Chapter 2

PRINCIPLE OF INDUCTION MELTING & SURVEY OF POWER TOPOLOGIES & DIFFERENT TUNING METHODS FOR PID

2.1 Introduction

In this chapter the introduction is given on the induction melting application and problem, which presents a brief state-of-art survey of research work carried out in the area of induction melting. Various power topologies are presented and the need for resonant converter is explained. The various resonant topologies have been presented for switching devices. The latest development on melting application and problem has been reviewed and lays down the motivation behind the research work carried out.

Electromagnetic induction refers to the phenomenon that electric current is generated in a closed circuit by the fluctuation of current in another circuit placed next to it. The basic understanding of induction heating, which is an applied form of Faraday's discovery, starts from the fact that the AC current flowing through a circuit affects the magnetic movement of a secondary located near to it. The fluctuation of current inside the primary was found to be the answer to the mysterious current generated in the neighboring secondary. The Faraday's discovery has served as a main starting point in developing electric motors, generators, transformers, wireless communications devices, etc. Its applications, however, have not been necessarily flawless. Heat loss that occurs during the induction heating process was a major headache undermining the overall function of a system. Researchers sought to minimize heat loss by laminating the magnetic frames placed inside a motor or transformer. The Faraday's Law was followed by a series of more advanced discoveries such as the Lentz's Law which explains the fact that inductive current flows in inverse to the direction of changes in induction magnetic movement.

Heat loss occurring in the process of electromagnetic induction could be turned into productive heat energy in an electric heating system by applying this law. Many different industries have benefited from this new breakthrough by implementing induction heating to furnacing, quenching, welding, etc. In these applications, induction heating has made it easier to set the heating parameters with no need of additional external power source. This substantially reduces heat loss while maintaining more convenient working environment. Absence of any physical contact to heating devices precludes unpleasant electrical accidents, and high energy density is achieved by generating sufficient heat energy within a relatively short period of time.

As the demand for a better-quality and less energy-consuming product is getting higher, the electronic appliances have more advanced in terms of quality, safety, and energy consumption. Safety in use and efficient and fast heating/melting make them more attractive.

2.2 Types of Electric Process Heating

Before entering the description of induction heating, some types of electric process heating are provided below.

- Resistance Heating
- Conduction Heating
- Infrared Radiation Heating
- **Induction Heating**
- Dielectric Hysteresis Heating
- Electric Arc Heating
- Plasma Heating
- Electron Beam Heating
- Laser Heating

Resistance heating is the most common type of electric process heating, which applies the relationship between the voltage and current of resistance in the Joule's Law.

Conduction heating exploits the heat energy generated when an object is placed between two electric poles, which is another application of the Joule's Law. In this case, however, a different relationship exists between voltage and current, especially when the circuit current is high, because the object itself contains both resistance and inductance features.

The main topic of this document is induction heating/melting, which is a combination of electromagnetic induction, the skin effect, and the principle of heat transfer. In short, induction heating refers to the generation of heat energy by the current and Eddy current created on the surface of a conductive object (according to the Faraday's Law and the skin effect) when it is placed in the magnetic field formed around a coil where the AC current flows through (Ampere's Law). Detailed descriptions of induction heating are presented in the following sections of the document.

2.3 Principle of Induction Melting

Induction melting is comprised of three basics: electromagnetic induction, the skin effect, and heat transfer. The fundamental theory is similar to that of a transformer. In this section, electromagnetic induction and the skin effect are demonstrated. Figure 2-1 illustrates a very basic system consisting of inductive melting coils and current to explain electromagnetic induction and the skin effect.

Figure 2-1-a shows the simplest form of a transformer, where the Secondary current is in direct proportion to the primary current according to the turn ratio. The primary and secondary losses are by Resistance of Windings and the Link coefficient between the two circuits is 1. Magnetic current leakage is ignored here.

When the coil of the secondary is turned only once and short-circuited, there would be a substantial heat loss due to the increased load current (secondary current). This is demonstrated in Figure 2-1-b.

Figure 2-1-c shows a system where the energy supplied from the source is of the same amount as the combined loss of the Primary and secondary. In the figure, the inductive coil of the primary has many turns while the secondary is turned only once and short-circuited. The inductive heating coil and the load are insulated from each other by a small aperture.

As the primary purpose of induction heating is to maximize the heat energy generated in the secondary, the aperture of the inductive heating coil is designed to be as small as possible and the secondary is made with a substance featuring low resistance and high Permeability. Nonferrous metals will undermine energy efficiency because of their properties of high resistance and low Permeability.

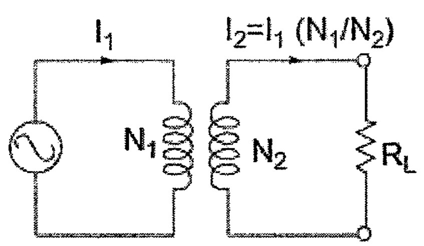

Figure 2-1a Equivalent circuit of a transformer

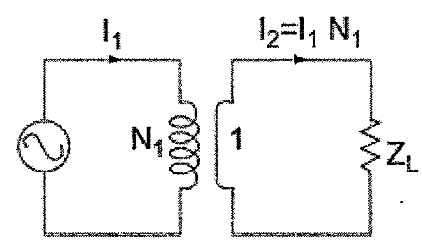

Figure 2-1b Secondary short

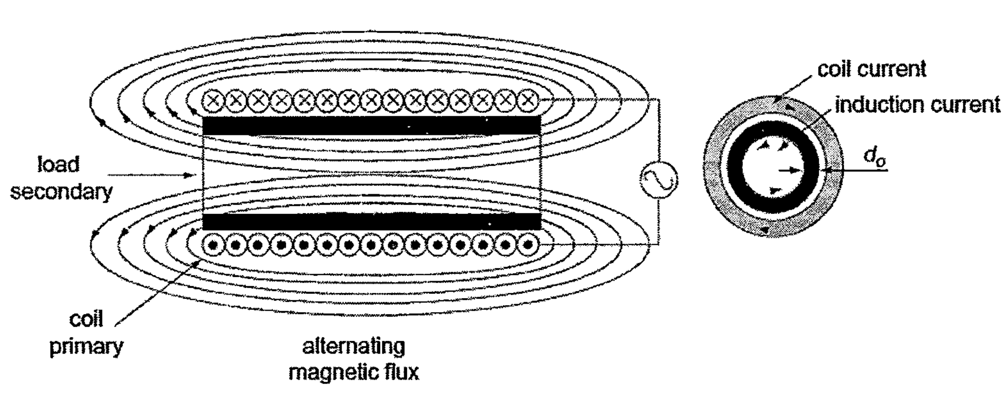

Figure 2-1c Basics of Induction Melting

2.4 Electromagnetic Induction

As shown in Figure 2-1, when the AC current enters a coil, a magnetic field is formed around the coil according to the Ampere's Law.

An object put into the magnetic field causes a change in the velocity of the magnetic movement.

The density of the magnetic field wanes getting closer to the center from the surface. According to the Faraday's Law, the current generated on the surface of a conductive object has an inverse relationship with the current on the inducting circuit as described in Formula 2-1. The current on the surface of the object generates Eddy Current.

$E = N \frac{d\Phi}{dt}$ (Equation 2-1)

As a result, the electric energy caused by the induced current and Eddy Current is converted to heat energy as in Formula 2-2.

$P = E2/R = i2R$ (Equation 2-2)

Here, resistance is determined by the resistivity (ρ) and permeability (μ) of the conductive object. Current is determined by the intensity of magnetic field. Heat energy is in inverse relationship with Skin Depth.

2.5 Skin Effect

To reach the melting temperature of Gold/Silver (around 1064°C) in a short time the frequency of ac supply must be kept of the order of medium frequency.

The higher the frequency of the current administered to the coil, the more intensive becomes the induced current flowing around the surface of the load. The density of the induced current diminishes when flowing closer to the center as shown in Equation 2-3 and 2-4 below. This is called Skin Effect or Kelvin Effect. From this effect, one can easily infer that the heat energy converted from electric energy would be concentrated on the skin depth (surface of the object).

$i_x = i_0 e^{-x/d_0}$ (Equation 2-3)

Here, i_x: distance from the skin (surface) of the object, current density at x.
i_0: current density on skin depth (x=0)
d_0: a constant determined by the frequency (current penetration depth or skin depth)

$d_0 = \sqrt{\frac{2\rho}{\mu\omega}}$ (Equation 2-4)

Here, ρ: resistivity
μ: permeability of the object
ω: Frequency of the current flowing through the object

2.6 PWM Techniques

It is generally recognized that PWM inverters offer a number of advantages over rival convertor techniques. These advantages are usually gained at the expense of more complex control & power-ckt configuration. The cost & complexity of PWM inverter systems will significantly reduce with continuing developments in LSI technology, fast switching thyristors & power transistors, GTOs & FETs. Combining the computing power of the μp with the fast switching characteristics of the new power electronic devices provides the possibility of realizing the full potential & versatility of power electronic control techniques. Because of advances in solid state power devices and microprocessors [x1], [x1], [x1], [x1], switching power converters are used in more & more modern three phase induction load to convert and deliver the required energy to the objet. The energy that a switching power converter delivers to an induction load is controlled by modulation techniques.

The fundamental of the modulation techniques have been well established.[x2], [x2], [x2], [x2], [x2]. Pulse Width Modulated (PWM) signals are applied to the gates of the power devices. PWM signals are pulse trains with fixed frequency and magnitude and variable pulse width. There is one pulse of fixed magnitude in every PWM period. However, the width of the pulses changes from pulse to pulse according to a modulating signal. When a PWM signal is applied to the gate of power devices, it causes the turn-on and turn-off intervals of the power devices to change from one PWM period to another PWM period according to the same modulating signal. The frequency of a PWM signal must be much higher than that of the modulating signal, the fundamental frequency, such that energy delivered to the load depends mostly on the modulating signal[x3].

The basic PWM techniques are:

1. Single Pulse Width Modulation
2. Multi Pulse Width Modulation
3. Sinusoidal Pulse Width Modulation

But when the technology progresses some advanced modulation techniques are also proposed by the different researcher like:

1. Trapezoidal Modulation
2. Staircase Modulation
3. Stepped Modulation
4. Harmonic Injection Modulation
5. Delta Modulation
6. Space vector Modulation
7. Random PWM

Generally, semiconductor switching devices operate in Hard Switch Mode in various types of PWM DCDC converters and DC-AC inverter topology employed in a power system. In this mode, a specific current is turned on or off at a specific level of voltage whenever switching occurs, as shown in Figure 2-2. This process results in switching loss. The higher the frequency the more the switching loss, which obstructs efforts to raise the frequency. Switching loss can be calculated in a simple way as shown in Equation 2-5 below. Switching also causes an EMI problem, because a large amount of di/dt and dv/dt is generated in the process.

$$Psw = \frac{1}{2} Vsw Isw fs(ton + toff) \qquad \text{(Equation 2-5)}$$

where, Psw: switching loss [W]
Vsw: switching voltage [V]
Isw: switching current [A]
fs: switching frequency [kHz]
ton: switch turn-on time [s]
toff: switch turn-off time [s]

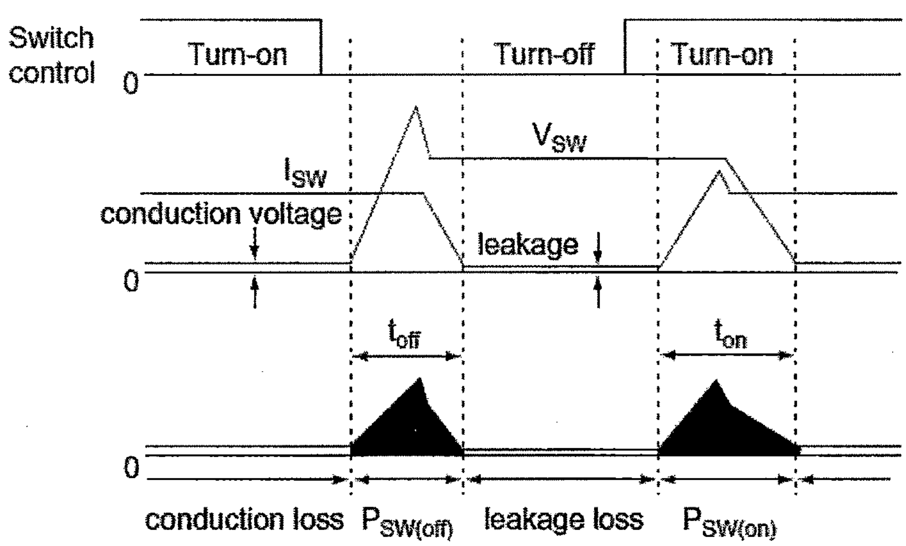

Figure 2-2 Waveform of a Switching Device

By raising the switching frequency, the size of a transformer and filter can be reduced, which helps build a smaller and lighter converter with high power density. But as presented earlier, switching loss undermines the efficiency of the entire power system in converting energy, as more losses are generated at a higher frequency. Higher energy conversion efficiency at high frequency switching can be obtained by manipulating the voltage or current at the moment of switching to become zero which can be subcategorized into two methods: Zero-voltage switching and Zero-current switching. Zero-voltage switching refers to eliminating the turn-on switching loss by having the voltage of the switching circuit set to zero right before the circuit is turned on. Zero-current switching is to avoid the turn-off switching loss by allowing no current to flow through the circuit right before turning it off which was presented by K.H.Liu and F.C.Lee at IEEE INTELEC Conference & IEEE Power Electronics Specialists Conference [1],[2].

The voltage or current administered to the switching circuit can be made zero by using the resonance created by an L-C resonant circuit. This topology is named a "resonant converter".

In Zero-current switching, the existing inductance is absorbed into the resonant circuit, eliminating the surge in voltage in a turn-off situation. A voltage surge resulting from an electric discharge of junction capacitance, which occurs upon turning on the switching circuit, cannot be avoided. This method has a defect of causing switching loss ($0.5CV^2f$). Zero-voltage switching, however, is free from such a defect by making both the existing inductance and capacitance to be absorbed by the resonant circuit. This eliminates any chance of causing a surge in current both at turn-off (caused by inductance) or turn-on (by capacitance) conditions. Zero-voltage switching enables switching with less loss while substantially reducing the problem of EMI at high frequency. This difference in features makes Zero-voltage switching more desirable than Zero-current switching.

As a resonant converter provides most of the energy conversion efficiency in a power system by minimizing switching loss, it is widely used in a variety of industries. And this is also the reason why the converter is adopted in the Induction Melting Power System Topology.

2.7 Resonant Topologies

First let us define a resonant converter as a power conditioning system which utilizes a resonant L-C circuit as a part of the power conversion process. All resonant converters operate in essentially the same way: a square pulse of voltage or current is generated by the power switches and this is applied to a resonant circuit. Energy circulates in the resonant circuit and some or all of it is then tapped off to supply the output. While basically simple, this principle can be applied in a wide variety of ways, creating a bewildering array of possible circuits and operating modes.

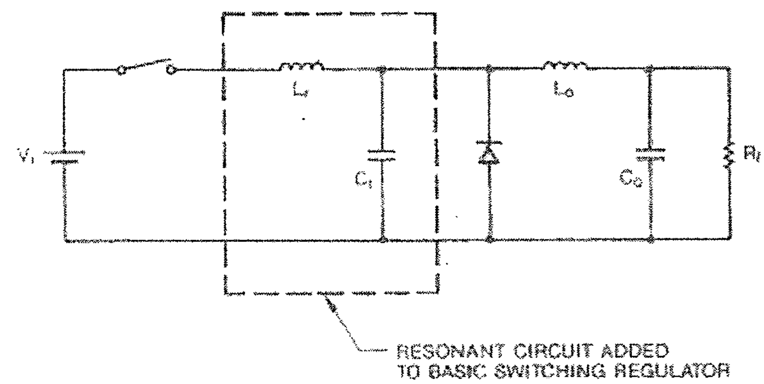

Figure 2-3 Basic Resonant Converter

A resonant switch consists of a switching device (a transistor with a steering diode, for example) in combination with a two-element resonant circuit. This resonant switch may be configured in several different ways, but they always perform the same function as the conventional switch in a square wave converter. It is a useful concept as most resonant mode circuit topologies can be visualized as a conventional PWM circuit with the power switch replaced with a resonant switch.

2.7.1 Series or Parallel Loading:

Since resonant converters operate by putting energy into a resonant circuit and then transferring some or all of it into the load, there are two ways this may be accomplished. If the load is in series with the resonant circuit elements, we call it a series loaded converter and the operating characteristics tend toward a current source with a high impedance output.

Parallel loading is the opposite, with a low impedance voltage source output..

Both modes have application to power systems with high voltage outputs usually using series loaded current source drive and low voltage supplies using parallel loading.

2.7.2 Fixed or Variable Frequency:

Resonant converters may be configured for either constant or variable frequency operation, but these choices infer significant differences in their operation. Fixed frequency control systems use conventional pulse width modulation to change the output in response to a control input. This forces a fixed-frequency system to have at least one non-zero switching transition and possibly two, thereby voiding one of the more significant reasons for choosing to use a resonant mode topology. This would usually preclude its use unless system considerations required a synchronized frequency operation.

Variable frequency operation, however, needs to be subdivided by the third classification: whether the resonant circuit current is continuous or discontinuous. A circuit operating in the continuous resonant mode uses the slope of the resonant circuit impedance curve to control the output. The circuit can operate either above or below resonance but the principle is the same: that the control circuit changes the frequency to move either toward or away from resonance, and thereby controls the amount of energy which is transferred into the resonant circuit and therefore to the load.

While many practical systems have used continuous conduction, variable frequency operation, there are several disadvantages:

1. The non-zero switching adds stress to the transistors.
2. As the frequency approaches resonance, peak currents or voltages can get very high, adding stress to the resonant components.
3. The control transfer function is very nonlinear following the resonant impedance curve.

The major advantage of the continuous mode of operation is that the frequency varies over a much smaller range than with the discontinuous mode.

2.7.3 Discontinuous Resonance:

The discontinuous operating mode works by supplying constant packets of energy to the load with the rate, i.e. frequency, determined by load power demand.

Perhaps the most popular and important class of resonant converters with variable frequency and discontinuous current is often called Quasi-Resonance. Within the Quasi- Resonant converter category there are still many variations in circuit operation.

Quasi-resonant circuit waveforms are not sinusoidal, but have two essentially linear portions interspersed with two sinusoidal portions.

A quasi-resonant converter control loop is usually configured with a pulse generator driving the resonant circuit at a repetition rate defined by the control circuit. The pulse generator may be set for constant pulse width defined by the resonant circuit -or set to sense zero crossing of either current or voltage. With maximum loading and low line voltage, a quasi-resonant converter can approach continuous resonance as a limit when the individual pulses run together.

Within the variable frequency, discontinuous mode of operation there are two remaining decisions a designer must make which will have significant effect on the characteristics of his power supply:

Zero current or Zero voltage switching.

2.7.4 ZERO CURRENT SWITCH

A typical Zero Current Switch consists of a switch S, in series with the resonant inductor L_{RES} and the resonant capacitor C_{RES} connected in parallel. Energy is supplied by a current source. The circuit and waveforms are shown in figure 2-4.

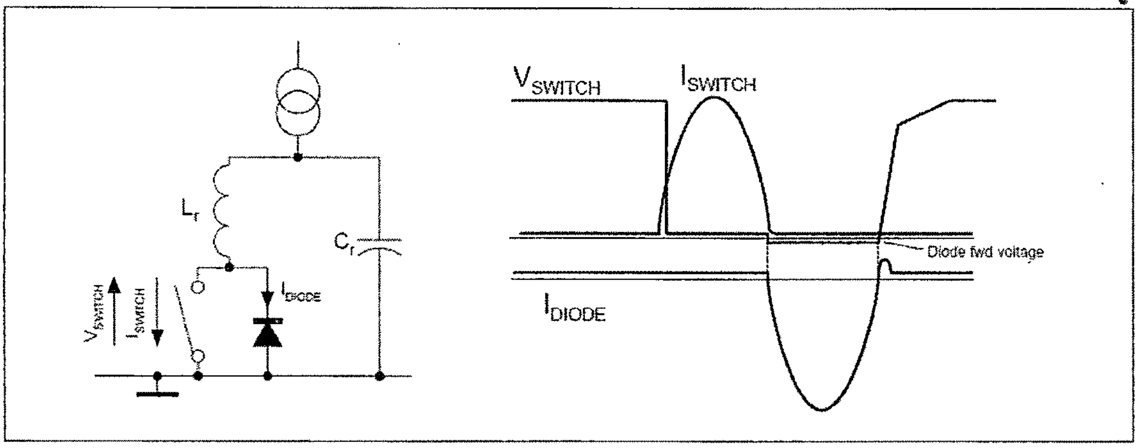

Figure 2-4 Zero-current switch - topology and waveforms

When the switch S is off, the resonant capacitor is charged up with a more or less constant current, and so the voltage across it rises linearly.

When the switch is turned on, the energy stored in the capacitor is transferred to the inductor, causing a sinusoidal current to flow in the switch. During the negative half wave, the current flows through the anti-paralleled diode, and so in this period there is no current through or voltage across the switch; and it can be turned off without losses.

2.7.5 ZERO VOLTAGE SWITCH

A typical Zero Voltage Switch consists of a switch in series with a diode. The resonant capacitor is connected in parallel, and the resonant inductor is connected in series with this configuration. A voltage source connected in parallel injects the energy into this system. The circuit and waveforms are shown in figure 2-5.

When the switch is turned on, a linear current will flow through the inductor. When the switch turns off, the energy that is stored in the inductor flows into the resonant capacitor. The resulting voltage across the capacitor and the switch is sinusoidal. The negative half-wave of the voltage is blocked by the diode. During this negative half wave, the current and voltage in the switch are zero, and so it can be turned on without losses.

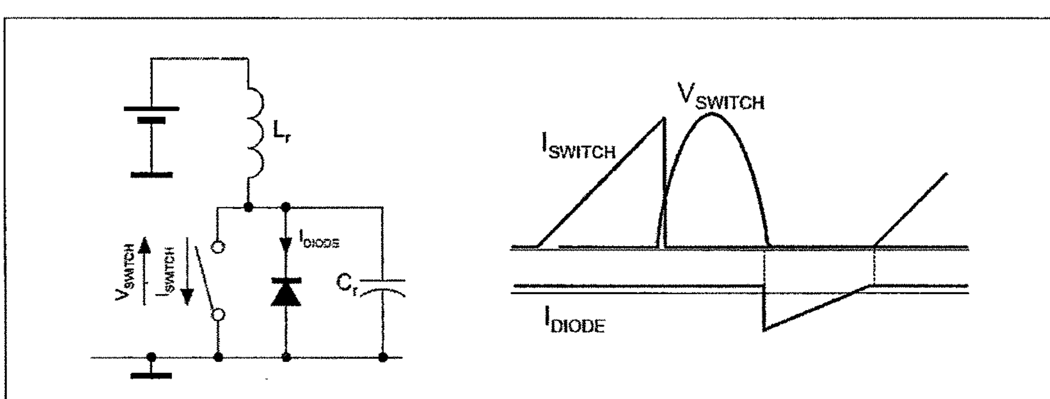

Figure 2-5 Zero-voltage switch - topology and waveforms

2.8 Survey of different tuning methods for PID

Proportional-Integral-Derivative (PID) control is still widely used in industries because of its simplicity. No need for a plant model. No design to be performed. The user just installs a controller and adjusts 3 gains to get the best achievable performance. Most PID controllers nowadays are digital.

Different forms of PID

A standard equation of PID controller is

$$u(t) = K\left\{e(t) + \frac{1}{Ti}\int_0^t e(t)dt + Td\frac{de(t)}{dt}\right\} \qquad \text{(Equation 2-6)}$$

where the error e(t), the difference between command and plant output, is the controller input, and the control variable u(t) is the controller output. The 3 parameters are K (the proportional gain), Ti (integral time), and Td (derivative time).

Proportional:

The proportional term, also called gain, must have a value greater than zero for the control loop to operate. The value of the proportional term is multiplied by the error (e) to generate the proportional contribution to the output.

If proportional is acting alone, with no integral, there must always be an error or the output will go to zero. A great deal must be known about the load, sensor, and controller to compute a proportional constant Kp. Most often, the proportional setting is determined by trial and error. The proportional setting is part of the overall control loop gain, as well as the heater range and cooling power. The proportional setting will need to change if either of these changes.

Integral:

In the control loop, the integral term, also called reset, looks at error over time to build the integral contribution to the output.

By adding integral to the proportional contribution, the error that is necessary in a proportional-only system can be eliminated. When the error is at zero, controlling at the set point, the output is held constant by the integral contribution. The integral setting (I) is more predictable than the proportional setting. It is related to the dominant time constant of the load. Measuring this time constant allows a reasonable calculation of the integral setting.

Derivative:

The derivative term, also called rate, acts on the change in error with time to make its contribution to the output.

By reacting to a fast changing error signal, the derivative can work to boost the output when the set point changes quickly; reducing the time it takes for temperature to reach the set point. It can also see the error decreasing rapidly when the temperature nears the set point and reduce the output for less overshoot. The derivative term can be useful in fast changing systems, but it is often turned off during steady state control because it reacts too strongly to small disturbances or noise. The derivative setting (D) is related to the dominant time constant of the load.

The proportional controller (KP) will have the effect of reducing the rise time and will reduce, but never eliminate, the steady state error. An integral controller (KI) will have the effect of eliminating the steady state error, but it may make the transient response worse. A derivative control (KD) will have the effect of increasing the stability of the system, reducing the overshoot and improving the transient response.

Closed loop response	Rise time	Overshoot	Settling time	Steady state error	Stability
Increasing Kp	Decrease	Increase	Small increase	Decrease	Degrade
Increasing Ki	Small decrease	Increase	Increase	Large decrease	Degrade
Increasing Kd	Small decrease	Decrease	Decrease	Minor change	Improve

Table-2.1 Effect of PID parameter on closed loop system

Controller Tuning

The selection of a controller type (P, PI, PID) and its parameters (K, Ti, Td) is intimately related to the model of the process to be controlled. The adjustment of the controller parameters to achieve satisfactory control is called *tuning*.

In the process-control field, it is quite common to first install a PID controller on a process with little analytical study being done beforehand, and then set the controller parameters by experiment. This 'experimental design' of controller settings is known as *controller tuning*.

Auto-tuning PID controllers

The ability of a controller to select and adjust the control parameters automatically via an algorithm is called *"Auto-tuning"* or *"Self-tuning"*. So, self-tuning controllers are capable of automatically readjusting the controller tuning settings. They are often referred to as auto-tuning controllers.

Numbers of the industrial processes are controlled by PID-proportional integral derivative controllers. The various settings of the controller have profound effect on loop performance. Proper tuning of a controller is not only essential to its correct operation but also improves product quality, reduces scrap, shortens downtime and saves money. Procedures for tuning conventional PID controllers are well established and simple to perform. Any time a controller is replaced; the new instrument must be re-tuned, which can be difficult under certain running conditions. Hence the need arises for a controller with auto tuning feature.

As previously said, it is important for the controller to be tuned when it is installed first. It also becomes a necessity when it is controlling a critical process. Proper tuning of parameters helps in controlling the process quickly and efficiently which requires trial and error. So, the main advantage of using auto-tuner is that it simplifies tuning drastically and thus contributes to improved control quality.

Different Tuning Method

- Ziegler & Nichols with Step Identification [ZN(OL)]
- Internal Model Control [IMC]
- Ziegler & Nichols with Relay Identification [ZN(CL)]
- Iterative feedback tuning

Ziegler & Nichols with Step Identification [ZN (OL)]:

The first Ziegler and Nichols method tunes the parameter of the PID according to the following table, on the basis of the parameters identified for a First Order PID with Delay Time model.

	K	Ti	Td
P	T/mL	0	0
PI	0.9T/mL	3L	0
PID	1.2T/mL	2L	0.5L

Table-2.2 Parameters for ZN (OL)

In the original version of method, the tuning formulas are given with respect to some characteristic of the process identified in terms of the points where the tangent to the step response in the point of maximum slope intersects the step response. However here the modified version has been used since it is more robust with respect to noise.

Internal Model Control [IMC]:

The principle of this method is explained in Astrom and Hagglund, 1995. The system is approximated by a model of the form,

$G(s) = Kp / (1 + sT)e^{-SL}$ (Equation 2-7)

If the actual system is unknown, the static gain Kp, the apparent time constant T and the apparent dead time L are determined from an open loop step response, from which an IMC controller is then computed. The controller given by the IMC method can be interpreted as a PID controller with the following choices:

$K = 2T + L / (2Kp(Tf + L))$ (Equation 2-8)

$Ti = T + L / 2$ (Equation 2-9)

$Td = TL / 2T + L$ (Equation 2-10)

Here the design parameter Tf corresponds to the desired closed-loop time constant. In each of our four simulations, we have optimized over this design parameter to achieve an IMC controller with minimum settling time. This optimization was performed by trial and error.

Ziegler & Nichols with Relay Identification [ZN (CL)]:

The Ziegler-Nichols tuning rules are based on what is called the ultimate sensitivity method" (Astrom and Witten mark, 1997). It consists of determining the point where the Nyquist plot of the open loop system intersects the negative real axis. This point is obtained by connecting a purely proportional to the system, and by increasing the controller gain until the closed-loop system reaches the stability limit, at which oscillations occur. The oscillation period is denoted Tc and the corresponding critical gain by Kc. The Ziegler-Nichols choice for the three PID parameters is then

$K = Kc/17$

$Ti = Tc/2$

Td = Tc/8

The second Ziegler and Nichols method tunes the parameter of the PID according to the following table, on the basis of a point of the frequency response identified by a relay experiment. The period of oscillation is denoted as T_u, while the gain margin is Ku = 4As/pi*A.

	K	**Ti**	**Td**
P	$0.5K_u$	0	0
PI	$0.4K_u$	$0.8T_u$	0
PID	$0.6K_u$	$0.5T_u$	$0.125T_u$

Table-2.3 Parameters for ZN (CL)

In the original version of method, the identification of the point requires to apply proportional control and increase the controller gain until the process output reaches a sustained oscillation. However it is a dangerous practice since it leads the model near the stability limit.

The Iterative Feedback Tuning (IFT) method:

For the simulations presented in the next section, the IFT method with mask was applied, with a mask of length t0. Unless otherwise specified, no weighting was applied to the control input in the criterion. Thus, the following criterion was minimized:

$$J(\rho) = \mathrm{E}\left\{\sum_{t=t_0}^{N}\left(y_t(\rho) - y_t^d\right)^2\right\}.$$

The initial values of the PID parameters were chosen in such a way as to give an initial response that was very slow, and with no overshoot. The length t0 of the mask was initially chosen to correspond with the settling time of this very slow response. This length was then successively reduced until oscillations appeared in the closed loop step response.

Tuning by Ziegler-Nichols Frequency Domain (ZNFD) method

There are some variants of autotunig methods suggested in the literature. Here we have used one of them, the relay feedback, which is closely related to a manual tuning scheme known as Ziegler-Nichols Frequency Domain (ZNFD) method.

To tune a PID controller manually by ZNFD method, we start by turning off both the integral and derivative terms. Then K is to be set up to the point that the closed-loop system starts to oscillate. At this point, the plant output will swing in a constant sinusoid motion, not growing and not dying out. Write this value down on a paper as Ku. Then find a way to measure the period of oscillation. Note this period as Tu. That's all. Suggested values of the 3 parameters can be found from Table 2.3. Example 1 demonstrates this procedure in simulation.

Example 1: We want to experiment ZNFD method on this plant

$$P(s) = \frac{1}{(s+1)^3} \qquad \text{(Equation 2-11)}$$

Figure 2.6 shows a SIMULINK setup used for this simulation. We turn off the I and D terms and adjust K until K = 8, the output oscillates. Figure 2.7 captures the oscillation. Hence Ku = 8, and from Figure 2.7 Tu = 3.5. Using Table 2.3, we get K = 4.8, Ti = 1.75 and Td = 0.4375. Figure 2.8 shows a step response when these values are used. Note that the overshoot is quite excessive (50%). In a sense, ZNFD just gives us some good values to start with. We can often fine-tune the PID to improve the response.

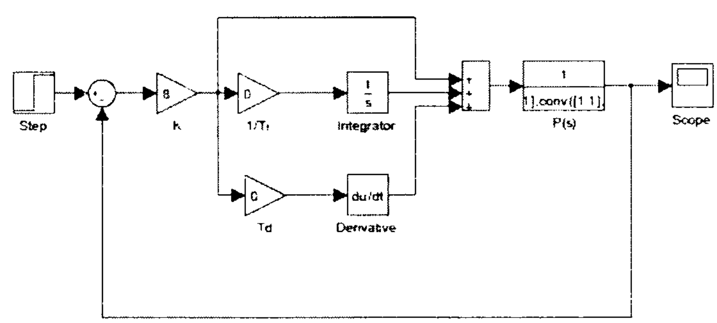

Figure 2-6 A SIMULINK setup for Example 1

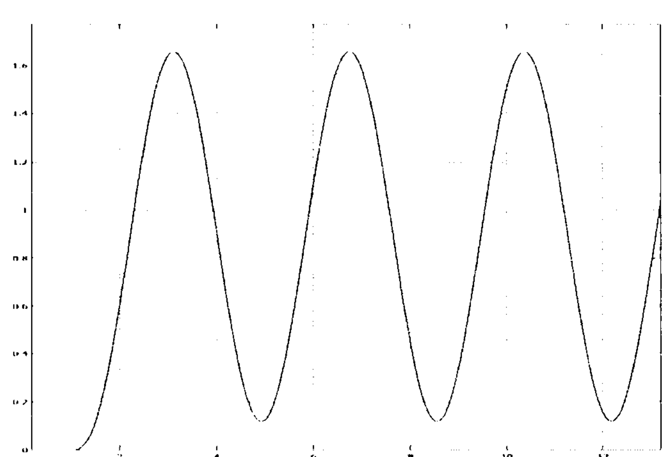

Figure 2-7 Oscillation captured from scope

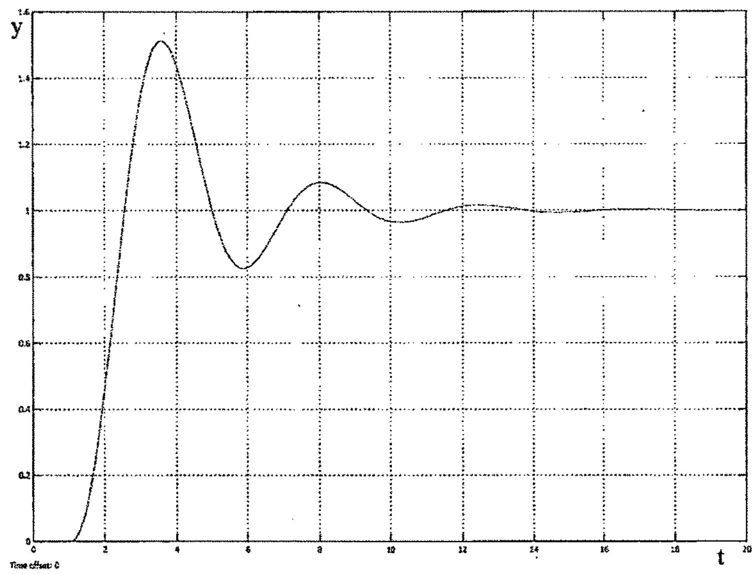

Figure 2-8 Step response from PID values given by ZNFD method

The ZNFD method could be explained using a Nyquist diagram in Figure 2.9. The diagram shows how a point x on the curve is moved related to the P, I, and D terms. Using the P term alone, x could be moved in radial direction only. The I and D terms help provide more freedom to move perpendicular to the radius. It can be shown that by using ZNFD method, the critical point (-1/Ku, 0) is moved to the point -0.6 – 0.28i. The distance of this point to the critical point is 0.5. So the sensitivity peak is at least 2. This explains the high overshoot in the step response.

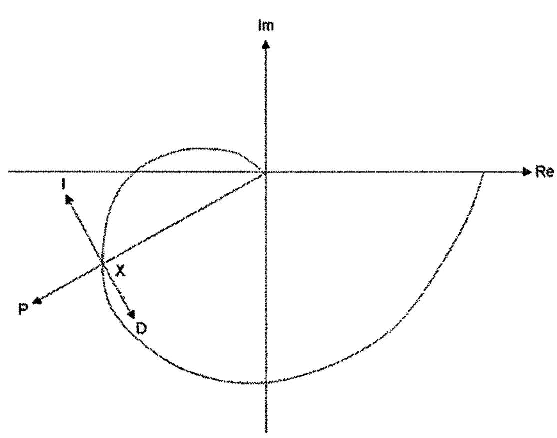

Figure 2-9 How a point on Nyquist curve is moved with PID control

2.9 Summary

The main finding of this chapter reveals following:

1. As a resonant converter provides most of the energy conversion efficiency in a power system by minimizing switching loss, they are best suited for DC-AC converters as compared to PWM converters.
2. Due to skin effect the high frequency switching creates heat on the surface of the load, hence medium switching frequency is used for melting applications.
3. Zero-voltage switching refers to eliminating the turn-on switching loss by having the voltage of the switching circuit set to zero right before the circuit is turned on.
4. Zero-current switching is to avoid the turn-off switching loss by allowing no current to flow through the circuit right before turning it.
5. Different Tuning methods for PID loop are surveyed. It is found that the Ziegler and Nichols method for tuning is simple, accurate and can be easily implemented in digital PID control.