

CHAPTER 3

THEORY OF INDUCTION HEATING

3.1. HISTORICAL OVERVIEW

The basic of electromagnetic induction is based mainly on an alternating voltage applied to an induction coil that results in alternating current pass through the coil circuit. This principle was discovered by the English physicist Michael Faraday in 1831. He wound two coils of wire around an iron ring and noted that when an alternating current was passed through one of the coils, a voltage was induced in the other (the operation of a transformer is based on this effect). Figure 3.1 shows the field of magnetic induction associated with a solenoid coil carrying an electric current that represents Faradays Law. Researchers worked over the next several decades concentrated on the development of equipment for generating high frequency alternating current. Lenz's law was formulated later by the German physicist Heinrich Lenz which states that the polarity of the induced e.m.f. (direction of the induced e.m.f. and current resulting from electromagnetic induction) tends to produce a current that will create a magnetic flux to oppose the change in magnetic flux through the loop. It provides a physical interpretation of the choice of sign in Faraday's law of induction, indicating that the induced e.m.f. and the change in flux have opposite signs. These effects were used to develop the design of the transformers and electrical machines. The drawback of this process was the heat generated in the magnetic core of the transformer. Laminated silicon steel sheets isolated from each others were made to reduce heat generated in the transformer core. The same concept was used in the machinery stator and rotor manufacturing [2], [5].

In induction heating, the drawback of undesired heat generated in the transformer core is used to heat or melt the work-piece, as the core is set to be a bulk of the material to be heated or melted forming a transformer with a short circuit secondary.

The first attempt to heat metals in induction was early at 1922s by the development of motor-generator set provides an ideal source of the coreless induction furnaces, which could supply power levels up to several hundred of kilowatts at frequencies up to 960 Hz. By developing of solid-state converters, motor-generators were replaced using a medium frequency range rather than high-frequency solid state converters. The efficiency of these converters has increased to almost 95% compared to line frequency energy converters. It is also results in a decrease in cost of the overall induction system [5].

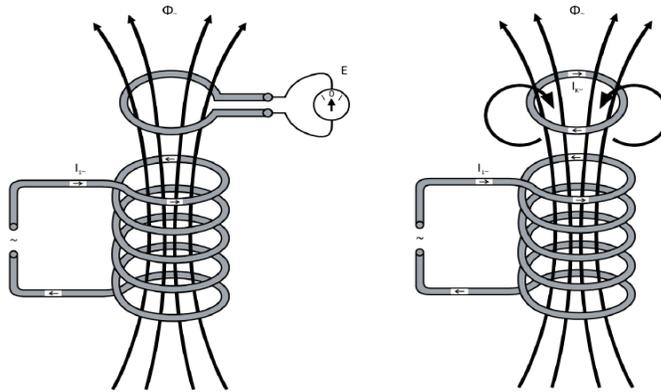


Figure 3.1 Faraday's Induction law

3.2. INDUCTION HEATING PRINCIPLES

Induction heating is built on three main principles:

1. Electromagnetic induction.
2. Skin effect.
3. Heat transfer.

Investigation of these three fundamental principles gives a clear understanding of induction heating process [1].

The energy is transferred to the heated object by electromagnetic induction. It is the process of using magnetic fields to produce voltage and current in a complete circuit. The electromagnetic induction can be created by moving of a conductive material through a Dc magnetic field. For transformers the moving magnetic field caused by the changing field (flux) induces a current in the secondary coil [5].

In induction heating system, the heating is caused by the induced eddy-current losses and hysteresis losses. The eddy currents will be induced if a massive conductor is placed in an alternating magnetic field. This eddy current will heat up the conductor. According to the Joule effect, when a current I [A] flow through a conductor with resistance R [Ohm], the power is dissipated in the conductor according to the following formula:

$$P = R \times I^2 \text{ [W]} \quad \text{Eq. 3.1}$$

Hysteresis loss is a friction between molecules when the material is magnetized in the two directions. The molecules act as small magnets, which turn around with each reversal of direction of the magnetic field. Therefore, in Ferro magnetic materials hysteresis losses improve the induction heating efficiency, and for a non-magnetic materials the heat generated in the work-piece is due to eddy-current loss only [3].

3.2.1 Skin Effect

The alternating current is concentrated on the peripheral layer of the conductor surface with a thickness (δ) called skin depth given by Eq. 3.2 [2], [5]; this is called a skin effect phenomena. Thus, most of the heat generated concentrates on the outer surface and is transferred to the whole conductor by the third fundamental principle of induction heating, the heat transfer.

There are three modes of heat transfer in induction heating [2]:

1. Conduction.
2. Convection.
3. Radiation.

Penetration depth is defined as the thickness of the layer, measured from the outside, in which 87% of the power is developed [2].

$$\delta = \sqrt{\frac{\rho}{\pi\mu f}} \quad \text{Eq. 3.2}$$

Where μ and ρ are the magnetic permeability and electrical resistivity of the work-piece, respectively, and f is the applied frequency.

Figure 3.2 shows the current distribution with depth, where I_s is the current at surface and I_x is the current at distance x . The current density falls off from the surface to the center of the work-piece and the rate of decrease is reversely proportional to frequency [20]. For applications of surface hardening where the heat depth need to be shallow, a high frequency is applied.

The skin depth is also depending on two properties of the materials: electrical resistivity ρ and magnetic permeability μ of the work-piece.

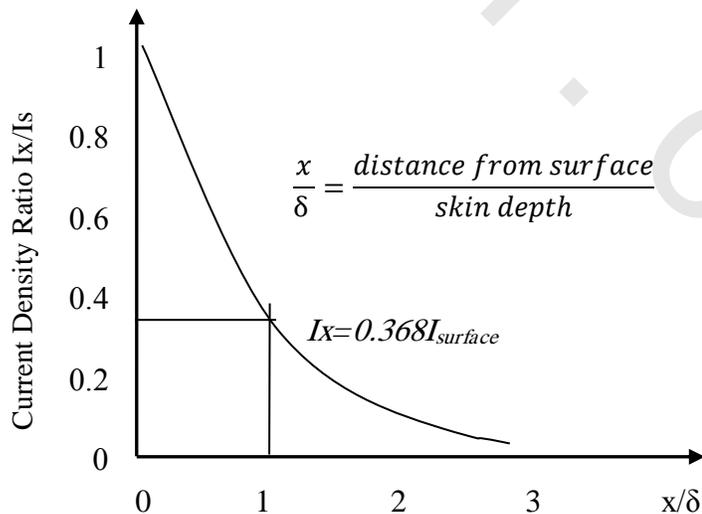


Figure 3.2 Current distribution due to skin effect [20]

Electrical resistivity ρ is the reciprocal of electrical conductivity σ in ($\Omega.m$) which is the ability of materials to easy conduct electrical current. The resistivity of pure metals is varying linearly with temperature as follows,

$$\rho_t = \rho_1[1 + \alpha(T - T_1)] \quad \text{Eq. 3.3}$$

Where ρ and ρ_1 are the resistivity at temperatures T and T_1 , respectively, and α is temperature coefficient for the material [5].

Relative magnetic permeability μ_r indicates the ability of a material to conduct the magnetic flux better than free space. The product of relative magnetic permeability and permeability of free space is called permeability ($\mu = \mu_r \cdot \mu_0$), where $\mu_0 = 4\pi \times 10^{-7}$ H/m. All materials based on their magnetization ability can be classified into, (i) Ferromagnetic materials $\mu_r \gg 1$ (ii) Diamagnetic materials $\mu_r < 1$ (iii) Paramagnetic materials $\mu_r > 1$. Due to insignificant difference of μ for both diamagnetic materials and paramagnetic materials, in induction heating these materials are called nonmagnetic materials.

3.2.1.1 Curie Temperature

Curie temperature is the temperature at which the ferromagnetic material becomes nonmagnetic. For Iron steel the Curie temperature is in range of 750~770 °C [2].

3.2.2 Required Power for Induction Heating

The power calculation analysis for induction heating tank circuit was proposed in [1], [2]. The value of specific heat, c , represents the amount of the required heat energy to be absorbed by a unit mass of the work-piece to achieve a unit temperature increase. The value of c is used to estimate the work-piece thermal power P_{th} . The required power in the work-piece (P_{th}) does not represent the power at coil terminals due to heat losses (radiation, convection, and conduction) [2].

$$Q_{th} = Mc\Delta T \quad \text{Eq. 3.4}$$

$$P_{th} = \text{heat content}(Kw.hr.Kg^{-1}) \times \text{production rate}(Kg.hr^{-1}) \quad \text{Eq. 3.5}$$

Where,

Q_{th} : Thermal energy (J).

ΔT : Temperature difference (°C).

M : Mass of the work piece (Kg).

c : Specific heat of the work-piece (J/Kg.°C).

P_{th} : Thermal power (KW).

Eq. 3.6 provides a correction between the required coil power P_c and required work-piece power P_{th} .

$$P_c = \frac{P_{th}}{\eta_{el}\eta_{th}} \quad \text{Eq. 3.6}$$

Where,

η_{el} : Electrical efficiency.

η_{th} : Thermal efficiency.

3.2.3 Frequency Selection

For effective induction heating, the frequency of the alternating magnetic field in the work-coil is given by [3]:

$$f_c = \frac{6.54 \rho}{\mu d^2} \quad \text{Eq. 3.7}$$

Where,

f_c : Critical frequency (Hz).

ρ : The electrical resistivity of the work-piece ($\mu\Omega\text{m}$)

d : The diameter of the work-piece (m)

μ : The permeability of the work-piece (Hm^{-1})

Equation 3.7 is defined as the critical frequency below which, a loss of heating would occur due to field cancellation in the work-piece. The critical frequency is calculated at a ratio of work-piece diameter to penetration depth (d/δ) > 4.5 . Where a free choice of frequency exists, it should be chosen greater than or equal to f_c .

3.3. POWER SUPPLY FOR INDUCTION HEATING

The main components of an induction heating system are: the high frequency power supply, load or tank circuit and the control circuit. Induction heating has been used in different applications; therefore the power supply specifications and switching elements are different for each application. In the past, the motor-alternator set and frequency multipliers were used as a high frequency power source for induction heating. The magnetic multipliers are more compact than motor-alternator and it is a fixed frequency supply. With a considerable progress in static power supplies using solid state power converters, many different power configuration and control schemes were developed and proposed [9], [14].

Solid state power supply illustrated in Figure 3.3 is a frequency changer that converts the available utility line frequency power to a single-phase with a suitable frequency value for the heating process.

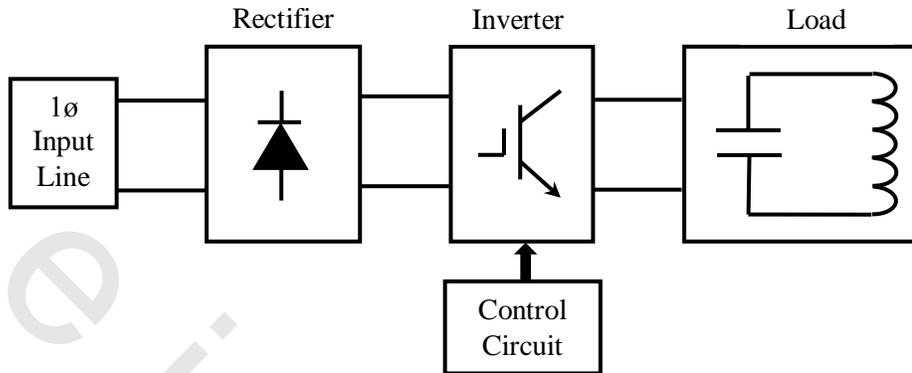


Figure 3.3 Layout of the high frequency solid state power source

3.3.1 Basics of Inverter Systems

Two systems are used for most induction heating solid state inverters, the load resonant generator and the swept frequency generator. Figure 3.4 shows the power control curve for each generator set. The swept-frequency generator, called variable frequency generator, consists of a variable frequency inverter and uncontrolled rectifier (i.e. fixed voltage DC supply). The load-resonant generator provides great range of power control by using variable DC source. It is suitable for higher power level applications [2], [5].

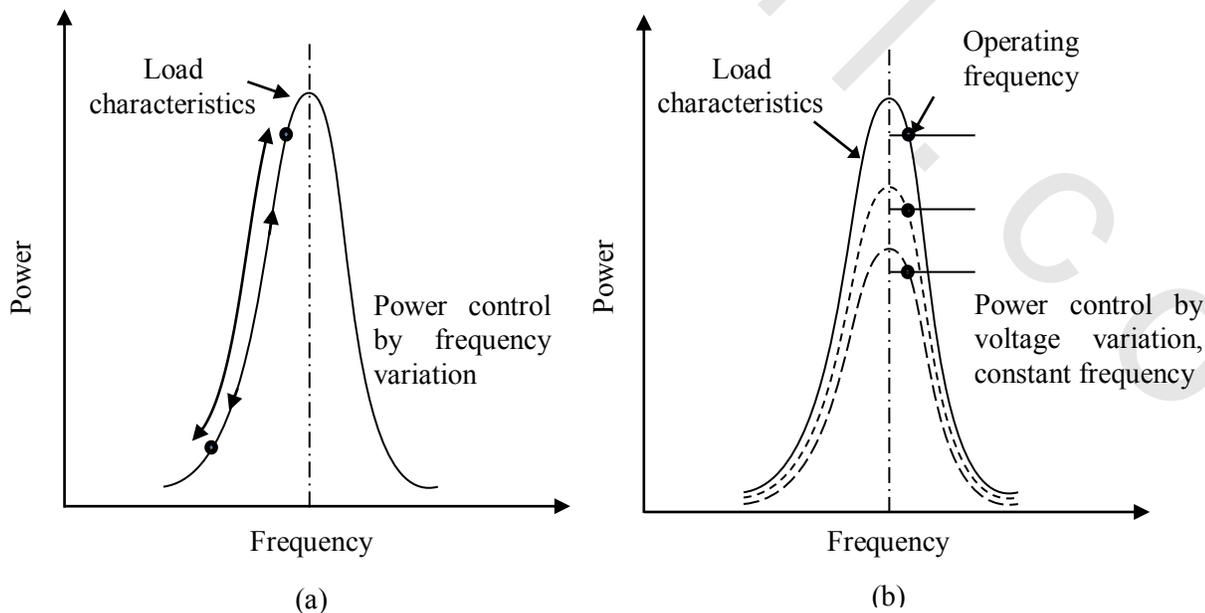


Figure 3.4 Inverter power control (a) swept frequency, (b) Load resonant [2]

The main drawbacks of load resonant generator are: it is not a self-starting system, it needs a complex external starting circuit, it has a complex control system, and it needs a variable DC source which reflects negatively on the system cost.

Also the swept-frequency generator has a limited power level up to a few hundred of kilowatt, limited range of power control, lower power efficiency especially at reduced power level, more complex power circuit than that of the load resonant generator, and it has higher switching losses. Each system has many advantages, load resonant generator has a higher efficient, greater range of power control, it's suitable for higher power levels and fast heating and melting rate. The swept frequency generator has a simple control circuit, and self-starting [2], [5].

In this thesis a new controller for another approach (PDM approach) is presented. The proposed controller has the advantages of the above mentioned two classical approaches, as it provides lower switching losses, simple control and power circuit, higher efficiency, self-starting system, it is suitable for high power levels, and has a great range of power control without using a variable DC source which reduces the system cost.

3.3.2 Resonant Converters

Resonant converters are one of the most efficient converters for induction heating. There are many resonant converter topologies as classified in Figure 3.5. Resonant converters hasn't been used in a wide range in power electronics industry since 1970s due to the unavailability of power semiconductor devices that can be operated at high power and frequency such as IGBTs, MOSFETs, and SCRs [20]. These converters generate a square pulse of voltage or current which is applied to a resonant circuit.

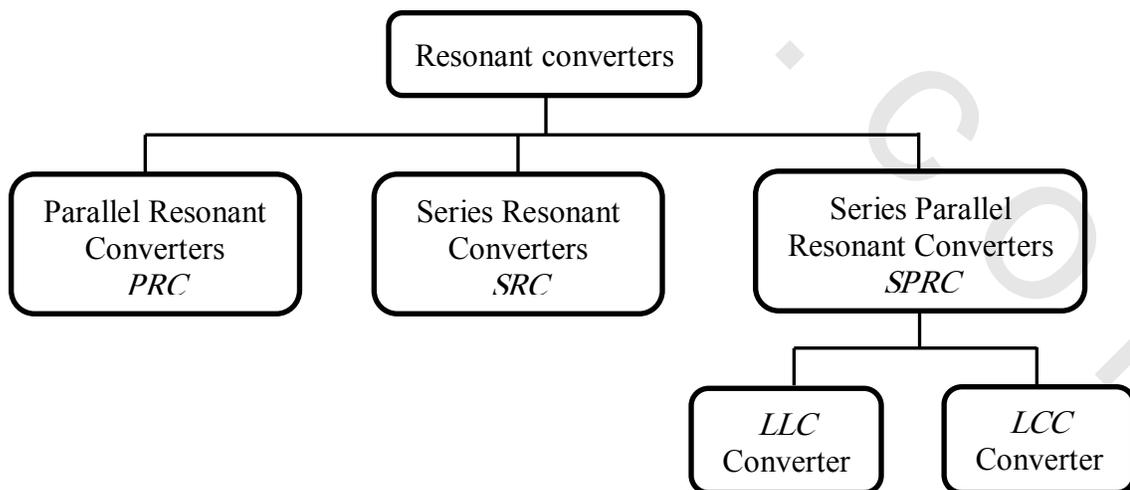


Figure 3.5 Classifications of resonant-converter topologies

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3.3.4 Parallel Resonant Converter (PRC)

The PRC is dual to SRC. The load is connected in parallel with the resonance capacitor, producing a large amount of circulating current. This makes it difficult to apply PRC in applications with high power density or large load variations. They are supplied by a current source and the converters generate a square wave input current that flows through the parallel resonant circuit. They offer better short circuit protection under fault conditions than the SRCs with a voltage source. The PRC is suitable for low output voltage high output current application [6], [20].

3.3.5 Series Parallel Resonant Converter (SPRC)

The SPRC is a combination of SRC and PRC. It combines the good characteristic of PRC and SRC. The circulating energy in this converter is reduced compared with PRC because of the input current is much smaller than PRC. The main disadvantages of the SPRC are: the conduction loss and switching loss which will increase at high input voltage and it has a narrow switching frequency range with load change compared to SRC [25].

3.3.6 Switching Techniques of Resonant Converters

Due to the problems associated with hard switching, the resonant converters use a resonant circuit to switch the transistors at zero current or zero voltage point. This reduces the stress on the switching transistors and the radio interference.

3.3.6.1 Zero Voltage Switching (ZVS)

The objective of a ZVS switch is to use the resonant circuit to shape the switch voltage waveform during the off time in order to create a zero voltage condition for the switch to turn on. This technique is applicable to all switching topologies. The benefits of ZVS are lower switching losses, reduced EMI, and have high efficiency with high voltage inputs at any frequency [20].

3.3.6.2 Zero Current Switching (ZCS)

Zero current switching is a soft switching technique that makes the transistor to turn-off at zero current. It eliminates the switching loss caused by IGBT current tailing and by stray inductances. It can also be used to commutate SCR's [6].

3.3.7 Power Semiconductors in Resonant Converters

Bipolar transistors (BJT) are not suitable for resonant converters especially at high power ratings because they require a substantial drive current and have lower current carrying capability.

Silicon controlled rectifier SCR or thyristor has a great range of current carrying capability. The main drawback of this switch is that it turns off only when current becomes zero requiring an external commutation circuit and it has limited switching time [6].

Power MOSFET is suitable for ZVS as there are no capacitive switching losses in this case. It has a fast switching time and not suitable in ZCS also it does not perform well in over current conditions [6], [23].

IGBT are voltage-controlled device, which require very small current during switching period. It has a simple gate drive circuit. IGBT can operate at frequencies up to hundreds of kilohertz. It is the most common choice for medium power converters due to simplicity of drive circuit, high ruggedness and has moderate conduction and switching losses [23]. Table 3.1 helps in choosing the best possible switching device according to power level.

Table 3.1 Relative properties of semiconductor devices [6]

Semiconductor Device	Power capability	Switching frequency
SCR	High	Slow
BJT	Medium	Medium
MOSFET	Low	Fast
IGBT	Medium	Fast

3.4. TANK CIRCUIT

As mentioned in section 3.3, the induction heating system comprises of three main elements, the high frequency power supply, tank circuit and the control circuit. Tank circuit can be modeled by means of a series combination of the equivalent resistance R_L and inductance L_L connected in series or parallel to a capacitive element C_r . These parameters depend on several variables including the shape of the work-coil, the space between the work-piece and work-coil (coupling), the electrical conductivities and the tuned frequency.

The tank circuit components may be connected in series or in parallel. Tuning of induction heating is required to make the frequency of tank circuit close to the power source frequency. This tuning is performed by adjusting the capacitance or inductance of a tank circuit [5].

3.4.1 Work-Coil and Work-Piece

Work coils are usually designed for specific applications and therefore found in a wide variety of shapes and sizes. It is usually made of copper pipes water cooled to remove the radiation and conduction losses from work-piece and eddy current I^2R losses. The practical representation of the coil is an inductive reactance X_c and the resistance of the coil R_c . the work-piece in turns represented by inductive reactance X_w and the resistance R_w .

J. Davies and P. Simpson [2] made the analysis of the induction tank circuit and concluded that it can be represented by a simple series combination of resistive and inductive elements as shown in Figure 3.8. The following equations proposed by J. Davies and P. Simpson in [2] are used to determine the values of these resistance and reactance:

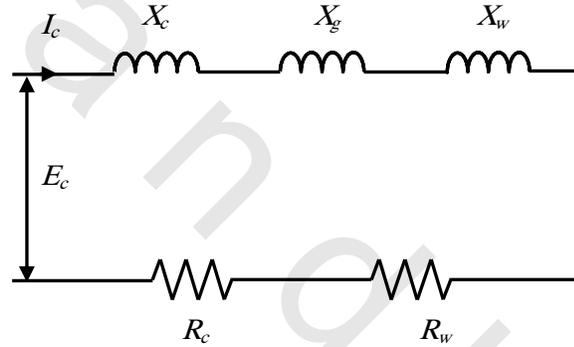


Figure 3.8 tank circuit electrical representation [2]

$$Z = (R_w + R_c) + j(X_w + X_c + X_g) \quad \text{Eq. 3.8}$$

$$|Z| = \sqrt{(R_w + R_c)^2 + (X_w + X_c + X_g)^2} \quad \text{Eq. 3.9}$$

$$R_w = K(\mu_r p A_w) \quad \text{Eq. 3.10}$$

$$R_c = K \left(\frac{\pi K_r D_c \delta_c}{2} \right) \quad \text{Eq. 3.11}$$

$$X_w = K(\mu_r q A_w) \quad \text{Eq. 3.12}$$

$$X_c = R_c \quad \text{Eq. 3.13}$$

$$X_g = K(A_g) \quad \text{Eq. 3.14}$$

$$K = \left[\frac{2 \pi f \mu_0 N_c^2}{l_c} \right] \Omega/m^2 \quad \text{Eq. 3.15}$$

$$\delta_c = \sqrt{\frac{\rho_c}{f \times 4 \times \pi^2 \times 10^{-7}}}, \rho_c = 2 \times 10^{-8} \quad \text{Eq. 3.16}$$

Where, R_w and R_c are the work-piece and work-coil resistance, respectively, X_w , X_c and X_g are the work-piece, work-coil and gap reactance, respectively, δ_c is the coil current penetration depth, A_w , A_g , l_c and D_c are work-piece, air gap cross section area, coil length and coil diameter, respectively. The values of these elements can be used to calculate the major tank circuit properties, i.e., efficiency, coil power factor, coil VA, active power, copper losses, coil number of turns, number of volts per turn and the number of ampere-turns. The equations of these parameters and examples of a coil design are presented in [2].

3.4.2 Resonance Circuit

The resonance circuits are a combination of R , L , and C elements having a frequency response characteristic similar to the one appearing in Figure 3.9. When the resonance occurs, due to the application of proper frequency f_r , the energy absorbed by one reactive element is the same as that released by another reactive element. When the ideal system reached a resonance state it will be self-sustaining. Due to the existing of coil and work-piece resistance, damping oscillations between reactive elements occurred [24].

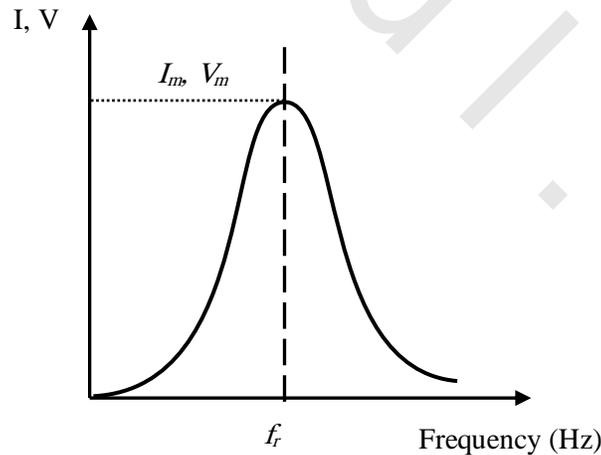


Figure 3.9 Resonance circuit frequency response [24]

The work-coil and work-piece represents the inductive and resistive elements of the resonance circuit. Capacitive element is connected in series or parallel forming the resonance circuit. The resonance frequency is defined by [24]:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad \text{Eq. 3.17}$$

Where L is inductance (in Henry) and C is capacitance (in Farad).

3.4.2.1 Parallel Resonance

Figure 3.10(a) shows the actual representation of the parallel resonant circuit for induction heating. The equivalent representation of the tank circuit as seen by the source is shown in Figure 3.10(b). At resonance, the inductive and capacitive reactance cancels each other and the resistance of the coil is transformed from R_L to R_p as shown in Figure 3.10(b), R_p is the impedance seen by the source at resonance. The analysis for conversion the actual network to parallel equivalent network (Figure 3.10(b)) is proved by L. Boylestad [24] getting the formula of R_p and X_p as follows,

$$R_p = \frac{R_L^2 + X_L^2}{R_L} \quad \text{Eq. 3.18}$$

$$X_p = \frac{R_L^2 + X_L^2}{X_L} \quad \text{Eq. 3.19}$$

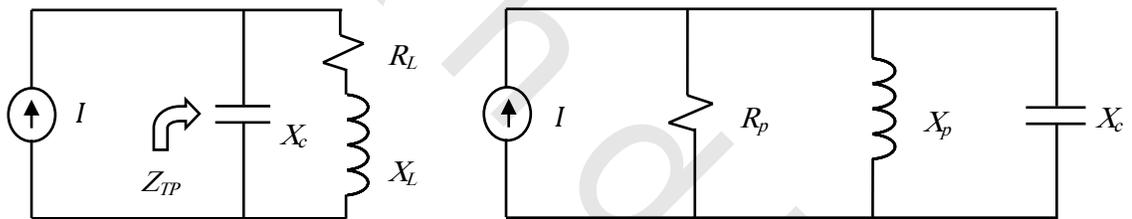


Figure 3.10 (a) parallel resonance in induction heating, (b) equivalent representation [24]

3.4.2.2 Quality Factor

The quality factor Q of the resonant circuit is determined by the ratio of the reactive power to real power. It is the ratio of the stored energy to the dissipated energy in the circuit per cycle [24]. The rate of energy loss reverses proportional to Q factor i.e. for lower rate of energy losses Q need to be high. It is a measure of sharpness of the resonance frequency response (Figure 3.9).

$$Q_P = \frac{\text{reactive power}}{\text{active power}} \quad \text{Eq. 3.20}$$

$$Q_P = \frac{R_p}{X_p} \quad \text{Eq. 3.21}$$

3.5. CONTROL CIRCUIT

The control circuit is the third main element of induction heating. It achieves the power control of induction heater as the power inverter has no ability to control the output power by itself. This control scheme may comprise of open or closed loop control system to accomplish the power control. Many control schemes have been proposed to overcome the problems of thyristor bridge rectifier as a DC power supply; such as frequency control (FC), Pulse Width Modulation (PWM), Phase Shift control (PSC), Duty Cycle control (DCC) and the Asymmetrical Voltage Cancellation (AVC). The differences between these methods are summarized in the following subsection.

3.5.1 Inverter Control Schemes

Two control schemes are related to the frequency control strategy, the pulse frequency modulation (PFM) [13] and the automatic frequency control (AFC) [3]. In the pulse frequency modulation control scheme the output power is controlled by adjusting the switch duty cycle and the inverter operates under zero voltage switching. It has a problem in efficiency due to switching losses at high frequency operation [16]. This method is preferred in the half bridge topology. It has relatively low line harmonic noises in the utility grid and it is verifying a wide power regulation range [13]. Automatic frequency control technique uses the gate voltage as a phase representative of the driving current to the load i.e. it is always monitor the phase relationship between the driving current and driving voltage [3].

The phase shift control (PSC) technique regulates the output power delivered to the load by controlling the phase shift of firing signals. The main disadvantage of this control technique is the operation over a narrow frequency range. This controller ensures the switch to turn on at zero voltage by controlling the frequency [10].

The asymmetrical voltage cancellation (AVC) controller is a fixed frequency control strategy. It has difficulty to control the output power due to variation of the resonant elements during the heating cycle. This scheme achieves zero voltage switching [16].

These control schemes couldn't make the switching devices to always turn on and off at zero current, which increase the switching losses and electromagnetic noises [7]. The pulse density modulation (PDM) control strategy regulates the output power by varying the period in which the inverter supplies high frequency current to the induction coil while achieving zero current and voltage switching regarding the load variation at the overall heating cycle [16]. Its main advantages are its simplicity with a good power factor and a low total harmonic distortion

(THD) [8]. PDM technique has a discrete and often nonlinear power control response. To solve this problem a large value of quality factor Q is required.

3.5.2 Pulse Density Modulation PDM [7]

A brief comparison has been highlighted to select appropriate resonant converter topology for induction heating. An investigation has been carried out as well, that the most suitable power converter topology for this application has been identified as series resonant converter SRC and the possibility of using uncontrolled bridge rectifier followed by LC filter. Another comparison has been made also between the proper control techniques which show that the PDM control strategy is an effective control strategy that could be applied on series resonant converter which allows turning on/off of switching device at zero current instant to reduce the switching losses and electromagnetic noises.

The power is regulated in PDM by operating the inverter in alternate run and stop modes. At a stop cycle PDM provides a free-wheeling circuit for the resonant current to flow through the load. At this mode the load voltage and the supply current are zero. During stop cycle the stored energy from series capacitive and inductive elements is dissipated into a resistive component, which results in decaying of AC current magnitude.

3.5.2.1 PDM Pattern

The PDM pattern is the switching scheme that applies to the alternate run and stop modes for inverter circuit. Figure 3.11 shows an example for PDM pattern sequences assuming that the summation of on and off cycles is ten. In this case, the modulation index M can be varied from 1/10 to 10/10. For $M = 10/10$ the inverter delivers full power to load and no stop cycles were applied at this value of modulation index. For $M = 1/10$ the delivered power to the load is at minimum possible value.

$$M = \frac{T_{on}}{T_{PDM}} \quad \text{Eq.3.22}$$

For 5/7 modulation index, the output current and voltage waveforms of the inverter with PDM is shown in Figure 3.12 (assuming $T_{on}=5$ cycles, $T_{off}=2$ cycles, i.e. $T_{PDM}=7$). It has to be noted that, the length of one PDM full cycle is a multiple of the load resonant period.

3.5.2.2 Operating Modes in PDM

Figure 3.13 shows the switching modes of the voltage source series resonant PDM inverter shown in Figure 3.13a. The inverter generates bipolar output voltage by switching the IGBTs in alternate sequence (S_1, S_4) and (S_2, S_3), as shown in Figs. 3.13b and 3.13c (Mode I and II). In

the third mode, the two lower side switches (S_2 and S_4) or the two upper side switches (S_1 and S_3) are turned on as shown in Fig. 3.13d or 3.13e respectively, which results in zero voltage at the inverter output terminals.

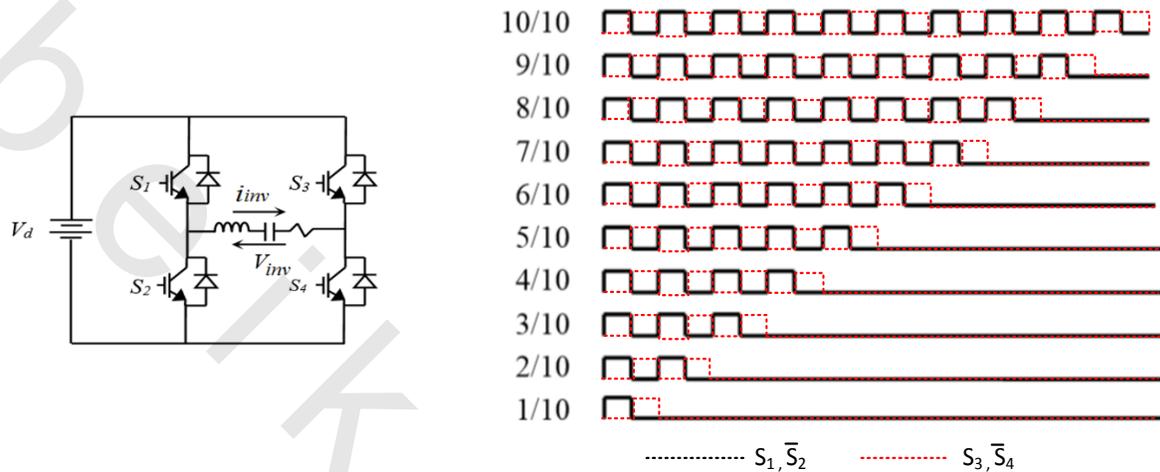


Figure 3.11 PDM pattern cycle waveforms (gate pulses of inverter switches).

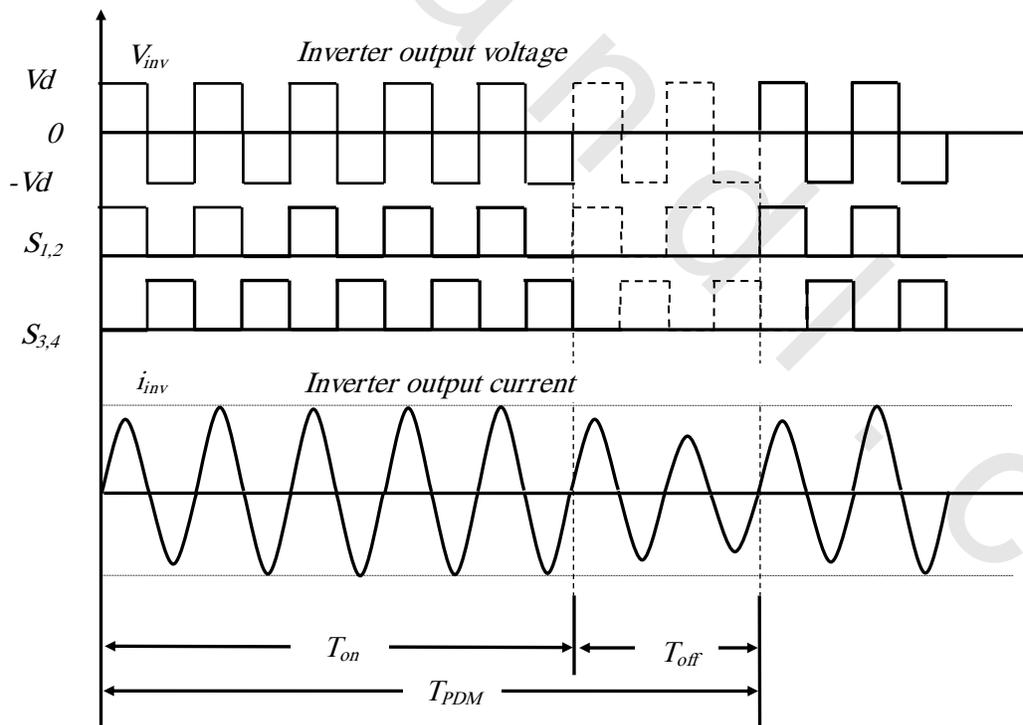


Figure 3.12 Output current and voltage waveforms with PDM.

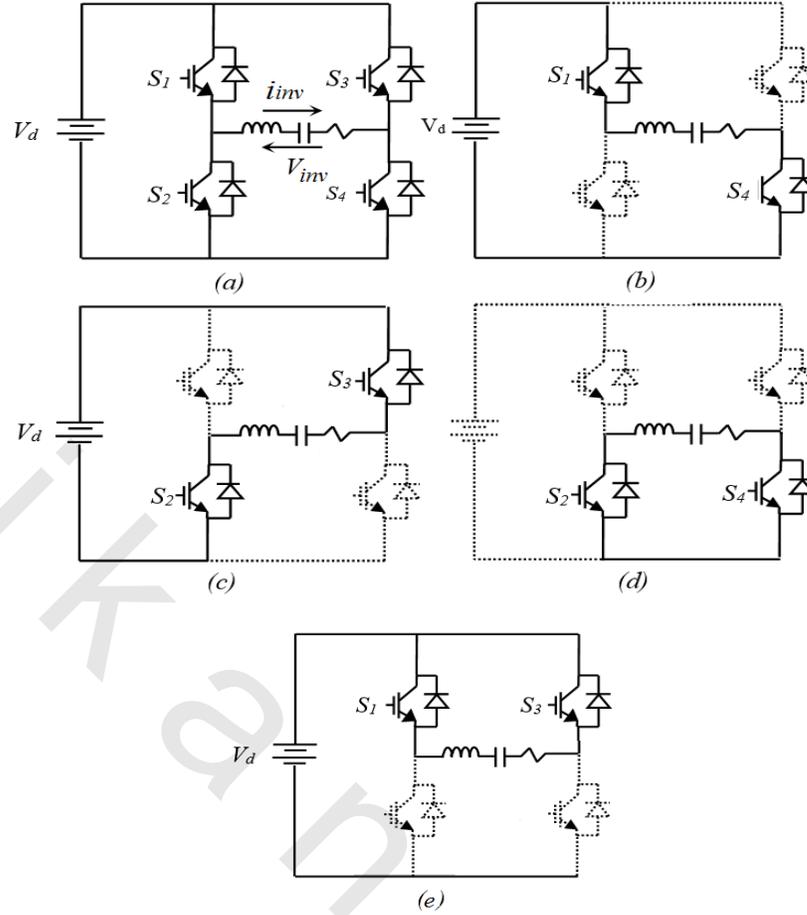


Figure 3.13 Operating modes in PDM (a) Main circuit, (b) Mode I, (c) Mode II, (d or e) Mode III

3.5.2.3 Analysis of Output Power

The inverter average power in PDM control is described by H. Fujita and H. Akagi [7], as follows,

$$P = P_{max} \left[\frac{T_{on}}{T_{PDM}} + \frac{\tau}{T_{PDM}} \left(\frac{1 - e^{-\frac{T_{on}}{\tau}}}{1 - e^{-\frac{T_{PDM}}{\tau}}} \right) \left(e^{-\frac{T_{on}}{\tau}} - e^{-\frac{T_{PDM}}{\tau}} \right) \right] \quad \text{Eq. 3.23}$$

$$P_{max} = \frac{2}{\pi} V_d I_{max} \cos \theta \quad \text{Eq. 3.24}$$

Where, I_{max} is the maximum current for a unity modulation index ($T_{ON}/T_{PDM} = 1$), τ is the time constant of the resonant circuit, and $\cos \theta$ is the load power factor seen by the inverter output.

3.6. DISCUSSION

The PDM control strategy can be used to drive resonant power converters. PDM is a simple control strategy that allows the switching devices to operate at zero current which achieve very low switching losses, high power factors and minimized electromagnetic noises.

The important features of PDM technique for resonant converters are [8]:

- Wide output power range.
- Unity power factor.
- Zero-current (or voltage) switching.
- Reduced switching losses and electromagnetic noise.
- Fixed switching frequency.
- Simple control circuit.