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Power Control of High-Frequency SRI using DC-Link Control Technique for Induction Heating System

Anand Kumar
Department of Electrical and Electronics Engineering
Sarala Birla University, Ranchi, India
anand.kumar@sbu.ac.in

***Abstract*— An effective power control technique for controlling the output power of a high-frequency full bridge series resonant inverter (HF-FBSRI) for induction heating applications has been developed in this study. This paper introduces a DC-link control technique for controlling the DC link voltage, which keeps the system in resonant mode. As a result, the system's performance is at its maximum. To manage the output power of the IH system, this controlled dc link voltage is applied to HF-FBSRI. This intended control mechanism ensures that the entire IH system runs smoothly. The ZVS condition has been obtained to limit switching losses across switches, resulting in regulated heating effects. Different output power is obtained with varied DC link voltage at different phase angles in this work, and it is validated with Matlab/Simulink environment for a 515W IH system.**

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

I. INTRODUCTION

In this era, it is seen that the usage of induction heating technology is increasing day by day in the fields of industrial as well as domestic applications [1]. There are numerous advantages to employing this technology, including great efficiency, controllability, speed, safety, and cleanliness. Many advancements have been made in this technology as a result of these benefits [2]. Induction heating is a method in which an object is heated using a foucault current created by the electromagnetic induction principle [3]. This Foucault current should be of high frequency in modern induction heating technologies. This high-frequency alternating current, known as eddy current, intrudes within the item, which is then heated according to the joules law of heating effect due to the resistance of the object to be heated. Nowadays, a high-frequency resonant inverter is employed to generate this high-frequency current [4]. For induction heating applications, a variety of topologies have been explored, including full bridge series resonant inverter (FB-SRI) [5], half bridge-SRI [6], single switch topology [7], class –D, Class-E, and so on. The only drawback of these converters is the high switching loss that occurs across the switches. Zero voltage switching (ZVS) and zero current switching (ZCS) [8] techniques are employed to eliminate this switching loss. It has been observed that full bridge topology is used for industrial applications and half bridge topology is used for household applications. To eliminate switching loss, a full bridge series resonant inverter with ZVS condition used in this study.

Different power control strategies have been developed in tandem with the resonant converter design, depending on the application's requirements [2]. In the resonant inverter, there are two techniques to manage output power. Either by adjusting the time period of Pulse width modulation (PWM) that is delivered to the inverter's switches or by delivering a variable DC link input voltage to the resonant inverter. PWM approaches are used to control the output power of these two techniques in general. Frequency modulation technique [9], Phase shift [10], Pulse density modulation [11], and Square wave are some of the numerous ways to modify the PWM signal. However, none of these approaches can guarantee that the system is in resonant mode. As a result, the system's performance has suffered, and switching losses have increased. It may be seen in frequency modulation technology, where the current and power passing through the resonant tank decreases as the frequency is varied. In order to overcome the aforementioned drawbacks, this paper proposes a variable DC link voltage method that is developed utilizing the phase angle control methodology. The block diagram of the proposed high frequency induction heating system is shown in Figure 1. First, AC 230Vpp, 50Hz (as per Indian standard) is applied to the regulated rectifier, as shown in this block diagram. Between the AC supply and the rectifier, an EMC filter is employed to lessen the voltage or current transient effect. After the rectifier, a non smoothening filter is employed to remove the high-frequency component generated at the load side of the resonant converter (superimposed at the input side of the inverter) [4]. As previously noted, a separate controller is utilized to obtain variable output power.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.

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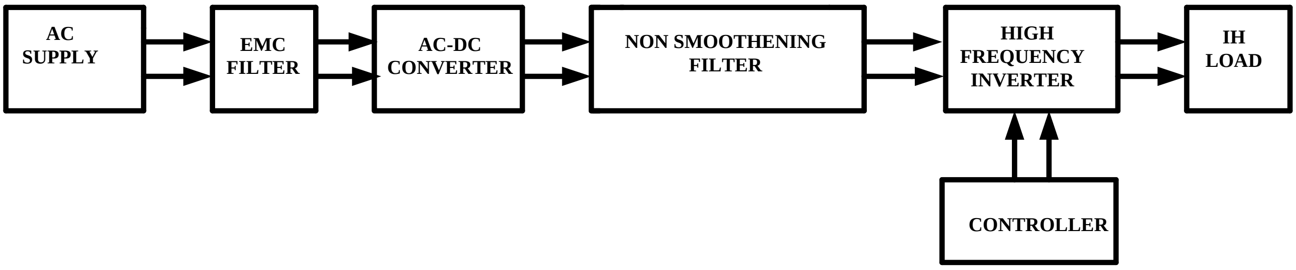

Fig. 1. Block diagram of High-Frequency Induction Heating System

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

A quick examination of FB-SRI with operating conditions is provided in this section. Four high-frequency power electronics switches and an anti-parallel diode make up a full bridge series resonant inverter (such as MOSFETs, IGBTs, GTO,). A quasi-square waveform is produced by simultaneously toggling two switches in one leg. MOSFETs are typically used where high power and high frequency are required, such as in a resonant converter for an IH application. The power circuit diagram for the FB-SRI is shown in Figure 2.

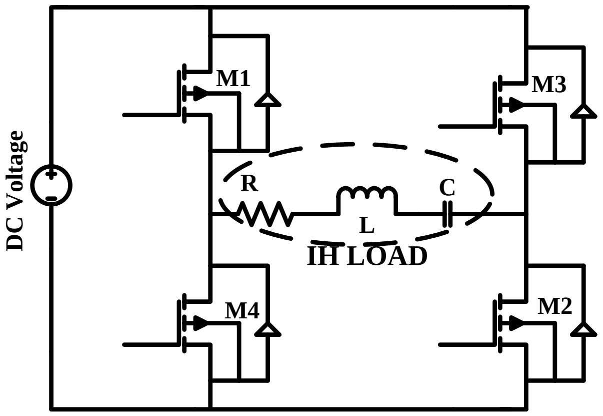

Fig. 2. Power circuit diagram of FB-SRI

In this case, the induction heating load is modelled as a series of *R* and *L*. *C* is a resonant capacitor that is used to generate a resonant situation for the purpose of analysis. The resonant converter is known to function at the resonant frequency (f_r). However, in order to achieve ZVS or ZCS conditions, the switching frequency should be greater or lower than the resonant frequency. In general, ZVS is preferable for IH applications. The full bridge series resonant inverter used in this study.

The operating mode of this FB-SRI can be explained with the four modes of operation:-

<u>Mode 1:</u> In this mode, the triggering pulses are used to turn on two switches (M1 and M2). Current flows from the source to V_{dc}, *M*1, IH load, *M*2, and back to the source. V_{dc} emerges from the load side in this mode. At the end of this mode, *M*1 must be switched off.

<u>*Mode2:-*</u> Due to the inductive load, the current cannot change direction instantly at the end of mode 1. When *M1* switches to the anti-parallel diode of *M4*, this mode is activated. The current now flows from the IH load to *M2*, then to the anti-parallel diode of *M4* and back to the IH load. Zero voltage is applied across the load in this mode. When the current flowing through the load reaches zero, this mode ceases.

<u>*Mode3:-*</u> This mode is identical to mode 1, except that the direction of current changes as the switches are switched. Pulses are sent to the *M3* and *M4* in this mode. Current is now flowing in the direction of V_{dc}, *M3*, IH load, *M4*, and back to the sources. -V_{dc} appears on the load side during this mode. At the end of this mode, *M4* must be turned off.

<u>*Mode4:-*</u> Due to the inductive load, the direction of current cannot change instantly at the end of mode 3. The transition of *M4* to the anti-parallel diode of *M1* initiates this mode. The current now flows from the IH load to the anti-parallel diode of *M1*, *M3*, and back to the load. In this state, there is no voltage across the load. The current through the load is reduced to zero at the end of this mode.

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

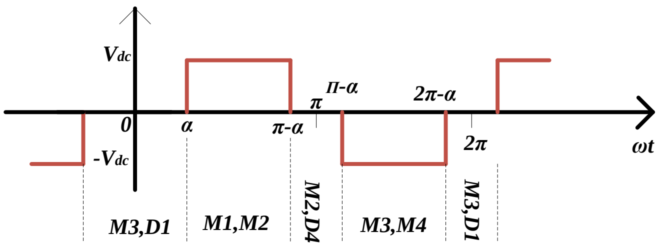

Fig. 3. Output voltage waveform of FB-SRI

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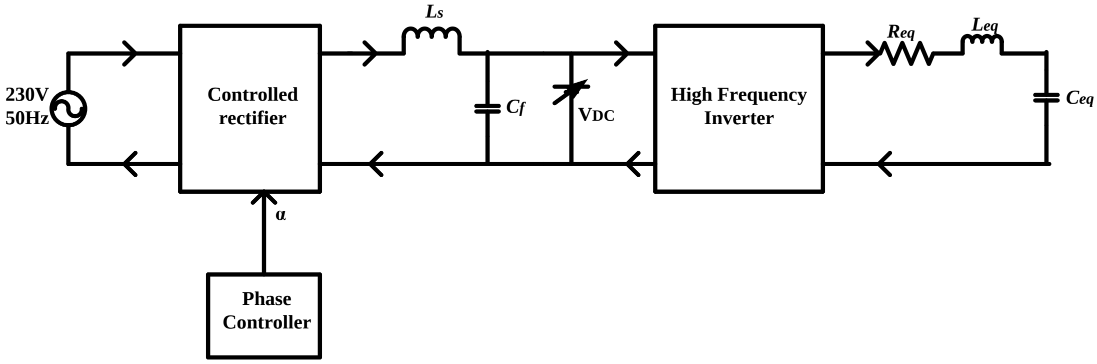

Fig. 4. Block diagram of proposed IH system

III. PROPOSED CONTROL TECHNIQUE

This section discusses a proposed phase control strategy for controlling the output power of an IH system when applied to a controlled rectifier. The suggested IH system with phase control approach is depicted in Fig. 4 as a block diagram. A single phase controlled rectifier is first fed with 230V, 50Hz, as shown in this block diagram. This controlled rectifier is linked to a phase controller, which is used to change the controlled rectifier's firing angle (α). Variable DC link voltage is obtained as a result of this. HF-FBSRI is provided with a changeable DC link voltage. This results in a high frequency oscillating alternating current, which is then applied to the IH load. The output power of the HF inverter can be adjusted by changing the DC link input voltage. The power variation in this IH system can be understood by following mathematical equation:-

P_{out}=Output power of controlled rectifier

P_{in}=Input power of HF-FBSRI

Output power of controlled rectifier can be calculated as:-

$$P_{\text{out}} = \frac{V_m}{\pi}\left(1+\cos\alpha\right)\times I_{out} \tag{1}$$

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

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

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:- The variable duty cycle of PWM is generated in this controller. Variable firing/phase angle is obtained as a result of this. It can be comprehended with the aid of a block diagram (Fig. 5). The comparator is fed a high-frequency sawtooth waveform (reference signal) and an adjustable DC voltage, as shown in the block diagram. This comparator compares the two signals and generates a variable duty cycle of PWM based on the variable DC voltage variance. The frequency (f_s) of generated PWM is determined by the reference signal's frequency (f_r). In this work, the peak voltage of saw tooth waveform is taken as 1V and magnitude of variable DC voltage is taken as 1V.

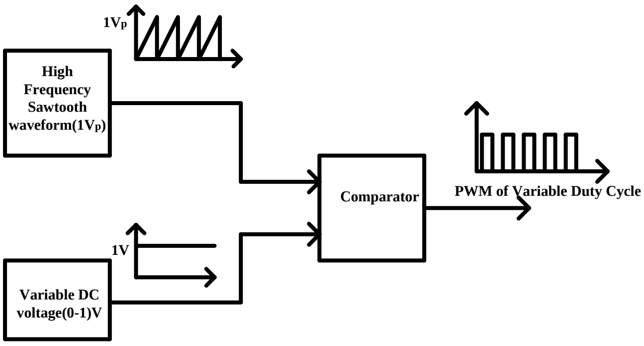

Fig. 5. Block diagram of Phase Controller

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

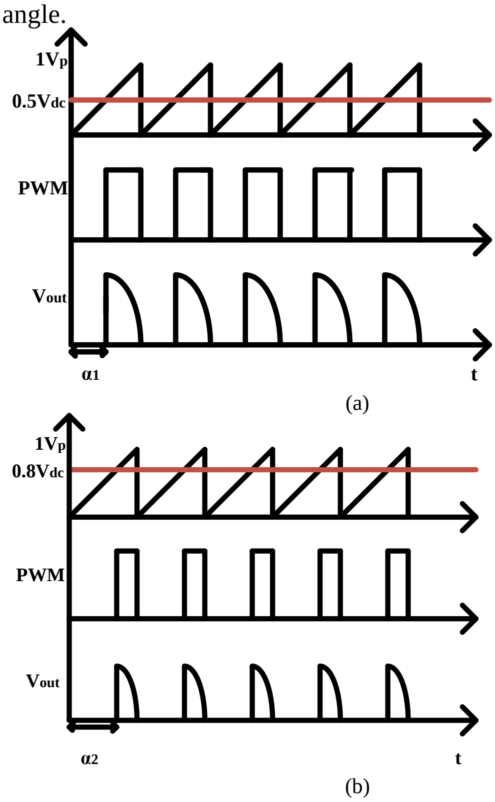

Fig. 6. Different output voltage at different firing angle (a) At α1 and (b) At α2

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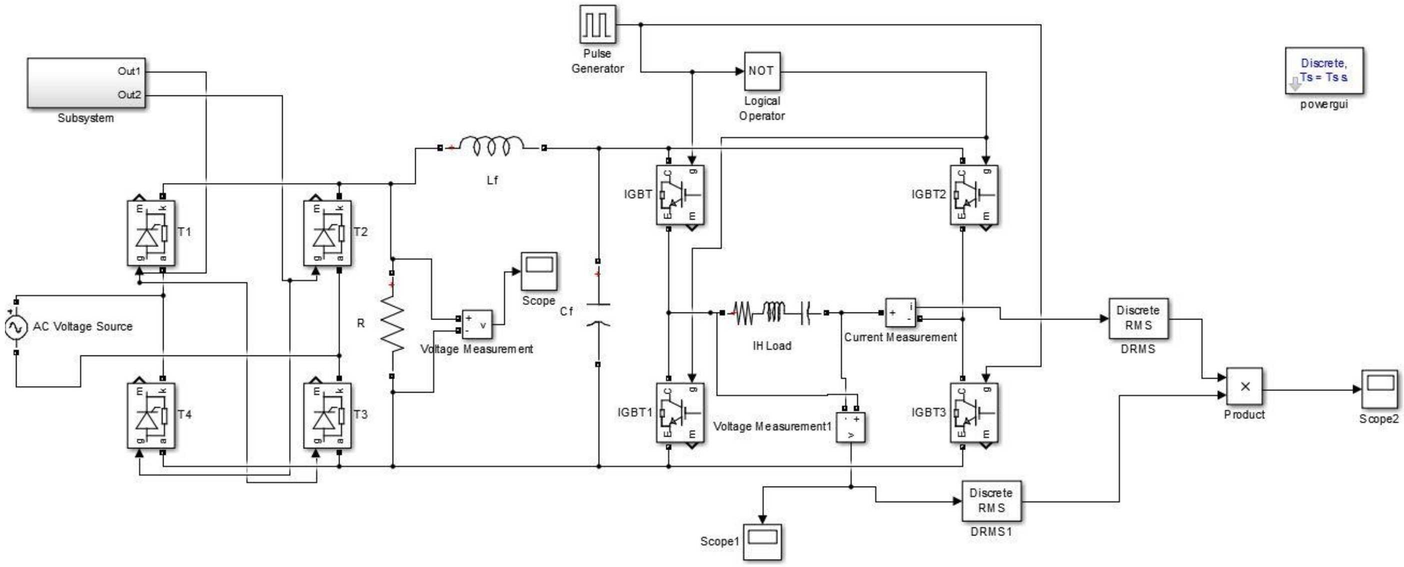


Fig. 7. Simulation model of proposed IH system

As a result of the above waveform, it can be inferred that output power may be adjusted by changing the duty cycle. The duty cycle changes when the DC voltage (0-1) V changes.

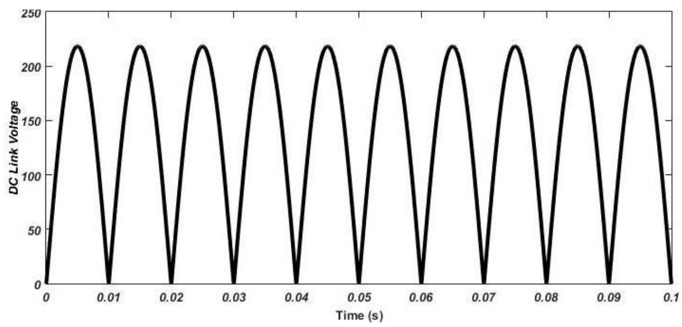
IV. SIMULATION MODEL AND ITS RESULTS

Using the Matlab Simulink environment, the proposed control strategy is validated. Table 1 lists the design parameters and their specifications. Figure 7 depicts the circuit of the proposed IH system, which has been created in the Matlab/Simulink environment. The use of a scope to measure various voltages and current waveforms may be observed in this model. The phase controller is used to generate PWM with a changeable duty cycle that is sent to the thyristors' gate terminal. Variable DC-link voltage is obtained as a result of this. Then, before applying DC voltage to FB-SRI, L_s and C_f are employed to eliminate the 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:- $f_r = \dfrac{1}{2\pi\sqrt{L_{eq}C_{eq}}}$.

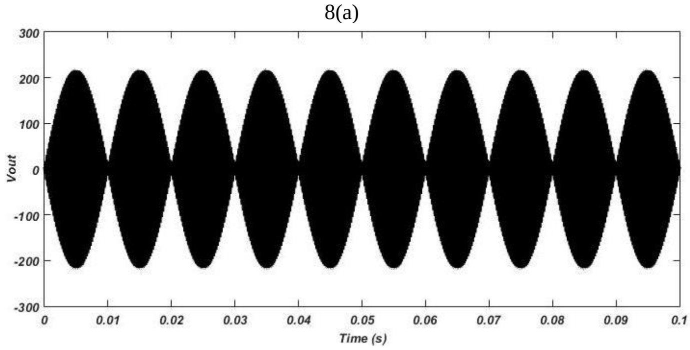
TABLE.I DESIGN PARAMETERS AND ITS SPECIFICATION

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 8(b) shows the simulated output of 1-ø controlled rectifier and full bridge series resonant inverter at zero degree firing/phase angle. At 0^0 firing angle, maximum power has been achieved. Fig. 9(a) and 9(b) are also shows the simulated result of controlled rectifier and full bridge series resonant inverter but at different firing/phase angle i.e. $\alpha=90^0$. At this firing/phase angle output power is reduced. So it can be concluded that, as the firing/phase angle increases, output power of induction heating system reduces.



8(a)



8(b)

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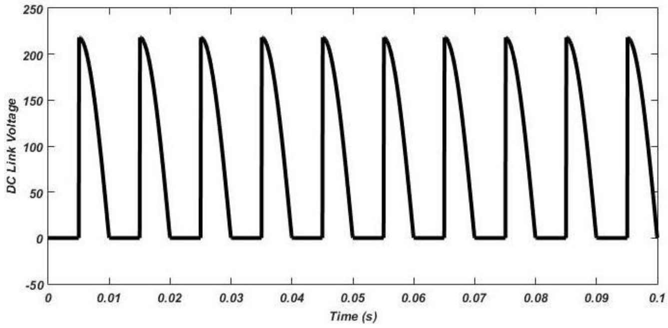
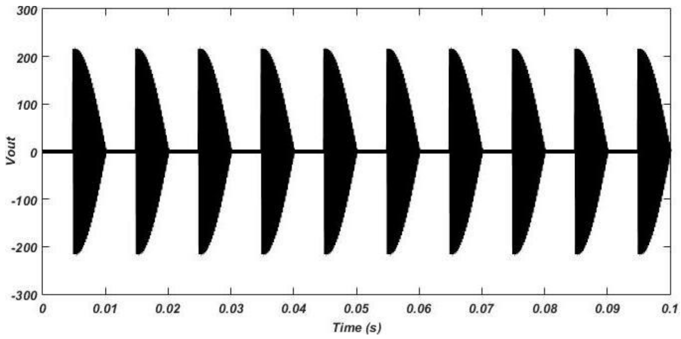
Fig. 8. Simulated results of output voltage for controlled rectifier and FB-SRI at $\alpha=0^0$

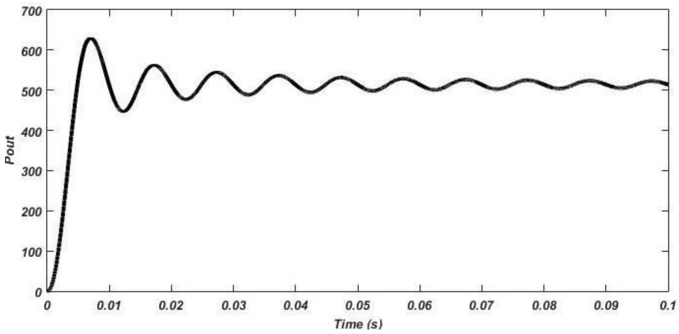


9(a)

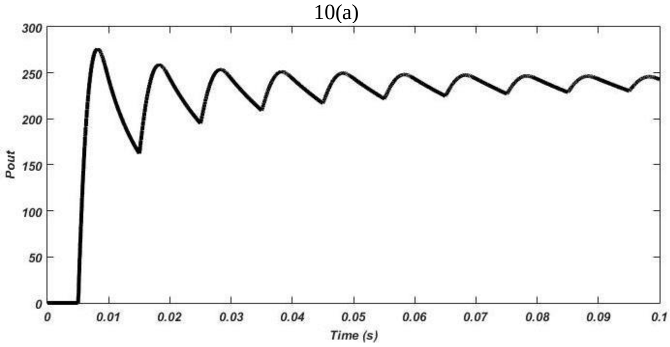


9(b)

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



10(a)



10(b)

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

(a) At $\alpha=0^0$, P_{out}=515W

(b) At $\alpha=90^0$, P_{out}=243.2W

V. CONCLUSION

In this research, a phase control technique for current induction heating systems is designed and tested using Matlab/Simulink. This IH system's behaviour is based on a variable output power of 515W. As a result, whatever the users' power requirements are, they can be adjusted up to the rated power. Because it is resonant in nature, this FB-SRI can transfer the maximum amount of current. Both home and industrial induction applications can benefit from this phase control technology.

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