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Dedication

The thesis is submitted for the fulfillment of the requirements for the degree of Mechatronics State Engineer at the Industrial and Maintenance Engineering Department in the National Higher School of Technology. It has not been submitted before for any degree at this or any other university. The authors confirm that this thesis is based on their own work.

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List of Abbreviations and Terms

Roman Items

C	Capacitance
c	Average value of the specific heat of a material
D	Duty cycle
d_c	Inner coil diameter
d_w	Workpiece diameter
f	Frequency
f_{sw}	Frequency of switching
I	Current
I_{RMS}	Average value of the steady-state through current
k	Thermal conductivity
L	Inductance
l_c	Coil length
l_w	Workpiece length
m	Mass
P_{act}	Active power
P_{react}	Reactive power
P_c	Power of the coil
P_w	Power of the workpiece
$P_{loss (cond)}$	Conduction losses
$P_{loss (sw)}$	Switching losses

$P_{thermal\ loss}$	Thermal losses
P_{θ}	Thermal power
Q	Quality factor
$Q_{parallel}$	Quality factor of the workpiece-coil parallel model
Q_{serie}	Quality factor of the workpiece-coil series model
R	Resistance
R_{eq}	Equivalent resistance of a workpiece-coil
$R_{eqparallel}$	Resistance of the workpiece-coil parallel model
$R_{eqserie}$	Resistance of the workpiece-coil series model
R_{θ}	Thermal resistance
S	Apparent power
t	Required heating time
T_A	Ambient temperature
T_{in}	Average value of the initial temperature
T_f	Average value of the final temperature
T_s	Sampling period
V	Voltage
v_{ac}	AC source voltage
V_D	Diode voltage
V_F	Diode forward bias voltage value
V_Z	Reverse breakdown voltage value
$Z_{eqparallel}$	Impedance of the workpiece-coil parallel model
$Z_{eqserie}$	Impedance of the workpiece-coil series model

Greek items

δ_c	Penetration depth of the coil
δ_w	Penetration depth of the Workpiece
ϵ_r	Penetration depth of the Workpiece
η_{el}	Electrical efficiency
η_{th}	Thermal efficiency
μ	Magnetic permeability
μ_r	Relative magnetic permeability
π	Mathematic constant
ρ_c	Electrical resistivity of the coil
ρ_w	Electrical resistivity of the workpiece

Acronyms

<i>AC</i>	Alternating Current
<i>BJT</i>	Bipolar Junction Transistor
<i>CFI</i>	Current-fed inverter
<i>DC</i>	Direct current
<i>EEPROM</i>	Electrically-erasable programmable read-only memory
<i>ESR</i>	Equivalent series resistance
<i>FET</i>	field effect transistor
<i>IGBT</i>	Insulated Gate Bipolar Transistor
<i>IH</i>	Induction heating
<i>MOSFET</i>	Metal Oxide Semiconductor Field Effect Transistor
<i>MCT</i>	MOS-controlled thyristor
<i>MSPWM</i>	Modified Sinusoidal Pulse Width Modulation

PWM Pulse Width Modulation

RAM Random Access Memory

RMS Root mean square

SPWM Sinusoidal Pulse Width Modulation

SCR Silicon Controlled Rectifier

VFI Voltage-fed inverter

ZCS Zero current switching

ZVS Zero voltage switching

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General Introduction

Induction heaters, infrared heaters, fluidized bed furnaces, gas-fired furnaces and other methods are used to heat metallic materials. Each method has its own advantages and disadvantages. There is no universal approach that is best in all circumstances. However, in the past four decades, heating by means of electromagnetic induction has become more popular for a variety of reasons, among them we mention:

- The ability to heat a workpiece quickly and in well-defined areas, both deeply and with a high level of heat;
- Intensity if needed;
- Repeatability;
- High controllability;
- Better efficiency in terms of energy;
- The decrease in heat exposure;
- More safely utilized, in conjunction with minimal equipment cost;
- Significantly improves the surface quality of heated metallic materials;
- Need less time to start and to shut down;
- Advanced monitoring;
- Piece-by-piece processing capability with component-by-component tracing.

The physical phenomenon of Induction heating (*IH*) is realized when an alternating current passes through a coil, this action leads to the creation of an alternating magnetic field around that coil. Now when we place a ferromagnetic workpiece inside the it, the alternating magnetic field creates circular currents on the surfaces of the workpiece, these circular currents are called Eddy Currents (currents created in a conductor by a changing magnetic field), the direction of these current is the opposite direction of the current flowing through the coil, but they have the same frequency. The final phenomenon is that Eddy Currents produce heat in the workpiece by joule effect (resistive heating).

IH is a complicated phenomenon comprising electromagnetics, heat transfer, materials science, and circuit analysis interactions. These phenomena are very nonlinear and interconnected. An *IH* system consists of a heating inductor, power supply, load-matching station, water cooling and quenching systems (for heat-treating applications), controls, bus network, and the workpiece itself.

Heating inductor, inductor, induction coil, and coil are synonymous words for the electrical equipment that produces the *IH* effect closest to the workpiece. Despite the fact that an inductor is commonly referred to as a coil, its geometry does not always mirror the classic circular coil shape. Fig. 1 depicts an array of an almost infinite range of heating inductor geometries required to fit a corresponding variety of workpieces.



Figure 1. A variety of geometries of heating inductors used in IH systems.[1]

Induction heating systems have several uses in various domains, including medical, domestic, and industrial applications. When discussing domestic uses, we can include, for instance, induction-cooking appliances. In addition, induction heating is utilized in the production of medical devices due to its reliability, cleanliness, and safety. In the industrial sector, heat treatment, mass heating, special applications, induction melting, and induction welding are the five most important applications of induction heating. Each of the five aforementioned sectors has unique uses for induction heating.

A brief description of each group appears in Fig. 2 below.

Heat treatment	Mass heating	Special applications
– Hardening – Tempering – Stress relieving – Annealing – Normalizing – Sintering, etc.	– Billet, bar, and rod heating – Slab and bloom heating – Strip and plate heating – Wire and cable heating – Tube and pipe heating – Slug heating, etc.	– Joining, brazing, soldering, bonding, and shrink fitting – Seam and full-body annealing – Banding and shaping – Sealing, coating, and plating – Miscellanies
Induction melting	Induction welding	

Figure 2. Industrial applications of IH.[1]

For an *IH* system to work efficiently with a good power consumption, two aspects should be taken into consideration; the first aspect is the power supply circuit, and the other one is the control and modulation technique. Many topologies of power supplies are available depending on the application, so in order to choose the topology, the application should be chosen first. We can say the same for the control method, depending on the chosen power supply , an appropriate control method should be also chosen.

A basic scheme of a simple induction heating setup is shown in Fig. 3

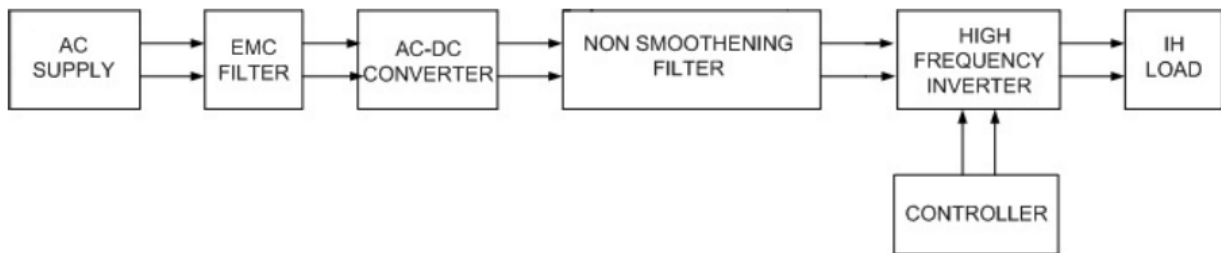


Figure 3. Block diagram of the induction heating system. [2]

CHAPTER 1

Induction Heating Systems

1.1 Introduction

Induction heating (*IH*) is a technique used to heat electrically conductive materials. In this method, the heat is produced by the joule effect generated by the Eddy Currents in the material. It has many advantages compared with other heating systems such as fast heating, low start up time, and high energy saving. This chapter introduces the history of induction heating and how it came from being a side effect into being one of the most used heating methods in different fields. After that, the basic working principle of *IH* is explained along with mentioning different industrial applications where *IH* is used widely.

1.2 Brief History

Since the end of the 1800s, *IH* technology has moved forward in the same way that industry and technology have. Michael Faraday discovered the *IH* principle when he discovered magnet-induced currents. James C. Maxwell later developed the unified theory of electromagnetics while James P. Joule defined the heat generated by a current in a conductor, establishing the essential principles of *IH*.

Sebastian Z. de Ferranti came up with the first industrial uses of *IH* in 1887 when he suggested using it to melt metals. He also filed the first patent on industrial uses of *IH*. F. A. Kjellin created the first completely operable induction furnace in 1891.

In 1916, Princeton's Edwin F. Northrup built the first high-frequency induction furnace, this was the first big step forward. M. G. Ribaud and Valentin P. Vologdin worked on high-frequency *IH* technology using spark-gap generators almost at the same time. Vologdin later made *IH* generators that used machine generators and vacuum tubes. These were the earliest examples of contemporary high-frequency *IH* systems. During and after World War II, the aerospace and automotive industries used *IH* technology more for melting metal and improving the way materials were treated, it made *IH* technology much more common in industrial processes.

The second significant technological advancement in *IH* occurred with the invention of solid-state devices. Utilizing innovative power semiconductor technology, namely thyristors, these devices are used to implement very efficient power converters. Later, when higher frequency power devices like the power Bipolar Junction Transistor (*BJT*) and the power Metal Oxide Semiconductor Field Effect Transistor (*MOSFET*) were invented, *IH* became the technology of choice for many applications. In conjunction with further advancements in semiconductor technology and the successful Insulated Gate Bipolar Transistor (*IGBT*), the level of performance and efficiency attained by *IH* systems, as well as the successful introduction of the *IGBT*, have expanded the applications of *IH* technology beyond the industrial setting.

Since the late 1980s, it has been used in many different domains, and *IH* cookers are now well-known in many countries. In addition, in the twenty-first century, there has been a strong interest in *IH* for medical applications due to its various advantages in terms of precise and local heating for hyperthermia treatment.

Today, *IH* technology is rapidly advancing toward more dependable and efficient systems, allowing the implementation of highly flexible systems that will make *IH* widespread. The following section outlines the current state of the technologies that make such systems possible. [3]

1.3 The working principal of IH

The main advantage of the *IH* method is that it produces the heat inside the workpiece without the need for any external heat source. In *IH* system, the surrounding is not exposed to any thermal and atmospheric pollution. Clean and fast heating can be supplied to the piece to be heated by meeting the increased requirements with regard to the environmental protection.

IH systems are developed using the principle of electromagnetic induction. Electromagnetic induction refers to the phenomenon by which electric current is generated in a closed circuit by the fluctuation of the current in another circuit next to it. The fluctuation of the current in the primary circuit is the reason for the mysterious current generated in the neighboring secondary circuit. This electromagnetic induction principle developed by Michael Faraday led to the development of electric motors, generators, and transformers. Heat loss, which occurs in the process of electromagnetic induction, has been a major problem since it causes power losses. In motors and transformers, this heat loss is minimized by the lamination of the magnetic core. Heat loss, occurring in the process of electromagnetic induction, can be turned into productive heat energy in *IH* system.

The piece that needs to be heated, also known as a *workpiece*, and the inductor or *coil* that creates the magnetic field required to generate the heat are the two fundamental components of an *IH* system. Fig. 4 depicts the *IH* system's configuration. Any shape of the workpiece is acceptable for the inductor, which is typically placed inside the coil for improved coupling. A large alternating current is generated through a coil using a high frequency electrical source. The passage of current through it generates a very intense and rapidly changing magnetic field in the space within the work-coil. This powerful alternating magnetic field is placed around the workpiece that needs to be heated. [4]

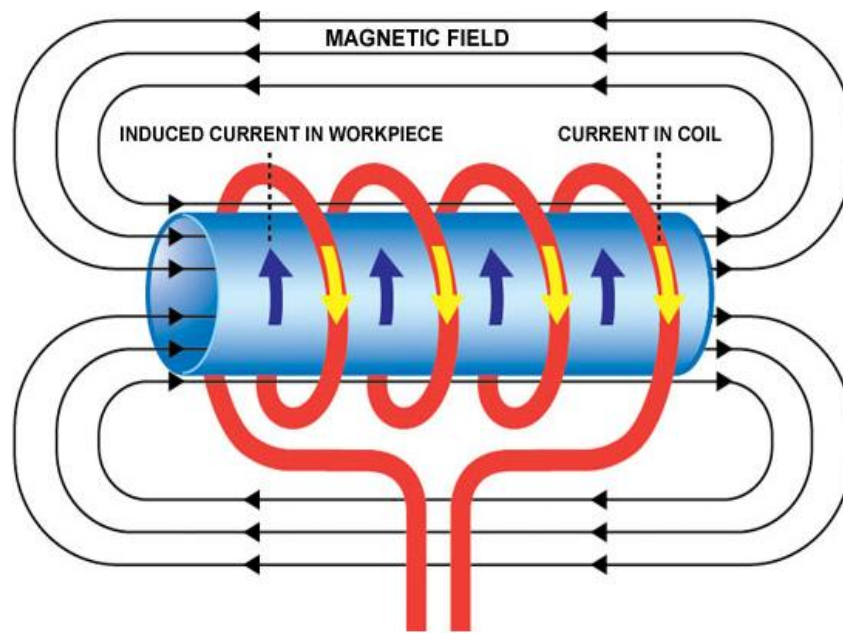


Figure 4. Schematic induction heating process.

1.4 IH in Industrial Applications

1.4.1 Heat treatment

The word heat treatment refers to a vast variety of operations. Although it is possible to heat treat other materials using electromagnetic induction, steels and cast irons account for the vast majority of metallic components that undergo induction heat treatment.[1]

1.4.1.1 Hardening

Hardening steels, cast irons, and powder metallurgy materials is one of the most common applications of induction heat treatment. Among other workpieces, Fig. 5 depicts components (e.g., camshafts, crankshafts, gears, constant-velocity front wheel drive components, transmission shafts, ball studs, pins, tool working surfaces, etc.) that are commonly hardened using electromagnetic induction to develop an attractive combination of properties.[1]



Figure 5. Induction hardening.

A typical hardening procedure for steels and cast irons includes heating the alloy to the austenitizing temperature range, holding it (if necessary) at a temperature long enough for the formation of a fully or primarily austenitic structure, and then rapidly cooling/quenching it below the critical temperature when martensite begins to form. Rapid cooling permits the diffusion-dependent transition of austenite to be replaced by a diffusion-free shear-type transformation, resulting in the creation of the considerably harder component martensite.

A material can be hardened to produce specific attributes or combinations of properties, such as strength and wear resistance, as well as a preferred distribution and size of residual stresses. In some instances, it is necessary to harden the entire cross section of the workpiece (so-called thorough hardening); while, in other cases, it is sufficient to harden only specific parts (e.g., surface hardening or hardening of a portion of the workpiece). [1]

1.4.1.2 Tempering and stress relieving

A component can experience both localized induction through hardening and surface (case) hardening (e.g., ends or middle sections). This method is often referred to as selective hardening. Components treated in this way include valve seats (hardened zone length is between 3 and 12 mm), clutch pusher disk spring (hardened zone length is between 4 and 7 mm), levers, shifting forks, blade cutting edges, tool joins, locking bolts, and other fasteners.

Similar to induction hardening, electromagnetic induction tempering has been discovered to be a viable commercial technique, replacing conventional furnace/oven operations in a number of high-volume manufacturing applications. [1]

1.4.1.3 Normalizing

After various steel processing procedures, such as casting, forging, cold drawing, and rolling, microstructures that are significantly heterogeneous are generated. Re-austenization during normalizing leads to the nucleation and development of new austenite grains, which, upon air-cooling, provide significantly more uniform ferritic/pearlitic microstructures composed of equiaxed grains. In the bulk of technological operations, homogenized structures are often extremely desired. For instance, it is frequently recommended to normalize parts before quick induction hardening in order to provide a consistent steel response to brief austenization and to minimize distortion. [1]

1.4.1.4 Annealing

Annealing is a broad term used by heat treatment professionals to represent a multitude of processes and features relating to microstructure, machinability, formability, easing internal tensions, boosting specific electrical properties. [1]

1.4.2 Mass heating

Induction mass heating is used to heat a variety of metallic materials to temperatures acceptable for warm and hot forming (i.e., forging, upsetting, rolling, extrusion, bending, thixoforming, etc.) as well as pre-/postheating for coating operations. In many instances, the primary objective is to raise the temperature of the workpiece to a specific level while preserving the required temperature uniformity. A nonuniformly heated piece of stock may cause premature wear on hammers and presses, as well as problems related to excessive force necessary to form the metal. [1]

1.4.3 Induction melting

In order to produce metal, it is necessary to heat the metal or ore to its melting point and frequently maintain it at that temperature for metallurgical processing. Induction, arc, and resistance electric furnaces are utilized in metal melting. The most common types of induction melting furnaces are the channel type and the crucible type, which can melt irons, steels, aluminum, copper, zinc, and nickel, among other metals and alloys. [1]

1.4.4 Induction welding

The manufacturing of tubes is one of the main industries where electromagnetic IH is used. This includes heating a sheet of metal that has been shaped into a tube and is restrained in a way that causes eddy currents in the workpiece to weld the seam between the two open ends of the sheet.

To accomplish this, the V-shaped open seam region of the tube is encircled by a cylindrical coil. The so-called forge weld is created by squeeze rolls pressing the strip edges together at the region of greatest induced current density (Fig. 6). The method is typically made more effective by inserting a water-cooled magnetic flux concentrator inside the tube. Induction welding commonly employs power between 50 and 1500 kW and relatively high frequencies between 200 and 600 kHz. [1]

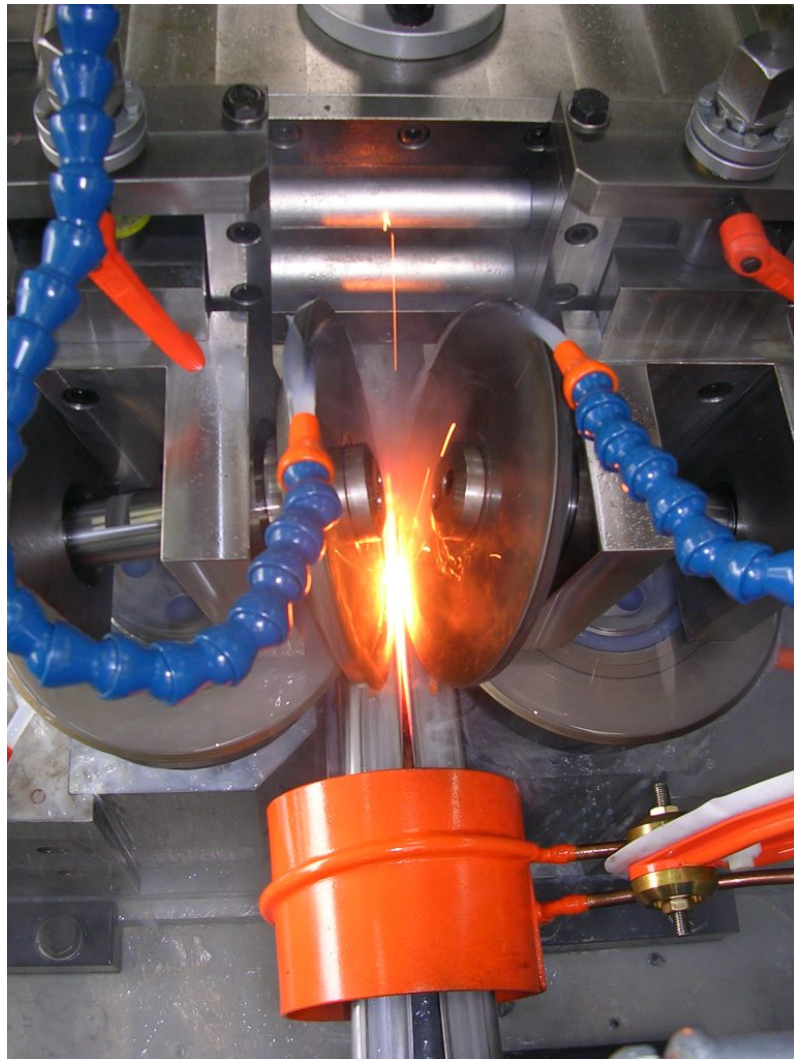


Figure 6. Tube welding. [5]

1.5 Conclusion

It all started with the discovery of electromagnetic induction by Michael Faraday, since then, this phenomenon has been investigated throughout the years, and used in many different applications.

If an alternating current is applied to a coil, an electromagnetic field is generated around the coil. If a workpiece is placed close enough to it, an electric current will be induced in it. The resistance of this electric current's flow causes the workpiece to heat up, this is the phenomenon of Induction heating briefly.

IH is used in many fields such as domestic, medical, and industrial domains, but since the industrial applications of *IH* are the most widely used applications around the world we have chosen to mention them in detail.

CHAPTER 2

Theoretical Background

2.1 Introduction

When it was discovered that heat was produced in transformer and motor windings, Induction heating was initially investigated. The theory of IH was studied so that motors and transformers might be manufactured with the least amount of heat loss possible. Induction's early uses were based on trial and error, with personal knowledge of specific applications but a lack of grasp of the fundamental concepts. Over time, our grasp of the fundamental concepts has grown, and we now have computer modeling of heating applications and processes.

When an induction coil is powered by an alternating current, an electromagnetic force field is created around the coil. If we place a workpiece close enough to it, an electric current is induced in the workpiece. The resistance of the flow of this electric current causes the piece to heat up. The actual heating is a complicated function including the interaction between the workpiece's physical and electrical properties as it is heated to higher temperatures. Thermal conductivity and specific heat, as well as electrical and magnetic properties like resistivity, permeability, and frequency, are all parameters that influence the heating process.

All metals conduct electricity and offer resistance to the flow of current. This resistance results in a power loss, which manifests as heat. The reason for this is the law of conservation of energy, which states that energy does not vanish but rather changes its form.

The dissipated power of a resistor is given by $P = R.I^2$, where I is the amount of current and R is the resistance. Due to the fact that the amount of power is proportional to the square of the current, doubling the current greatly increases the amount of power (or heat) produced. Silver and copper, for instance, have extremely low resistance and are hence good conductors. Silver is a pricey metal that is infrequently employed in electrical wire. Copper wires are utilized for energy transmission across power lines due to their minimal heat loss during transmission. Other metals, including steel, have a high resistance to electric current; therefore, sending an electric current through them generates a great deal of heat. The heating coil atop an electric stove is an example of resistance used to generate heat by the 60 Hz home electric current.[6]

2.2 Electromagnetic phenomenon

Due to various electromagnetic phenomena, the current distribution inside an inductor and workpiece is not uniform. This inhomogeneity of the heat source results in temperature gradients in the workpiece. Nonuniform current distribution is linked to a number of electromagnetic phenomena.

These phenomena have a significant impact on the performance of an *IH* system. It is essential to comprehend the different electromagnetic properties of heated materials before investigating the elements that influence magnetic field distribution and eddy current flow.

2.2.1 Electromagnetic properties of metallic materials

When talking about electromagnetic properties, we are talking about many concepts and characteristics, but we will only focus on the properties that affect the efficiency of an *IH* system.

2.2.2 Electrical resistivity

Metals and alloys are considered to be good electrical conductors and have much less electrical resistance to the current flow compared to other materials.

There are metals and alloys that are considered being low-resistive metals (e.g., silver, copper, gold, magnesium, aluminum) and high-resistive metals and alloys (e.g., titanium, carbon steel, stainless steel, tungsten, Ni-based superalloys).

Electrical resistivity of metallic materials varies with temperature, chemical composition, microstructure, and grain size. For most metals, rises with temperature. For some electrically conductive materials, decreases with temperature.

One should not confuse electrical resistivity with electrical resistance which is a property of an electrical circuit.[1]

2.2.3 Magnetic permeability and Penetration depth of the Workpiece

Relative magnetic permeability (μ_r) indicates the ability of a material (e.g., metal) to conduct the magnetic flux better than a vacuum or air. Penetration depth of the Workpiece (ϵ_r) (or dielectric constant) indicates the ability of a material to conduct the electric field better than a vacuum or air.

On the basis of their magnetic properties, all substances can be classified as paramagnetic, diamagnetic, or ferromagnetic. Paramagnetic materials have a relative magnetic permeability slightly larger than 1. For diamagnetic materials, the value of μ_r is somewhat less than 1. Due to the negligible changes in μ_r between paramagnetic and diamagnetic materials, these materials are referred to as nonmagnetic in *IH* practice. Unlike paramagnetic and diamagnetic materials, ferromagnetic materials have a μ_r greater than one. [1]

2.2.4 Skin effect

When a direct current travels through a conductor that stands alone, the electrical current distribution within the conductor's cross section is uniform. Nevertheless, the current distribution is not uniform when an Alternating Current (*AC*) travels through the same conductor.

The maximum value of the current density is always located at the surface of a conductor, the current density decreases from the conductor's surface to its center [1]. Therefore, nearly all of the heat is produced at the surface. [6]

This phenomenon of nonuniform current distribution inside the cross section of a conductor is known as the skin effect, and it always happens when AC flow is present. [1]

This phenomenon is one of the primary causes of eddy current concentration in the surface layer ("skin") of the workpiece.

Due to the skin effect, approximately 86% of the power will be focused in the reference depth, which is the surface layer of the conductor. [1]

The depth of heating is dependent on the frequency of the alternating current field, the electrical resistivity of the workpiece, and its relative magnetic permeability. The reference depths decrease as frequency increases and increase as temperature increases.

If the ratio of workpiece diameter to reference depth for a round bar falls below around 4:1, the heating efficiency decreases, Consequently, the cross-sectional area of the heated object must be four times the depth of reference.[6]

2.3 Thermal phenomenon

2.3.1 Thermal properties of materials

2.3.1.1 Thermal conductivity

Thermal conductivity (k) designates the rate at which heat travels across a thermally conductive workpiece. A material with a high k value will conduct heat faster than a material with a low k . [1]

2.3.1.2 Specific heat

An Average value of the specific heat of a material (c) represents the amount of the required energy to be absorbed by a unit mass of the material to achieve a unit temperature increase.[1]

2.3.2 Modes of heat transfer

When talking about IH systems, all three heat transfer modes are present, these modes will be explained next.

2.3.2.1 Thermal conduction

By conduction, heat is transmitted from high-temperature parts of the workpiece to low-temperature regions.

2.3.2.2 Thermal convection

Unlike thermal conduction, heat transfer by convection is carried out by fluid, gas, or air.

2.3.2.3 Thermal radiation

In thermal radiation, heat can be transferred from a hot workpiece to its surroundings, which may include a nonmaterial region (vacuum). The impact of heat transfer through radiation is a phenomenon of electromagnetic energy propagation resulting from a temperature difference.

2.4 Power estimation

Once the workpiece (form and material) and the heat treatment (temperature and productivity) have been determined, the process frequency, and power needs of the converter feeding the resonant tank must be determined.

2.4.1 Frequency selection

The power converter must be able to commutate at a frequency that produces a wire penetration depth that is less than one-fourth of the wire's diameter.

2.4.2 Power requirements

Since the value of specific heat c represents the amount of thermal energy required to be absorbed by a unit mass of the workpiece to achieve a unit temperature increase, an c can be used to estimate the Power of the workpiece (P_w) necessary to heat it to an average temperature rise at the required production rate.

$$P_w = m \cdot c \frac{T_f - T_{in}}{t} \quad (2.1)$$

Where:

- m : is the heated body's mass [kg]
- c : is the average specific heat [$J/(kgC)$]
- T_{in} and T_f : are the average initial and final temperatures [$^{\circ}C$]
- t : is the needed heating time [s]

It is essential to understand that the P_w does not correspond to the power at the coil terminals (the so-called coil power). Equation 2.2 establishes a relationship between Power of the coil (P_c) and Power of the workpiece (P_w):

$$P_c = \frac{P_w}{\eta_{el} \cdot \eta_{th}} \quad (2.2)$$

where:

- η_{el} : Electrical efficiency
- η_{th} : Thermal efficiency

2.5 Joules and hysteresis losses

IH phenomenon is characterized by two energy dissipation mechanisms:

2.5.1 Energy dissipation due to joule effect

When an alternating voltage is applied to an induction coil, the coil generates an alternating current. This current generates an alternating magnetic field (Ampere's law), which creates a voltage in the workpiece that opposes this magnetic field's variation (Lenz's law). This voltage induces eddy or Foucault currents in the workpiece, which have the same frequency but opposite direction as the initial current. The Joule effect causes these eddy currents to produce heat in the object. [4]

2.5.2 Energy dissipation due to hysteresis

When ferromagnetic materials are magnetized in opposite directions, friction between dipoles is responsible for these losses. They manifest themselves in ferromagnetic materials below their Curie temperature (temperature at which the material becomes non-magnetic). In the majority of IH applications, hysteresis losses account for less than 7% of eddy current losses. Consequently, eddy currents are the primary mechanism of energy dissipation and the most significant in IH . [4]

2.6 The electrical model of the inductor and the workpiece

In the majority of engineering fields, it is important to identify the physical phenomenon in order to construct a model with similar behavior to the actual situation. The objective of this model is to reduce the complexity of the actual problem to a formulation that enables examining the behavior of the system. In the case of IH , this requirement has led to the development of numerous models based on various simplifications and assumptions. Typically, inductor-workpiece systems are modeled using inductors and resistors.

Usually, an Inductance (L) and a resistance R_{eq} are used to electrically simulate the induction coil and the workpiece. The equivalent resistor represents both the workpiece's resistance and the inductor's resistance. Its value relies on the geometries and materials of the coil and workpiece, the frequency of the operation, and other variables.

As illustrated in Fig. 7, there are two primary models representing the induction coil and the workpiece: the series model and the parallel model.[4]

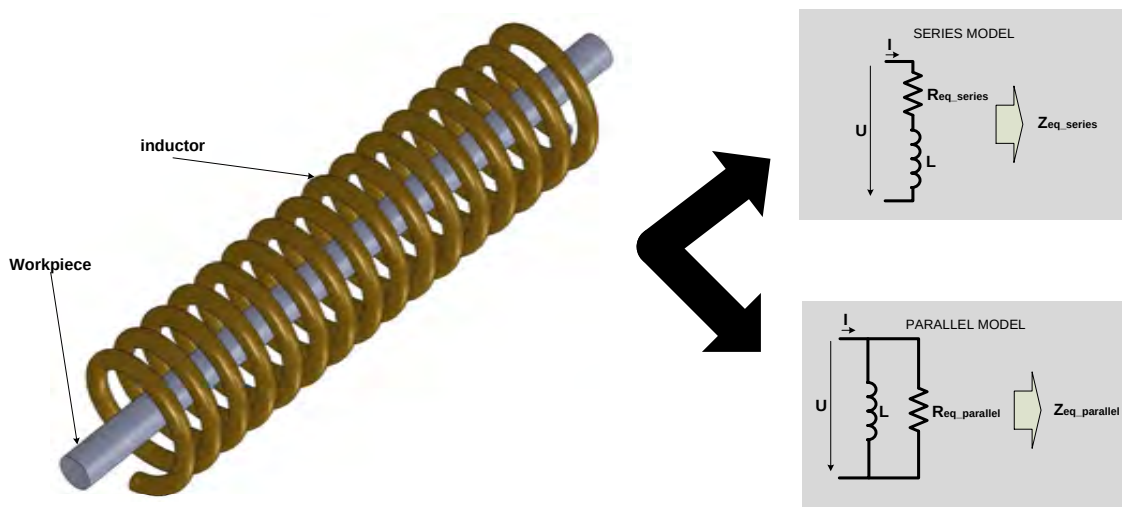


Figure 7. Electrical model of the inductor-workpiece.

2.6.1 Series model

In any IH application, one of the parameters that characterizes the inductor workpiece system is the Quality factor (Q). This factor is defined as the ratio between the Reactive power (P_{react}) and the Active power (P_{act}) of the system.

$$Q = \frac{|P_{react}|}{P_{act}} \quad (2.3)$$

In the case of the series model, the inductor and the equivalent resistor are in series. Thus, the apparent power is equal to:

$$S = I^2 Z_{eqseries} = I^2 (R_{eqseries} + j\omega L) \quad (2.4)$$

Then, the quality factor can be expressed as:

$$Q_{serie} = \frac{|P_{react}|}{P_{act}} = \frac{\omega L}{R_{eqserie}} \quad (2.5)$$

2.6.2 Parallel model

In the parallel model, the inductor and the equivalent resistor are in parallel, in this case the power is equal to:

$$S = \frac{V^2}{Z_{eqparallel}} = V^2 \left(\frac{1}{R_{eqparallel}} + \frac{1}{j\omega L} \right) \quad (2.6)$$

and the quality factor becomes:

$$Q_{parallel} = \frac{\frac{1}{\omega L}}{\frac{1}{R_{eqparallel}}} = \frac{R_{eqparallel}}{\omega L} \quad (2.7)$$

it is possible to pass from one model to another by using the following condition:

$$R_{eqparallel} = R_{eqserie} \times Q^2 \quad (2.8)$$

2.7 Conclusion

As it was stated before, *IH* comprises many phenomena; electromagnetism, thermal, and also circuit analysis. In this chapter we mentioned and explained each phenomenon in depth starting from electromagnetic properties of metallic materials, the skin effect phenomenon, thermal properties of metallic materials, and different modes of heat transfer during the *IH* process. Furthermore, we discussed the frequency selection and power estimation for an *IH* application. Also, we talked about the two types of losses of an *IH* system which are losses due to joule effect and losses due to hysteresis. Finally, the electrical model of the inductor and the workpiece was introduced.

CHAPTER 3

Power Supply and Control Techniques

3.1 Introduction

Induction heating (*IH*) power supplies are frequency converters that convert the utility line frequency to a single-phase frequency suitable for the *IH* application chosen. In general, they are a combination of converters, inverters, and oscillators. The converter section of the power supply converts the input line frequency *AC* to Direct current (*DC*), while the inverter or oscillator portion converts the *DC* to the required heating frequency single-phase *AC*.

The application will determine the frequency, power level, and other inductor parameters, such as coil voltage, current, and power factor. This link between power and frequency is illustrated in Fig. 8 for popular induction heating applications.

As previously noted, frequency is a crucial characteristic because it is the fundamental determinant of the depth of current penetration. The power components must be rated for operation at the given frequency, hence frequency plays a vital role in the design of power supplies. The power circuit must guarantee that these components are operated with a sufficient margin to achieve good dependability at the chosen frequency.[1]

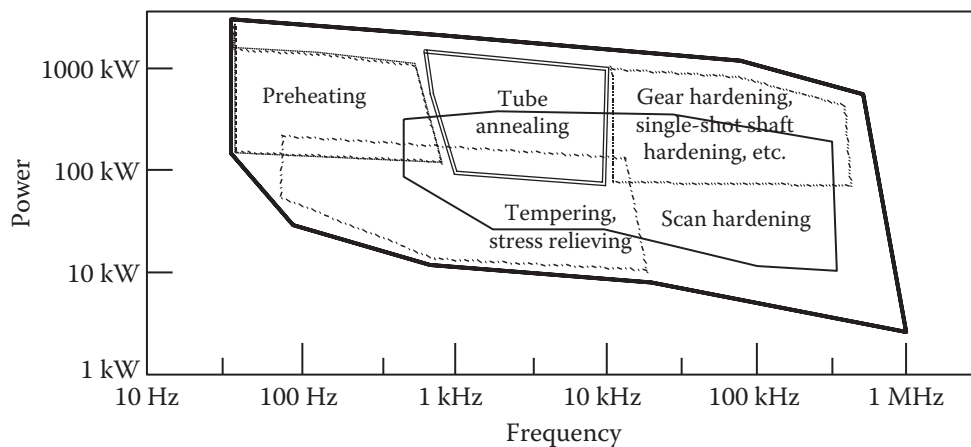


Figure 8. Power–frequency diagram for typical induction heat-treating applications.

3.2 Elements of power electronics

The majority of current *IH* power supplies are load-resonant. This indicates that the inductive and resistive components of the power supply circuit are given by the heating coil and the resistance of the induction-heated object. The geometry of this coil, which is often defined by the application requirements, dictates the inductance and resistance of the circuit.

Capacitors used in *IH* equipment must be able to handle high voltage and high current at *IH* frequency. The various sizes and shapes of these capacitors are depicted in the fig. 9. Most are water-cooled and housed in aluminum enclosures with big power hookup studs for bus bars. To reduce power loss and voltage drop within the capacitor, it is imperative that these capacitors have extremely low internal resistance and inductance values. [1]

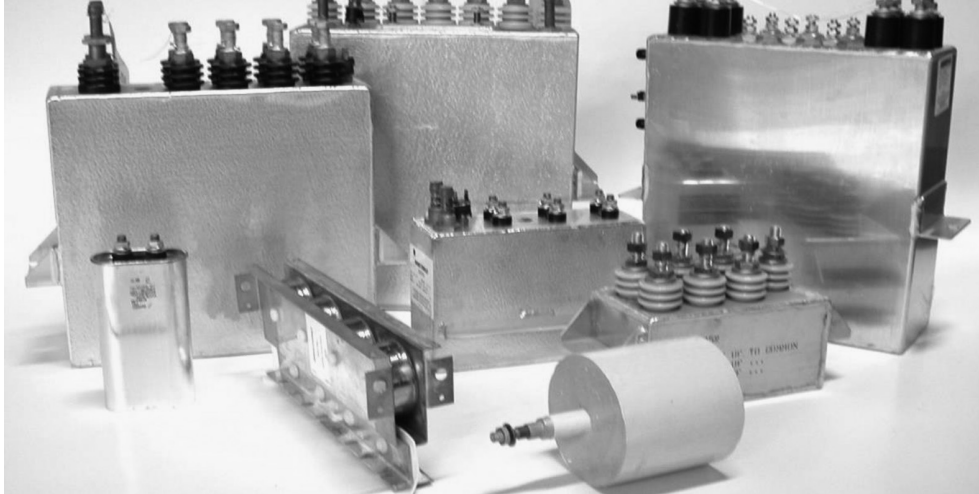


Figure 9. Power capacitors used in *IH* equipment come in a variety of sizes and shapes.

Utilizing Litz cable minimizes losses caused by high-frequency skin effect in cables used within and to interconnect power supply. This cable is composed of small, individually insulated copper wire strands. These strands are then coiled and twisted in a way that minimizes skin effect losses even further.

The frequency utilized for *IH* was initially generated using high-power vacuum tubes in an oscillator circuit. Modern power supplies use power semiconductors such as Silicon Controlled Rectifier (*SCR*), diodes, and transistors to switch the direction of current flow from a direct current source to produce alternating current at an application-specific frequency. [1]

3.2.1 Diodes

A diode is the most simple power semiconductor. When forward-applied voltage is provided to a diode, it will conduct current. When the voltage is inverted, the diode begins to block current flow.[1]

It is a conductor in the positive direction, and an insulator in the negative direction. Once it starts conducting, the resistance of it is negligible. It is like a closed switch. The voltage and current relationship across a diode has three regions: forward bias region, reverse bias region, and reverse breakdown region. When the voltage is larger than the forward

bias voltage value ($V_F = 0.3\text{V}$ for germanium diode, $V_F = 0.6\text{V}$ to 0.7V for silicon diode), $V_D > V_F$, the diode becomes a conductor and acts as a closed switch. Hence, the current increases very fast indicating very low resistance at this device. The actual value of the current is determined by the rest of the circuit. In this region, the diode can be considered as a closed switch with negligible resistance and a small voltage drop of V_F . When the diode is in the reverse bias region, $V_Z < V_D < V_F$, then the diode acts as an insulator or open switch. In other words, it acts like a very large resistor. When the $V_D < V_Z$, the diode operates in the break down region, and acts as a closed switch. [7]

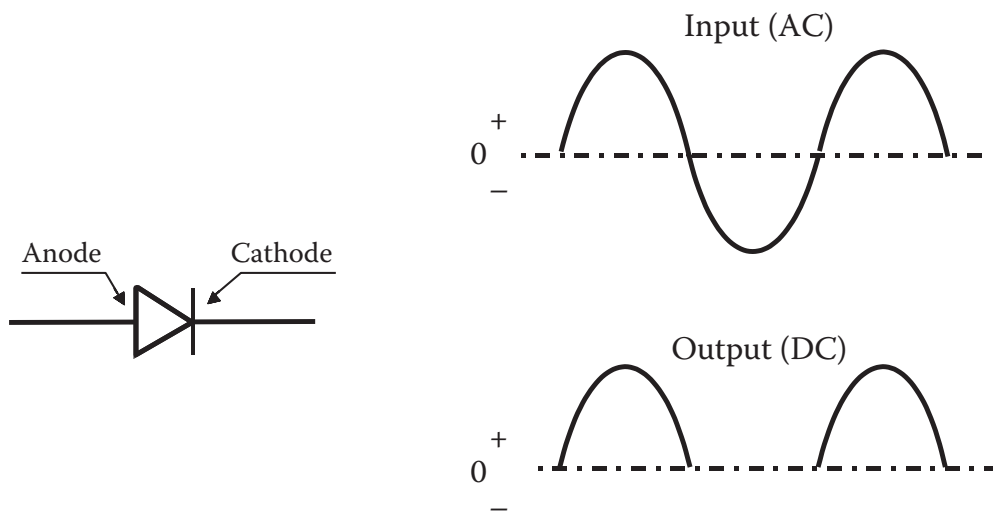


Figure 10. Symbol and waveshapes of a diode

3.2.2 Transistors

A transistor can operate in two distinct ways, either as an ON/OFF switch or as a proportional amplifier. It is an electronic switch that can be fully or partially opened or closed. A transistor can also be viewed as a variable resistance whose value is determined by the gate current. It is an element that controls the flow of electricity from source to load. A transistor is a three-terminal device constructed from two junctions of p- and n-type semiconductors. If the junctions are in n-p-n order, the transistor is referred to as a npn-type transistor. If the connections are in p-n-p order, the transistor is pnp-type. The most prevalent transistors are Bipolar Junction Transistor (*BJT*). Metal Oxide Semiconductor Field Effect Transistor (*MOSFET*) have a lower gate current need, greater efficiency, and a higher switching frequency. Insulated Gate Bipolar Transistor (*IGBT*) are a relatively new type of transistor that aims to combine the benefits of *BJT* with *MOSFET*. [7]

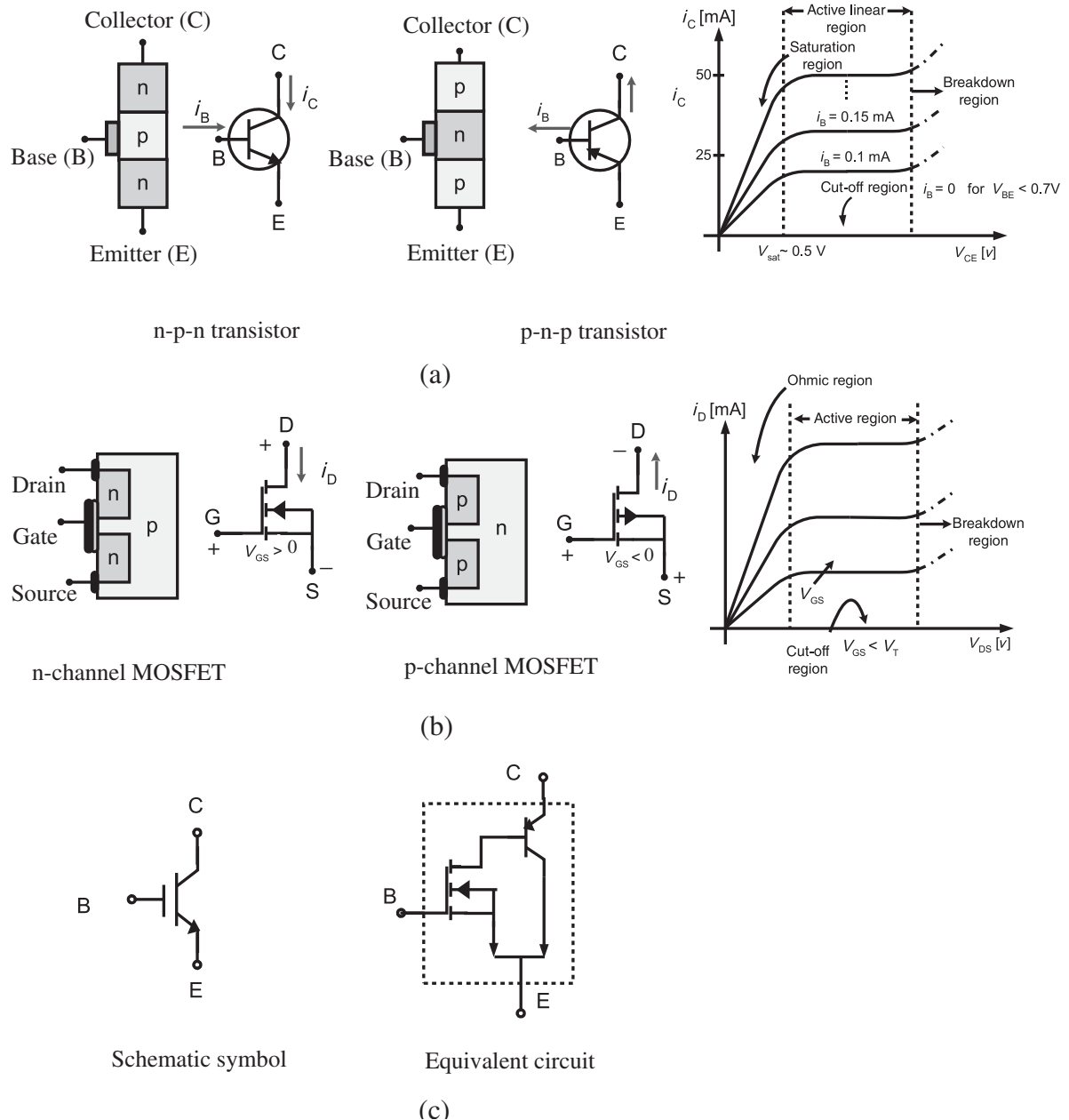


Figure 11. Some semiconductor devices: transistors. (a) Bipolar junction transistors (BJT), (b) metal oxide semiconductor field effect transistor (MOSFET), and (c) insulated gate bipolar transistor (IGBT).

The graph below illustrates the many combinations of power and frequency that are covered by power supply employing various semiconductor technologies. Clearly, there are numerous applications where more than one type of power source can be used.[1]

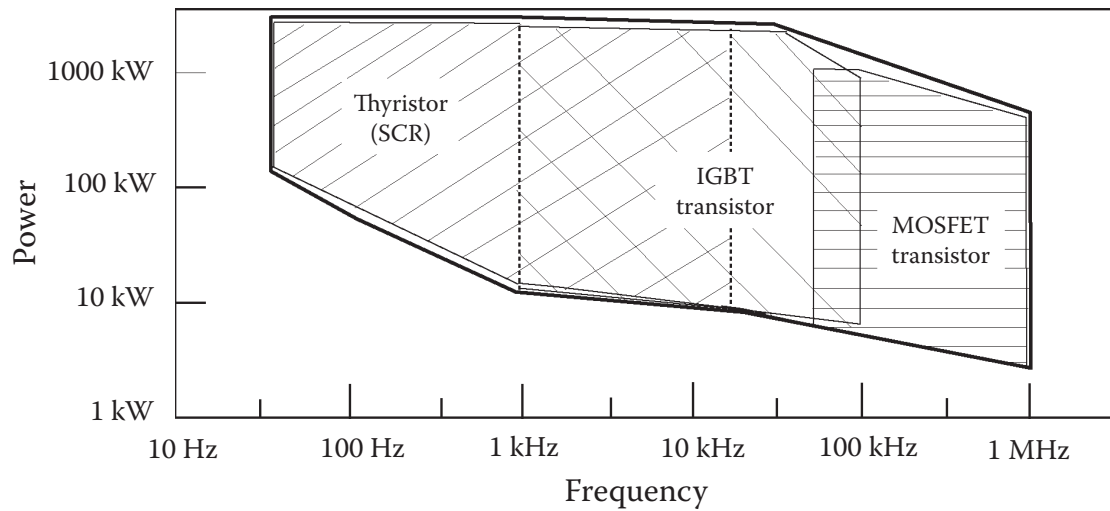


Figure 12. Power semiconductors used for IH.

3.3 Computation and analysis

3.3.1 Root mean square

Various forms of *DC* and *AC* are typically present in power electronics. It is essential to identify a standard for quantifying the equivalence and difference. This results in the definition of Root mean square (*RMS*). When a V_{DC} source of constant *DC* voltage is supplied to a resistor, the instantaneous power does not vary over time. Instantaneous power varies with time when a time-varying voltage, $v(t)$, is applied. When $v(t)$ is a periodic signal, the power delivery throughout each cycle is constant and reflective of the steady state. The question is how to achieve power consumption parity when multiple power profiles are used.

3.3.2 Loss analysis and reduction

Heat generated by power loss in converter circuits causes aging, damage, and a shortened lifespan of power equipment. Modeling loss is essential for identifying loss resources and hotspots. The total power loss of converters is equal to the sum of the projected power losses for each of the following:

- Conduction loss.
- Switching loss.

3.3.2.1 Conduction losses

All physical components experience conduction loss, which is caused by Equivalent series resistance (ESR) or voltage drop across power semiconductor devices. $ESRs$ cause the conduction loss of passive components, such as conductors, capacitors, and inductors. For ESR -based power computation, the loss is evaluated using the following equation, where I_{RMS} is the RMS value of the steady-state through current.

$$P_{\text{loss(cond)}} = R_{CE(ON)} \times I_{RMS}^2 \quad (3.1)$$

During the on-state, a field effect transistor (FET) is analogous to a resistor rated at $R_{CE(ON)}$. The properties become identical to the loss estimation impact of $ESRs$. I_{RMS}^2 is used to determine the conduction loss (on).

A collection of power semiconductors, including diodes, BJT , $IGBT$, and thyristors, exhibit forwarding voltage drop as a non-ideal characteristic. During steady-state operation, the voltage remains generally stable. The loss can be described as the circuit's constant-voltage load. The conduction loss can be calculated using the formula:

$$P_{\text{loss(cond)}} = V_{CE(SAT)} \times I_{RMS} \quad (3.2)$$

where:

- $V_{CE(SAT)}$: Voltage drop traversing power semiconductors during onstate.
- I_{RMS} : Average value of the steady-state through current.

3.3.2.2 Switching losses

As depicted in Fig. 13, an ideal hard switching occurs when the cross-voltage drops to zero and the through current jumps to the rated level without any delay during the turning-on transition. During the turning-off transition, the through current drops to zero and the voltage across builds up to the rated level without any delay. Since there is no overlap period between the voltage and the current, there are no switching losses.[8]

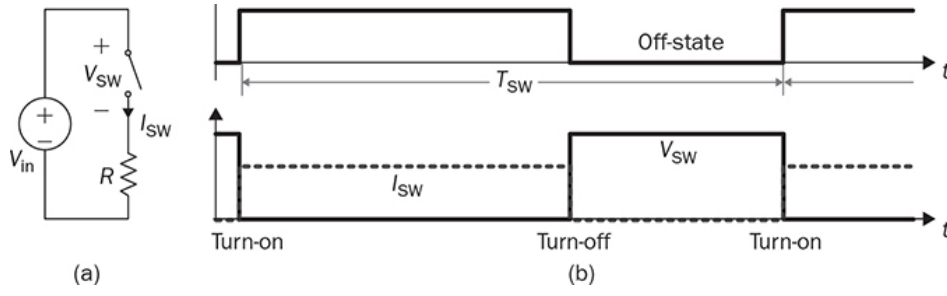


Figure 13. Demonstration of ideal hard switching operation: (a) switching circuit; (b) waveforms.

However, modern power semiconductor technology cannot reach the desired hard switching. Fig. 14 below demonstrates the principle that leads to switching loss when a power *MOSFET* is switched on and off. The power switch initiates current flow without reducing the voltage to zero. Voltage and current values that are simultaneously nonzero result in power consumption and power loss, and the same holds true for the turning-off phase. The overlap between the on and off phases of each switching cycle produces energy loss and power dissipation within the device.[8]

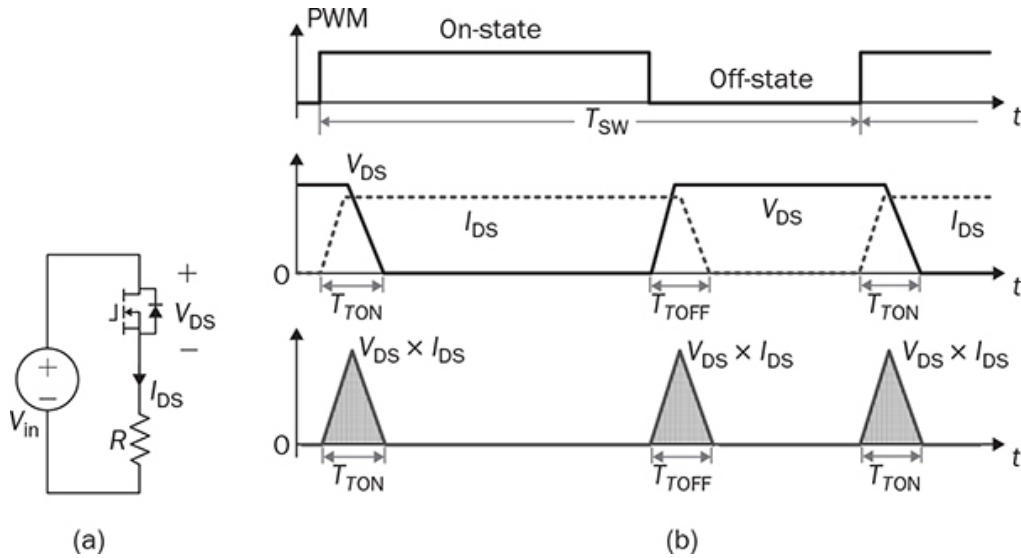


Figure 14. Demonstration of switching loss of a MOSFET.

Switching loss can be determined by:

$$P_{loss (sw)} = \frac{V_{CE} \times I_{CE}}{2} (T_{TON} + T_{TOFF}) f_{sw} = ((E_{ON,T} + E_{OFF,T}) \times f_{sw}) \quad (3.3)$$

It demonstrates that the switching loss is related to the Frequency of switching (f_{sw}). The dissipation of power within the *MOSFET* body causes the core temperature to rise. Since power electronics tend to increase switching frequency, switching loss is increasingly significant.

3.3.2.3 Minimization of switching losses

The switching loss minimization should focus on reducing the size of the overlapping area and that's by reducing these parameters:

1. Transition time: T_{TON} and T_{TOFF}
2. Voltage amplitude during each transition: V_{CE}
3. Current amplitude during each transition: I_{CE}

As seen in the preceding equation, the switching loss is zero when either V_{CE} or I_{CE} is zero during the transition. Soft switching results from the lowering of voltage and current preceding a transition. Zero voltage switching (*ZVS*) is accomplished by reducing the voltage level to zero just prior to activating the switch for switching. Accordingly, Zero current switching (*ZCS*) can be accomplished by reducing the current level to zero just prior to applying the gate signal.

3.3.3 Heat sinks and thermal calculations

Conduction and switching losses occur in electronic devices, as stated above. These losses indicate the conversion of electrical energy to thermal energy, and the removal of thermal energy is critical for maintaining the device's interior temperature below its maximum rated value.

The difference in temperature between two points is typically a function of thermal power and thermal resistance. Thermal resistance is defined by the following:

$$R_{\theta} = \frac{T_1 - T_2}{P_{\theta}} \quad (3.4)$$

where:

- R_{θ} : Thermal resistance [$^{\circ}C/W$] (also listed as [K/W] on some datasheets)
- T_1 and T_2 : Temperature difference [$^{\circ}C$]
- P_{θ} : Thermal power [W]

The junction temperature of an electrical switching device is its internal temperature. In many cases, the power absorbed by a device causes an excessive junction temperature, necessitating the use of a heat sink.

A heat sink reduces the junction temperature for a given power dissipation in a device by lowering the junction to ambient thermal resistance.

Typically, the case of the device is bonded to the heat sink using a thermal compound to fill the small spaces between the case and sink's uneven surfaces. There are heat sinks of every size, from tiny clip-on devices to enormous extruded aluminum structures.

Common heat sinks are depicted in Fig. 15 below. [9]

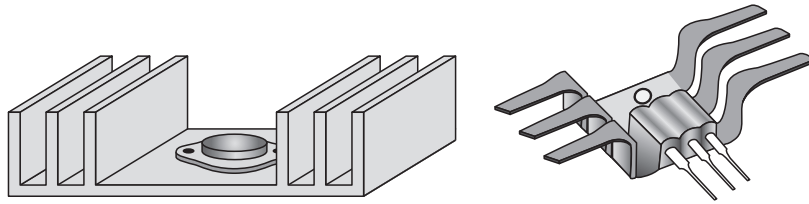


Figure 15. Power transistors mounted on heat sinks.

For an electronic device with a heat sink, thermal power flows from the junction to the case, from the case to the heat sink, and then from the heat sink to the ambient.

The temperature at the device junction is calculated via this formula:

$$T_J = P_{\theta} (R_{\theta,JC} + R_{\theta,CS} + R_{\theta,SA}) + T_A \quad (3.5)$$

3.4 Different types of induction heating power supplies

The amount of power required for a certain application relies on the volume and kind of material to be heated, the rate of heating, and the heating process's efficiency. Small regions heated to a shallow depth may require as little as 1 or 2 kW of heating power, but big slabs or wide, rapidly moving steel strips may require many megawatts.

Specific coil voltage, current, and power factor are determined by the geometry of the workpiece and coil, the electromagnetic properties of the material to be heated, and the production rate. Defining these parameters is required to ensure that the output of the power supply can meet the coil's specifications.

Each form of power supply, which will be explained in depth later in this chapter, has distinct benefits that may directly influence its applicability for a given application.

Fig. 16 depicts a simple block diagram applicable to practically all IH power supplies. Typically, the input is three-phase, 50 or 60 Hz, between 220 and 575 V. The first block is the rectifier or AC-to-DC converter. This portion may produce a constant DC voltage or a variable DC voltage. The second block represents the inverter or oscillator portion, which converts direct current to a single-phase alternating current output. The third block consists of the load-matching components, which adapts the inverter's output to the appropriate level for the induction coil. The control portion compares the system's output to the command signal and changes the *DC* output of the converter, the phase or frequency of the inverter, or both, to achieve the appropriate level of heating. [1]

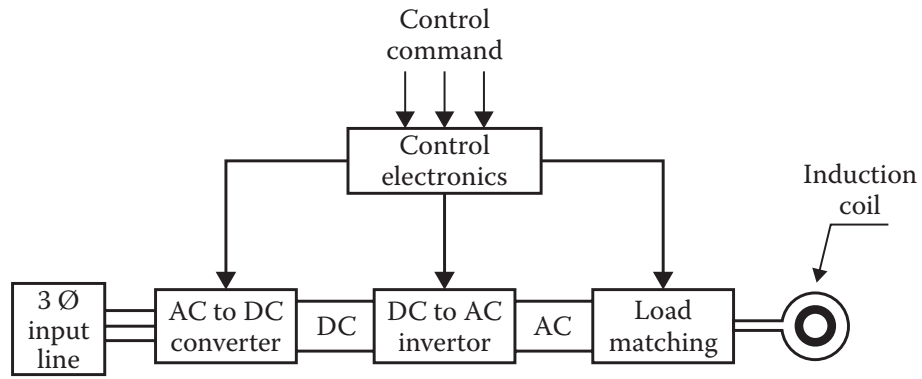


Figure 16. IH power supply basic block diagram.

3.5 The AC to DC conversion

Single-phase AC supplies most homes and offices due to relatively low power demand and simple wiring. Since more and more devices are DC-based, *AC/DC* conversion is required. The *AC/DC* conversion and converter are commonly called the rectification and rectifier, respectively. Diodes automatically pass forward current and block reverse current. The feature of one-direction conduction supports circuit constructions for the *AC/DC* conversion.[8].

3.5.1 Full-wave bridge rectifier

The diagram below (Fig. 17) depicts the passive four-switch bridge used to convert single-phase AC to DC. The diagonal pair D_{AH} and D_{BL} are forward-biased during the positive half-cycle of the input voltage (v_{ac}). The current flow is from D_{AH} to R and back to the source through D_{BL} . Another diagonal pair, D_{BH} and D_{AL} , is also reverse biased. When the negative half-cycle of the input voltage is present, the diagonal pair D_{BH} and D_{AL} are biased forward. The present flow direction is from D_{BH} to R to D_{AL} for return. Full wave rectification refers to a process in which the output voltage is always positive, regardless

of the polarity of v_{ac} . [8]

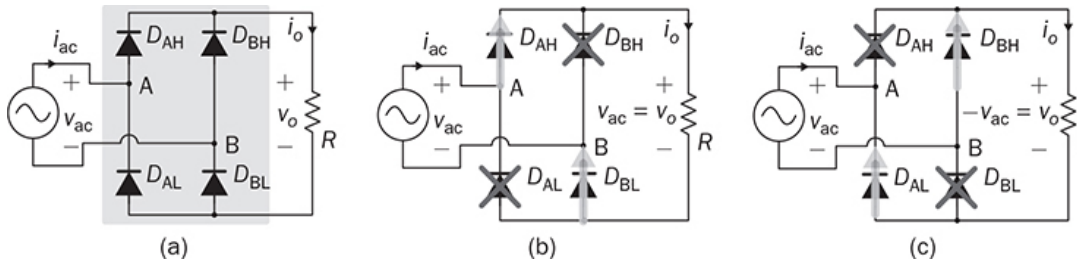


Figure 17. Full-wave rectifier for single-phase AC to DC conversion: (a) circuit; (b) positive cycle; (c) negative cycle.

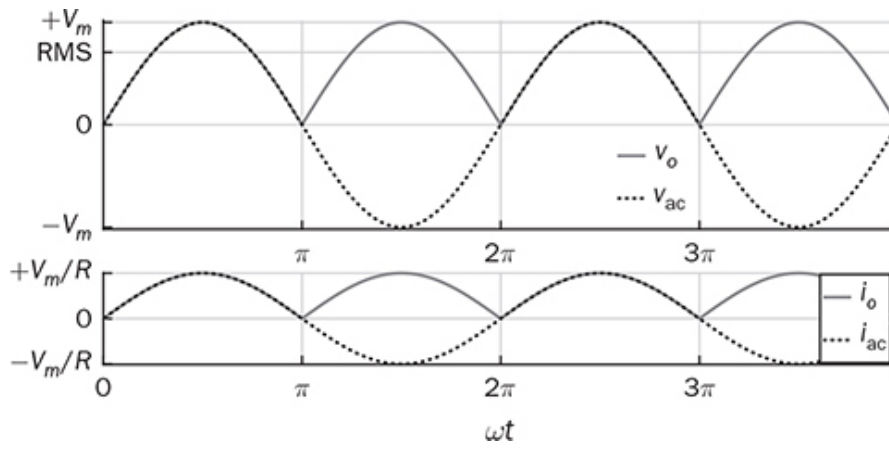


Figure 18. Waveform of full-wave rectifier in operation with resistive loads.

A capacitor can be also used in a full-wave bridge rectifier to smoothen the DC voltage output as shown in Fig. 19:

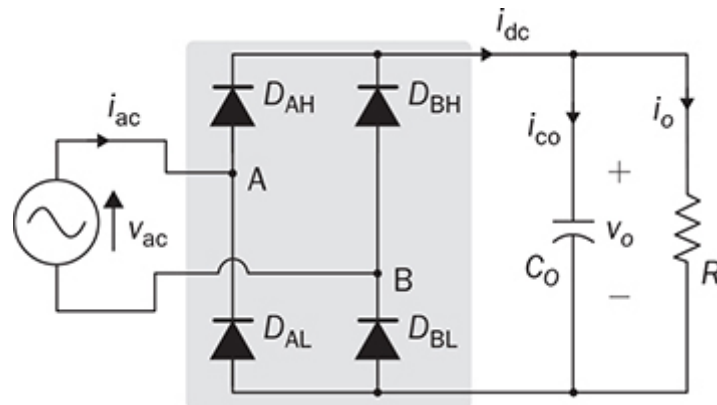


Figure 19. Circuit of full-wave rectifier in operation with C and R.

The voltage drop of V_o , as shown by the zoom-in plot in Fig. 20:

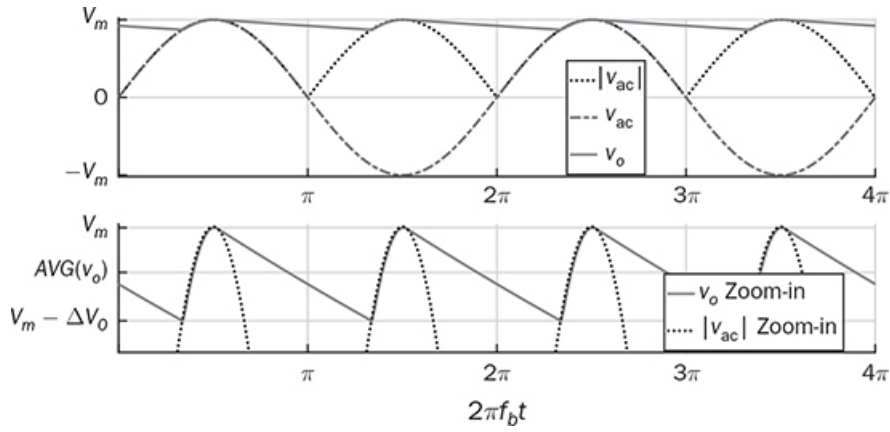


Figure 20. Waveform of full-wave rectifier in operation with resistive loads.

3.6 The DC to AC conversion

Inverters are the term for DC-to-AC converters. An inverter transforms a DC input voltage into a symmetric AC output voltage with the desired magnitude and frequency. The output voltage might be fixed or variable, and the frequency could be fixed or variable. Variable output voltage can be achieved by adjusting the input DC voltage while keeping the inverter's gain constant. Alternatively, if the DC input voltage is fixed and cannot be controlled, a variable output voltage can be achieved by altering the gain of the inverter, which is often achieved through Pulse Width Modulation (*PWM*) control within the inverter. The inverter gain is the ratio between the AC output voltage and the DC input voltage[10].

IH converters are under the category of load-resonant converters. Commutating at resonant frequency enables more efficient equipment, which may be essential in some high frequency applications, but the fundamental reason is that it permits larger inductor current. [11]

As we will be working on single phase voltage fed inverters only, these are the types of inverters we will be discussing next.

3.6.1 Single phase full bridge inverters

As depicted in the diagram below (Fig. 21), the most typical inverter configuration is the full bridge. It is sometimes referred to as a *H bridge* and comprises four legs, each of which has a switch. When switches S1 and S2 are closed, electricity will flow from the DC supply through the output circuit from left to right. Current flows in the reverse direction,

from right to left, when switches S1 and S2 are open while switches S3 and S4 are closed. The pace at which the switches are opened and closed determines the frequency of the alternating current produced as this process is repeated. [1]

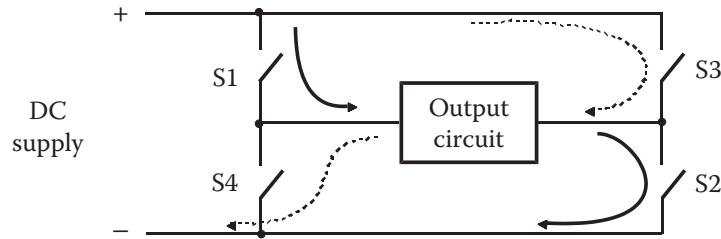


Figure 21. Basic full-bridge inverter.

Fig. 22 shows the entire bridge topology is commonly made using either field effect transistor (*FET*) or Insulated Gate Bipolar Transistor (*IGBT*). The selection of the switch is determined by the power and voltage levels. The entire bridge consists of two parallel legs, denoted A and B. $V_{ab} = V_{ag} - V_{bg}$ represents the *AC* output, where V_{ag} and V_{bg} represent the voltage potential of Leg A and Leg B to the common DC ground. The voltage potential difference drives the alternating current output, V_{ab} . When one switch is activated, the other in the same leg should be deactivated concurrently to prevent cross conduction or shoot through. [8]

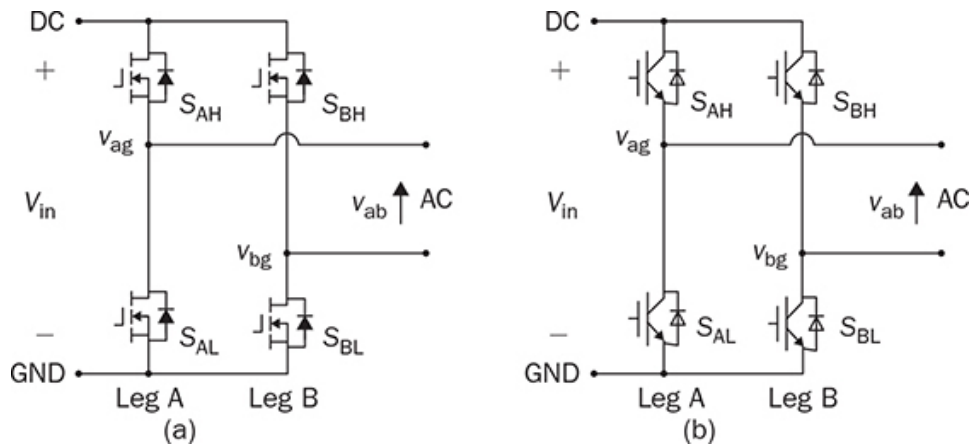


Figure 22. Bridges for DC to single-phase AC conversion by (a) FETs; (b) IGBTs.

The switching action is straightforward for the four-switch bridge to generate square AC waveforms at a preset frequency, such as 50 or 60 Hz. The modulation cannot, however, regulate the output AC voltage, V_{ab} . The amplitude and RMS of V_{ab} are locked to the V_{in} DC level.

3.7 Modulation techniques

A modulation technique generates the power semiconductors gate signals of a power converter obtaining a switched output waveform in such a way that the fundamental component can be adjusted with an arbitrary magnitude, frequency and phase, which are essential for the proper control of the process fed by the inverter. [12]

Taking into account this fact, the modulation concept that has been the mainstream solution for two-level power converters in general, including inverters, from the early beginnings of power electronics is Pulse Width Modulation (*PWM*), which is a simple and effective way to produce a pulse or switched voltage (or current) waveform whose time average is equal to a desired reference. [12]

The commonly used techniques are:

- Single pulse width modulation.
- Multiple pulse width modulation.
- Sinusoidal pulse width modulation.
- Modified sinusoidal pulse width modulation.
- Phase displacement control.

Among all these techniques, the Sinusoidal Pulse Width Modulation (*SPWM*) is commonly used for a voltage control. However, the multiple-pulse-width modulation provides a foundation for better understanding of the *PWM* modulation techniques. The modified *SPWM* gives limited ac output voltage control. The phase-displacement control is normally used for high-voltage applications, especially phase displacement by transformer connections. [10]

3.7.1 Pulse Width Modulation

PWM is a systematic way to produce pulsed signals to control the on/off switching of power semiconductors and the level of power flow. The signals should be regulated to a specified sequence regarding the frequency and pulse width. The PWM signal can be formed by either digital microcontrollers or analog circuits, which generally follow the same comparison mechanism and principle. Fig. 23 illustrates the mechanism to form PWM signals, using a comparator. [8]

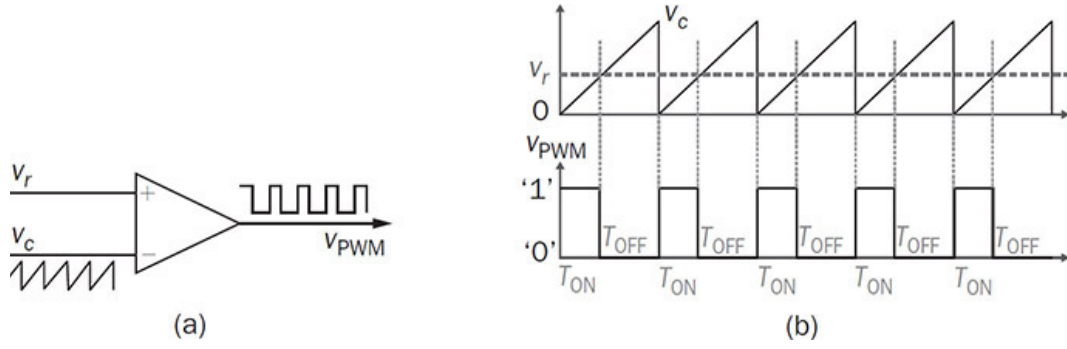


Figure 23. Demonstration of PWM signal generation: (a) comparator circuit; (b) waveforms.

3.7.2 Modulation principle for voltage source inverters

To acquire the desired phase voltage V , the modulator produces a switched waveform with an average value equal to the desired value across the sampling period T_s . Therefore, the modulator must calculate a switching sequence to switch the power semiconductor devices using the usual Duty cycle (D) (specified as the ratio t_{on}/T_s). The resulting switched waveform has a harmonic spectrum with unwanted harmonic distortion as a result of the switching. This unwanted distortion must be maintained below specified limits, which may entail the employment of expensive and laborious passive filters. Therefore, there is a trade-off between the maximum switching frequency of the modulator (which is directly related to the switching losses of the power converter and, thus, its cooling needs) and the filter size. [12]

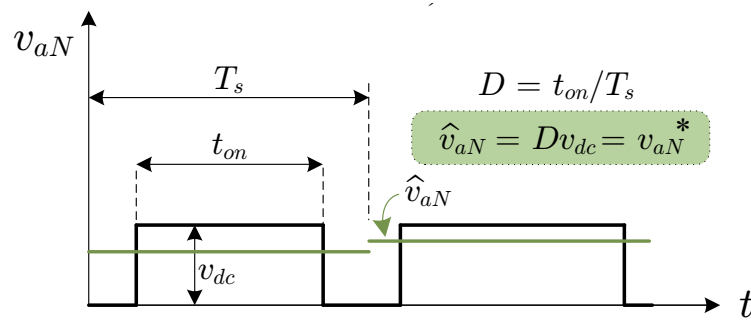


Figure 24. Switched waveform and average value of the phase voltage v_{aN} .

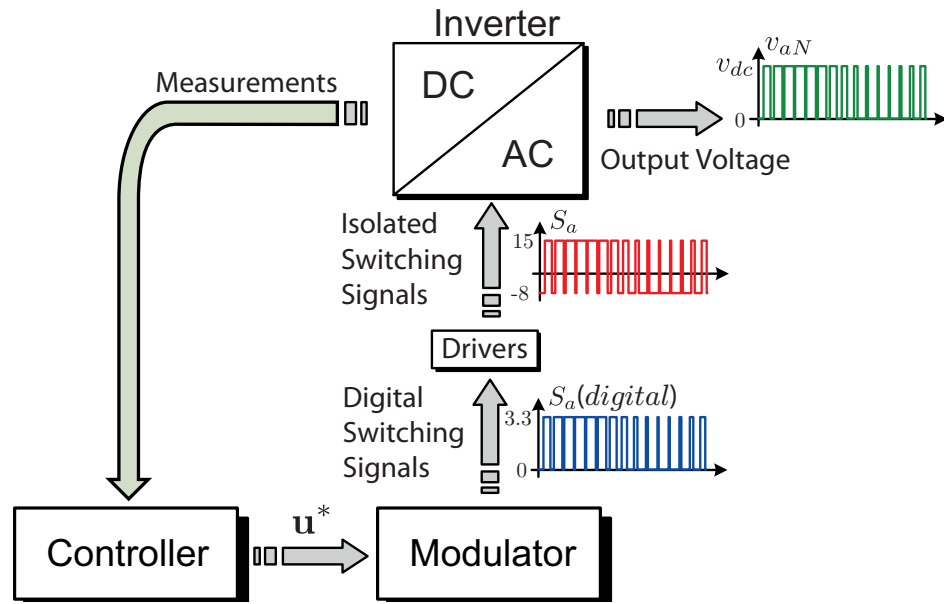


Figure 25. Typical structure of a control and modulation method of a voltage source inverter.

3.8 The load matching part

A very important facet of *IH* that is often overlooked in the initial design stages is the ability to successfully deliver to the workpiece the maximum available power from a given power supply at the minimum cost. Circumstances do not always allow for optimal design of a complete *IH* system in which the power supply design is based on the application including the specific induction coil parameters. Quite often, the induction coil is designed to achieve the desired thermal conditions of the workpiece without regard for the power supply that will be used. When this is the case, a flexible interface is required to match the output characteristics of the power supply to the input characteristics of the induction coil and workpiece combination. If this match is not provided, the power supply may not be able to deliver its rated power because the coil requires more voltage or current than the supply can deliver. [1]

3.9 Conclusion

Power electronics is used to convert, and regulate electric power flow in terms of voltage and current from one form to another. It represents the bigger part of any induction heating system, which means that the development and the advance of power electronics and semiconductor technologies can lead directly to the development of induction heating systems by improving their efficiency. This chapter discusses different elements of power electronics used to build power supplies, different power supply topologies used for *IH* application, *AC* to *DC* conversion, and also *DC* to controllable *AC* conversion. Furthermore, this chapter talks about the power computations and different energy losses of power electronic devices that can affect the efficiency of the *IH* system, and also thermal calculation to choose the right heat sink for the right component. Power conversion cannot function successfully unless the level of voltage, current, or power is controlled and regulated, this regulation cannot be achieved without modulation, modulation is the process of varying one of the three characteristics(current, voltage, frequency), and it is used to control different electronic devices, different modulation techniques for voltage fed inverters were discussed in depth in this chapter.

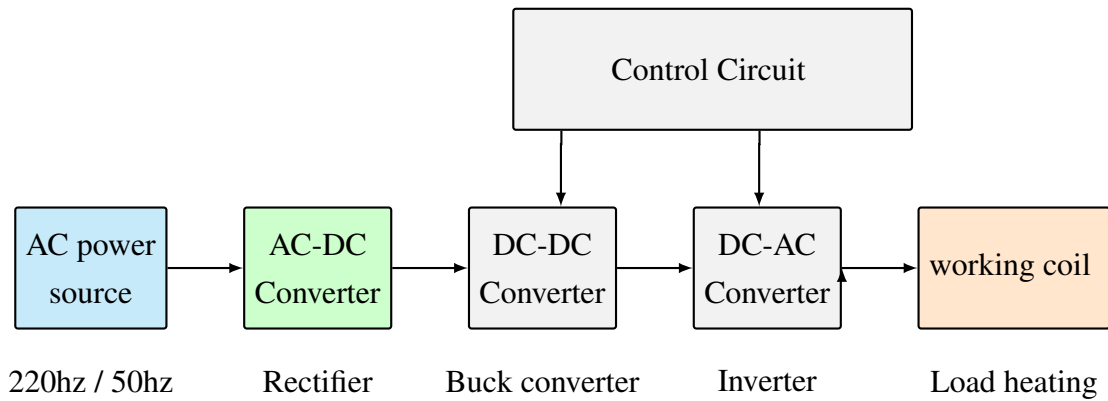
CHAPTER 4

Simulation & Experimental Results

4.1 Introduction

After understanding the different advantages of induction heating and studying all the theoretical information needed to understand, simulate, and build an IH system, in this chapter we will choose a specific application in order to simulate and build a small prototype based on the fixed requirements. First we will start by the power estimation stage, and then move to simulating the different parts of the induction heating power supply, and then we will interpret the simulation results, and finally we will build a small prototype aiming to achieve the fixed requirements.

4.2 The general setup used in the simulation and the experimentation



4.3 System Architecture

4.3.1 Hardware

4.3.1.1 Arduino ATmega2560 Microcontroller

Arduino is a printed circuit, consisting of several electronic components and a microcontroller to receive, analyze and produce electrical signals, the main advantage of the Arduino technology is an open-source platform and you can directly load the programs into the device without the need of a hardware programmer to burn the program. Arduino board based on an ATmega2560 microcontroller is shown in the Fig. 26 It consists of 54 pins, Where 14 digital inputs/outputs pins and 6 analogue inputs/outputs pins, a 16MHz clock, has 256 KB of flash memory, 8 KB of *RAM* and 4 KB of *EEPROM*. [13]

In several applications, which are powered by inverters, it is necessary to control the output voltage, *PWM* as one of the most efficient techniques to vary the voltage gain. Modern microcontrollers (PIC Microcontroller, ARM Cortex M, PIC, ARDUINO UNO card,

ARDUINO ATmega2560 card, etc.) all have peripherals or pins dedicated specifically to PWM generation. The method of this work has programmed the TIMER of the ARDUINO ATmega2560 card to transform it into a digital *PWM* generator, the principle is to create a digital configured signal of frequency and duty cycle. A timer is a register located in the microcontroller that is incremented or decremented each time it receives a pulse from a clock signal. Therefore, a timer is a counter, capable of counting the time that elapses, hence its name counter timer. [14]

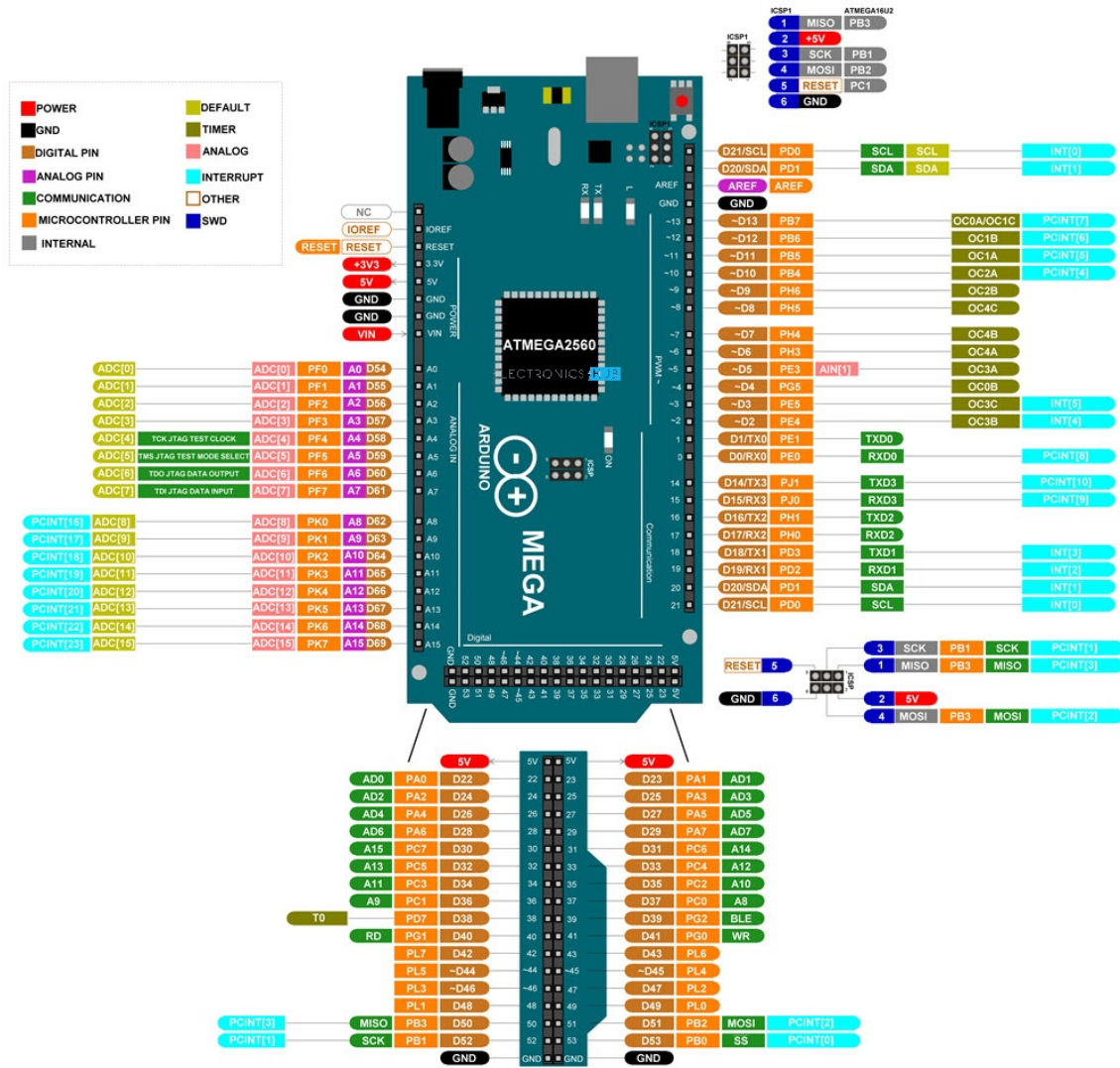


Figure 26. Arduino Mega ADC Pins. [15]

The ATmega 2560 microcontroller has one 8-bit counter timer numbered 0 and four 16-bit counter timers numbered 1, 3, 4 and 5. The Timer configured with two control registers TCCRnA and TCCRnB. The clock used is the main clock of the Arduino ATmega 2560, which has a frequency of 16 MHz.

The selection of the clock mode operation is made on bits 2, 1 and 0 of the TCCRnB

register. To produce the waveform signal, it is necessary to use the Timer in a wave generator mode. The main generator modes are Normal Mode, Fast *PWM* Mode, and Phase Correct *PWM* Mode. [16]

4.3.1.2 Interfacing 128×64 Graphical LCD Display

At first glance, the 128×64 Graphical LCD Module seems like a bigger brother to the famous 16×2 LCD or 20×4 LCD Modules, with their similar construction and almost similar pin layout.

But there is a significant difference between those two. 16×2 or 20×4 LCDs are essentially character displays. They can only display alpha-numeric characters and some simple custom characters that are confined to a 5×8 matrix.

Coming to the 128×64 Graphical LCD, as the name suggests, it is a Graphical Display consisting of 128×64 i.e., 8192 individually controllable dots.

By using different combinations of pixels, we can basically display characters of various sizes. But the magic doesn't end there. You can display images and graphics (small animations) as well. In a 128×64 LCD Module, there are 64 rows and 128 columns. [17] This module has 20 pins. The pinout of this module is shown in Fig. 27 below:

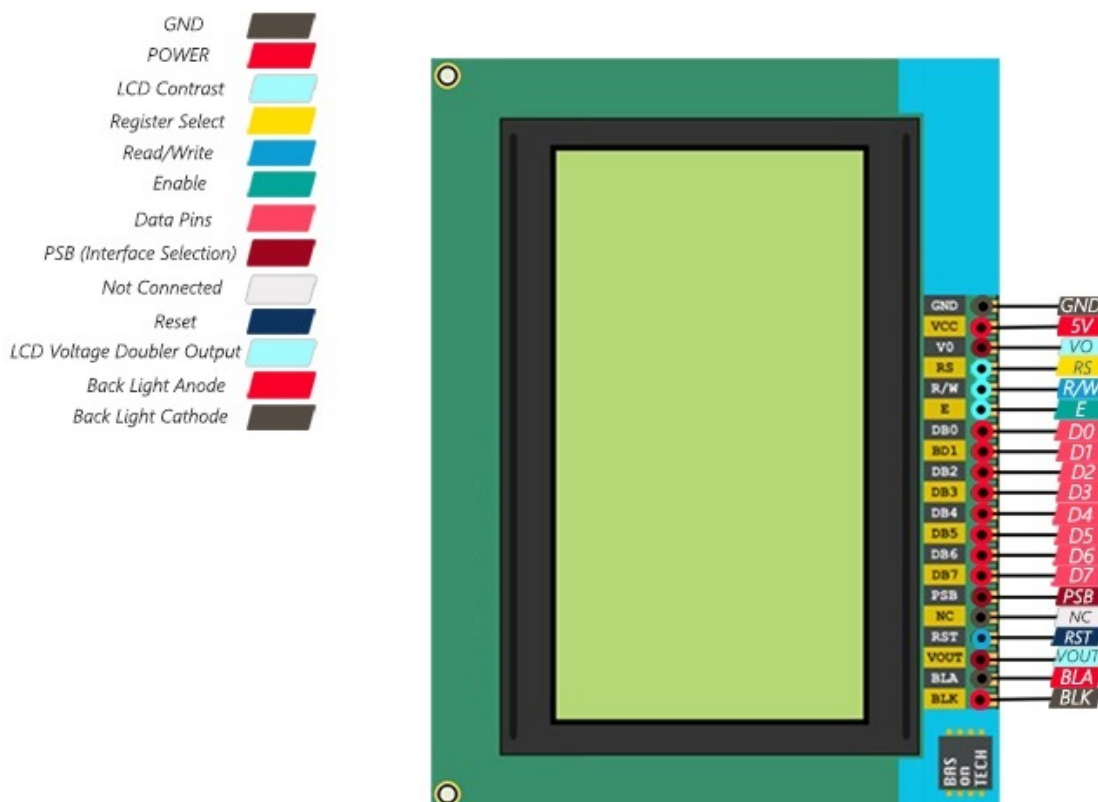


Figure 27. 128x64 Graphical LCD Display Pinout [18]

4.3.1.3 Thermocouple Temperature Sensor

A thermocouple is a device that consists of two different electrical conductors that form an electrical junction—thermal junction. The change in temperature at the junction creates a slightly but measurable voltage at the reference junction that can be used to calculate the temperature.

A thermocouple can be made of different metals. The metals used will affect the voltage range, cost, and sensitivity. There are standardized metal combinations that result in different thermocouple types: B, E, J, N, K, R, T, and S. [19]

A J Type Thermocouple Temperature Sensor is a very common and general purpose thermocouple. It has smaller temperature range and a shorter lifespan at higher temperatures. It consist of positive leg made of an Iron wire and negative leg made of an Constantan (Copper-Nickel) alloy wire. Due to the Curie Point of the iron at 770 °C Type J has a limited temperature range of -40°C to 750°C. [20]

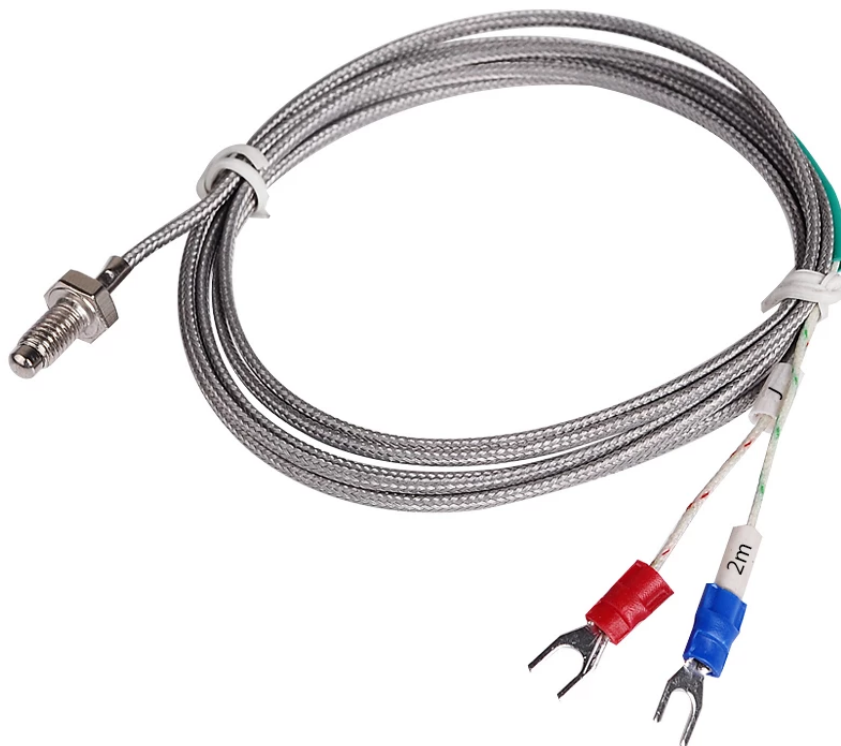


Figure 28. J-Type M6 Screw Probe Thermocouple Temperature Sensor with 2M Cable for Industrial Temperature Controller.

4.3.2 Software

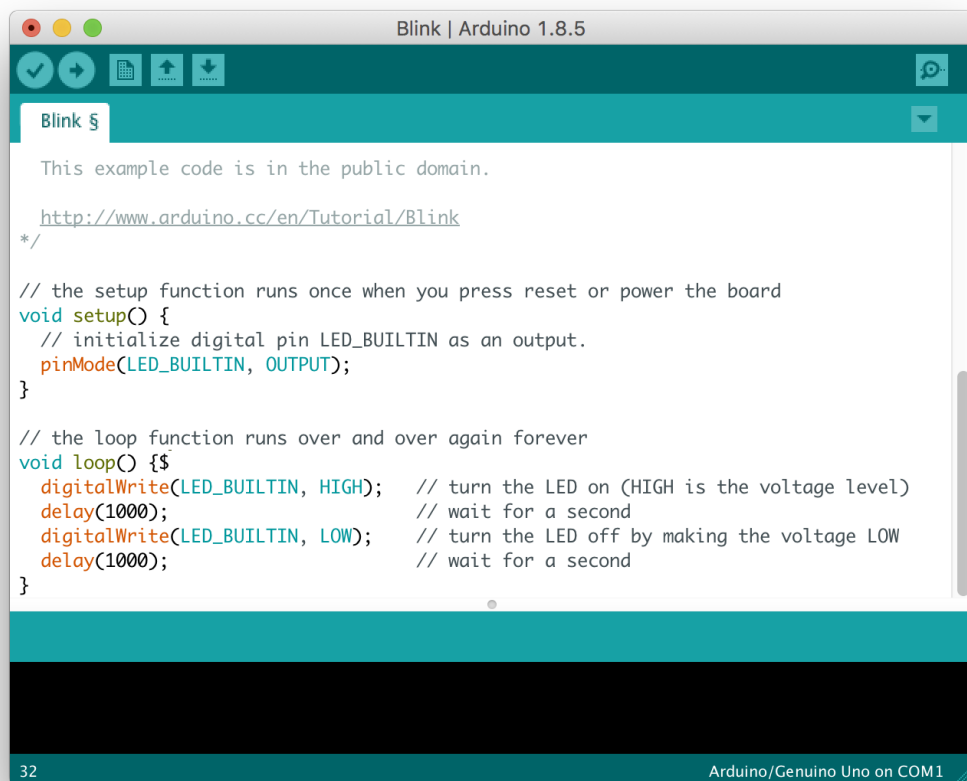
Arduino Mega uses the firmware Atmega2560. The updates versions of the arduino UNO uses the Atmega16U2 version of the firmware. We program the arduino using arduino IDE

(Fig. 29). In order to run the arduino efficiently for our project, we needed to download additional libraries:

4.3.2.1 Libraries

We had to download additional libraries in order to run the hardware from the arduino Mega. The following libraries were downloaded:

- One Wire Library
- Adafruit ADS1X15
- LiquidCrystal
- U8g2

A screenshot of the Arduino IDE interface. The title bar reads "Blink | Arduino 1.8.5". The menu bar includes "File", "Edit", "Tools", "Window", and "Help". The toolbar contains icons for opening files, saving, compiling, uploading, and erasing. The main text area shows the "Blink" example code. The code starts with a comment "This example code is in the public domain." followed by a URL "http://www.arduino.cc/en/Tutorial/Blink". The code defines a setup function to initialize the LED_BUILTIN pin as an output and a loop function to toggle the LED on and off with a 1000ms delay. The status bar at the bottom shows "32" on the left and "Arduino/Genuino Uno on COM1" on the right.

```
Blink | Arduino 1.8.5

This example code is in the public domain.

http://www.arduino.cc/en/Tutorial/Blink
*/

// the setup function runs once when you press reset or power the board
void setup() {
  // initialize digital pin LED_BUILTIN as an output.
  pinMode(LED_BUILTIN, OUTPUT);
}

// the loop function runs over and over again forever
void loop() {
  digitalWrite(LED_BUILTIN, HIGH); // turn the LED on (HIGH is the voltage level)
  delay(1000);                     // wait for a second
  digitalWrite(LED_BUILTIN, LOW);  // turn the LED off by making the voltage LOW
  delay(1000);                     // wait for a second
}

32 Arduino/Genuino Uno on COM1
```

Figure 29. Arduino IDE.

4.4 Project requirements and power calculations

The goal we are aiming to achieve is to heat a workpiece made of iron from the room temperature of $25^{\circ}C$ to $1000^{\circ}C$.

The workpiece has the following specifications:

- Mass: $m = 200\text{ g}$
- Specific heat: $c = 0.45\text{ J}^{\circ}C/g$
- Workpiece diameter: $d_w = 2\text{ cm}$
- Workpiece length: $l_w = 4\text{ cm}$
- Electrical resistivity: $\rho_w = 9.71 \cdot 10^8\ \Omega.m$
- Penetration depth: $\delta_w = 14.02 \cdot 10^{-6}\text{ m}$
- Relative magnetic permeability: $\mu_r = 5000$

In order to calculate the power needed at the input of our power supply, we need to calculate the power of the workpiece using the formula 2.1 stated in chapter 2, and then move backwards and calculating the power in each stage of power conversion, first of all, let's start by calculating the power of the workpiece:

$$P_w = m.c \frac{T_f - T_{in}}{t} \implies P_w = 200 \times 0.45 \times \frac{1000 - 25}{20} = \mathbf{4.3875\text{ KW}}$$

Now moving from the power required for the workpiece to the power of the coil using the formula (2.2) :

$$P_c = \frac{P_w}{\eta_{th} \cdot \eta_{el}}$$

To calculate the coil power, we need to calculate the thermal and electrical efficiency first. The thermal efficiency is calculated by the following formula:

$$\eta_{th} = \frac{P_w}{P_w + P_{\text{thermal loss}}} \quad (4.1)$$

$$P_{\text{thermal loss}} = 3.74 \cdot 10^{-4} \frac{l_c}{\log_{10}\left(\frac{d_c}{d_w}\right)} \quad (4.2)$$

Where:

- coil length: $l_c = 7 \text{ cm}$
- Inner coil diameter: $d_c = 6 \text{ cm}$
- Workpiece diameter: $d_w = 4 \text{ cm}$

$$\Rightarrow P_{\text{thermal loss}} = \mathbf{14.86 \text{ W}}$$

$$\Rightarrow \eta_{\text{thermal}} = \mathbf{99 \%}$$

The electrical efficiency is calculated using the following formula:

$$\eta_{\text{electrical}} = \frac{1}{1 + \frac{d_c + \delta_c}{d_w - \delta_w} \times \sqrt{\frac{\rho_c}{\mu_r \rho_w}}} \quad (4.3)$$

Where:

- δ_c and δ_w : are coil's and workpiece's penetration depth, respectively.
- ρ_c and ρ_w : are coil's and workpiece's electrical resistivity, respectively.
- μ_r : is the relative magnetic permeability of the workpiece.
- $\rho_c = 1.72 \cdot 10^{-8} \Omega.m$
- $\delta_c = 417.22 \cdot 10^{-6} \text{ m}$

$$\Rightarrow \eta_{\text{electrical}} = \mathbf{99\%}$$

Now we can calculate the coil power:

$$\Rightarrow P_c = \mathbf{4.45 \text{ KW}}$$

As it was stated before, there are two types of losses when using electronic devices, conduction losses and switching losses.

To calculate the losses of the inverter we need to calculate both the switching and conduction losses for each IGBT and each diode. From the IGBT's datasheet we can find the following parameters:

- $E_{ON} (IGBT) = 8 \text{ mJ}$ (In 600 V)
- $E_{OFF} (IGBT) = 18 \text{ mJ}$ (In 600 V)
- $V_{CE \text{ sat}} (IGBT's \text{ voltage DROP}) = 2 \text{ V}$

- V_D (Diode voltage DROP) = 1.6 V
- $I_{AVG} = 100/\pi = 31.83$ A
- $f_{sw} = 25$ KHz
- $E_{on} (Diode) = 12.5$ mJ (In 600 V)

Switching and conduction losses of the IGBT:

$$(3.2) : P_{\text{loss(cond)}} = V_{CE \text{ sat}} \times I_{AVG} \implies P_{\text{loss(cond)}} = 2 \times 31.83 = \mathbf{63.66 \text{ W}}$$

$$\begin{aligned} (3.3) : P_{\text{loss(sw)}} &= \frac{V_{CE} \times I_{CE}}{2} (T_{TON} + T_{TOFF}) \cdot f_{sw} \\ \implies P_{\text{loss(sw)}} &= (E_{ON (IGBT)} + E_{OFF (IGBT)}) \cdot f_{sw} \\ \implies P_{\text{loss(sw)}} &= \frac{(8 + 18) \times 25}{6} = \mathbf{108.33 \text{ W}} \end{aligned}$$

Total losses of IGBTs is:

$$P_{\text{tot(IGBT)}} = (P_{\text{loss(cond)}} + P_{\text{loss(sw)}}) \times 4 \implies P_{\text{tot(IGBT)}} = (63.66 + 108.33) \times 4 = \mathbf{687.89 \text{ W}}$$

Switching and conduction losses of the diode:

$$P_{\text{loss(cond)}} = V_D \times I_{AVG} \implies P_{\text{loss(cond)}} = 1.6 \times 31.83 = \mathbf{50.92 \text{ W}}$$

$$P_{\text{loss(sw)}} = (E_{ON (diode)} + E_{OFF (diode)}) \cdot f_{sw} \implies P_{\text{loss(sw)}} = \frac{(12.5 + 0) \times 25}{6} = \mathbf{52.08 \text{ W}}$$

The total losses of diodes:

$$P_{\text{tot(diode)}} = (P_{\text{loss(cond)}} + P_{\text{loss(sw)}}) \times 4 \implies P_{\text{tot(diode)}} = (50.92 + 52.08) \times 4 = \mathbf{412 \text{ W}}$$

Total losses of the inverter:

$$P_{\text{tot(loss)}} = P_{\text{tot(igbt)}} + P_{\text{tot(diode)}} \implies P_{\text{tot(loss)}} = 687.96 + 412 = \mathbf{1.099 \text{ KW}}$$

Now calculating the power of the inverter:

$$P_{\text{inv}} = P_c + P_{\text{tot(loss)}} \implies P_{\text{inv}} = 4.450 + 1.099 = \mathbf{5.549 \text{ KW}}$$

We estimate that the efficiency of our buck converter is about : 90%.

The power of the buck converter is:

$$P_b = P_{inv}/0.9 = 5.549/0.9 = \mathbf{6.16\text{ KW}}$$

Now after finishing all power calculations, we can move to the components selection and simulation.

4.5 Design of Power Electronics Circuit for IH Prototype

After discussing different modules and circuits that are necessary for an IH system, we will know choose the topology for our IH system:

4.5.1 Rectification

For rectification part, we opt for a **full bridge rectifier** that can give double the power than a **half bridge rectifier**, also the full bridge rectifier reduces the size of the capacitor needed for **filtering** the ondulation of ac main sinusoidal voltage.

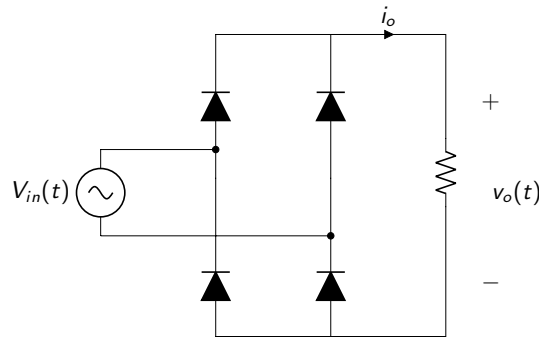


Figure 30. Full bridge rectifier.

4.5.2 Buck converter

The output voltage of the filtering capacitor after rectification is around **300V**, we need to decrease this voltage to a level suitable for supplying the heating coil and the workpiece. So we opt for a **Buck Converter** with variable output voltage **12V - 100V**

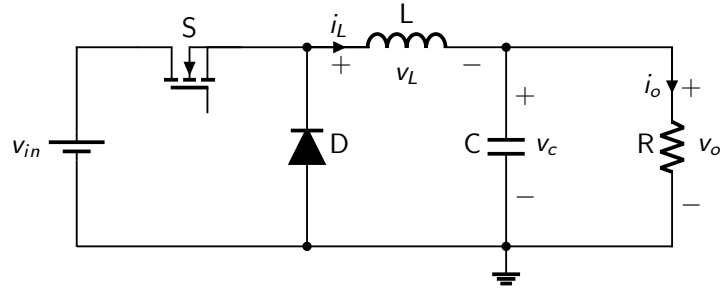


Figure 31. Buck Converter.

4.5.3 Full bridge inverter

For a similar reason, we have chosen a **Full Bridge Inverter** topology to increase the output power.

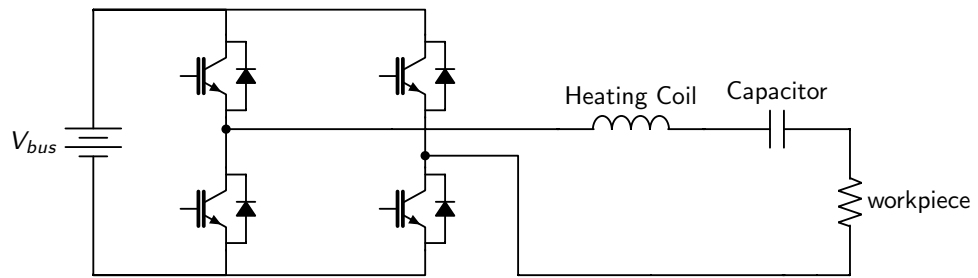
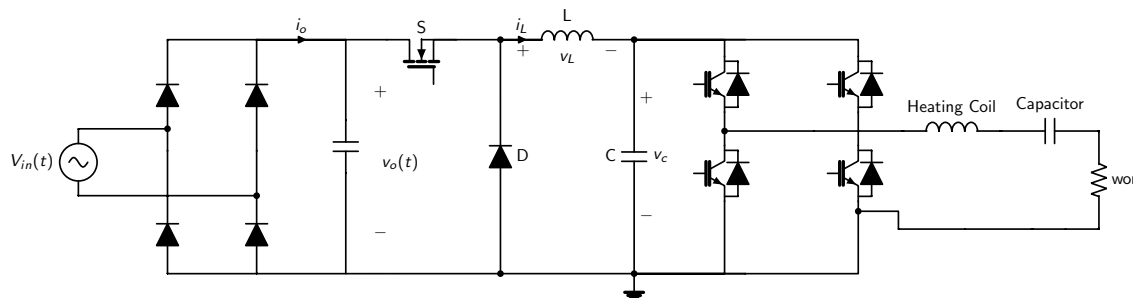


Figure 32. Full Bridge Inverter.

So, the overall topology of the proposed IH system is illustrated in the figure below:



4.6 The simulation circuits and results

4.6.1 The AC power source

We have worked with a 220 Volts, 50 Hz power source.

4.6.2 The rectification

We have chosen the full bridge topology to get the maximum power from our AC source. In order to smooth the rectifier's output and keep the voltage constant, we need to add a capacitance, the value of the capacitance is chosen to minimize the change in voltage and to get **35 A** at the output.

Now calculating the value of the needed capacitance:

$$i = C \frac{dV_c}{dt} \implies I \approx C \frac{\Delta V_c}{\Delta T} \quad (4.4)$$

Where:

- $\Delta V_c = 10\% V_{c \max}$
- $V_{c \max} = 300 \text{ V}$
- $\Delta T = \pi/2 = 10 \text{ ms}$
- $I = 35 \text{ A}$

$$\implies C = I \times \frac{\Delta T}{\Delta V_c} = 35 \times 0.01/30 = 11666 \mu F$$

Now we will simulate the circuit to verify the results, the simulation and the results are shown in Fig. 33 and Fig. 34:

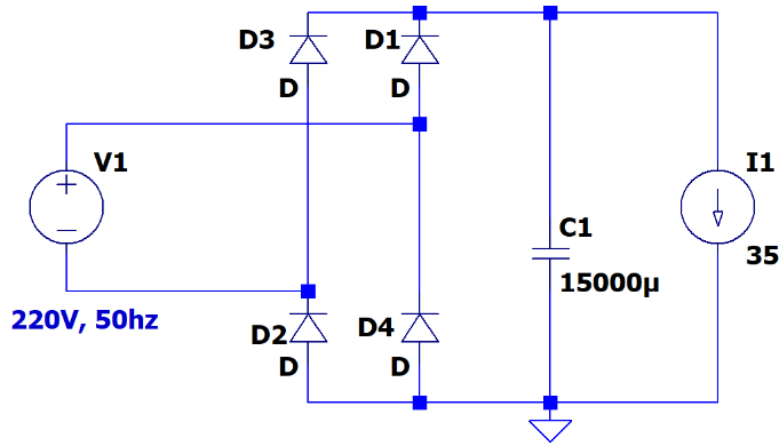


Figure 33. Full Bridge Rectifier.

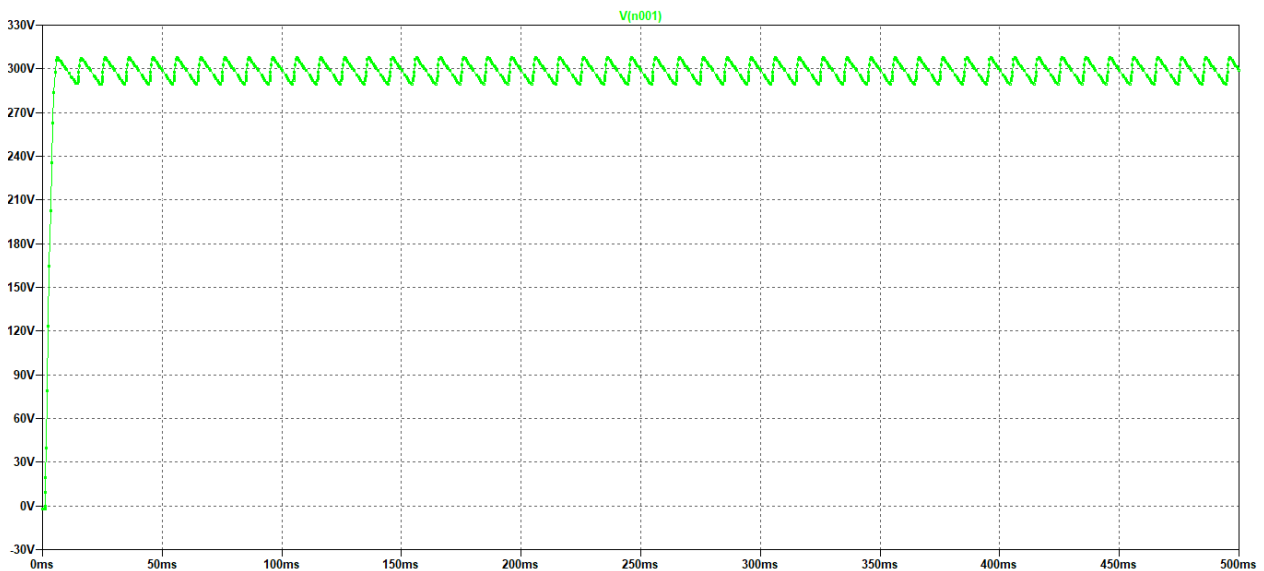


Figure 34. Rectifier's Output Voltage.

We can see that the change in voltage is very small, thus the voltage is approximately constant as we stated before.

4.6.3 The buck converter

As we have stated before, we added a buck converter to our circuit instead of a load matching station to lower the voltage. Fig. 35 shows the simulation circuit of the buck converter. And the graph below (Fig. 36) represents the output voltage of the buck converter, we can notice that the voltage is down to 85V.

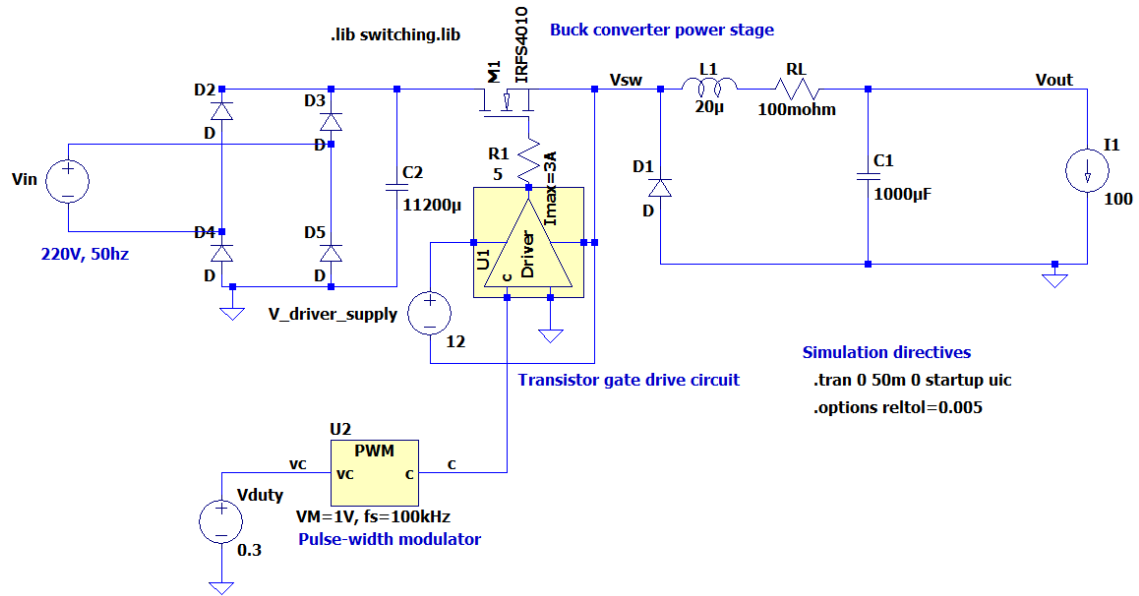


Figure 35. Full Bridge Rectifier with the buck converter.

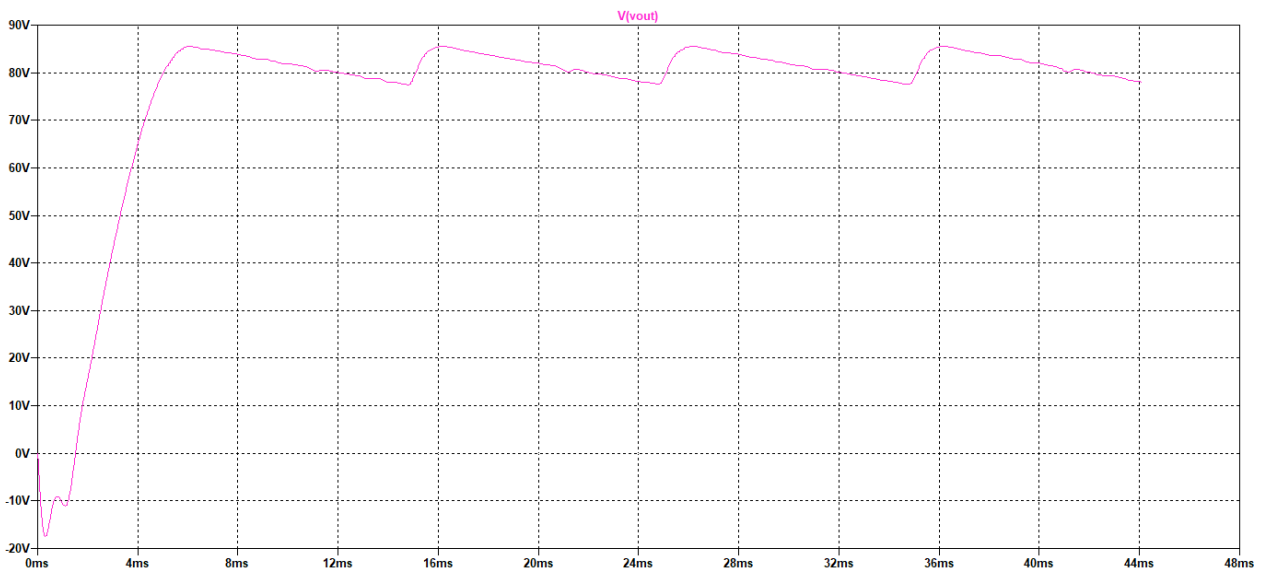


Figure 36. The buck converter's Output voltage.

4.6.4 The inverter

The final stage of our circuit is the full bridge inverter which is used to create a controllable AC voltage using IGBT power modules. Fig. 37 shows the simulation circuit full bridge inverter along with the buck converter and the rectifier, and the the graphs below (Figs. 38, 39, 40) represents the output voltage, the current, and the output power across the load.

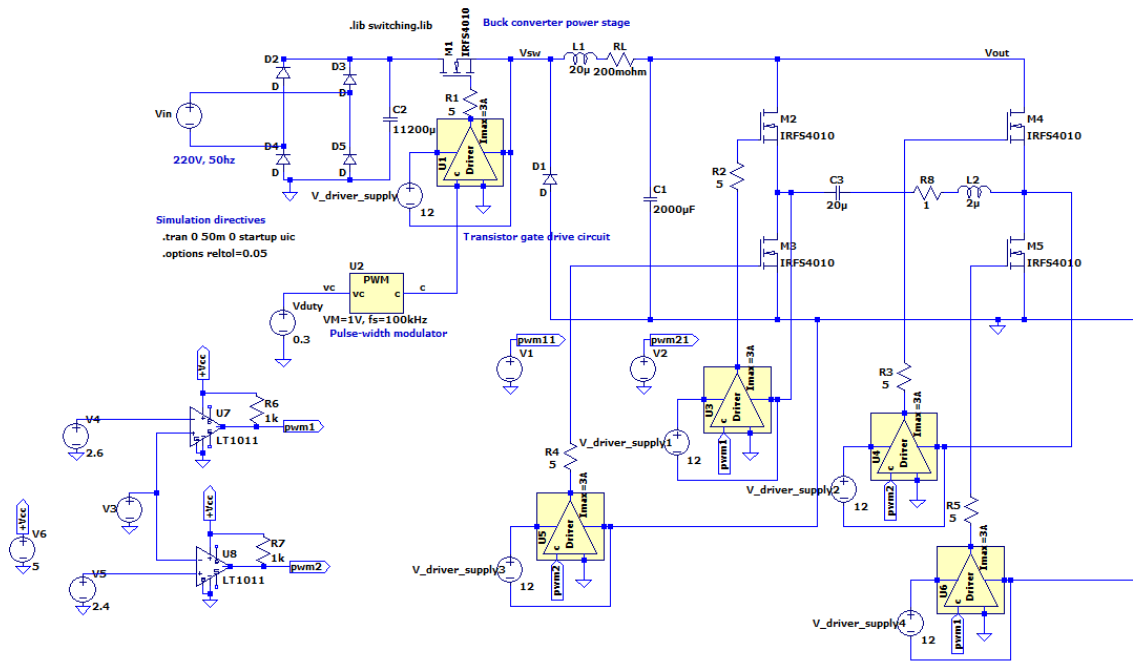


Figure 37. The complete power supply circuit.

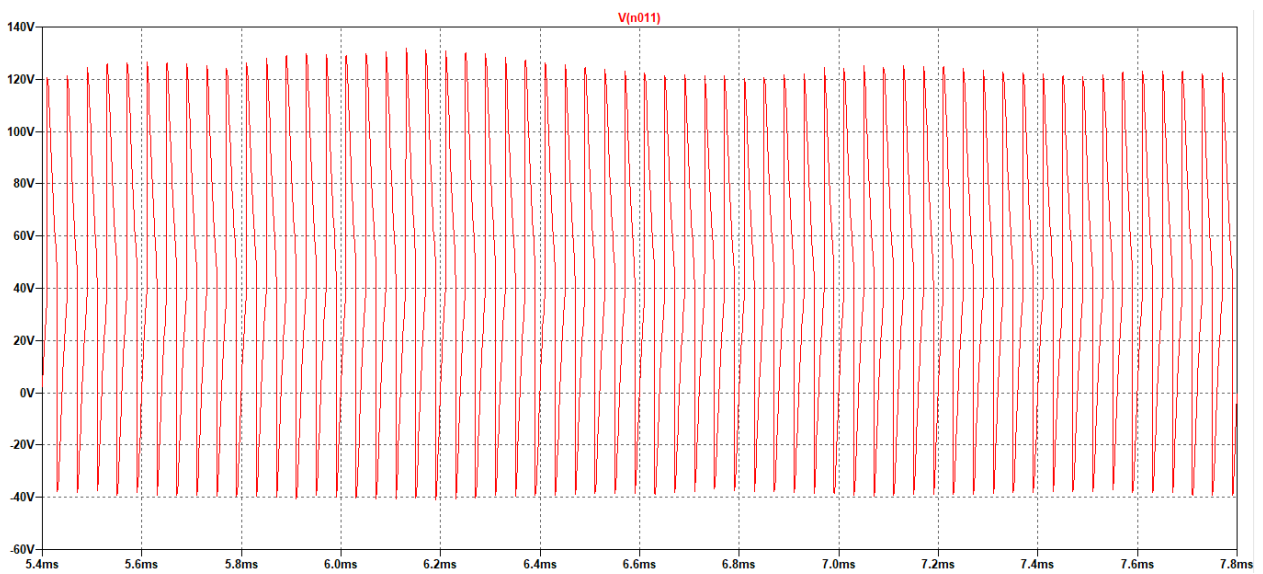


Figure 38. Voltage across the load.

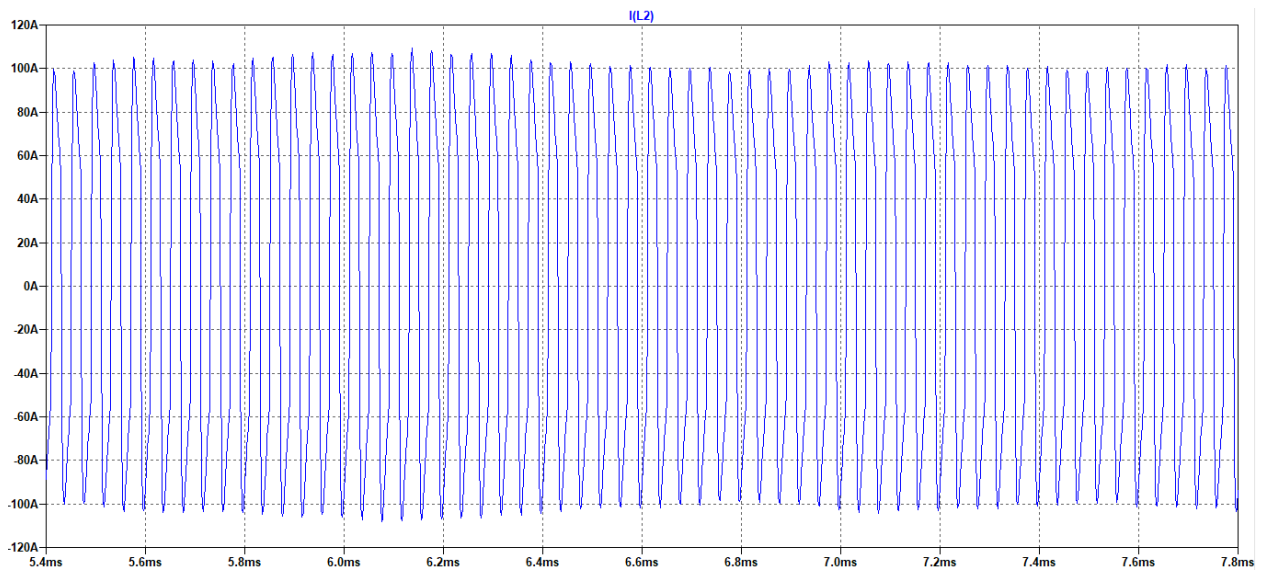


Figure 39. Current across the load.

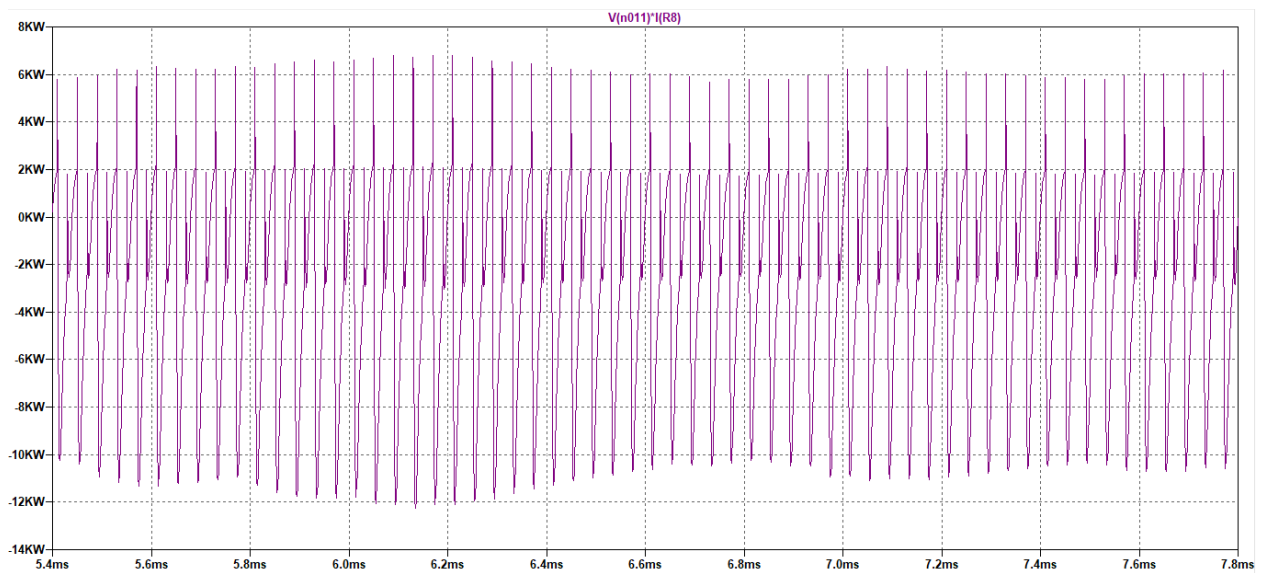


Figure 40. Output Power.

The average output power is: **6.6506 KW**.

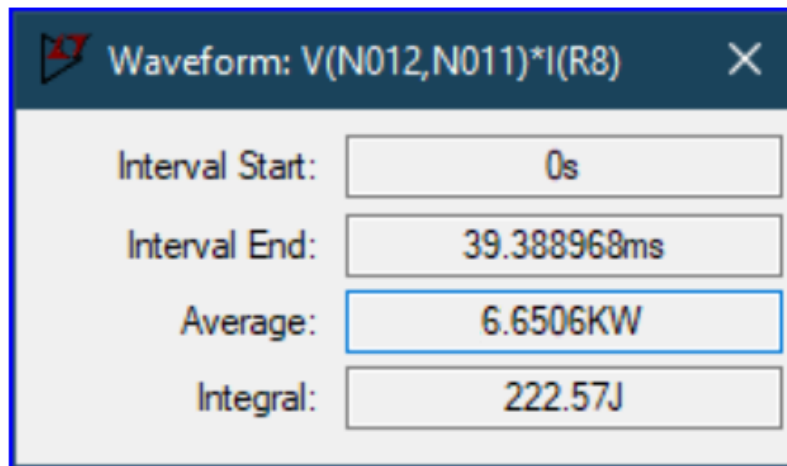


Figure 41. The average output power.

4.7 Design and implementation of a voltage-fed full bridge series resonant inverter

An overview of the high frequency induction heating system is shown in Fig. 42 .The system is supplied with single-phase mains voltage. A cooling fan circulates air by blowing it across the heat sink. An analog meter is used to indicate the current supplied to the load, which the user adjusts by means of a panel mount potentiometer. A latching circuit is used to activate or trip the DC bus when necessary.

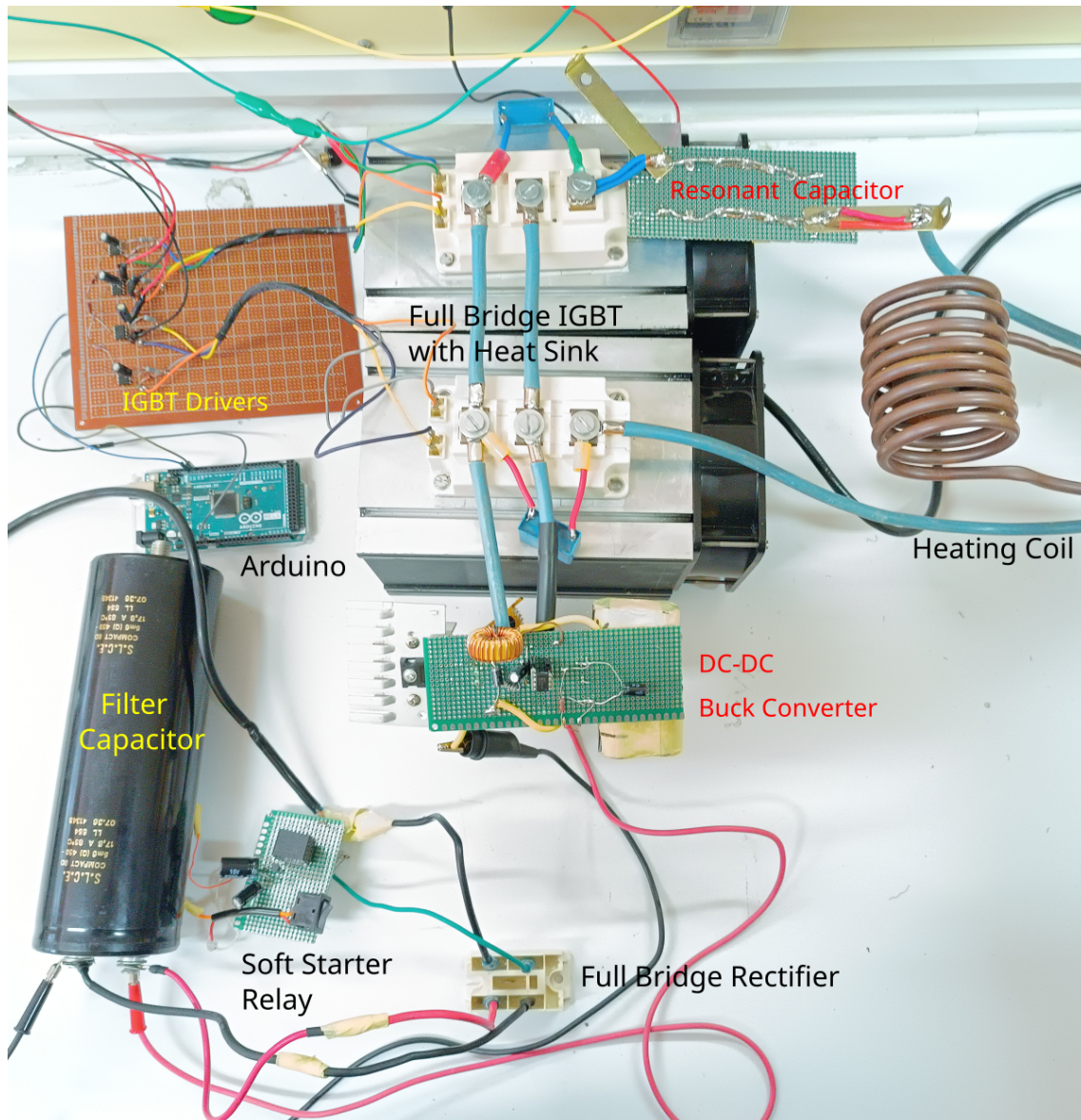


Figure 42. Implementation of a voltage-fed full bridge series resonant inverter.

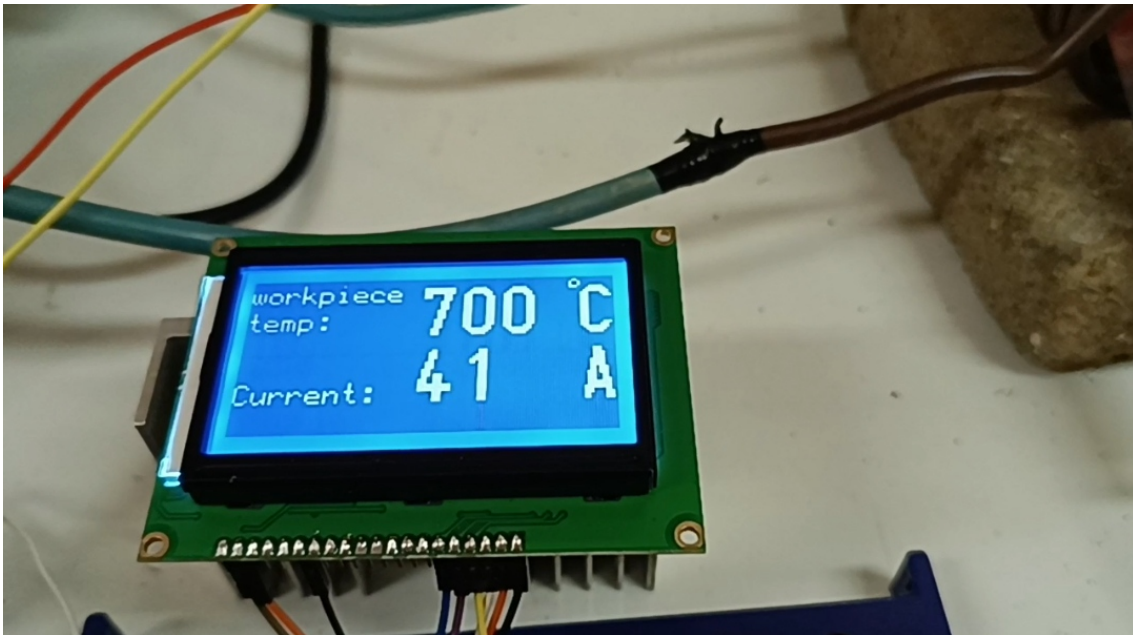


Figure 43. Display of parameters (Temperature + Current).

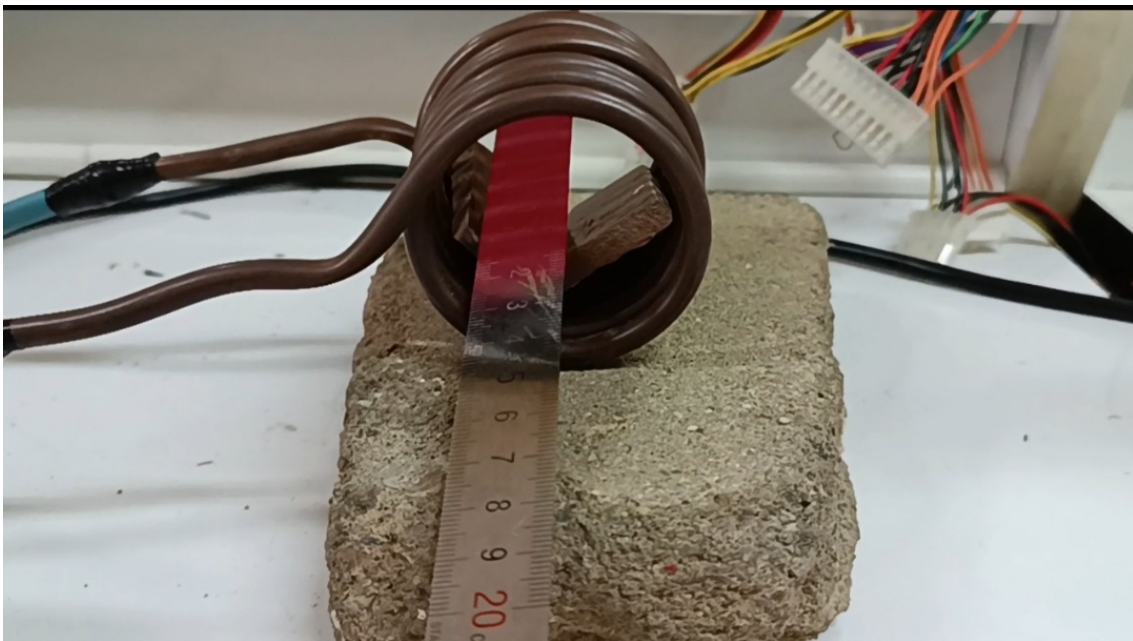


Figure 44. Heated workpiece.



Figure 45. Rectifier Output Voltage.



Figure 46. Buck Converter Output.

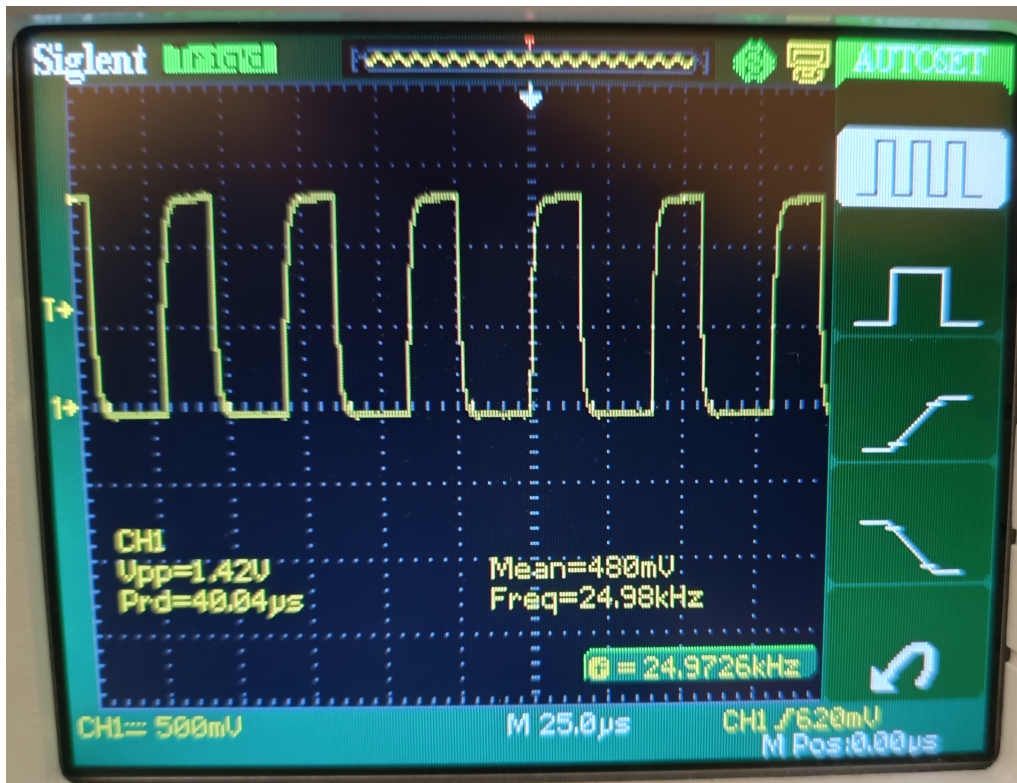


Figure 47. IGBT Driver Output Signal.



Figure 48. Voltage across the load.

General Conclusion

Conclusion

In this work, we have introduced and explained the induction heating technique which is used in many applications and many fields. We have started with the development of induction heating over the past decades, investigated the working principle, the basic setup, and the theoretical background of induction heating systems, and mentioned its different industrial applications.

The most important part of an IH setup is the power supply circuit that delivers the needed power to the working coil, and for that, we have explained different power devices used in power conversion applications and power supplies such as diodes, thyristors, and transistors.

We moved then to showcasing the different types of induction heating power supplies, furthermore, we have investigated each part of the power supply circuit, starting from rectification, and finishing with the inversion. As we mentioned before, the power supply circuit is the most important part of an IH setup, but the control and the modulation techniques has the same importance, because without the right modulation technique and control circuit, the IH system would not function as efficient as we want it to be, and because of that, we have talked about different modulation techniques used for voltage fed inverters.

Coming to the most important part in this work, which is the experimental results, we have fixed our project requirements in terms of the needed power, we have started with simulating our different power supply circuits, and then simulated the whole power supply circuit, and simulation results confirmed the theoretical studies we have done.

Finally, we have designed and implemented a voltage-fed full bridge series resonant inverter, and the results were promising, we were able to fulfill our project requirements and confirm all the simulations and the theoretical studies.

Further Works

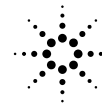
- Simulate and implement a PID controller.
- Implement remote monitoring and control.
- Implement a graphic interface.
- Install a water cooling circuit for the coil and also for the power devices.
- Design and build a proper case.

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Appendices



2.0 Amp Output Current IGBT Gate Drive Optocoupler

Technical Data

HCPL-3120
HCPL-J312
HCNW3120

Features

- **2.0 A Minimum Peak Output Current**
- **15 kV/ μ s Minimum Common Mode Rejection (CMR) at $V_{CM} = 1500$ V**
- **0.5 V Maximum Low Level Output Voltage (V_{OL})**
Eliminates Need for Negative Gate Drive
- **$I_{CC} = 5$ mA Maximum Supply Current**
- **Under Voltage Lock-Out Protection (UVLO) with Hysteresis**
- **Wide Operating V_{CC} Range: 15 to 30 Volts**
- **500 ns Maximum Switching Speeds**
- **Industrial Temperature Range: -40°C to 100°C**
- **Safety Approval**
UL Recognized
2500 Vrms for 1 min. for HCPL-3120
3750 Vrms for 1 min. for HCPL-J312
5000 Vrms for 1 min. for HCNW3120

CSA Approval

VDE 0884 Approved

$V_{IORM} = 630$ Vpeak for HCPL-3120 (Option 060)

$V_{IORM} = 891$ Vpeak for HCPL-J312

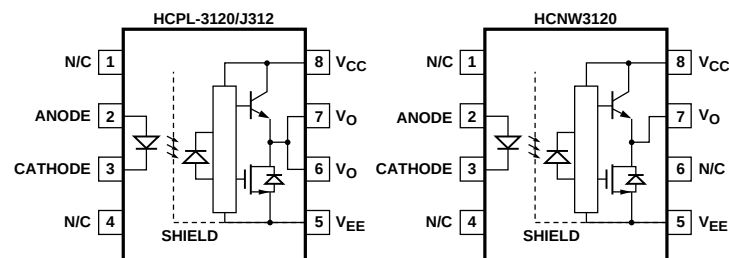
$V_{IORM} = 1414$ Vpeak for HCNW3120

BSI Certified (HCNW3120 only) (Pending)

Applications

- **IGBT/MOSFET Gate Drive**
- **AC/Brushless DC Motor Drives**
- **Industrial Inverters**
- **Switch Mode Power Supplies**

Functional Diagram



TRUTH TABLE

LED	$V_{CC} - V_{EE}$ "POSITIVE GOING" (i.e., TURN-ON)	$V_{CC} - V_{EE}$ "NEGATIVE GOING" (i.e., TURN-OFF)	V_O
OFF	0 - 30 V	0 - 30 V	LOW
ON	0 - 11 V	0 - 9.5 V	LOW
ON	11 - 13.5 V	9.5 - 12 V	TRANSITION
ON	13.5 - 30 V	12 - 30 V	HIGH

A 0.1 μ F bypass capacitor must be connected between pins 5 and 8.

CAUTION: It is advised that normal static precautions be taken in handling and assembly of this component to prevent damage and/or degradation which may be induced by ESD.

IGBT, Wechselrichter / IGBT, Inverter**Höchstzulässige Werte / Maximum Rated Values**

Kollektor-Emitter-Sperrspannung Collector-emitter voltage	$T_{vj} = 25^{\circ}\text{C}$	V_{CES}	1200	V
Kollektor-Dauergleichstrom Continuous DC collector current	$T_C = 80^{\circ}\text{C}, T_{vj\text{ max}} = 150^{\circ}\text{C}$ $T_C = 25^{\circ}\text{C}, T_{vj\text{ max}} = 150^{\circ}\text{C}$	$I_{C\text{ nom}}$ I_C	200 295	A A
Periodischer Kollektor-Spitzenstrom Repetitive peak collector current	$t_P = 1\text{ ms}$	I_{CRM}	400	A
Gesamt-Verlustleistung Total power dissipation	$T_C = 25^{\circ}\text{C}, T_{vj\text{ max}} = 150$	P_{tot}	1050	W
Gate-Emitter-Spitzenspannung Gate-emitter peak voltage		V_{GES}	+/-20	V

Charakteristische Werte / Characteristic Values

			min.	typ.	max.	
Kollektor-Emitter-Sättigungsspannung Collector-emitter saturation voltage	$I_C = 200\text{ A}, V_{GE} = 15\text{ V}$ $I_C = 200\text{ A}, V_{GE} = 15\text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	$V_{CE\text{ sat}}$		1,70 2,00	2,15 V V
Gate-Schwellenspannung Gate threshold voltage	$I_C = 8,00\text{ mA}, V_{CE} = V_{GE}, T_{vj} = 25^{\circ}\text{C}$		V_{GEth}	5,0	5,8	6,5 V
Gateladung Gate charge	$V_{GE} = -15\text{ V} \dots +15\text{ V}$		Q_G		1,90	μC
Interner Gatewiderstand Internal gate resistor	$T_{vj} = 25^{\circ}\text{C}$		R_{Gint}		3,8	Ω
Eingangskapazität Input capacitance	$f = 1\text{ MHz}, T_{vj} = 25^{\circ}\text{C}, V_{CE} = 25\text{ V}, V_{GE} = 0\text{ V}$		C_{ies}		14,0	nF
Rückwirkungskapazität Reverse transfer capacitance	$f = 1\text{ MHz}, T_{vj} = 25^{\circ}\text{C}, V_{CE} = 25\text{ V}, V_{GE} = 0\text{ V}$		C_{res}		0,50	nF
Kollektor-Emitter-Reststrom Collector-emitter cut-off current	$V_{CE} = 1200\text{ V}, V_{GE} = 0\text{ V}, T_{vj} = 25^{\circ}\text{C}$		I_{CES}			5,0 mA
Gate-Emitter-Reststrom Gate-emitter leakage current	$V_{CE} = 0\text{ V}, V_{GE} = 20\text{ V}, T_{vj} = 25^{\circ}\text{C}$		I_{GES}			400 nA
Einschaltverzögerungszeit, induktive Last Turn-on delay time, inductive load	$I_C = 200\text{ A}, V_{CE} = 600\text{ V}$ $V_{GE} = \pm 15\text{ V}$ $R_{Gon} = 3,6\ \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	$t_{d\text{ on}}$		0,25 0,30	μs μs
Anstiegszeit, induktive Last Rise time, inductive load	$I_C = 200\text{ A}, V_{CE} = 600\text{ V}$ $V_{GE} = \pm 15\text{ V}$ $R_{Gon} = 3,6\ \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	t_r		0,09 0,10	μs μs
Abschaltverzögerungszeit, induktive Last Turn-off delay time, inductive load	$I_C = 200\text{ A}, V_{CE} = 600\text{ V}$ $V_{GE} = \pm 15\text{ V}$ $R_{Goff} = 3,6\ \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	$t_{d\text{ off}}$		0,55 0,65	μs μs
Fallzeit, induktive Last Fall time, inductive load	$I_C = 200\text{ A}, V_{CE} = 600\text{ V}$ $V_{GE} = \pm 15\text{ V}$ $R_{Goff} = 3,6\ \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	t_f		0,13 0,18	μs μs
Einschaltverlustenergie pro Puls Turn-on energy loss per pulse	$I_C = 200\text{ A}, V_{CE} = 600\text{ V}, L_s = 80\text{ nH}$ $V_{GE} = \pm 15\text{ V}$ $R_{Gon} = 3,6\ \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	E_{on}		15,0	mJ mJ
Abschaltverlustenergie pro Puls Turn-off energy loss per pulse	$I_C = 200\text{ A}, V_{CE} = 600\text{ V}, L_s = 80\text{ nH}$ $V_{GE} = \pm 15\text{ V}$ $R_{Goff} = 3,6\ \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	E_{off}		35,0	mJ mJ
Kurzschlußverhalten SC data	$V_{GE} \leq 15\text{ V}, V_{CC} = 900\text{ V}$ $V_{CE\text{ max}} = V_{CES} - L_{sCE} \cdot di/dt$ $t_P \leq 10\ \mu\text{s}, T_{vj} = 125^{\circ}\text{C}$		I_{SC}		800	A
Wärmewiderstand, Chip bis Gehäuse Thermal resistance, junction to case	pro IGBT / per IGBT		R_{thJC}			0,12 K/W
Temperatur im Schaltbetrieb Temperature under switching conditions			$T_{vj\text{ op}}$	-40		125 $^{\circ}\text{C}$

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Technische Information / Technical Information

IGBT-Module
IGBT-modules

FF200R12KE3



Diode, Wechselrichter / Diode, Inverter

Höchstzulässige Werte / Maximum Rated Values

Periodische Spitzensperrspannung Repetitive peak reverse voltage	$T_{vj} = 25^{\circ}\text{C}$	V_{RRM}	1200	V
Dauergleichstrom Continuous DC forward current		I_F	200	A
Periodischer Spitzenstrom Repetitive peak forward current	$t_P = 1 \text{ ms}$	I_{FRM}	400	A
Grenzlastintegral I^2t - value	$V_R = 0 \text{ V}$, $t_P = 10 \text{ ms}$, $T_{vj} = 125^{\circ}\text{C}$	I^2t	7800	A^2s

Charakteristische Werte / Characteristic Values

			min.	typ.	max.	
Durchlassspannung Forward voltage	$I_F = 200 \text{ A}$, $V_{GE} = 0 \text{ V}$ $I_F = 200 \text{ A}$, $V_{GE} = 0 \text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	V_F		1,65 1,65	2,15 V V
Rückstromspitze Peak reverse recovery current	$I_F = 200 \text{ A}$, $-di_F/dt = 2000 \text{ A}/\mu\text{s}$ ($T_{vj}=125^{\circ}\text{C}$) $V_R = 600 \text{ V}$ $V_{GE} = -15 \text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	I_{RM}		150 190	A A
Sperrverzögerungsladung Recovered charge	$I_F = 200 \text{ A}$, $-di_F/dt = 2000 \text{ A}/\mu\text{s}$ ($T_{vj}=125^{\circ}\text{C}$) $V_R = 600 \text{ V}$ $V_{GE} = -15 \text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	Q_r		20,0 36,0	μC μC
Abschaltenergie pro Puls Reverse recovery energy	$I_F = 200 \text{ A}$, $-di_F/dt = 2000 \text{ A}/\mu\text{s}$ ($T_{vj}=125^{\circ}\text{C}$) $V_R = 600 \text{ V}$ $V_{GE} = -15 \text{ V}$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$	E_{rec}		9,00 17,0	mJ mJ
Wärmewiderstand, Chip bis Gehäuse Thermal resistance, junction to case	pro Diode / per diode		R_{thJC}			0,20 K/W
Temperatur im Schaltbetrieb Temperature under switching conditions			$T_{vj \text{ op}}$	-40		125 $^{\circ}\text{C}$

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Abstract:

When we talk about heating technologies, Induction Heating (IH) is one of the most important and most used technologies nowadays for many reasons, for instance, it's environmentally friendly which means zero pollution, it has the advantage of homogeneous heating, and also, it's used in many applications: industrial, medical, and domestic applications. This thesis investigates the theoretical background behind IH, discusses different industrial applications of IH, also different types of power supplies and converter topologies used in IH systems for power regulation are mentioned in detail. However, the efficiency of IH systems don't just depend on the power supply, but also on the control and modulation techniques, that is why this thesis also explains different modulation techniques used for voltage-fed inverters. At the end, a simulation of the power supply circuit was performed and confirmed with a small prototype.

Keywords: Induction heating systems; High frequency converters; resonant power conversion; Phase-Shift Control; Pulse Width Modulation (PWM) Control; Variable Frequency Duty Cycle.

ملخص:

عندما نتحدث عن تقنيات التسخين، فإن التسخين الحثي هو أحد أهم التقنيات وأكثرها استخدامًا في الوقت الحاضر لأسباب عديدة، على سبيل المثال، إنه صديق للبيئة مما يعني عدم وجود تلوث، وله ميزة التدفئة المتجانسة، وكذلك يمكن استخدامه في العديد من التطبيقات: التطبيقات الصناعية والطبية والمنزلية. تبحث هذه الرسالة في الجانب النظري للتسخين الحثي، وتناقش التطبيقات الصناعية المختلفة له، كما تم ذكر أنواع مختلفة من إمدادات الطاقة وطوبولوجيا المحولات المستخدمة لتنظيم الطاقة بالتفصيل. ومع ذلك، فإن كفاءة أنظمة التسخين بالحث لا تعتمد فقط على مصدر الطاقة، ولكن أيضًا على تقنيات التحكم. ولهذا السبب تشرح هذه الأطروحة أيضًا تقنيات التحكم المختلفة المستخدمة لمحولات التغذية بالجهد. في النهاية، تم إجراء محاكاة لدائرة إمداد الطاقة وتأكيدها بنموذج أولي صغير.

الكلمات المفتاحية: أنظمة التسخين بالحث؛ محولات التردد العالي؛ تحويل طاقة الرنين؛ التحكم في تغيير الطور؛ التحكم في تعديل كثافة النبض؛ دورة تشغيل التردد المتغير.

Résumé:

Lorsque on parle de technologies de chauffage, le chauffage par induction (IH) est l'une des technologies les plus importantes et les plus utilisées de nos jours pour de nombreuses raisons, par exemple, il est respectueux de l'environnement, ce qui signifie zéro pollution, il a l'avantage d'un chauffage homogène, et aussi, il est utilisé dans de nombreuses applications : applications industrielles, médicales et domestiques. Cette thèse étudie le contexte théorique de l'IH, aborde différentes applications industrielles de l'IH, ainsi que différents types d'alimentations et les topologies de convertisseurs utilisés dans les systèmes IH pour la régulation de puissance sont mentionnés en détail. Cependant, l'efficacité des systèmes IH ne dépend pas seulement de l'alimentation, mais aussi des techniques de contrôle et de modulation, c'est pourquoi cette thèse explique également différentes techniques de modulation utilisées pour les onduleurs alimentés en tension. A la fin, une simulation du circuit d'alimentation a été réalisée et confirmée avec un petit prototype.

Mots clé : Systèmes de chauffage par induction ; convertisseurs de haute fréquence ; conversion de puissance résonnante ; contrôle de déphasage ; contrôle de modulation (PWM) ; rapport cyclique à fréquence variable.