CHAPTER 2
LITERATURE REVIEW

In literature, many researchers have been represented the interest in the field of induction heating and its control strategies, they have carried out numerous laboratory experiments as well to validate their concepts. Some of these researches focused on the configuration of induction heating system by studying different types of inverters and switching elements, and the others focused on the effective control schemes that led to reduce the switching losses and enhance the overall system performance.

2.1. POWER SYSTEM CONFIGURATION

S. N. Okeke 1978 [9]: this article reviews the design of thyristors controlled inverters in induction heating and melting industry. Commutation methods for thyristors are illustrated in this paper, as they can be classified into:

1. A.C. line commutation.
2. Forced commutation.
3. Natural or resonant commutation.

The first is used in the commutation of AC-to-DC converters which called rectifiers; the forced commutation is mainly used in the commutation of DC-to-AC converters or inverters, the third uses the resonant load “tank circuit” to generate a sinusoidal waveform to commutate “turn off” the inverter switches (the thyristors). The resonant frequency of the tank circuit determines the operating frequency of the inverter, i.e. the variation of the tank circuit parameters results in variation of the output frequency of the inverter circuit. In this work, the advantages of thyristor inverters over the older methods of frequency conversion are illustrated, and the design requirements and procedures are mentioned. The range of system frequency for each induction application and power selection is also described in this work. The author of this paper classified the functions of the control circuit to three main parts, trigger, feedback, and protection.

L. Grajales, J. A. Sabatk, K. R. Wang, W. A. Tabisz, and F. C. Lee 1993 [10]: In this paper, employment of phase shift control (PS) technique for controlling series resonant inverter (PSC-SRI) for induction heating is investigated. They achieved zero voltage switching as it is preferred soft switching technique for MOSFETs in a bridge topology. This system requires no pre-regulator (controlled rectifier) and operates at a very narrow frequency range. Based on classification presented in [9], Reference [10] uses the third type of commutation methods which is natural “resonance” commutation in the design with the MOSFET as a switching device, as it uses the transformer leakage inductance and load inductance as the resonant inductor to reduce the power components. In [10], a complete design and implementation of a10 kW, 500 kHz induction heating system is described. Control strategy was developed to provide output power regulation by varying the phase-shift, and to obtain zero voltage switching (ZVS) by varying the switching frequency.

W. Komatsu and W. Po 1997 [11], the authors discussed control and protection aspects in series resonant inverters for induction furnaces with interaction modes between them. Phase locked loop (PLL) control strategy is used in this work, but the oscillator is the power inverter itself. This approach increases electrical noise immunity of the controller. This research depends on relatively low variation of resonant frequency with load variation to achieve inverter switching control through the measurement of zero current transitions at the inverter output to generate trigger delays.

Irshad Khan 1999 [12] and Young-Sup Kwon 1999 [13], both researches use the phase locked loop (PLL) as a control strategy for induction heating. The first deals with automatic frequency control (AFC) as a power control technique. It uses high frequency power source, and a current source inverter (CSI) to drive a parallel resonant induction-heating load. Automatic frequency control was achieved by locking the gate voltage of a power transistor to the driving voltage across the load or tank circuit. The gate voltage is used as a phase representative of the driving current to the load. The rapid change of system frequency at Curie-point has proven by utilize phase locked loops PLL while resonance locked loop can track fast changes and maintain lock at the natural resonant frequency of the tank circuit. The use of PLL provides more accurate and effective closed loop feedback controller.

The second research by Young-Sup provides a pulse frequency modulation (PFM) as a power controller for a voltage fed half-bridge series resonant inverter for induction heating. PLL is used to perform load adaptive tuned frequency tracking control strategy. This work ensures stable operation characteristics for the inverter and achieves zero voltage switching.

B. Sami 1999 [14], use a single switch resonant inverter operated with Discontinuous Conduction Mode (DCM) that allows the switching device to turn off under zero current conditions, therefore switching losses are reduced. A Thyristor is used as the switching element. This research illustrates the equivalent coil design method for induction heating which gives values of the load resistance, reactance, and equivalent circuit of the tank circuit.

R. Fuentes, P. Lagos and J. Estrada 2009 [15]: this article uses the natural frequency of the load to control the resonant frequency of resonant inverter. This research is related to the load resonant generator mentioned in chapter 1. Full-bridge inverter topology with IGBTs is employed in this paper forming a series parallel combination resonant converter. The authors use a controlled rectifier to generate a variable DC voltage followed by a DC-to-DC boost converter which reflects negatively on the system cost. This system is operated exactly at resonant state, and has high power factor.

S. Peram, V. Ramesh, J.S. Ranganayakulu, 2013 [16]: this paper proposes a full bridge LLC (an inductive-inductive-capacitive) resonant inverter for induction heating. The power system is controlled using asymmetrical voltage cancellation (AVC) control technique. The disadvantage of the LLC resonant load is that the output current may no longer be sinusoidal in the case of low Quality factor Q ($Q < 10$). Also the current in the induction coil (work-coil) is small and distorted. Therefore, system efficiency is poor. The operating frequency is controlled using phase locked loop (PLL) to track the resonant frequency. The output power is controlled by adjusting the switch duty cycle. The authors provide a steady-state analysis of the full-bridge LLC inverter assuming constant DC source, ideal components and negligible stray capacitances.

2.2. PDM CONTROL STRATEGY

Many researches considered the pulse density modulation (PDM) technique as a power control for resonant inverters in induction heating, proving that it is a suitable technique for improving the system efficiency in addition to its simplicity(simple control circuits are needed). Eventually, PDM technique has lower electrical stresses on switching devices as well. The following section presents some of published work related to PDM topic.

H. Fujita, H. Akagi 1996 [7]: PDM technique concept as a control technique for induction heating is proposed in this paper. This research uses a voltage source inverter, and power control is achieved via PDM concept. PDM technique achieves zero current switching which reduces switching losses and improves system efficiency. The power system configuration for the developed technique consists of single phase uncontrolled rectifier, single phase full bridge voltage source inverter with four MOSFETs, matching transformer, series resonant load circuit. The principle of PDM operation with switching pattern and the switching modes are described in the paper. They presented a detailed output power analysis assuming the quality factor of the resonance circuit is finite; this led to present a final formula for the output power. In this work, the control circuit forms a type of phase locked loop, which consists of (i) current detection, (ii) phase comparator, (iii) voltage controlled oscillator (VCO), (iv) ROM, (v) synchronization and latching circuit. The PDM pattern is stored in a ROM in order to recall it by a five steps counter. They proved that the pulse density modulated inverter is more suitable for induction heating systems from a practical point of view.

D. Pimentel, M. Ben Slima and A. Cheriti 2006 [8]: they introduce the PDM as a good alternative to the conventional inverter control strategy (PWM). The strategy used to drive the converter is a single low cost digital signal microcontroller. They use a feedback control technique that combines an anticipation algorithm and a hysteresis control. The system configuration contains an uncontrolled rectifier with a DC inductive filter used to supply a bridge IGBT resonant inverter with a series RLC load.

V. Esteve, *et al* 2011 [17]: this paper proposed a voltage-source series-resonant PDM inverter for induction heating. The power regulation is based on PDM strategy. A zero voltage and current switching are achieved. They made a quantitative comparison between the classical power control by frequency variation (FV) and PDM and conclude that the PDM inverter would be more suitable for various induction heating applications, particularly those of high frequency when IGBT transistors are applied. The typical system configuration is a three-phase uncontrolled rectifier supplying a single-phase IGBT inverter. The output of the inverter is connected to a series-resonant circuit with a matching transformer. The authors use the power analysis in [7] to obtain the active output power of the inverter. A simple block diagram of the control circuit is presented based on the PLL. They mentioned that the inverter efficiency increases due to some points, which are:

1. Zero voltage switching (ZVS) and zero current switching (ZCS) conditions that minimize the switching energy losses.
2. Switching power losses are low because the equivalent working frequency is less than that of the power control by frequency variation method.

J. Essadaoui, P. Sicard, E. Ngandui, and A. Cheriti 2003 [18]: they use a PDM as a control strategy for IGBT power inverter control. A Fixed length switching patterns (16 sequence) are used and chosen to maximize power factor whilst keeping controller implementation simple. a simple digital closed loop controller is developed, The proposed fully digital controller contains two terms: a feed-forward term based on the inverse model with desired power as an input and control sequence as an output; and a feedback term to correct the error between the measured power and the reference power. The control scheme is based on the hysteresis dead-band plus control function, which receive the difference between the desired power and the measured power. The experimental waveforms obtained with the prototype system 60V/60Hz, and 160 kHz switching frequency, the phase-shift between the output voltage and current is almost negligible.

S. Dalapati, S. Ray, S. Chaudhuri, and C. Chakraborty 2004 [19], this article uses a half bridge series resonant DC-to-DC topology controlled by PDM to achieve the power regulation through a voltage control. The control is executed by modulating the train of pulses applied to the resonance network.

As shown from the previous researches the PDM achieves a large growth in induction heating power control instead of the conventional power control strategies such as PS [10], AFC [12], PFM [13], DCM [14] and PWM.

The PDM guarantees a zero current switching which reduces the switching losses, it has higher power factor and no pre-regulator (variable DC supply) is needed, and it has simple control circuit, and it has a wide output power range [7]. The detailed illustration of PDM technique will be presented in the following chapter.

Because of all these features of the PDM over the conventional control strategies, we choose to contribute in the developing of induction heating field by using a PDM as a power control strategy but with a new feedback control circuit. In this thesis, modeling and simulation of a series resonant bridge inverter with new controller for PDM technique is presented.

2.3. PROPOSED PDM CONTROLLER

Many studies use phase locked loop [11-13], [16, 17] and hysteresis control [8], [18] to build their own control algorithm. In this research, we propose a three stages feedback circuit for PDM control that combines (i) phase detector (PD), (ii) pulse density modulation control and (iii) power feedback (PFB) as shown in Figure 2.1.

The first circuit is responsible for forcing the phase angle between inverter voltage and current to be near to zero, the second one is responsible for generating the required PDM pattern according to the power feedback circuit, the third one generates the proper modulation index for the inverter.

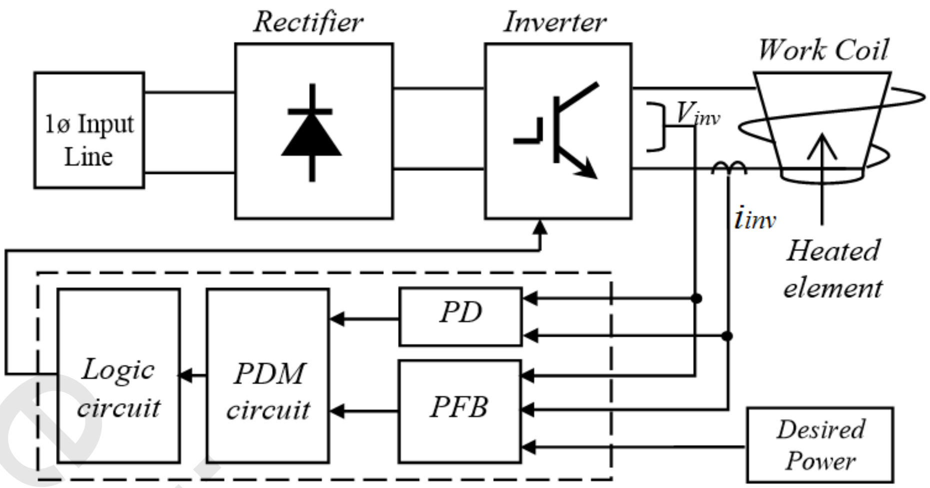

Figure 2.1 Proposed feedback and power circuit block diagram

Based on Figure 2.1, the power circuit, of the system under study, uses a full-bridge series RLC inverter topology with four Insulated Gate Bipolar Transistors (IGBT) as switching devices. A single-phase diode bridge rectifier is applied at the front-end of the inverter to provide fixed DC voltage. Detailed illustration for the concept of the proposed controller will be presented in chapter 4.

The overall heating system is modeled using Matlab/Simulink, to validate the performance of the proposed power controller, and to show the effectiveness of PDM technique as it provides zero current switching (ZCS), producing minimum switching losses with a simple control circuit.

It is to be noted that, in this study, the equivalent circuit coil design, presented in [2], is used to convert the load (tank) circuit into an equivalent resistance R_L in series with equivalent inductance L_L.