

Chapter 1

INTRODUCTION

1.1 General

Electric heating can be accurately applied at the precise point needed in a process, at high concentration of power per unit area or volume. Electric heating apparatus can be built in any required size and can be located anywhere within a plant. Electric heating processes are generally clean, quiet and do not emit much by-product heat to the surroundings. Electrical heating equipments have high speed response, lending it to rapid-cycling and mass-production equipment.

Design of heating system starts with assessment of the temperature required, the amount of heat required and the feasible modes of transferring heat energy. In addition to conduction, convection and radiation, electrical heating methods utilize electric and magnetic fields to heat the material.

Methods of electric heating include resistance heating, induction heating and dielectric heating. In some processes (for example, arc welding), electric current is directly applied to the work-piece. In other processes, heat is produced within the work-piece by induction or dielectric losses. The heat can be produced and transferred to the work-piece by conduction, convection or radiation.

Induction heaters produce heat by means of a periodically varying electromagnetic field within the body of a nominal conducting material [12]. This method of heating is sometimes called eddy-current heating and is used to achieve temperatures below the melting point of metal [77]. Induction heating is used to temper steel, to heat metals for forging, to heat the metal elements inside glass bulbs and to make glass-to-metal

joints [109], [110], [117].

Dielectric heaters use high frequency currents, which generate heat by dielectric hysteresis (loss) within the body of a nominal non-conducting material. These heaters are used to warm up to moderate temperature of certain materials, that have low thermal conducting properties; for example, to soften plastics, to dry textiles and to work with other materials like rubber and wood [61], [82].

Figure 1.1 shows a schematic classification of electroheat processes [61], according to the voltage frequency used, from DC ($0Hz$) to frequencies up to $10^{12}Hz$.

1.2 State of The Art

Out of many heating methods, a few of them related to electric heating have been described in this section. These includes

- Resistance Heating (RH)
- Induction Heating (IH)
- Dielectric Heating (DH)
- Multiphase Induction heating (MIH)

Resistance heating:

Electric resistance furnaces offer a safe, efficient, reliable and clean method for heat treating, melting and heating prior to forming and brazing metals [102]. Electric furnaces are also easy to control and operate over a wide temperature range. In addition to heating metals, they are used for melting glass, sintering ceramics and curing coatings [61], [65]. The number of applications continues to grow as technological developments broaden the operating temperature range of electric furnaces and the demand for automatic process control increases [56].

Resistance heating is based on the principle of converting electric energy into thermal energy [102]. The thermal energy is then transferred to the part by convection, radiation and/or conduction [61]. There are two types of resistance heating, Indirect resistance heating is described in [56] and discusses the technical and economic factors to consider while deciding whether the process could benefit a particular application or product. Direct resistance heating and encased resistance heaters are discussed in [26]. Direct resistance heating works only for electrically conductive work-pieces; while any material, either solid or liquid can be heated with an encased resistance heater [26], [61]. Encased

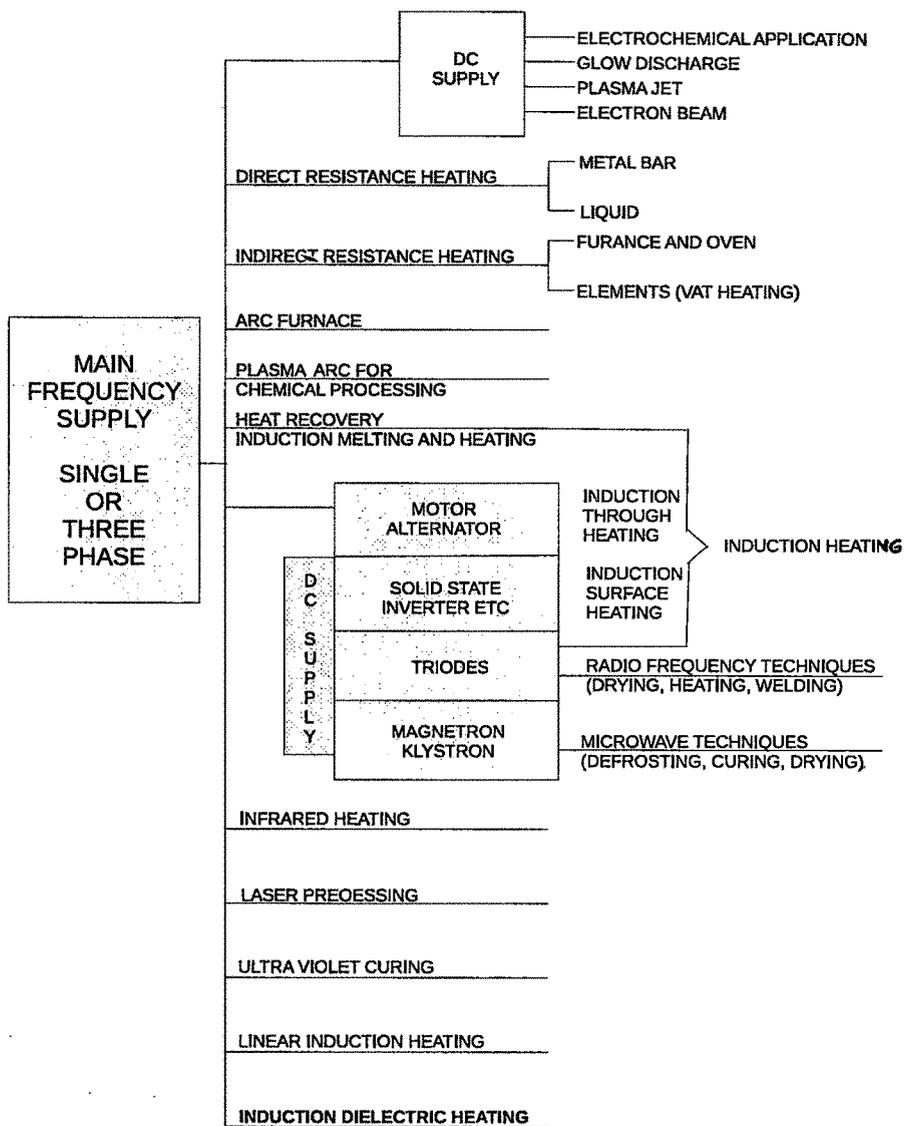


Figure 1.1: Classification of Some Electroheat Processes in Industry

resistance heaters, available in a wide range shapes, sizes and electrical rating are generally used when reliable, long-term heating at low to medium temperature is required [26], [102].

Induction heating:

Induction heating has been used to heat electrically conductive materials [36], [41]. Industrial application of the technology include metal melting and heat treating, crystal growing, semiconductor wafer production, high speed sealing and packaging, preheating for forging operations, brazing, food cooking and curing of organic coating [13], [29], [36], [40], [41], [63], [88], [98], [103], [116].

Induction heating is the process of heating an electrically conducting material (usually a metal) by electromagnetic induction, where eddy currents are generated within the work-piece and resistance leads to Joule heating (I^2R) of the material in the form of temporal and spatial volumetric heating [36], [40], [61]. Induction heating provides a number of advantages such as; quick heating, high production rates, ease of automation, control, safe and clean working [6], [29], [36], [86], [103].

The energy transferred from an induction heating unit to an object can be controlled by various methods like varying DC link voltage or duty ratio of the high frequency inverter [37], [39], [50], [60], [72], [90], [97], [116]. The most common method is by varying the operating frequency of the inverter [1], [8], [17], [38], [49].

A large number of topologies have been developed in this area, among them current fed and voltage fed inverters are most commonly used [114], [116]. Important advantage of voltage source inverter is their various control methods such as Pulse Frequency Modulation [74] and Pulse Amplitude Modulation to control output power [101], [107]. The current source inverter has limited control methods. But, it is less affected by input voltage ripple and has short circuit protection capability [39], [71], [116].

If frequency is too low, then an eddy current cancellation within the billet can occur, resulting in poor coil efficiency [4], [77], [116]. When the frequency is too high, the skin effect will be highly pronounced, leading to a current concentration in a fine surface layer compared to the diameter of the billet [4]. In this case, a long heating time will be required in order to provide sufficient heating of the billets core [11]. Prolonged heat time corresponds to a longer heating line, which in turn, increases surface heat losses due to thermal radiation and convection. The choice of frequency is always a reasonable compromise [21], [81]. These methods use single phase supply system.

Dielectric heating:

Electromagnetic fields are used for dielectric heating in industrial processes and domestic applications since the early 1960s. Plastics, food, pharmaceutical, textile and wood industries are well established sectors in which operations such as welding, heating, tempering, defrosting, drying, baking, etc., are carried out using radio-frequency (RF) or microwave (MW) heating applicators [27], [31], [43], [61], [93], [105].

Dielectric heating for industry employs two different types of power system each covering a band of frequencies, radio (RF) and Microwaves (MW) frequencies [31], [33], [82]. The difference between microwave and radio frequency heating is that the operating frequency of the microwave radiation is in the range 433 MHz and 40 GHz, which is much higher than the dimensions of the objects being heated are usually much bigger than the wavelength of the microwave heating and it is necessary to move the object to ensure even heating [33]. In both techniques, the material that is heated is exposed to an electromagnetic field that is continuously reversing direction (alternating) at a very high frequency [82].

Dielectric heaters use high frequency currents, which generate heat by dielectric hysteresis (loss) within the body of a nominally non-conducting material. These heaters are used to warm up to moderate temperature, certain materials that have low thermal conducting properties; for example, to soften plastics, to dry textiles and to work with other materials like rubber and wood [2], [27].

The advantages of dielectric heating equipment are high rate of heating, uniform heating of materials having a low thermal conductivity and the feasibility of local and selective heating [105].

Microwave heating takes place due to the polarization effect of electromagnetic radiation at frequencies between 300 MHz and 300 GHz [22], [66]. Microwave heating has also found applications in the food industry, including tempering of frozen foods for further processing, pre-cooking of bacon for institutional use and final drying of pasta products [66]. In those applications, microwave heating demonstrates significant advantages over conventional methods in reducing process time and improving food quality [5], [7]. But in general, applications of microwave heating in industrial food processing are much less common than home applications. Reasons for this difference include a lack of basic information on the dielectric properties of foods and their relationship to microwave heating characteristics and the historically high cost of equipment and electricity [100], [105].

The way in which a material will be heated by microwaves depends on its shape, size, dielectric constant and the nature of the microwave equipment used [66], [95], [100].

Multiphase Induction heating:

The induction heating of metal strips is widely applied in the metal industry and different types of inductors are used according to the process requirements. Two different types of inductors, namely Transverse Flux (TF) inductors and Travelling Wave (TW) inductors are considered. While Transverse Flux Induction Heating (TFIH) systems have been studied for many years, Travelling wave induction heating (TWIH) inductors are not yet fully appreciated with respect to their main advantages and possible industrial applications [15], [59], [68], [73], [87], [91].

The main attractive characteristics of TF inductors are: 1) a high electrical efficiency, including the heating of strips of low resistivity materials; 2) the possibility of using low frequencies (in particular 50 Hz); 3) more useful "open" inductor geometry [73].

Travelling Wave Induction Heating (TWIH), as one of the multiphase induction heating systems, has particular features which make them attractive for application to some heating and melting processes in industry [15], [48]. Among the advantages, which can be mentioned are the possibility to heat quite uniformly thin strips or regions of a body without moving the inductor above its surface [73], [118], to reduce the vibrations of inductor and load due to the electrodynamic forces and also the noise provoked by them, to obtain nearly balanced distributions of power and temperature [15].

TWIH introduces three-phase induction heating, using the typical three-phase windings and parametric analysis to assess the key parameters (transfer of electricity to the work-piece, efficiency, power factor, etc) and the distribution of electricity [15], [78]. Compared with the single-phase induction heating of Transverse Flux Induction Heating inductors [73], three-phase induction heating not only has the same advantages, but also owns the ability to produce more uniform temperature distributions and reduces industrial noise with low vibration. Especially in the conditions that electromagnetic force increases significantly and heating parameters change with the rise of temperature, the advantage is very important [57].

A fundamental problem in the TWIH design is the prediction of the electromagnetic forces acting on inductor and work-piece, which can give rise to drag forces and vibrations and noise dangerous for the induction heating system itself and for the workers near the system [53], [57], [118].

Transverse Flux and Travelling Wave induction heating methods present some drawbacks because of the intrinsic uneven distribution of the heat distribution inside the workload. In both cases a high concentration of power density is localized at the edge of the work-piece with their consequent possibility of mechanical deformation of the strip during the heating process [73], [118].

Because of advances in solid state power devices and microprocessors [19], [20], [23], [24], switching power converters are used in more and more modern three phase induction load to convert and deliver the required energy to the object [10], [18], [25], [35], [44], [45], [67], [69]. The energy that a switching power converter delivers to an induction load is controlled by modulation techniques.

Modulation Techniques:

The fundamental of the modulation techniques have been well established in [9], [10], [14], [18], [25], [32]. The maximum voltage transfer ratio has been found to be $\sqrt{3}/2$ for sinusoidal input and output waveforms [8], and can be obtained by adding third harmonic voltage components to the desired ac output voltage [32].

Pulse Width Modulated (PWM) signals 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 turns 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 the energy delivered to the load depends mostly on the modulating signal [64].

The basic PWM techniques are:

- Single Pulse Width Modulation
- Multi Pulse Width Modulation
- Sinusoidal Pulse Width Modulation (SPWM)

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

- Trapezoidal Modulation

- Staircase Modulation
- Stepped Modulation
- Harmonic Injection Modulation
- Delta Modulation
- Space vector Modulation (SVM)
- Random PWM

The pulse width modulation (PWM) DC-AC converter has well known for more than three decades. Due to limitations imposed by conventional PWM technique (e.g. over modulation, high switching loss and reduced fundamental component), the SVM technique has gained a lot of importance over PWM technique [92]. Space Vector Modulation became a standard for the switching power converters. The theory of Space Vector Modulation is already well established [30], [34], [35], [46], [47], [52], [80], [84]. Diverse implementation methods were tried and some dedicated hardware pieces were developed based on this principle. The initial use of Space Vector Modulation at three-phase voltage-source inverters has been expanded by application to novel three-phase topologies as AC/DC Voltage Source Converter, AC/DC or DC/AC Current Source Converters, Resonant Three-Phase Converters, Inverter, Multilevel Converters, AC/AC Matrix Converters and so on [47], [58], [75], [79], [85], [89], [96], [107], [111], [113].

The SVM has been concept to compute the duty cycle of the switches. It is simply the digital implementation of PWM modulators [62], [79], [111], [113]. An aptitude for easy digital implementation and wide linear modulation range for output line-to-line voltages are the notable features of space vector modulation as following:

- Immediate comprehension of the required commutation processes.
- Wide linear modulation range.
- Less switching loss.
- Less total harmonic distortion (THD) in the spectrum of switching waveform.
- Easy implementation and less computation time.

- No synchronization requirement with input voltage waveforms.
- Simplified control algorithm.
- Full utilization of the DC bus voltage.

1.3 Motivation

The present technique used for induction heating is to heat the object by single phase coil through converter inverter technique. Where there is more loss of power conversion, poor power factor, poor efficiency and increase cost and space.

3-phase linear induction heating system is very rarely and lately introduced [3], [53], [99]. It works on the principle of linear induction motor using travelling wave technique to flat surface heat up [53]. In this method, power can be fed at any frequency and accordingly the electronic system device is selected as discussed [99]. It has been mainly used for surface heating and gluing of two dissimilar metals.

Hence, the motivation behind the research work reported in this thesis was

- (i) To develop three phase control circuit for three phase induction dielectric heating system.
- (ii) To develop the induction dielectric heating system which is applicable for both conducting and non-conducting material to heat up.
- (iii) To explore a new method to determine the material characteristics and performance.
- (iv) To study the effectiveness of optimal adjustment of control circuit, switching losses and IDH output in temperature stability.
- (v) To develop high efficiency heating system for conducting and non-conducting.
- (vi) To explore a new concept to preserve food (lemon) using IDH. It is also useful for industrial and commercial application like drying, forging, surface hardening etc.

1.4 Thesis Organization

The present Chapter 1 introduces the electric heating application and problem, which presents a brief state-of-art survey of research work carried out in the areas of induction

heating and dielectric heating. The various modulation techniques have been presented for switching devices used for heating to material. The latest development on three phase linear induction heating application and problem has been reviewed and lays down the motivation behind the research work carried out.

In chapter 2, a symmetrical space vector modulation pattern has been proposed, to reduce Total Harmonic Distortion (THD) without increasing the switching losses. The design and implementations of a 3 phase PWM inverter for 3 phase IDH to control temperature using space vector modulation (SVM) has been carried out.

Chapter 3 presents the mathematical model for steady state IDH process for conducting & non-conducting material and its numerical solution using Matlab and finite element method (FEM).

Chapter 4 describes the three phase MOSFET based inverter for non-conducting material sample as dehydration of food (lemon) application. The operating frequency has been adjusted by the micro controller to maintain constant leading phase angle when parameters of IDH load are varied. The output power can be controlled by setting frequency. The load voltage is controlled to protect the MOSFETs.

Chapter 5 deals with experimental verification of three phase IDH, which converts main frequency AC power into three phase high frequency AC power. The control system presented here control the output temperature of the load and responds accordingly by adjusting the driving frequency of the three phase inverter, to keep the IDH load at resonance throughout the heating cycle.

Chapter 6 summarizes the main finding and significant contributions of the thesis and provides a few suggestions for further scope of research work in this area.