necessary calculations we will find that x(parallel) is equal to 5.305 ohm and that z(tank) is equal to 5 + j5.305 ohm. Finally getting the magnitude of the z (tank) using the following rule:

$$|Z_{\text{tank}}| = \sqrt{R^2_{\text{Load}} + jX^2_{\text{para}}} \qquad (3.8)$$

We will get that the magnitude of z(tank) is 7.29 ohm, and in this case z(tank)=z(source) so we move on to the last stage which is getting the l-match which is the matching in- ductors value using the following formula:

$$L_{\text{match}} = \frac{|Z_{\text{source}}|}{2\pi f}, \tag{3.9}$$

And we will get our final value as 0.00007735h which was added to the configuration of the matching inductors as shown in table 3.5. Table 3.5: matching inductor's configurtion

| Component (matching inductors) | Configuration |
|---|---|
| Matching inductor 1 (h) | 0.00007735 |
| Matching inductor 2 (h) | 0.00007735 |

**3-5- closed-loop simulation:** as for the closed-loop simulations which is used in this phase to replicate the behavior of our system where the outputs are fed back as inputs through a control system that we design. This simulation will help us evaluate the overall performance of this electronic device and check whether it is stable or not to be able to finally conclude whether our

**3-5- Closed-loop simulation 13:** desired output will be attained or not. To be able to obtain the closed loop control circuit we will design a control system that takes the output voltage and measure the percentage error by subtracting it from the constant calculated. This design is attained to generate a pwm for induction heating applications in addition to many other applications we mentioned before. The process begins with an input signal of our desired value of the output voltage and the frequency that we would like this control system to work at. The value of the (vo) is attained from a sensor and is fed into a summation block. This block subtracts the feedback signal from the reference signal we set to be able to generate an error signal, which is the difference between the reference and feedback values. The error signal is then input into a proportional-integral (pi) controller, which adjusts the output to minimize the error over time, ensuring the system reaches the desired performance. The output of the pi controller is sent to a pwm generation block (pwm1), which also receives a 2.6868 khz clock signal and controls frequency and phase. This block generates pwm signals (pwm1, pwm2, pwm3, pwm4) based on these inputs. Pwm1 and pwm4 are routed directly to outputs, while pwm2 and pwm3 pass through additional blocks such as inverters or amplifiers before reaching the outputs. As shown in figure 3.2

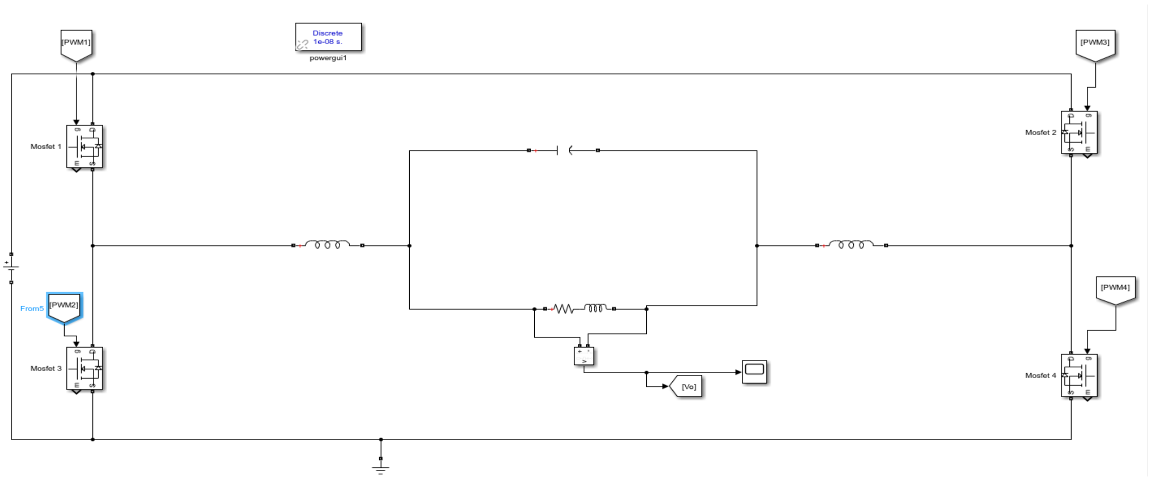


**Figure 3.2: closed-loop circuit of parallel lc resonant converter**

As for figure 3.3, it shows the closed-loop system we created for our circuit in which we have our desired value as the input which is the 11.91v going in a summation block with (vo) which is the voltage reference of the output voltage. Move on to the pi block which helps us fix any over-shoot in the output voltgae of our system and smoothens any noise or fluctuations.we then move on the frequency block where we will input our desired frequency of operation, and then a time block which is based on the simulation time or the stop time.finally, as an output we have the 4 pwm's which are connected to the 4 mosfet's in respect to its original configuration in the open - loop circuit.

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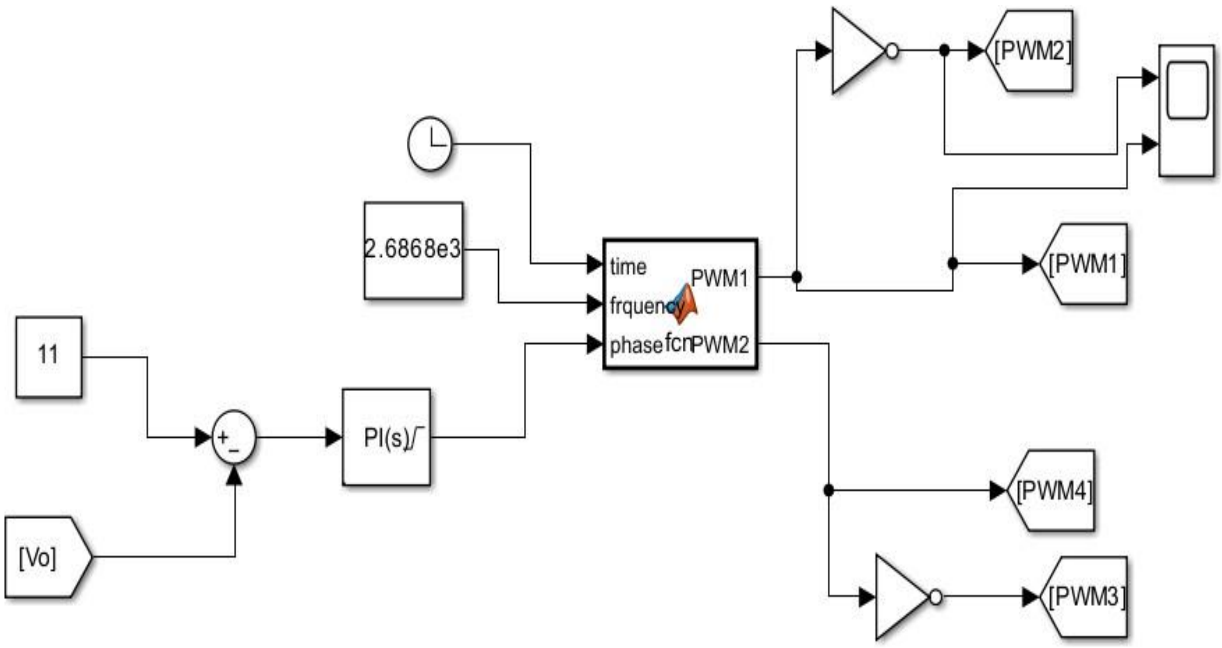


**Figure 3.3: closed-loop system**

## Chapter 4

**Simulation results :** this section summarizes the results of the simulation and the anyalys of the full-bridge parallel lc resonant converter designed for induction heating.

**4-1- full h-bridge:** the full h-bridge circuit, in straightforward terms, is a type of bridge circuit or controlled electronic switch composed entirely of mosfet transistors that operate effectively at the designated voltage. By safely toggling between pairs of mosfets, it converts a low-voltage dc source into a high-voltage ac output. In this setup, diagonal mos- fet pairs are always on, ensuring the others remain within the safe operating area. This operation is clearly demonstrated during the positive half-cycle where the top-left and bottom-right mosfets conduct, and during the negative half-cycle, conduction switches to the top-right and bottom-left mosfets. The correct direction of current for the positive half-cycle's forward active phase is controlled by the active device at the current-carrying terminal, as shown in figures 4.1 and 4.2.

**16- chapter 4. Simulation resu**

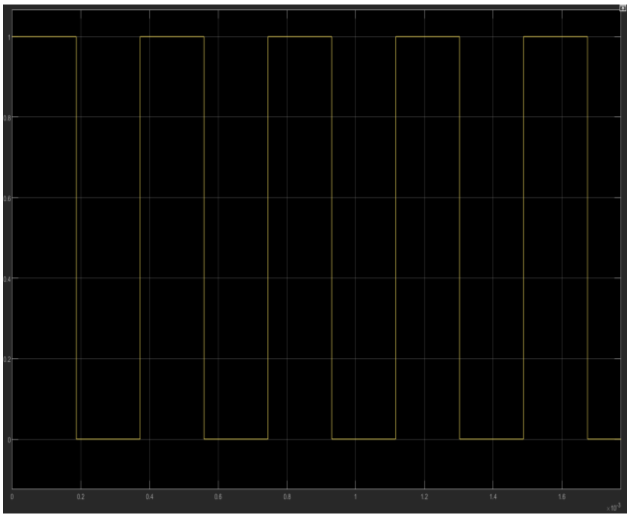

**Figure 4.1: v vs. T mosfet's 1 & 4 results**

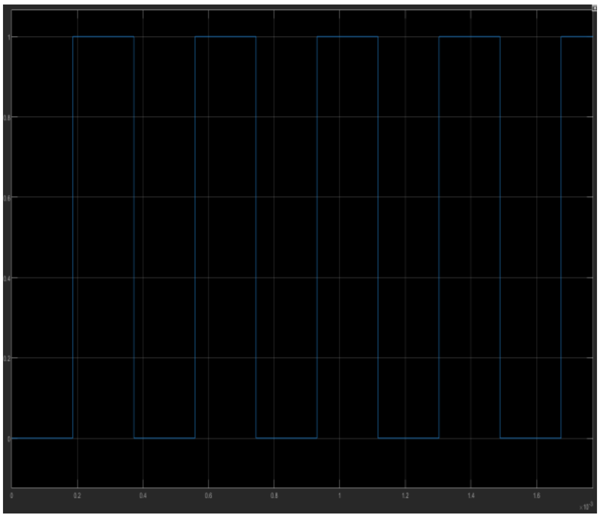

**Figure 4.2: v vs. T mosfet's 2 & 3 results**

**4-2- voltage measurement on the capacitor located in the resonant tank:** it will be noticeable in the waveform below figure 4.3 that it is a sine wave due to the constant charging/discharging of the capacitor during operation, which is the result we wanted to attain and also due to the current always changing direction which makes the

**4-3- voltage measurement from the source 17:** capacitor change poles and continue in the charge/discharge cycle. At the end, once the system reaches its steady state the magnitude of the wave becomes constant.

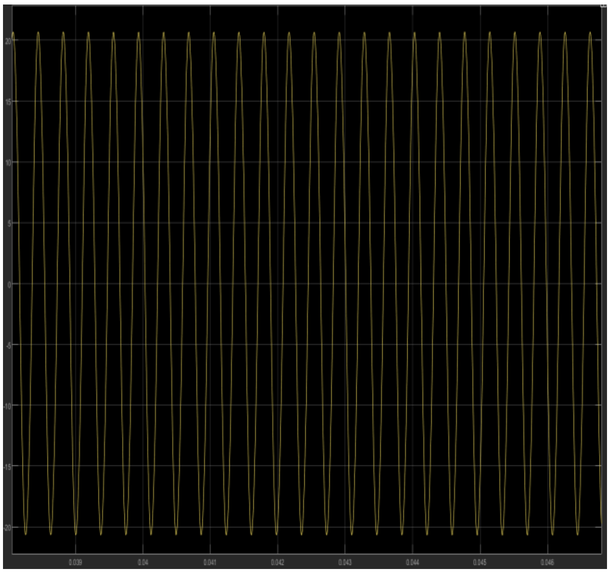

**Figure 4.3: v vs. T of voltage measurement on capacitor result**

**4-3- voltage measurement from the source**

The following graph from figure 4.4 is for the voltage reading due the full h-bridge in motion and the result is a square wave due to the switching of the mosfet's

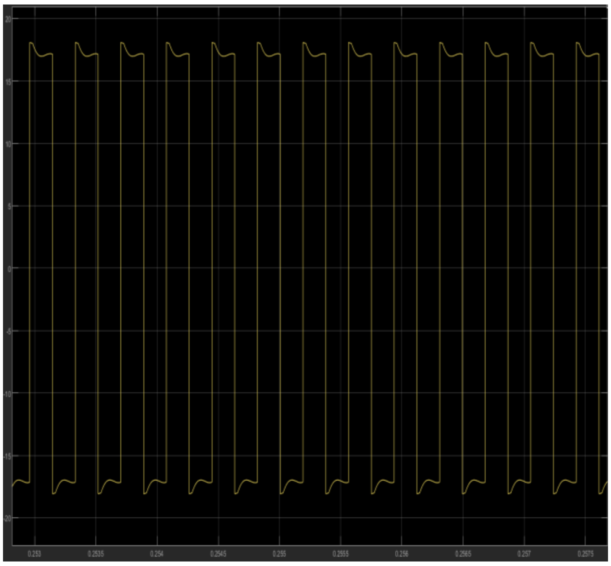

**Figure 4.4: v vs. T voltage measurement from source result**

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**4-4- current measurement on the inductor located in the resonant tank:** as shown in figure 4.5 below is the current measurement on the inductor that is a sine wave due to the constant change in the current path due to the mosfet's operation in pairs.

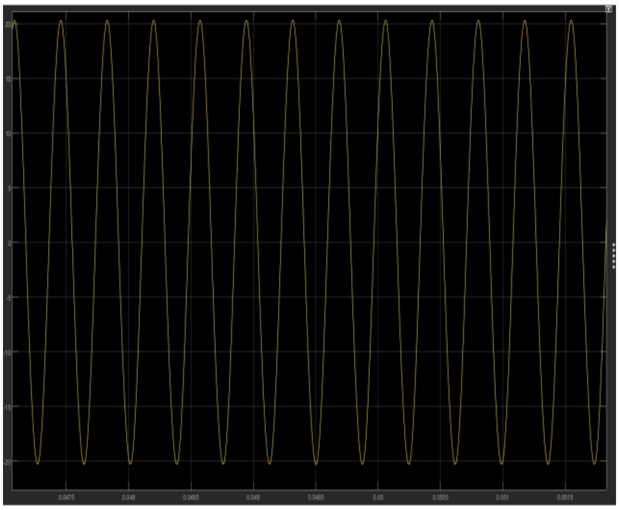

**Figure 4.5: i vs. T current measurement on inductor result**

**4-5- impedance calculations in resonant tank and source:** referring to simulink to help us with the impedance calculations, that output we desired was that the impedance of the resonant tank should be equal to each other as in xl=xc and the impedance becomes a pure resistive load, another result we desired is that the impedance of the source and the resonant tank should be equal to each other so that we prove that the matching inductors has the correct values and are doing their functionality correctly.

In figure 4.6 is the figure of the impedance of the capacitor, and in figure 4.7 is the figure of the impedance of the inductor and finally figure 4.8 is the figure of the impedance of the source. Another thing we wanted to prove is that in a parallel resonant converter and while operating at the resonance frequency which is around 2.7khz, the circuit has the highest impedance, and that can be seen throughout the 3 figures is that the same is operating at the highest recorded impedance.

4-6- proteus simulation for pcb board 1

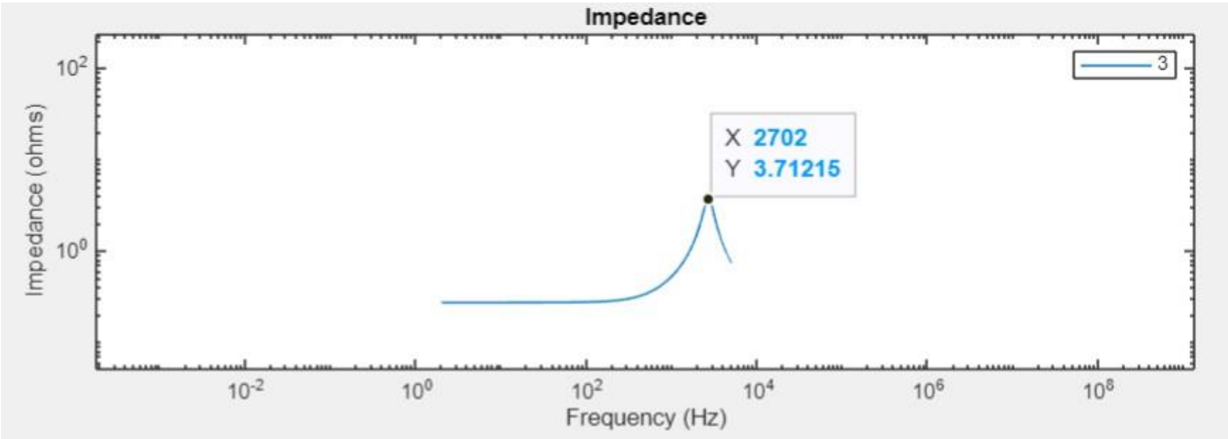


**Figure 4.6: impedance calculator on capacitor result**

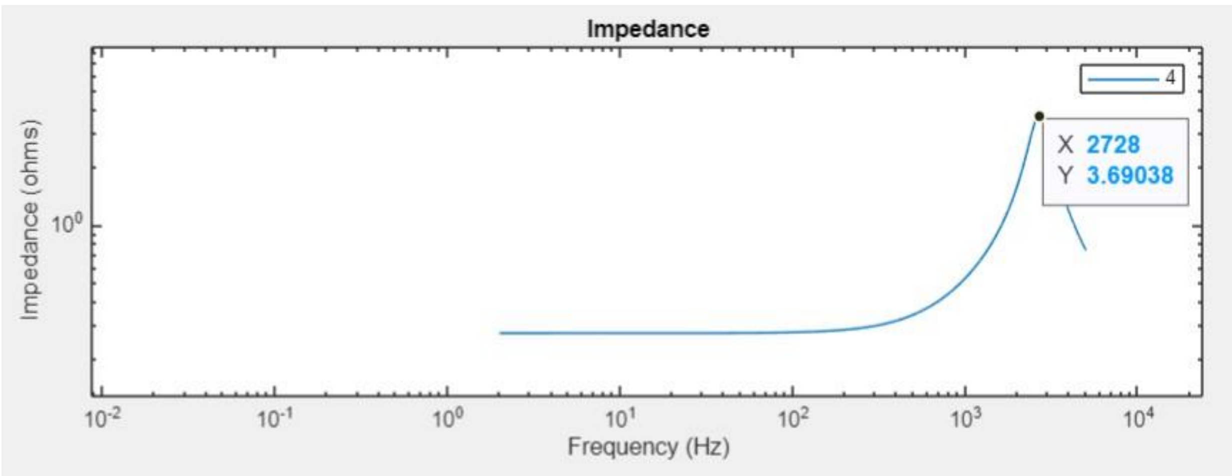


**Figure 4.7: impedance calculator on inductor result**

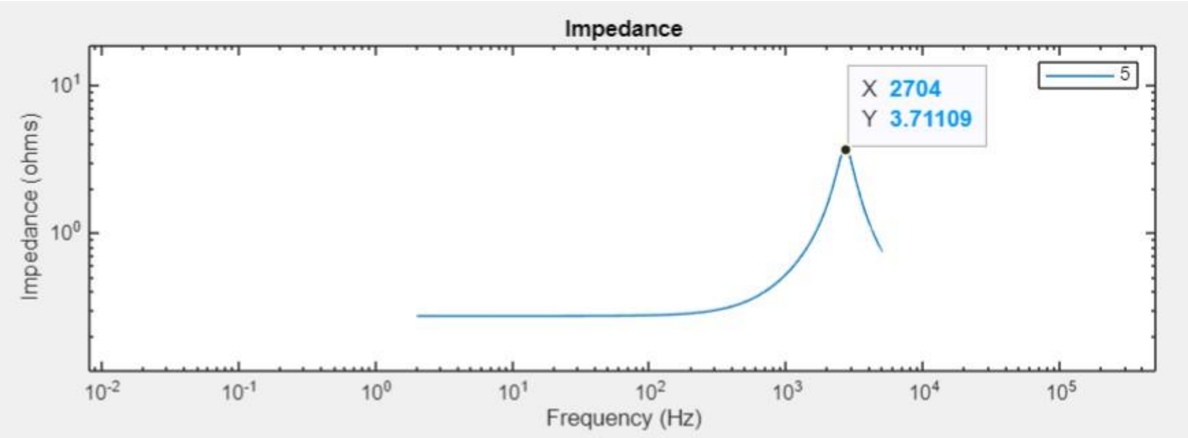


Figure 4.8: impedance calculator on source result

**4-6- proteus simulation for pcb board:** now referring to proteus to be able to create the circuit that will be printed and then we will attach our components to it to be able to have a functional hardware to test and

**20- chapter 4. Simulation results:** analyze both the gate driver and our converter as shown in figure 4.9 and 4.10. Each value has been added and tested before printing it to make sure that any excess current or sudden voltage spikes does not damage the component and affects its functionality.

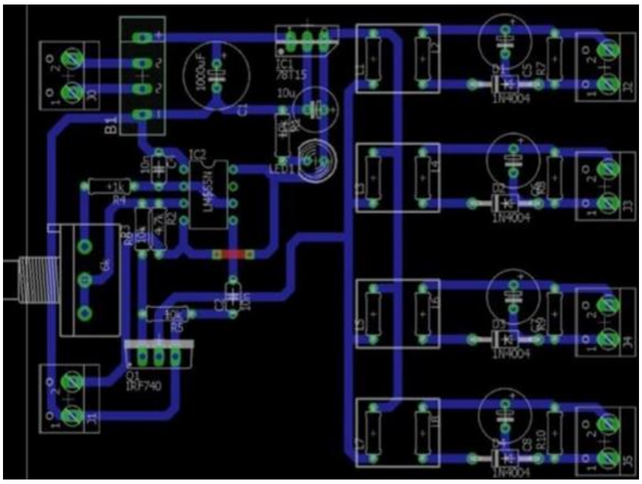

Figure 4.9: schematic of gate driver

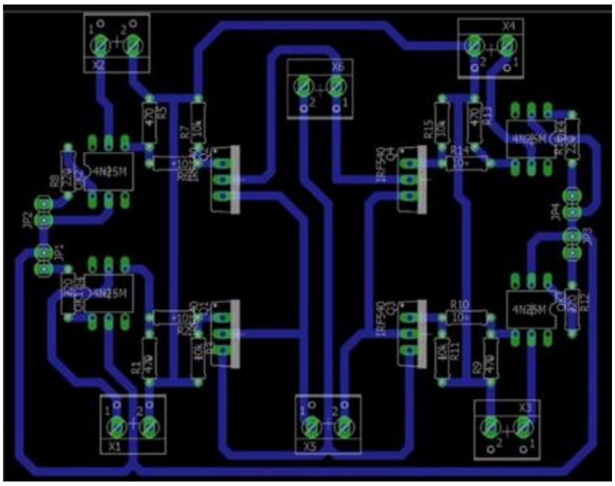

Figure 4.10: schematic of inverter circuit

## Chapter 5

**Hardware & implementation:** the implementation of the parallel lc resonant converter mainly focuses on having a prototype to test its performance in real-life. In this chapter, we will go over all the components used and how they were assembled from the capacitor to the inductor and the mosfets and most importantly the gate drives.

### 5-1- hardware components

**5-1-1-mosfet:** the irf740 mosfet as shown in figure 5.1 is a type of power switch designed to handle high voltages, making it great for things like power supplies, lights, and devices that convert power. It can work with up to 400 volts and is known for losing very little power and switching quickly. It's commonly used in machines that control motors, change power types, and manage how power is used, proving to be reliable and effective in both business and industrial uses.

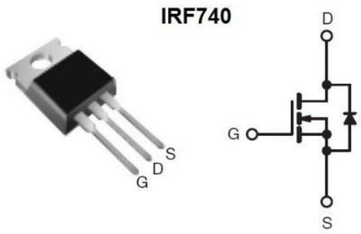


Figure 5.1: irf-740

## 22- chapter 5. Hardware & implementation

**5-1-2- ceramic capacitor:** ceramic capacitors are commonly utilized in induction heating systems, especially in high-frequency resonant circuits, due to their excellent high-frequency performance, low equivalent series resistance (esr), and low equivalent series inductance (esl). These ca- pacitors are capable of handling the rapid oscillations of current typical in these systems and offer good temperature stability, which is essential in the varying thermal conditions of induction heating. Additionally, ceramic capacitors as shown in figure 5.2 can with- stand high voltages, making them suitable for the significant power levels used in these applications. Their compact size and high capacitance-to-volume ratio are beneficial for integrating into tight circuit designs, such as those in portable induction heaters. More- over, their durability and ability to withstand physical stresses and thermal cycles make ceramic capacitors a reliable choice for the demanding environments of induction heating systems, contributing to their frequent use in forming resonant tank circuits that dictate operational frequency and manage energy transfer to the work coil.


Figure 5.2: ceramic capacitors

**5-1-3- optocouplers:** the 4n25 optocoupler is a useful component in electronic circuits like parallel lc reso- nant converters, primarily for its ability to provide electrical isolation between its input and output. This feature is crucial in applications involving high voltages or different ground potentials, where it prevents high voltage from reaching the low voltage side of the circuit, enhancing safety and protecting sensitive microcontroller or logic circuitry. In a parallel lc resonant c

Onverter, the 4n25 as shown in figure 5.3 can be used to isolate and control switching devices, such as transistors or mosfets, ensuring that signals can be transferred between different parts of the circuit without direct electrical connec- tion. This optocoupler allows for accurate control signals to pass through while blocking harmful voltage levels and noise, leading to more stable operation and reduced risk of damage. Additionally, its small size, low cost, and effectiveness in reducing electromag- netic interference (emi) are significant advantages, making it an essential component in designing efficient and robust power electronics.

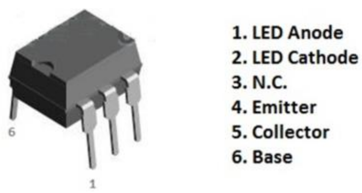


Figure 5.3: optocouplers 4n25

## 5-1- Hardware components 23

**5-2- 5-1-4- pulse transformer:** pulse transformers are critical components in parallel lc resonant converters, primar- ily used for driving power switches like mosfets and igbts.

These transformers are specialized to handle the rapid pulses needed to switch the power devices on and off efficiently. In a parallel lc resonant converter, the pulse transformer helps to isolate the control circuitry from the high-power section, safely transferring the pulse signals needed to control the switching behavior without exposing the low-voltage control side to high voltages and currents. This isolation protects the control circuits from potential voltage spikes and electrical noise, which can cause malfunction or damage. Additionally, pulse transformers as shown in figure 5.4 ensure that the signal integrity is maintained across the circuit, allowing for precise control of the switching timings, which is crucial for main- taining efficiency and performance in resonant converters. Their ability to handle high voltages and power levels while providing excellent isolation and signal integrity makes pulse transformers an advantageous choice in high-frequency, high-power applications.


**Figure 5.4: pulse transformers**

**5-1-5-three 5 timer:** the 555 timer is a versatile and widely used ic that can function as an oscillator, pulse generator, and timer, making it particularly useful in applications like parallel lc reso-

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nant converters. In such converters, the 555 timers can be configured as shown in figure 5.5 to generate precise, stable, and adjustable frequency pulses that control the switching of mosfets or other power electronic devices. This ability to produce consistent and controllable oscillations helps maintain the resonance condition of the lc circuit, which is crucial for efficient energy transfer and optimal performance. The advantages of using a 555 timer in this context include its low cost, ease of use, and reliability. It also offers flexibility in adjusting the frequency and duty cycle of the output waveform, allowing for fine-tuning of the converter's operation to match specific load requirements. Addition- ally, its robustness against voltage spikes and noise contributes to the overall stability and durability of the system.


**Figure 5.5: 555 timers**

**5-1-6- arduino uno:** the arduino uno is an invaluable microcontroller board that can significantly enhance the functionality of a parallel lc resonant converter. It enables precise control over the converter's operations through programmable logic and real-time adjustments. By inte- grating an arduino uno as shown in figure 5.6, you can dynamically adjust frequency, duty cycle, and other critical parameters based on feedback from the converter, ensuring optimal performance and adaptability to varying load conditions. This ability to pro- gram and monitor the system in real time allows for more efficient energy management and potentially higher efficiencies. Additionally, the arduino uno's extensive community support and availability of numerous libraries and examples make it easy to implement and troubleshoot, reducing development time and complexity. Its low cost, ease of use, and versatility make the arduino uno an excellent choice for enhancing control in power electronics applications like parallel lc resonant converters, providing a user-friendly in- terface and robust data handling capabilities.

Figure 5.6: arduino-uno

## 5-2- hardware implementation and circuit design 25

## 5-2- Hardware implementation and circuit design

**5-2-1- gate driver:** a gate driver is a critical component in a parallel lc resonant converter, especially when using power switching devices like mosfets or igbts. Gate drivers serve the essen- tial function of efficiently controlling the gates of these switches, providing the necessary drive voltage to turn the switches on and off rapidly. This rapid switching is crucial for maintaining the high-frequency oscillation required in resonant converters. By ensuring that the switches operate efficiently and precisely, gate drivers help minimize switching losses and improve the overall performance of the system. Additionally, gate drivers as shown in figure 5.7 can provide protective features such as under-voltage lockout, over- current protection, and thermal shutdown, which enhance the reliability and safety of the converter. The use of gate drivers in parallel lc resonant converters also allows for better isolation between the control circuits and the power stages, reducing the risk of electronic noise and interference affecting the control logic. Overall, gate drivers play a pivotal role in optimizing the efficiency and operational stability of resonant converters.

Figure 5.7: hardware of gate driver

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**5-2-2- inverter circuit:** this configuration utilizes a full-bridge inverter composed of four irf740 mosfets arranged in an h-bridge layout, integrated with 4n25 optocouplers to separate the low- voltage control signals from the high-power section. Each optocoupler receives a control signal via a current-limiting resistor (r4, r8) and subsequently activates the gate of its associated mosfet. The mosfets are organized into two pairs (q1-q4 and q2-q3). Activating one pair, such as q1 and q4, allows current to flow in one direction through the inverter, while activating the opposite pair (q2 and q3) reverses the current flow. Gate resistors (r5, r9) are used to limit the gate drive current and stabilize switching. This setup enables microcontrollers to independently control the power supply, offering flexibility to adjust output voltages. The use of optocouplers ensures that the high- voltage parts of the circuit are electrically isolated, enhancing safety by protecting the control side from potential power surges, as illustrated in figure 5.8

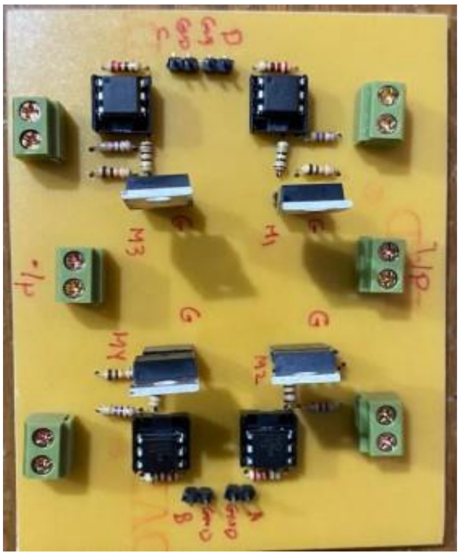

Figure 5.8: hardware of inverter circuit

## 5-3- hardware results

**5-3-1- pulses from the arduino:** the blue waveform represents the pulses entering mosfets 1 and 4, while the yellow waveform represents the pulse entering mosfets 2 and 3. As shown in figure 5.9

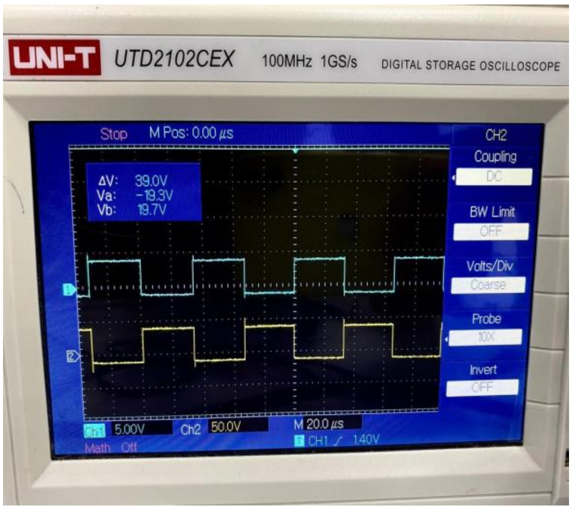


Figure 5.9: mosfet's results

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**5-3-2- output of the full-bridge converter:** the result of the full-bridge converter is a square signal as shown which has a constant magnitude from the positive to the negative. The positive and negative values shown in figure 5.10 are due to the polarity being constantly revered due to the switching devices and the way we configured them to be working in pairs.

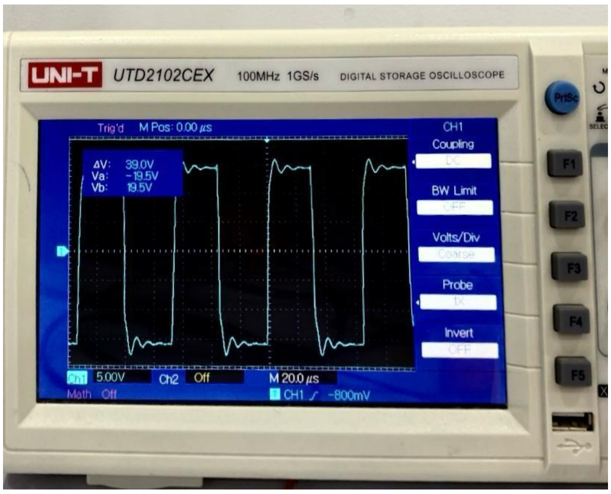


Figure 5.10: full-bridge results

# Chapter 6

## conclusion

**6-1- conclusion:** this paper addressed the parallel lc resonant converter design, implementation, and testing. As a result, we were able to test the converter under real-life conditions and we were able to conclude that the operation of the converter has been improved from efficiency and operation. Being able to design it from scratch helped us choose the com- ponents based on our goal, in addition to giving us the time to calculate everything necessary to know each and every single detail about this converter, and finally gave us the opportunity to learn more about the operation of each component used under real-life conditions and not just simulating it under ideal conditions.

The data analysis presented in this study proved the converters capacity to work at near resonance frequency to achieve our main goal, which is increasing the efficiency, due to that we deduced that we had less losses which led us to have a more stable voltage and current levels during switching of the mosfets. Using smoothing techniques gave us also a huge bonus to decrease the losses and this time we decreased the switching losses of the mosfets while being turned on/off. This technique helped us fix the timing of the switching on/off to be only done once the current through the switching device is zero and this technique is called zcs which resulted in stabilizing the voltage and current coming from the source to the tank.

Finally, this research brings value by setting a foundation for making a high-performance and reliable power conversion system based on the published method of the parallel lc resonant converter. The findings underlined the crucial role of resonant topologies, con- trol techniques, and system integration which are the means to remain in line with the development of these power electronic devices. In future studies it might bring out the testing of more advanced semi-conductors which have been proved to have lower losses or higher temperature tolerances, which is a perfect fit for this concept. In addition, study- ing an improved cooling solutions or thermal management techniques and testing them

**30 chapter 6. Conclusion:** in this field might be a breakthrough to achieve better overall efficiency and power con- version. Another potential study can be about the developing of a more enhanced control system to have a better response time, and stability in the converter which makes it more flexible during implementation and can have various applications not just in induction heating, but also for charging electric vehicles, wireless power transfer, etc.

**Appendix**

**Appendix a lists**

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