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PUBLICATIONS

A.Gaber, A. Elserougi and M. El-Geneidy, "Modeling and Simulation of Induction Heating Systems Based on Pulse Density Modulation Technique," MEPCON, 2014.

Modeling and Simulation of Induction Heating Systems Based on Pulse Density Modulation Technique

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***Abstract* – This paper presents modeling and simulation of an effective control scheme for a series-resonant voltage-source inverter based on pulse density modulation (PDM) control strategy for induction heating applications. The proposed control strategy ensures well regulated output power as well as zero-current (or voltage) switching, which reduces the switching losses as it mainly depends on switches curents, and voltages. Power feedback, pulse density modulation control and phase angle feedback are used in the proposed approach to achieve proper load power regulation and unity power factor. Simulation models have been built using Matlab/Simulink software package.**

***Index Terms* – Pulse density modulation; induction heating; series resonant-inverter.**

I. Introduction

Induction heating is a flame free, non-contact heating method. The main advantages of induction heating over conventional heating systems is the fast heating, low running and maintenance cost, and improves working conditions [1].

There are three main power systems used in induction heating [1]-[2], namely, motor alternator, radio frequency, and solid state converters. Solid state converters are the most common power source of induction heating [1]. The output power of these systems varies, depending on the application, from several kilowatts to tens of megawatts [1]. Three types of solid state converters used in induction heating systems [3], (i) frequency converters with thyristors which has a limited frequency range from 100 Hz to 10 KHz, (ii) frequency converters with transistors with larger frequency range up to 500 KHz [3], and (iii) frequency converters with vacuum tubes with a frequency range up to 3 MHz.

Resonant converters are widely used in applications that require higher output power control capability such as induction heating [4],[5]. Many control schemes have been proposed for controlling output power of the resonant converters, namely, pulse frequency modulation (PFM) [5], phase shift control (PS) [5], and duty cycle control [4],[5]. These control schemes may result in increasing of switching losses and electromagnetic noises because the switching devices are not turned on and off at zero current [4]. When PDM control technique is used to control the series-resonant inverter, the switching devices operate at zero current which allows the resonant inverter to operate with very low switching losses at high power factors [4], in addition there is no need to use a controlled rectifier which reflects positively on the system cost.

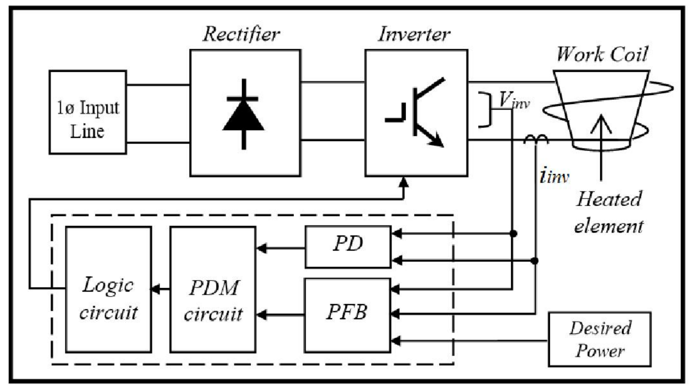


Fig. 1 Induction heating block diagram

Despite its advantages, PDM converters output power response is discrete and often nonlinear. A new closed loop controller for the output power using a three stages feedback control system is presented to regulate PDM converters output power. Fig. 1 shows the block diagram of heating system with PDM technique, power feedback (PFB), and the phase difference (PD) blocks.

This paper is divided into the following sections. Section II describes the principles of induction heating and its main components. Section III describes the output power control of the series-resonant converter using pulse density modulation (PDM) technique. It also illustrates the operation of the three main feedback circuits for the PDM control technique. Section IV illustrates the modeling of the system (i.e. Simulink sub-systems for power inverter, rectifier section, and closed loop feedback circuits). Finally, simulation results are presented with discussion.

II. Induction Heating System

A. *Principles of Induction heating*

The basic concept of the induction heating systems is similar to the well-known transformer theory, but with single secondary turn causing very high secondary current which is needed to heat the metal [1].

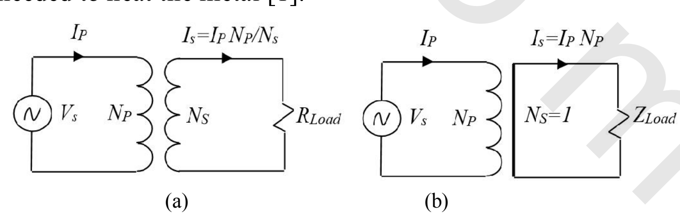


Fig. 2 Basic concepts of induction heating. (a) Transformer. (b) Short circuit secondary effect.

The frequency of the induced eddy currents in the work-piece is determined by the frequency of the power source. These eddy currents are induced into a peripheral layer of the work-piece with a thickness (δ) called skin depth [1] given by:

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} \tag{1}$$

Where μ and ρ are the magnetic permeability and electrical resistivity of the workpiece, respectively, and f is the applied frequency. According to [1], 63% of the current and 86% of the power in the work-piece within a surface layer of thickness δ will be concentrated.

For effective induction heating, the frequency of the alternating magnetic field in the work-coil is given by:

$$f_c = \frac{6.45 \times \rho}{\mu \times d^2} \tag{2}$$

Where, d is the diameter of the workpiece, and f_c is the critical frequency [8].

The main components of an induction heating system are the power supply, work coil, and the work-piece. Work coils are usually designed for specific applications and are therefore found in a wide variety of shapes and sizes [2]-[7]. Power supply comprised of a rectifier and inverter. IGBTs are selected as the switching devices for this application because of the high switching frequency requirement. The work-piece is the material to be heated, is referred to equivalent resistance R_L and inductance L_L [1].

B. Basics of Inverter Systems

Two systems are used for most induction heating inverters, the load resonant generator and the swept frequency generator [1]-[2]. The swept-frequency generator consists of a variable frequency inverter and uncontrolled rectifier (i.e. Fixed voltage DC supply), while the load-resonant generator provides great range of power control by using variable DC source.

The main drawback of load-resonant generator is that it is not a self starting system, and it has a complex control system, and needs a variable DC source. Also the swept-frequency generator has a lower power efficiency, limited range of power control, and higher switching losses [1]-[2].

III. PDM BASED INDUCTION HEATING SYSTEM

The typical system configuration of the PDM based induction heating system is shown in Fig. 3. The power circuit of the resonant converter consists of a single-phase voltage source inverter with four IGBTs, each is connected with anti-parallel freewheeling diode. A parallel *RC* snubber circuit is connected across each IGBT as shown in Fig.3.

Uncontrolled rectifier bridge is used to generate fixed DC voltage for inverter input. Uncontrolled rectifiers is less complex, less expensive [9], and no need for voltage control circuit, that gives the PDM system an advantage over the load resonant generator [6]. In the presented case study, the uncontrolled bridge rectifier is connected to suitable AC voltage source with to produce a DC voltage of approximately

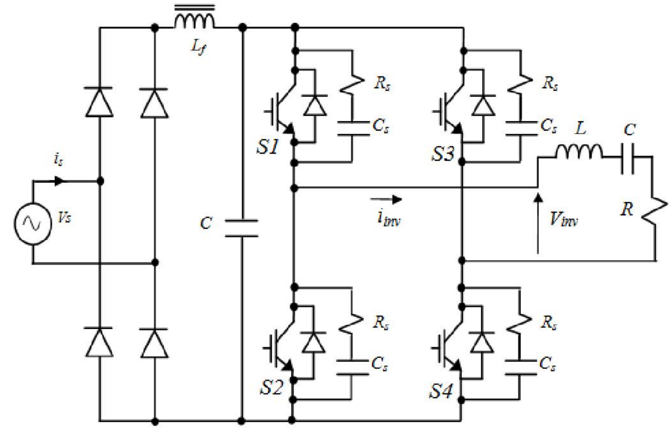


Fig. 3 Typical system configuration for PDM based induction heating system.

100V across the LC filter terminals.

The inverter output terminals are connected to series RLC load to configure the series resonant inverter. In this system, zero current switching (ZCS) can be achieved simply by keeping the resonance condition. Operation under ZCS minimizes the inverter switching losses. The work coil, and the work piece can be modeled by means of a series combination of its equivalent resistance R_L and inductance L_L, the analysis of load circuit described in [1]. In spite of the operating frequency of the pulse density modulated heating system is constant, it achieves full controllability on the output power [9],[10] , in contrast to the swept frequency generator [6].

The important features of PDM technique for resonant converters are [4]: (i) wide output power range, (ii) near-unity power factor, (iii) zero-current (or voltage) switching which reduces the system switching losses, (iv) fixed switching frequency, and finally (v) simple control circuit.

A. PDM pattern

Fig.4 shows an example for PDM sequences assuming that the summation of on and off cycles is ten. In this case, the modulation index M can be varied from 1/10 to 10/10. For 5/7 modulation index, the output current and voltage waveforms of the inverter with PDM is shown in Fig. 5 (assuming T_{on}=5 cycles, T_{off}=2 cycles).

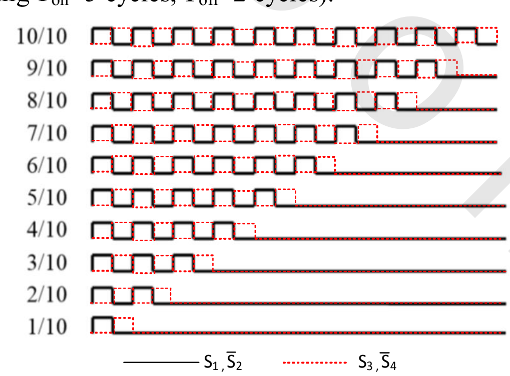


Fig. 4 PDM pattern generation cycle waveforms (gate pulses of inverter switches)

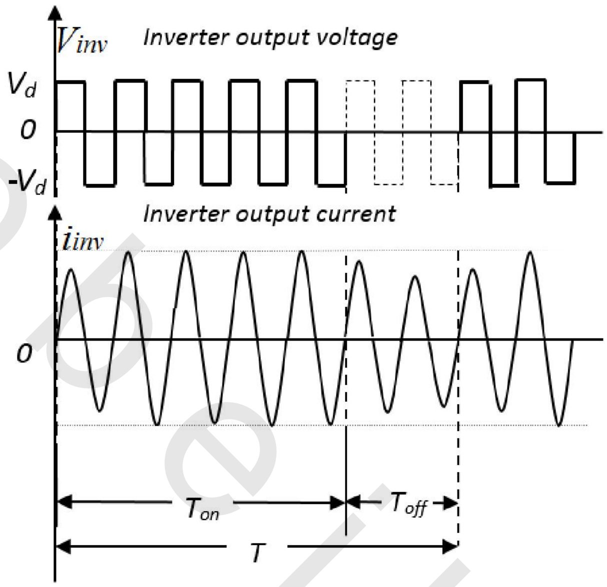


Fig.5. Output current and voltage waveforms with PDM.

The term T_{on}/T is defined as modulation index M or pulse density D [11], and its value controls the output power. It has to be noted that, the length of one PDM full cycle is a multiple of the load resonant period.

B. *Operating Modes*

Fig. 6 show the switching modes of the voltage-source series-resonant PDM inverter. The simplified circuit is shown in Fig. 6a. The inverter generates bipolar output voltage by switching the IGBTs in alternate sequence $S_{1,\,4}$ and $S_{2,3}$, as shown in Figs. 6b and 6c (Mode I and II). In the third mode, the two lower side switches (S_2 and S_4) or the two upper side switches (S_1 and S_3) are turned on as shown in Fig. 6d or 6e respectively, which results in zero voltage at the inverter output terminals.

C. *Power Control*

The PDM control technique operates the inverter in run and stop modes alternatively. At full power, the inverter has no stop cycles and delivers continuous output voltage to the load [9]. By including a stop periods to the inverter cycles load power can be controlled. At the stop cycles, PDM provides a free-wheel circuit for the resonant current to flow through the load [9]. The stored energy in series capacitive and inductive elements is dissipated in the resistive component which results in decaying of AC current magnitude as shown in Fig.5. To reduce the effect of discrete power response of the PDM converter, due to alternating running and stopping cycles, a large value of quality factor Q is needed [4].

D. *Control Circuit*

Fig. 7 shows the proposed output power closed loop controller for series-resonant inverter under PDM technique. Inverter instantaneous output current and voltage (i_{inv},V_{inv}) are fed to two feedback circuits, the first circuit detects the phase difference between the voltage and current. The phase difference is compared with zero (resonance condition). The phase difference error is fed to PI controller, the controller output is used as an input to voltage controlled oscillator (VCO) which generates the suitable switching frequency for the inverter.

The second feedback circuit is used to compare the reference power with the actual output power. The power error is fed to other PI controller (PFB PI-controller).

The sinusoidal output of the VCO is converted to unipolar square wave and fed with the output of power feedback (PFB) PI-controller to the PDM control circuit. This circuit is responsible for generating the inverter gate pulses as shown in Fig. 8.

The main components of the proposed PDM control circuit (Fig.8) are: (i) integrator, (ii) comparator C_1, (iii) comparator C_2, (iv) D-flip flops, and (v) simple logic gates.

Figs. 7, 8, and 9 illustrate how the PDM pattern can be generated using the proposed concept. The inverter output current (i_{inv}) is converted to unipolar square wave (I_{inv}) ,then it is fed to the integrator. The integrator generates a saw tooth signal (I_{inv}*). The integrator output is reset when its output (I_{inv}*) reached to certain predetermined value (which represents the number of desired cycles per T). Comparator C_1 is responsible for resetting the integrator output.

On the other hand, Comparator C_2 is responsible for generating the unsynchronized pulses (M*) which produced by comparing the output of the PFB PI-controller with (I_{inv}*) signal. Then, M* pulses and VCO output are fed to simple logic circuits (Fig.8), to produce the proper gate pulses for the inverter IGBTs.

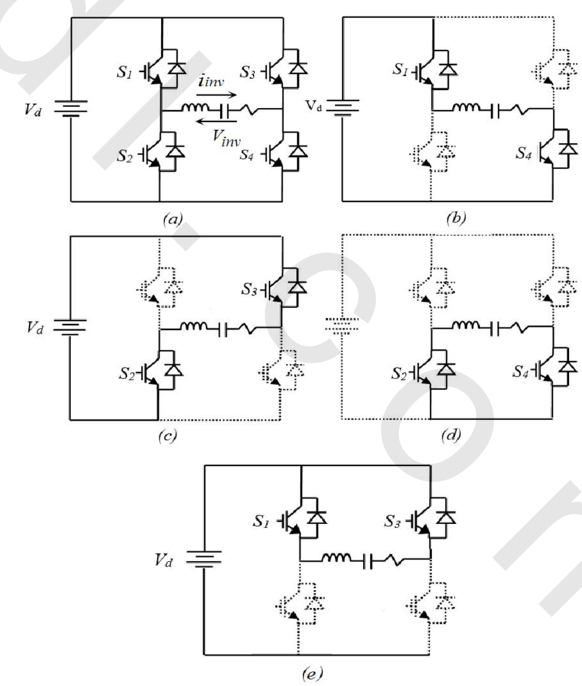


Fig. 6 Operating modes in PDM. (a) Simplified circuit, (b) Mode I, (c) Mode II, (d or e) Mode III

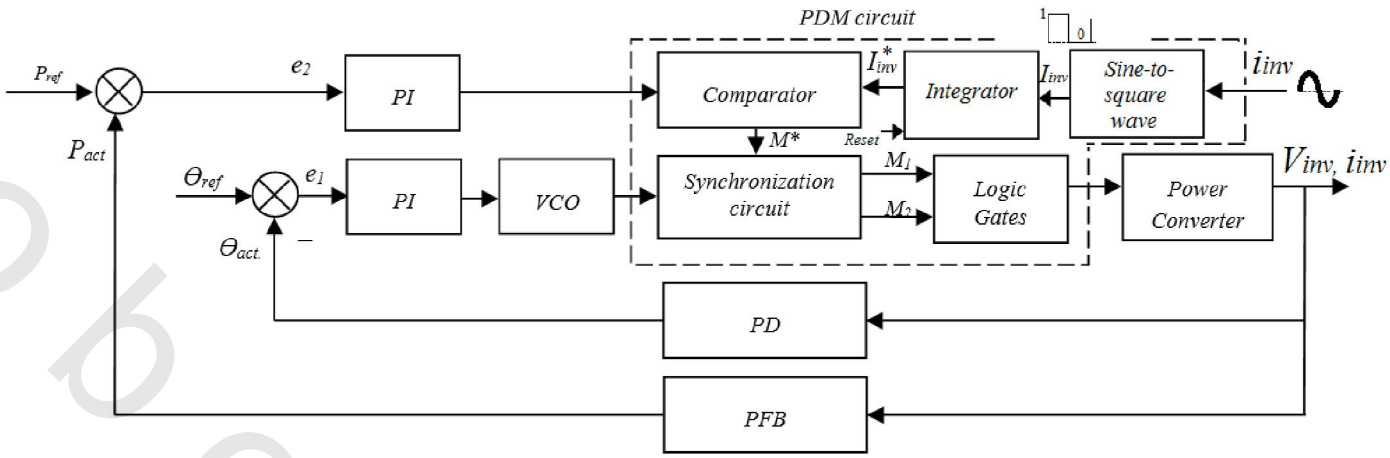


Fig.7 Control circuit block diagram for PDM.

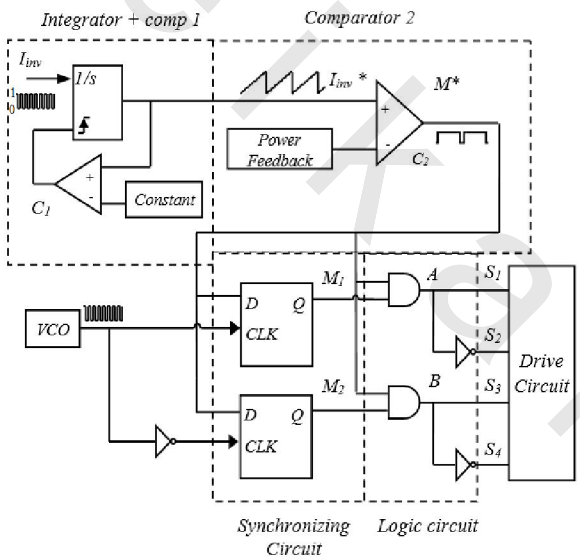


Fig. 8 PDM control circuit

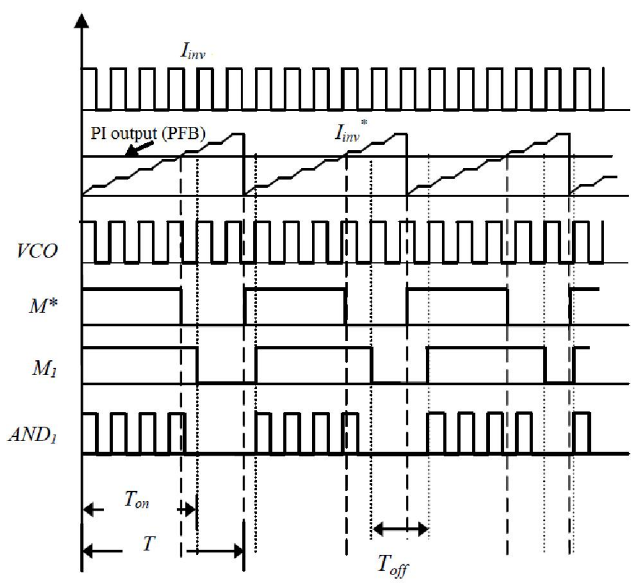


Fig 9 PDM pattern generation

Based on Fig.8, The proposed synchronizing circuit which contains D-type flip-flops is employed to avoid the change of the current state during the resonant cycle. The VCO output and the unsynchronized pulses M^* are applied to this synchronizing circuit to hold M^* until reaching the next rising edge of the VCO output producing a synchronized pulses M_1 and M_2. These synchronized pulses are fed to simple logic gates (Fig.8), to generate proper gate pulses for the inverter IGBTs.

IV. Simulation

The heating system under study has been simulated using Matlab/Simulink software package. The detailed power circuit topology is shown in Fig. 3, the input AC voltage source is applied to single-phase uncontrolled rectifier. The resonant converter with snubber circuits has been implemented using the simpowerSystems toolbox. A commutating inductor L_c and a commutating capacitor C_c are connected in series with the load equivalent resistance R_L at the output terminals of the single-phase IGBT inverter to form a series resonance converter. The feedback model is divided into three sub-systems, (i) phase difference (PD) sub-system which detects the phase difference between inverter voltage and current, then compares it with zero as shown in Fig. 10. The phase difference error is fed to the PI controller to generate the suitable input for the VCO, (ii) power feedback sub-system (PFB): in this sub-system, the actual output power is calculated and subtracted from the desired output power. The power difference is fed to the other PI controller. The output of power feedback PI controller is used to determine the duration of T_{on} period by comparing its level by the sawtooth signal (I^*_{inv}). Fig. 11 shows the Simulink blocks for power feedback sub-system, (iii) the PDM sub-system blocks receive the output of the power feedback PI controller, output of VCO, and the inverter output current i_{inv} as shown in Fig.7. Fig.12 shows the PDM control sub-system based on the proposed concept.

TABLE I
SYSTEM PARAMETERS

Parameter	Description	Value	Unit
P	Desired maximum rated power	16	kW
V_{dc}	DC-Link voltage	100	Volt
f_s	Switching frequency	30	kHz
L_f	Filter inductor	2	mH
C_f	Filter capacitor	2500	µF
L_c	Series Commutating inductor	795	µH
C_c	Series Commutating capacitor	35.3	nF
C_s	Snubber capacitor	2.2	nF
R_s	Snubber resistance	100	Ω
R_L	Load equivalent resistance	500	mΩ

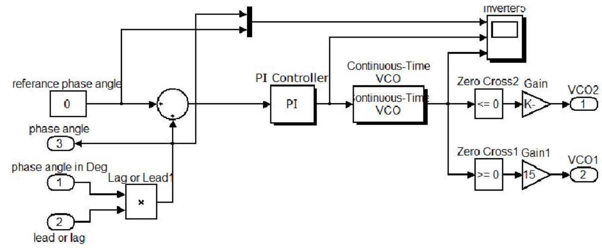


Fig. 10 Phase angle feedback sub-system

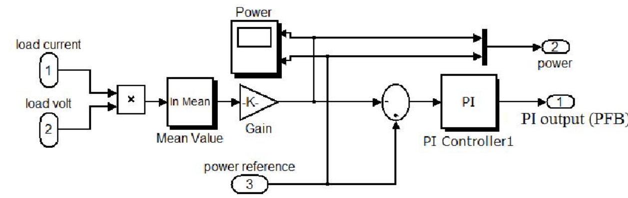


Fig. 11 Power feedback sub-system

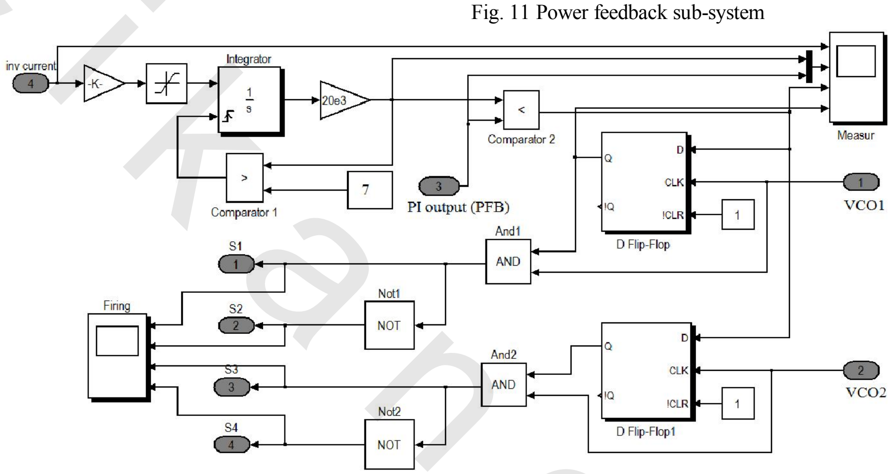


Fig. 12 PDM sub-system

V. RESULTS

Fig. 13 show the inverter voltage and current at rated power (16 kW). It is clear that the system achieves unity power factor (zero phase between V_{inv} and i_{inv}), i.e. The switching happens at the zero current (ZCS). In this case, the pulse density is 10/10, and there are no off (or stop) cycles.

Fig 14, and 15 show the simulation results for 9kW, and 1kW reference average output power respectively. It is clear that the inverter output current and voltage are in-phase in all of these different reference power levels, which guarantees ZCS operation.

Fig. 16 shows the corresponding PDM pattern generation at reference average power of 1 kW.

The inverter output current and power in case of reference average power of 12kW are shown in Fig. 17. It is clear that the controller is able to trace the desired power level. Finally, Fig. 18 shows the step response of the heating system for ten ranges of reference average power. It can be observed that the average of output power oscillates successfully around the desired value.

VI. CONCLUSION

In this paper modeling and simulation of 16kW 30kHz heating system based on pulse density modulation (PDM) has been presented. The presented control strategy provides smooth power regulation. The output power of the inverter is controlled by controlling pulses density not by controlling the input DC voltage, i.e. uncontrolled rectifier is applicable in this system, which reflects positively on the system cost. The system always operates at the unity power factor, and is capable of controlling the load power without losing the ZCS feature, which leads to reduction of switching losses compared with other control techniques.

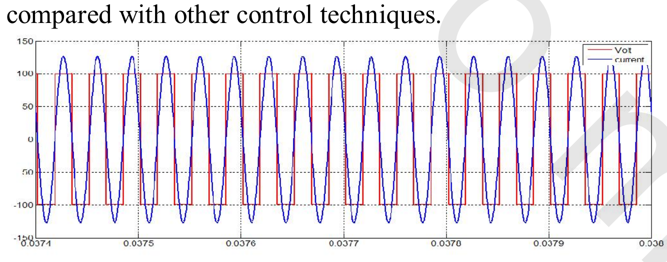
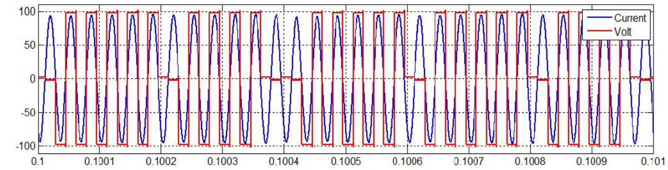
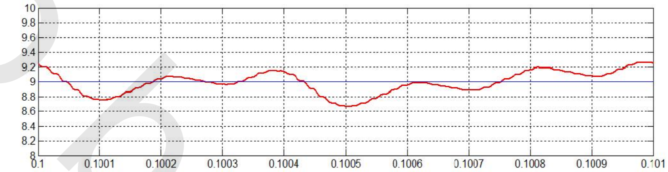


Fig. 13 Inverter voltage in [V] , and current in [A] for output average power of 16kW

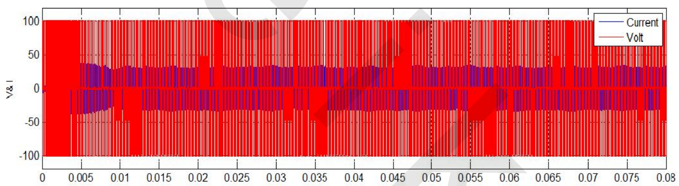


(a)

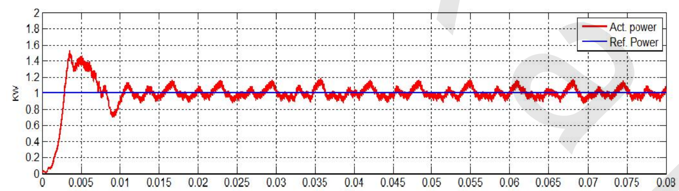


(b)

Fig. 14 (a) Inverter voltage in [V] and current in [A] ,(b) System reference and actual average power in [kW] assuming reference average power of 9 kW



(a)



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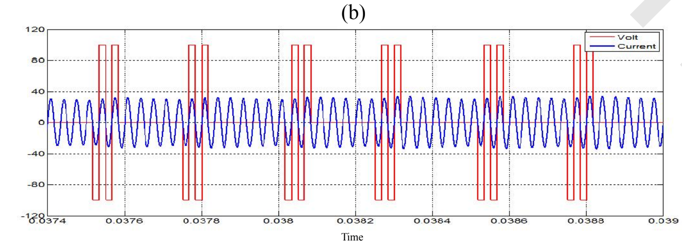


(C)

Fig. 15 (a) Inverter voltage in [V] and current in [A], (b) System reference and actual average power in [kW], at a reference average power of 1 kW and (c) Zoom in for Fig.15a.

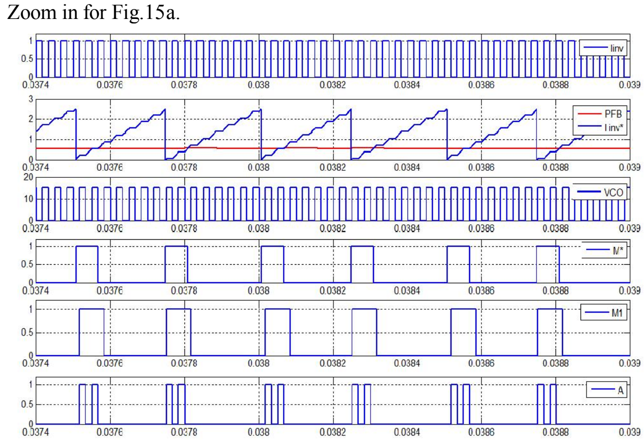
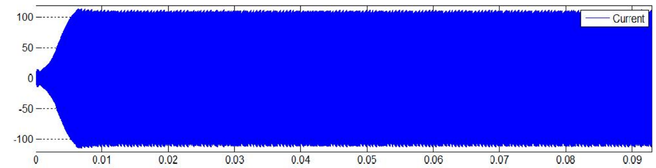


Fig. 16 PDM pattern generation at reference average power of 1 kW



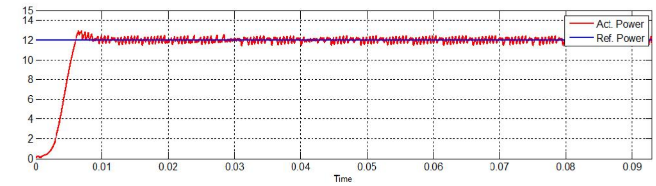


Fig. 17 Inverter current in [A] (top), reference and actual average power in [kW] (bottom) at reference average power of 12 kW.

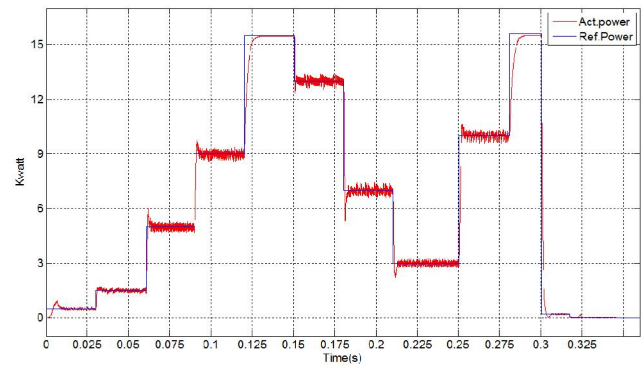


Fig. 18 Step response of the heating system for different average power levels

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