3 Phase Induction Heating System Using Bi-Directional Switching Transformer

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***Abstract*— MOSFETs are now widely used in many power electronics and induction heating applications. This is due to their several advantages such as relatively small size, low losses, market availability, and low cost. In this paper three phase induction heating system (IHS) using bidirectional switching transformer (BST) is describes. Proposed BST contain primary bidirectional switch, high frequency isolation transformer(HIT), matching coil, and heating system. Switching routine is applied in such a way that the output voltage regulation is achieved in the full load variations, even at asymmetrical utility conditions. Simulations are obtained for proposed BST which consist of three phase input voltage and three phase high frequency output voltage. The simulation analysis is compared with mathematical analysis.**

Key Words: Bidirectional Switching transformer, High frequency isolation transformer, Induction heating system,matching coil.

I. INTRODUCTION

In the last decades, the production of power electronics switches has been plentiful and diverse. Some of these switches are thyristors, GTO's, bipolar power transistors, MOSFET's, IGBT's, and MCT's [1],[2]. Even with these devices, the basic MOSFET still constitutes a robust, simple and economical devices, that has many applications. MOSFETs are widely used for control of power in both AC and DC systems. This is due to their several advantages such as relatively small size, low losses, and fast switching. Apart from many other uses, such a controller can be used to control the three-phase AC power in induction motor, illumination control, reactive power control and starting as well as speed control of AC motors.

Transformers are used widely in electric power distribution/conversion systems in order to perform many functions such as isolation, voltage transformation, noise decoupling, etc. Owing to the bulky iron cores and heavy copper winding in the composition, the transformers are one of the heaviest and most expensive part in an electrical distribution system. The size and weight of transformer is primarily a function of both, the saturation flux density of the core material and the maximum allowable temperature rise in cores and windings. Saturation flux density is inversely proportional to the frequency and hence increasing the frequency allows to reduction in transformer size [3],[4],[5].

BST has been used for motor drive applications and excitation control[10]. Solid state frequency converters have been also used for induction heating and melting systems [11]-[13]. Because induction heating system (IHS) are classified as unusual or special load [13].

To increase the quality and the efficiency of the power supply and the power usage three phase BST becomes a modern energy converter and has emerged as one of the best energy conversion substitution which fulfils all the requirements of the conventionally used rectifier/ DC link / inverter structures. Some advantages of the BST can be seen as follows: the use of a compact voltage source, providing sinusoidal voltage with variable amplitude and frequency beside the adjustable power factor. As shown in Fig1, BST has the simple topology and allows a compact design due to the lack of DC link capacitor for energy storage.

In this paper a three-phase induction heating system using bidirectional switching transformer is presented. Proposed IHS-BST is designed to have equal power consumption between phases with unity power factor, so a resistive symmetric load from the utility point of view can be considered. Isolation of input/output and voltage or frequency regulation are other features of proposed IHS-BST. Additionally, this new topology provides high power density due to the minimization of magnetic components and the full utilization of HIT. BST are controlled high frequency voltage source to supply induction coil through a matching coil. A circuit model for $380V/3\phi/50Hz$ to $380V/3\phi/10KHz$ converter has been simulated with PSIM software. The simulation results show the good performance of proposed circuit and verify the mathematical analysis.

II. OPERATION OF THE PROPOSED INVERTER

Three-phase BST module include nine bidirectional switches is shown in Fig.1. The voltages and current at the input side of BST are denoted by a,b,c while the output sides are denoted by A,B,C. There are 27 switching configuration states, which means 27 possible space vectors can be used to control heating load and can be split respectively into 3 groups as shown in Table I. However group I is not useful, only 18 non-zero space vector in group II $(\pm 1, \pm 2, ... \pm 9)$ and 3 zero space vector on group III $(0_a, 0_b, 0_c)$ can be usefully employed in circuit control techniques for BST such as space vector modulation.

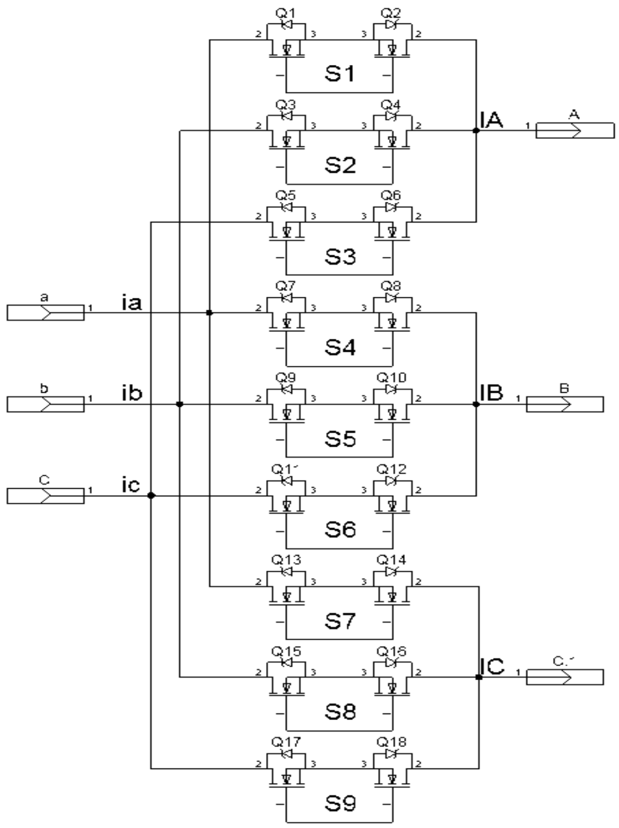


Fig. 1. 3 Phase Power Circuit of IHS-BST

The three-phase BST is supplied by sinusoidal voltage sources.

$$v_a = V_m \cos(\omega_i t) \quad (1)$$

$$v_b = V_m \cos(\omega_i t - 2\pi/3) \quad (2)$$

$$v_c = V_m \cos(\omega_i t - 4\pi/3) \quad (3)$$

Hence, for the space vector modulation of BST , the input and output phase space vector voltages of BST can be expressed in terms as

$$v_i = \frac{2}{3}\left(v_{ab} + v_{bc}e^{j2\pi/3} + v_{ca}e^{j4\pi/3}\right) = V_i e^{j\alpha_i} \quad (4)$$

$$v_o = \frac{2}{3}\left(v_{AB} + v_{BC}e^{j2\pi/3} + v_{CA}e^{j4\pi/3}\right) = V_o e^{j\alpha_o} \quad (5)$$

In the same way, the input and output phase currents can be expressed as given below.

$$i_i = \frac{2}{3}\left(i_a + i_b e^{j2\pi/3} + i_c e^{j4\pi/3}\right) = I_i e^{j\beta_i} \quad (6)$$

$$i_o = \frac{2}{3}\left(i_A + i_B e^{j2\pi/3} + i_C e^{j4\pi/3}\right) = I_o e^{j\beta_o} \quad (7)$$

It may be noted from above equations that the resulting output line voltage is expressed as a function of the input line voltages and the resulting input line current is expressed as function of the output line currents.

As it is shown in Table I, for the 6 combinations of group I, each output phase is connected to a different input phase. In the 18 combinations of group II, two output phase are short-circuited, in the 3 combinations of group III all the output phase are short-circuited.

Each combination of group I determines an output voltage vector having a phase angle α_0 which is dependent on the phase angle $\alpha_i$of the corresponding input voltage vector. In the same way, the input current vector has phase angle β_i which is related to the phase angle β_0 of the output vector. Hence, in order to apply the SVM technique, these combinations cannot be usefully employed.

On the contrary, the 18 configurations of group II determine six prefixed positions of the output voltage space (Fig. 2) which are not dependent on α_i. The 18 configurations of group II also determine 6 prefixed positions of the input current space vector (Fig. 3) which are not dependent on β_0 .

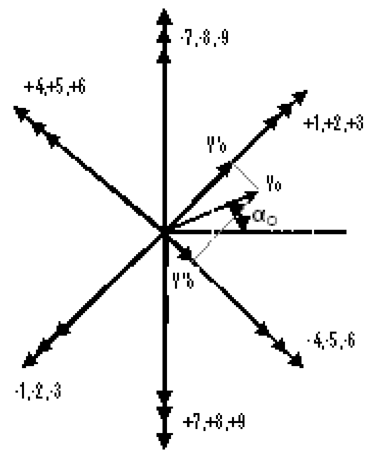


Fig. 2. Output voltage space vector corresponding to the permitted switching combinations.

Finally, the 3 configurations of group III determine zero output voltage and zero input current vectors.

Duration of non zero intervals, T_{ON}, is given by (8):

$$t_{ON} = D(kT_s)\frac{T_s}{2} \quad (8)$$

$$D(kT_s) = \frac{V_{ref}}{v_{\max}(kT_s)} \quad (9)$$

TABLE I

SWITCHING COMBINATIONS AND THEIR VOLTAGE AND CURRENT VECTOR REPRESENTATIONS

Group	#	Name	A	B	C	v_{AB}	v_{BC}	v_{CA}	i_a	i_b	i_c	V_o	α_o	I_i	β_i
I	1	-	a	b	c	v_{ab}	v_{bc}	v_{ca}	i_A	i_B	i_C	v_i	α_i	i_o	β_o
	2	-	a	c	b	$-v_{ca}$	$-v_{bc}$	$-v_{ab}$	i_A	i_C	i_B	$-v_i$	$-\alpha_i+4\pi/3$	i_o	$-\beta_o$
	3	-	b	a	c	$-v_{ab}$	$-v_{ca}$	$-v_{bc}$	i_B	i_A	i_C	v_i	$-\alpha_i$	i_o	$-\beta_o+2\pi/3$
	4	-	b	c	a	v_{bc}	v_{ca}	v_{ab}	i_C	i_A	i_B	$-v_i$	$\alpha_i+4\pi/3$	i_o	$\beta_o+2\pi/3$
	5	-	c	a	b	v_{ca}	v_{ab}	$-v_{ca}$	i_B	i_C	i_A	v_i	$\alpha_i+2\pi/3$	i_o	$\beta_o+4\pi/3$
	6	-	c	b	a	$-v_{bc}$	$-v_{ab}$	v_{bc}	i_C	i_B	i_A	$-v_i$	$-\alpha_i+2\pi/3$	i_o	$-\beta_o+4\pi/3$
II_a	7	+1	a	b	b	v_{ab}	0	$-v_{ab}$	i_A	$-i_A$	0	$2\sqrt{3}v_{ab}$	$\pi/6$	$2\sqrt{3}i_A$	$-\pi/6$
	8	-1	b	a	a	$-v_{ab}$	0	v_{ab}	$-i_A$	i_A	0	$-2\sqrt{3}v_{ab}$	$\pi/6$	$-2\sqrt{3}i_A$	$-\pi/6$
	9	+2	b	c	c	v_{bc}	0	$-v_{bc}$	0	i_A	$-i_A$	$2\sqrt{3}v_{bc}$	$\pi/6$	$2\sqrt{3}i_A$	$\pi/2$
	10	-2	c	b	b	$-v_{bc}$	0	v_{bc}	0	$-i_A$	i_A	$-2\sqrt{3}v_{bc}$	$\pi/6$	$-2\sqrt{3}i_A$	$\pi/2$
	11	+3	c	a	a	v_{ca}	0	$-v_{ca}$	$-i_A$	0	i_A	$2\sqrt{3}v_{ca}$	$\pi/6$	$2\sqrt{3}i_A$	$7\pi/6$
	12	-3	a	c	c	$-v_{ca}$	0	v_{ca}	i_A	0	$-i_A$	$-2\sqrt{3}v_{ca}$	$\pi/6$	$-2\sqrt{3}i_A$	$7\pi/6$
II_b	13	+4	b	a	b	$-v_{ab}$	v_{ab}	0	i_B	$-i_B$	0	$2\sqrt{3}v_{ab}$	$5\pi/6$	$2\sqrt{3}i_B$	$-\pi/6$
	14	-4	a	b	a	v_{ab}	$-v_{ab}$	0	$-i_B$	i_B	0	$-2\sqrt{3}v_{ab}$	$5\pi/6$	$-2\sqrt{3}i_B$	$-\pi/6$
	15	+5	c	b	c	$-v_{bc}$	v_{bc}	0	0	i_B	$-i_B$	$2\sqrt{3}v_{bc}$	$5\pi/6$	$2\sqrt{3}i_B$	$\pi/2$
	16	-5	b	c	b	v_{bc}	$-v_{bc}$	0	0	$-i_B$	i_B	$-2\sqrt{3}v_{bc}$	$5\pi/6$	$-2\sqrt{3}i_B$	$\pi/2$
	17	+6	a	c	a	$-v_{ca}$	v_{ca}	0	$-i_B$	0	i_B	$2\sqrt{3}v_{ca}$	$5\pi/6$	$2\sqrt{3}i_B$	$7\pi/6$
	18	-6	c	a	c	v_{ca}	$-v_{ca}$	0	i_B	0	$-i_B$	$-2\sqrt{3}v_{ca}$	$5\pi/6$	$-2\sqrt{3}i_B$	$7\pi/6$
II_c	19	+7	b	b	a	0	$-v_{ab}$	v_{ab}	i_C	$-i_C$	0	$2\sqrt{3}v_{ab}$	$3\pi/2$	$2\sqrt{3}i_C$	$-\pi/6$
	20	-7	a	a	b	0	v_{ab}	$-v_{ab}$	$-i_C$	i_C	0	$-2\sqrt{3}v_{ab}$	$3\pi/2$	$-2\sqrt{3}i_C$	$-\pi/6$
	21	+8	c	c	b	0	$-v_{bc}$	v_{bc}	0	i_C	$-i_C$	$2\sqrt{3}v_{bc}$	$3\pi/2$	$2\sqrt{3}i_C$	$\pi/2$
	22	-8	b	b	c	0	v_{bc}	$-v_{bc}$	0	$-i_C$	i_C	$-2\sqrt{3}v_{bc}$	$3\pi/2$	$-2\sqrt{3}i_C$	$\pi/2$
	23	+9	a	a	c	0	$-v_{ca}$	v_{ca}	$-i_C$	0	i_C	$2\sqrt{3}v_{ca}$	$3\pi/2$	$2\sqrt{3}i_C$	$7\pi/6$
	24	-9	c	c	a	0	v_{ca}	$-v_{ca}$	i_C	0	$-i_C$	$-2\sqrt{3}v_{ca}$	$3\pi/2$	$-2\sqrt{3}i_C$	$7\pi/6$
III	25	0	a	a	a	0	0	0	0	0	0	0	-	0	-
	26	0	b	b	b	0	0	0	0	0	0	0	-	0	-
	27	0	c	c	c	0	0	0	0	0	0	0	-	0	-

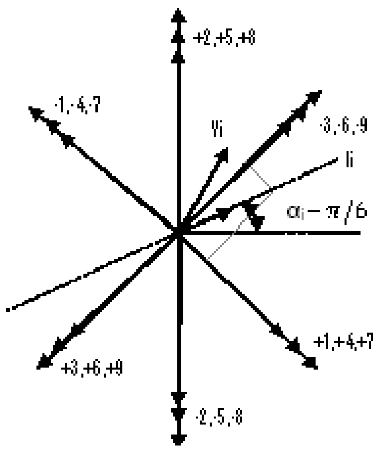


Fig. 3. Input current space vectors corresponding to the permitted seitching combinations.

Where T_s, D and V_{ref} are switching period, duty cycle and reference adjusting voltage respectively. Secondary side of HIT is coupled to parallel resonance tank circuit through matching (or filter) coil L_C.

III. CALCULATION OF SWITCHING FREQUENCY

Circuit of proposed 3 phase IHS equivalent to BST is shown is Fig. 4. R_M indicates core losses.L_M, L_{l1} and$L_{l2}$are mutual and leakage inductances of HIT. Fig. 5 shows the simplified circuit where L_F is obtained as follows:

$$L_F = L_C + L_{l1} + L_{l2} \tag{10}$$

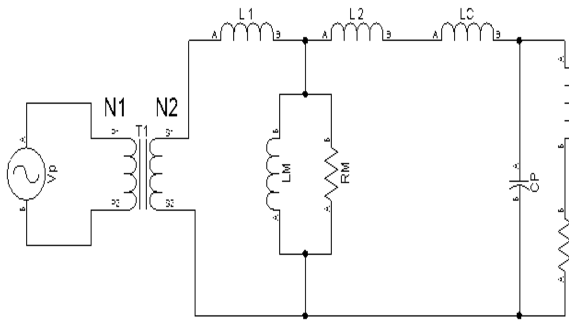


Fig. 4. Circuit of proposed IHD equivalent to BST

Secondary side of isolation transformer provides a rectangular voltage v_s. An LC circuit feeds an inductive load with typical power factor less than 0.1[9]. Parallel resonance tank equivalent impedance matching coil is given by

$$Z_T\left(j\omega\right) = j\omega L_F + \frac{1}{j\omega C_P + \frac{1}{j\omega L_P + R_o}} \tag{11}$$

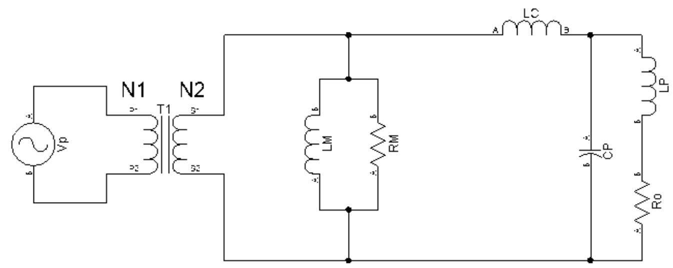


Fig. 5. Simplified circuit

To obtain proper switching angular frequency, ω_0, imaginary part of (11) should be taken equal with zero. Due to low power factor of the induction coil, it is possible to assume $R_0^2 << (\omega_0 L_P)^2$, therefore (11) can be simplified as (12):

$$Z_T(j\omega) \approx j\omega L_F + \frac{\frac{R_O}{\omega_0^2 L_P^2} - j\omega_0 \left[C_P - \frac{1}{\omega_0^2 L_P}\right]}{\omega_0^2 \left[C_P - \frac{1}{\omega_0^2 L_P}\right]^2} \tag{12}$$

Imaginary part of (12), taken equal with zero , is solved to obtain f_0 as the following equation:

$$\omega_0 = \sqrt{\frac{L_P + L_F}{C_P L_P L_F}}; \omega_0 = 2\pi f_0 \tag{13}$$

Equation (13) shows the proper switching frequency, f_0, to transfer maximum power to the load. The value of impedance Z_T at frequency f_0 is obtained as (14):

$$Z_T(j\omega) \approx R_O \left(\frac{L_F}{L_P}\right)^2 \tag{14}$$

Maximum transferred power to R_0 at switching frequency f_0, is achieved by(12).V_{S1} and N_2/N_1 are effective main component of secondary voltage and winding ratio of transformer, respectively.

$$P_O = \frac{V_S^2}{Z_T(j\omega_0)} \approx \frac{V_{S,1}^2}{R_O \left(\frac{L_F}{L_P}\right)^2} \tag{15}$$

$$P_O \approx \left(\frac{2\sqrt{2}}{\pi}.\frac{N_2}{N_1}.\frac{L_P}{L_F}\right)^2 .\frac{V_{ref}^2}{R_O}$$

It is clear from (15) that output can also be determined by winding ratio of HIT. Also the type of HIT must be selected according to operation frequency.

IV. CALCULATION OF MATCHING COIL VALUE

There are several methods to determine matching coil value. To obtain a good filtering performance of output stage and almost sinusoidal waveform of the induction coil, following relationship may be assumed.

$$L_F >> L_P \tag{16}$$

Also, startup current must be limited by L_F. The maximum possible startup primary current variation, neglecting transformer inrush current, can be approximated by (17):

$$\max\{\triangle I_{primary}\}_{startup} \approx \frac{1}{L_F}\left(\frac{N_2}{N_1}\right)^2 \frac{T_s}{2}\sqrt{2}V_m \tag{17}$$

V_m is the peak voltage of the utility. Maximum allowable switching devices current can be found from the specifications supplied by manufacturer. It must be greater than maximum primary startup current. Thus L_F can be determined by considering (16) and (17).

V. SIMULATION RESULTS

Sample circuit parameters are given by Table II. The switching frequency calculated from (13) is $9931.80 H_Z$. Consequently, from (11) we have $Z_T(j\omega_o) = 1.969\angle -10°$ which gives a power factor close to $1(0.9999)$ .Fig.V and Fig. V shows waveforms of supply voltage and primary side output voltage, respectively. Secondary side of isolation transformer, load voltage and induction coil current are shown in Fig. V and Fig. V respectively. Simulation summaries are given in Table III. Fig. V shows FFT of output volage.

TABLE II
CIRCUIT PARMETERS

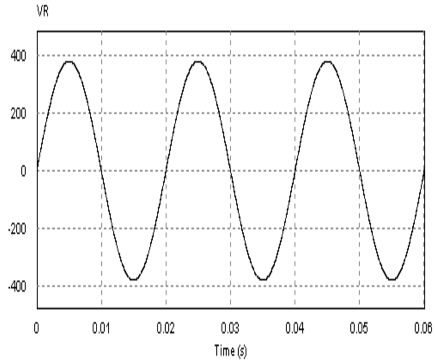
Parameter	Value	Parameter	Value
Utility	380V/50H_Z	N_1/N_2	1
V_{ref}	300V	L_F	$200\mu H$
L_P	$10\mu H$	C_P	26.96μF
R_o	50mΩ	L_M	20mH

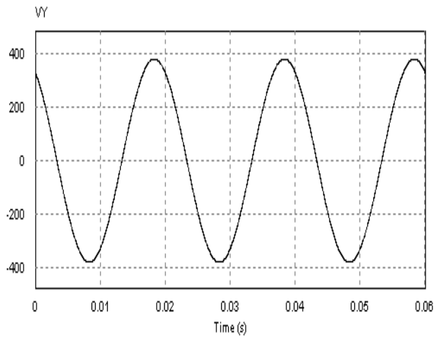
TABLE III
SIMULATIONS SUMMARIES

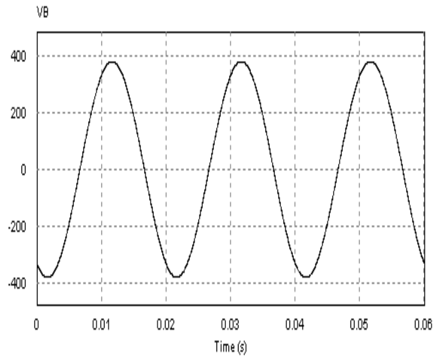
Parameter	Value	Parameter	Value
V_{ab}	84.874V	I1	92.275A
V_{bc}	84.882V	I2	92.274A
V_{ca}	84.883V	I3	92.265A
PF	0.9999	THD(V_O)	0.7%
F_s	9956H_Z	Pout	7831.61W

TABLE IV
SIMULATIONS RESULTS

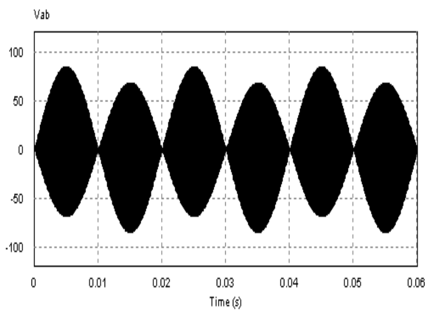
Frequency in H_z	Output Voltage in volt
0.5k	732.00
1.0k	416.24
1.5k	324.20
2.0k	159.41
5.0k	90.50
10.0k	84.874

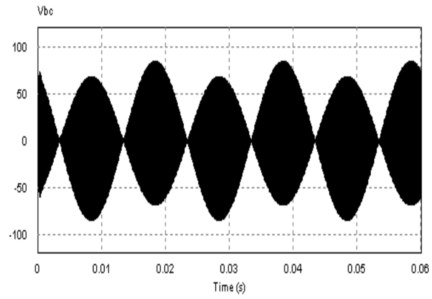


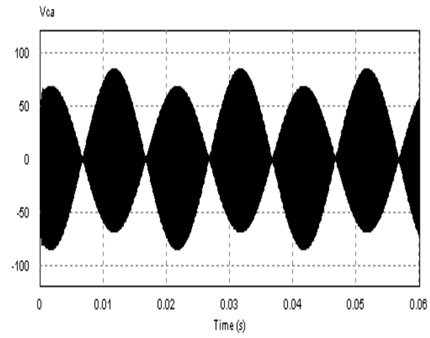




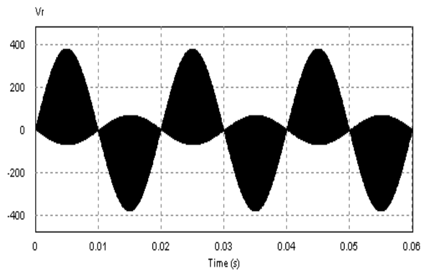
Waveform of supply voltage

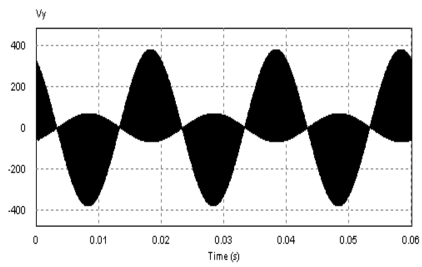


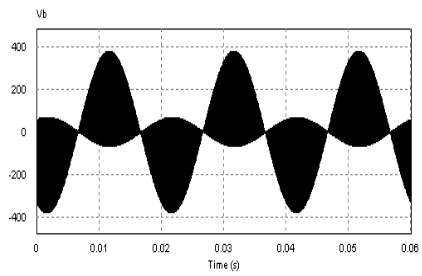




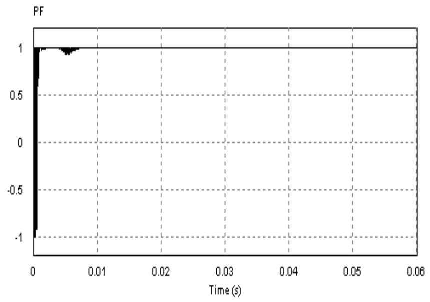
Waveform of secondary load {Induction Coil} voltage



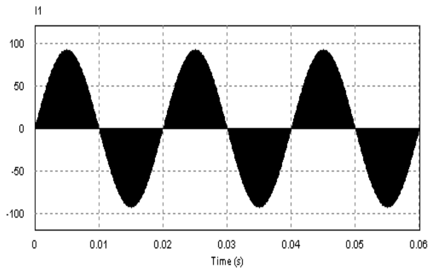


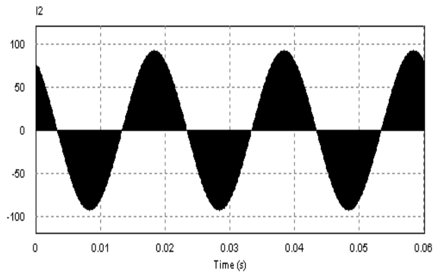


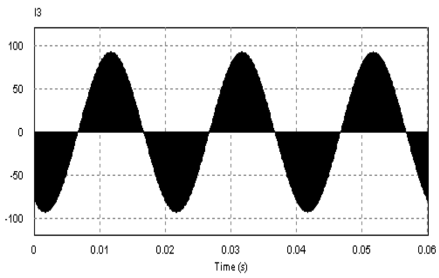
Waveform of primary output voltage



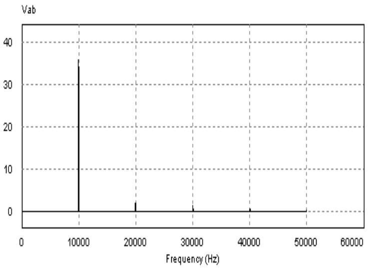
Power Factor

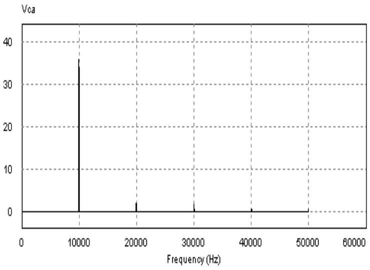


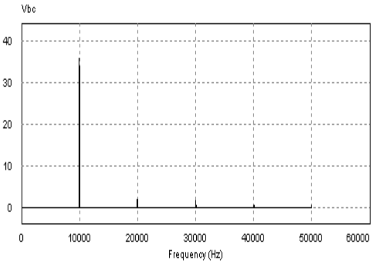




Waveform of Induction coil current







FFT of output voltage

VI. **CONCLUSION**

In this paper an induction heating system with bidirectional switching transformer structure has been described. Comparison of proposed circuit is carried out by both mathematical analyses and simulation results. It shows that value of power factor obtained is nearest to unity. Flexibility aspects of BST leads to several advantages such as unity power factor without using any storage elements, symmetric loading from utility point of view, isolation of working coil, compact dimensions and almost uniform sinusoidal output . Additionally, this topology can provide voltage regulation ability at full load variation, even at asymmetrical utility conditions. Furthermore, proposed topology provides maximum output power and low output THD utilization.

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