Power Control of High-Frequency SRI using Phase Angle Control Technique for Induction Heating System

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***Abstract*: In this paper, an efficient power control technique has been designed which is used to control the output RMS power of high-frequency full bridge series resonant inverter (HF-FBSRI) for induction heating application. A phase control technique is introduced in this work to control the dc link voltage. This controlled dc link voltage is applied to HF-FBSRI to control the RMS power of IH system. This intended control method assures a stable operation of whole IH system. To reduce the switching losses across switches, ZVS condition has been achieved, due to this, regulated heating effects occur. In this work, different RMS power is obtained at different phase angle and it is validated with Matlab/Simulink environment for IH system rated at 515W.**

Keywords—Induction Heating (IH) System, Phase control, Full bridge Series resonant inverter (FB-SRI), Resonant frequency

I. Introduction

In this era, it is seeing that usage of induction heating technology is increasing day by day in the field of industrial as well as domestic applications [1]. There are so many advantages of using this technology like highly efficient, controllable heating, fast heating, safety, and cleanness. Due to these advantages, plenty of developments have been done regarding this technology [2]. It is known that induction heating is a process in which object is heated by means of a foucault current which is generated by electromagnetic induction principle [3]. In modern induction heating technology, this Foucault current should be of high frequencies. This high-frequency alternating current intrudes inside the object called eddy current and after that due to the resistance of the object which is to be heated get heated according to joules law of heating effect. So for generating this high-frequency current, the high-frequency resonant inverter is being used nowadays [4]. There are so many topologies have been developed for induction heating applications such as full bridge series resonant inverter (FB-SRI) [5], half bridge-SRI [6], single switch topology [7], class –D, Class-E, and etc. Only disadvantages of these converters are that large switching loss occurs across the switches. To discard this switching loss, zero voltage switching (ZVS) and zero current switching (ZCS) [8] techniques are used. For industrial application, generally full bridge topology is applied and for domestic purpose, half bridge topology is applied. In this work, the full bridge series resonant inverter has been applied incorporated with ZVS condition to remove the switching loss.

Along with resonant converter topology, different power control techniques have been developed according to the requirement of its application [2]. There are two ways that output power could be controlled in the resonant inverter. Either by applying variable DC input voltage to the resonant inverter or by controlling the time period of Pulse width modulation (PWM) that is given to the switches of the inverter. Among these two techniques, generally, PWM techniques are applied for controlling the output power. There are different ways to modulate the PWM signal such as – Frequency modulation technique [9], Phase shift [10], Pulse density modulation [11], and Square wave. Fig. 1 showing the basic block diagram of the general high frequencies induction heating system. From this block diagram, it can be seen that, in general induction heating system, first AC 230V_{pp}, 50Hz (as

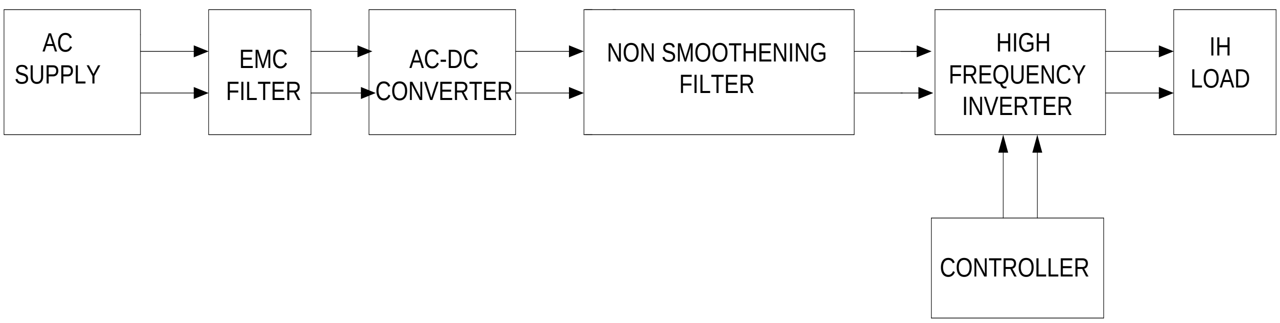


Fig. 1. Block Diagram of High-Frequency Induction Heating System

per Indian standard) is applied to the rectifier (it may be controlled or uncontrolled rectifier). Between these two (AC supply and rectifier) EMC filter is used to reduce the transient effect of voltage or current. After rectifier, non smoothening filter is used for removing the high-frequency component (superimposed at the input side of the inverter) which is generated at the load side of the resonant converter [4]. For getting variable output power, the different controller is used as mentioned above is shown in block diagram. In this paper, to getting variable output power, phase control technique has been proposed which control the firing angle of controlled rectifier. Owing to this, variable dc link voltage is obtained which is given to HF-FBSRI (high frequency-full bridge series resonant inverter) to get variable output power. This proposed control technique can be used in both industrial as well as domestic induction heating applications.

The rest of the section is as follows: - In Section II, a brief description of the full bridge series resonant inverter is given. Proposed control technique has been described in Section III. Simulation work and its results are given in section IV. And at last section V concludes all work that is presented in this paper.

II. FULL BRIDGE SERIES RESONANT INVERTER

In this section, a brief review on FB-SRI has been discussed with operating conditions. A full bridge series resonant inverter consists of 4 high-frequency power electronics switches with an anti-parallel diode (such as MOSFETs, IGBTs, GTO,). Due to simultaneous switching of two switches in one leg, create a quasi-square waveform. Generally, MOSFETs is preferred where high power with high frequency is needed i.e. in the resonant converter for IH application. Fig. 2 shows the power circuit diagram of FB-SRI.

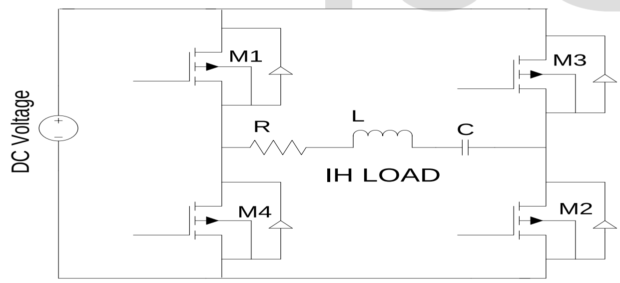


Fig. 2. Power circuit diagram of FB-SRI

Here, Induction heating load is modeled as a series combination of R and L. C is a resonant capacitor which is used to creating a resonant condition for analyzing purposes. It is already known that resonant converter is operated at the resonant frequency i.e.. But for practical application, switching frequency should be higher or lower than the resonant frequency to create ZVS or ZCS condition. Generally, for IH applications, ZVS is to be preferred. In this work, the full bridge series resonant inverter has been used. The operating mode of this FB-SRI can be explained with the four modes of operation:-

Mode1:- In this mode, two switches (i.e. M1 and M2) is turned on by applying the triggering pulses. Current flow in the direction of V_{dc}, M1, IH load, M2 and returned to the source. During this mode, V_{dc} comes out at the load side. M1 is to be turned off at the end of this mode.

Mode2:- At the end of mode1, the direction of current cannot change instantaneously, due to the inductive load. This mode begins when the transition of M1 to the anti-parallel diode of M4. Now the direction of current follows from IH load, M2, anti-parallel diode of M4, and again returned to the IH load. At this mode, zero voltage comes out across the load. This mode ends with the reduction of current through the load to zero.

Mode3:- This mode is same as mode1 but the direction of current changes according to the switching of switches. In this mode, pulses are given to the M3 and M4. Now current flow in the direction of V_{dc}, M3, IH load, M4 and returned to the sources. During this mode, -V_{dc} come out at the load side. M4 is to be turned off at the end of this mode.

Mode4:- At the end of mode4, the direction of current cannot change instantaneously, due to the inductive load. This mode begins when the transition of M4 to the anti-parallel diode of M1. Now the direction of current follows from IH load, anti-parallel diode of M1, M3 and returned to the load. At this mode, Zero voltage comes out across the load. This mode ends with the reduction of current through the load to zero.

Fig. 3 shows the waveform of above-explained mode.

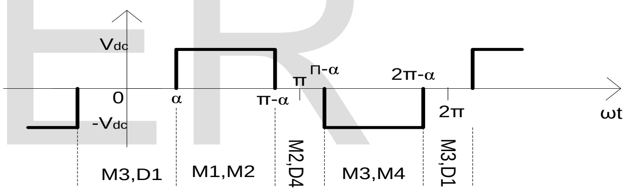


Fig. 3. Output voltage waveform of FB-SRI

III. PROPOSED CONTROL TECHNIQUE

In this section, proposed phase control technique has been discussed which is applied to the controlled rectifier to control the output RMS power of IH system. Fig. 4 shows the block diagram of proposed IH system with phase control technique.

In this block diagram, it can be seen that 230V, 50Hz is first applied to a single phase controlled rectifier. This controlled rectifier is connected with phase controller which is used to vary the firing angle (α) of controlled rectifier. Due to this, variable DC link voltage will be obtained. This variable DC link voltage is given to HF-FBSRI. Owing to this, high frequency oscillating alternating current is obtained which is applied to IH load. With the variation of this DC link input voltage to the HF inverter, output power could be varied. The power variation in this IH system can be understood by following mathematical equation:-

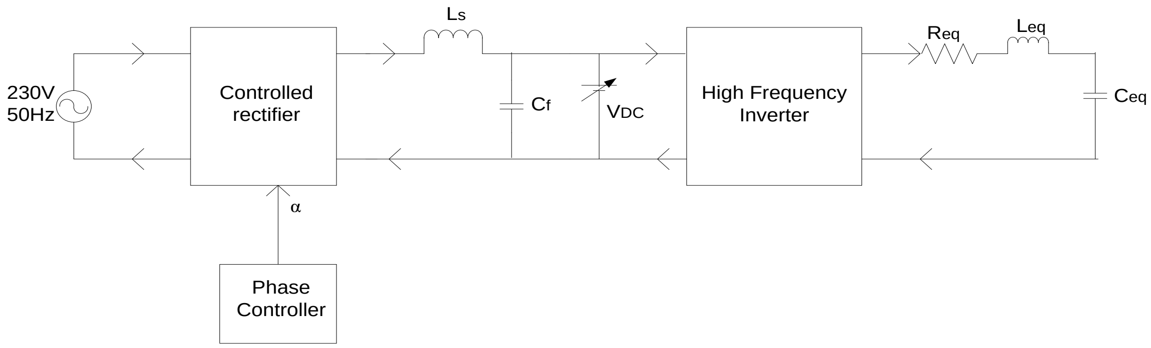


Fig. 4. Block diagram of proposed IH system

P_{out}=Output power of controlled rectifier

P_{in}=Input power of HF-FBSRI

Output power of controlled rectifier can be calculated as:-

$$P_{out} = \frac{V_m}{\pi}(1+\cos\alpha)\times I_{out} \qquad (1)$$

R.M.S power can be calculated as:-

$$P_{out(rms)} = V_s\left(\sqrt{\frac{1}{\pi}\left\{(\pi-\alpha)+\frac{\sin 2\alpha}{2}\right\}}\right)\times I_{out(rms)} \qquad (2)$$

From above these equations, if α will be varied, then output power of controlled rectifier will be varied. This power act as input power for the HF-FBSRI. So automatically output power of FB-SRI will be varied.

Phase Controller:- *In* this controller, the variable duty cycle of PWM is generated. As a result of this, variable firing/phase angle α is obtained. It can be understood with the help of block diagram (Fig. 5). It can be seen from the block diagram that, high-frequency sawtooth waveform (reference signal) and adjustable DC voltage are applied to the comparator. This comparator compares these two signals and generates a variable duty cycle of PWM according to the variation in adjustable DC voltage. The frequency (f_s) of generated PWM depends upon the frequency of reference signal (f_r). In this work, the peak voltage of sawtooth waveform is taken as 1V and magnitude of variable DC voltage is taken as 1V.

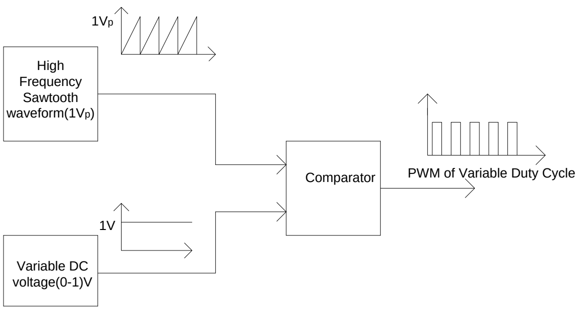


Fig. 5 Block diagram of Phase Controller

Fig. 6 shows the variation in output voltage at different firing angle.

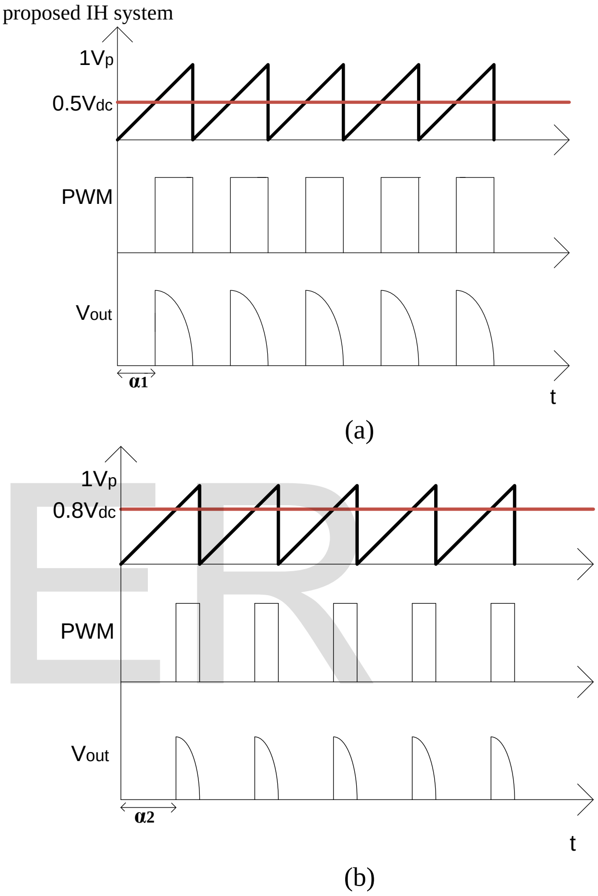


Fig. 6. Different output voltage at different firing angle
(a)At α1
(b)At α2

So from the above waveform, it can be concluded that output power could be varied with a variation of the duty cycle. This duty cycle is varied with the variation in DC voltage (0-1) V.

IV. Simulation Model and its Results

The proposed control scheme is validated by using Matlab Simulink environment. The design parameters and its

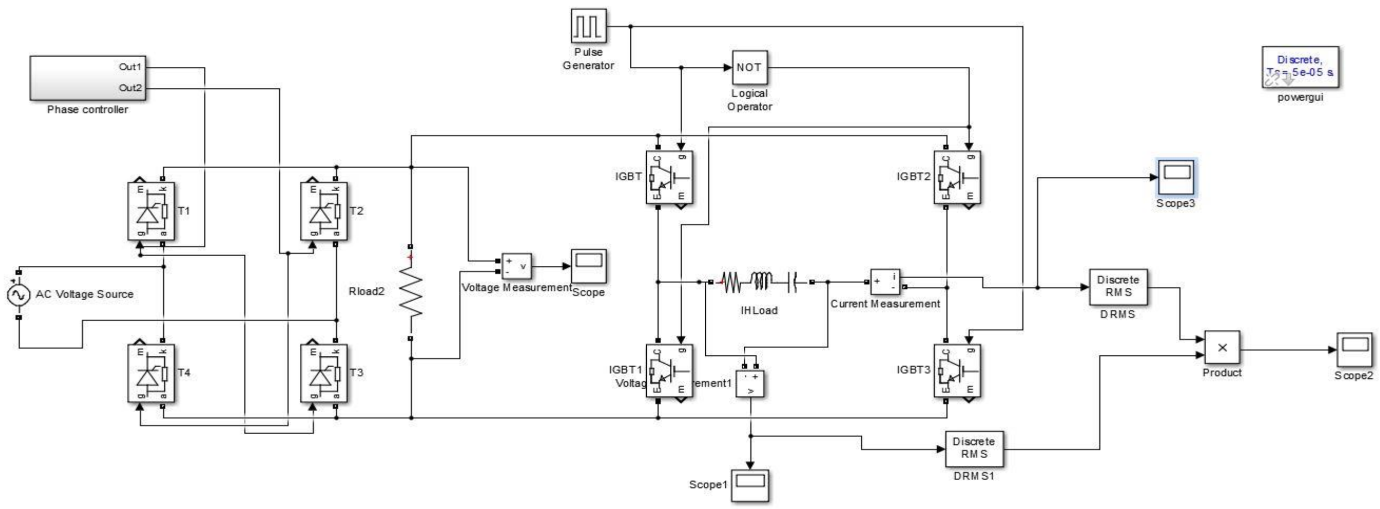


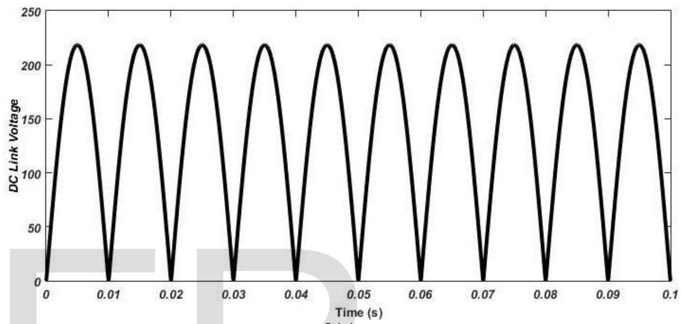
Fig. 7. Simulation model of proposed IH system

specification are given in table1.Fig. 7 show circuit of proposed IH system that has been implemented in Matlab/Simulink environment. In this model, it can be seen that various voltages and current waveforms are measured with the help of scope. Phase controller is used for generating PWM of variable duty cycle which is given to gate terminal of thyristors. Owing to this, variable DC-link voltage is obtained. After that, Ls and Cf are used before DC voltage is applied to FB-SRI because it eliminates high-frequency component at the DC link voltage. The switching frequency and duty cycle of FB-SRI are kept at 25 kHz and 50%. It is already mentioned that FB-SRI works at the resonant frequency and it is calculated by using relation: - $f_r = \frac{1}{2\pi\sqrt{L_{eq}C_{eq}}}$.

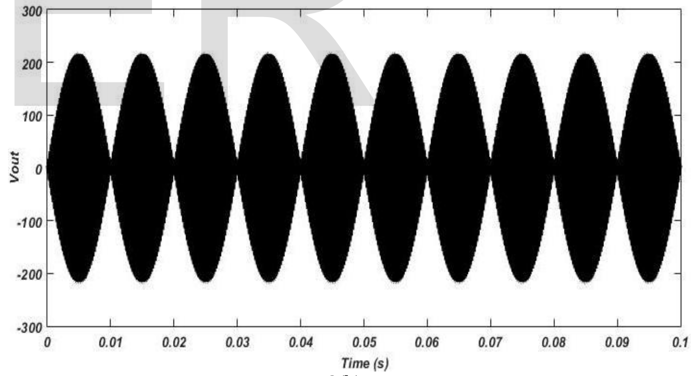
TABLE.I DESIGN PARAMETERS AND ITS SPECIFICATION

Designed Parameters	Specifications
Source Voltage (V_{pp})	220V
Switching Frequency (f_s)	25KHz
Resonating Capacitor (C_r)	0.8uF
Equivalent Inductance (L_{eq})	52.7uH
Equivalent Resistance (R_{eq})	5Ω
Maximum RMS output power (P_{out})	515W

Fig. 8(a) and (b) shows the simulated output of DC link voltage and correspond with the output voltage of full bridge series resonant inverter at different firing/phase angle. Fig. 9(a) and (b) are showing that how RMS output of FB-SRI is varying at different firing/phase angle.

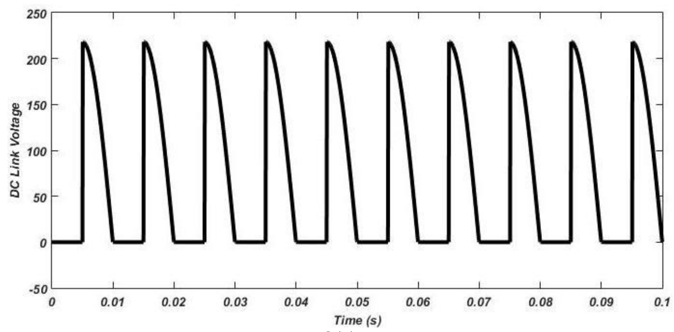


8(a)

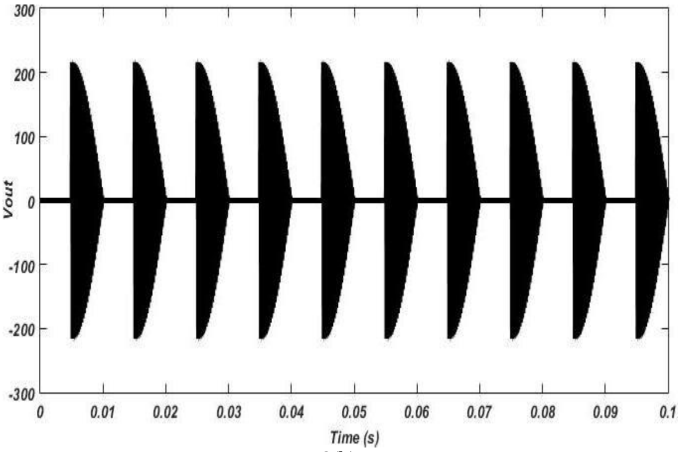


8(b)

Fig. 8. Simulated results of output voltage for controlled rectifier and FB-SRI at $\alpha=0^0$

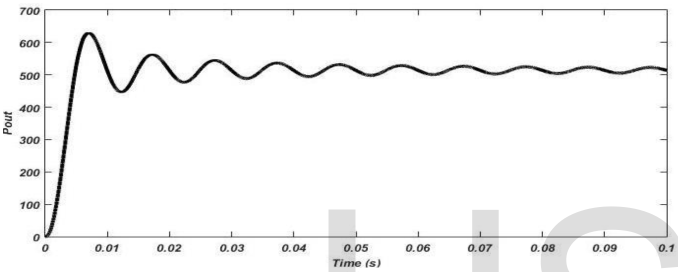


9(a)

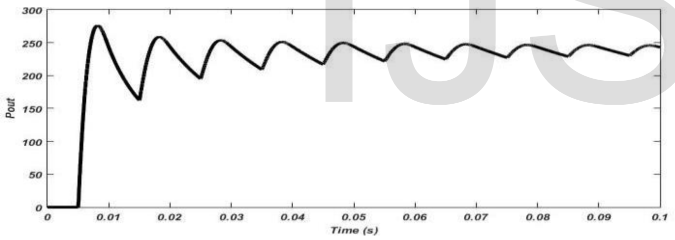


9(b)

Fig. 9. Simulated results of output voltage for controlled rectifier and FB-SRI at α=90^0



10.(a)



10.(b)

Fig. 10. Simulated output of RMS power at different firing/phase angle

(a) At α=0^0, P_{out}=515W

(b) At α=90^0, P_{out}=243.2W

V. CONCLUSION

In this paper, a phase control technique has been developed for modern induction heating system and it is validated with Matlab/Simulink environment. The behavior of this designed IH system works at variable RMS power of 515W. Owing to this, whatever be the requirement of power by the users, can be adjusted. This FB-SRI can transfer the maximum amount of current because it is resonating in nature. This phase control technique can be applied for both domestic as well as industrial induction application.

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