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SINUSOIDAL PWM BASED T-SOURCE INVERTER FOR INDUCTION HEATING

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ABSTRACT

T-Source Inverter (TSI) is proposed for Induction Heating (IH) applications to obtain higher efficiency with reduced Total Harmonic Distortion (THD). Sinusoidal Pulse Width Modulation (SPWM) technique is used to control the switches of T-source inverter. Utilization of shoot through switching operation provides voltage boost ability to the inverter. Operation of induction heating load is based on the principle of electromagnetic induction. Skin effect and eddy current is used to produce heat in working pot. The operating performance of T-Source Inverter was shown through experiment results.

Keywords: T-source inverter (TSI), total harmonic distortion (THD), sinusoidal pulse width modulation (SPWM), shoot through switching.

1. INTRODUCTION

Nowadays, domestic induction heating (IH) systems have been evolved into a standard cooking appliance. Some significant advantages include the fast heating times, the cleanness and the high efficiency achieved. Using this technology, the cooking object is directly heated by means of a high frequency magnetic field. IH systems normally consist of inverter, induction heating coil and heating object. Alternating current flows through the surface of a conductor and IH systems produce heat based on eddy current and skin effect resistance of the coil and metal pots. A high frequency current, in the range of tens of kilohertz, is used to supply the inductor-pot system. Inverter stage is used to generate the high frequency current required for the IH application [1, 7, 8]. Figure-1 shows an example of high-frequency skin effect of a conductor.

The High-frequency current moves around the surface of the conductor, as shown in Figure-1, it is necessary to use litz wire planar-type induction coil for utilizing whole area of the conductor [4]. IH load functions like a transformer in which metallic pot is considered as a single turn. The induction coil and the metallic pot function as the primary and the secondary of a transformer, respectively. Induction heating load simply consist of IH coil and a heating object. Induction heating system works directly with conductive materials, like metals. Non-conductive materials can be frequently heated indirectly by first heating a conductive metal subsector which transfers heat to the non-conductive material. A well designed inductor provides the proper heating pattern for pot and maximizes the efficiency of the induction heating power supply. High-frequency IH appliances are to save energy while serving the same temperature and to take less heat loss [9] & [10]. In IH applications, higher switching frequency provides reduced components size, and higher flux density around the surface of the heating objects. Subsequently, high frequency reduces the size of the converter at the same power rating.

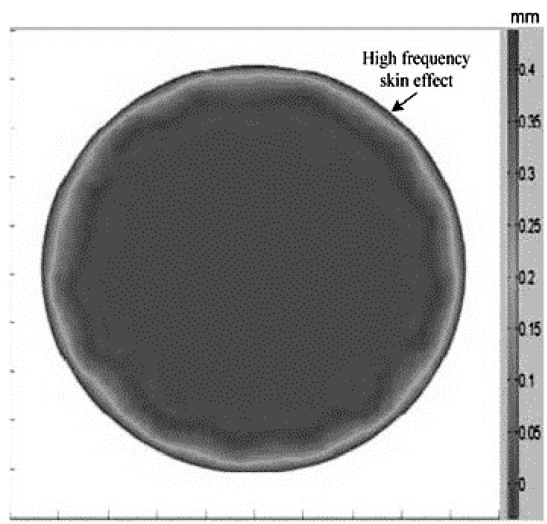

Figure-1. High frequency skin effect of a conductor.

The block diagram of proposed high efficiency TSI was shown in Figure-2. Single phase AC supply is applied to the Single phase bridge rectifier and it is convert AC supply into DC supply. LC Filter was used to remove the ripples present in the input supply. T-Source inverter converts DC supply into AC supply. Output voltage of TSI is greater than the input voltage because of shoot through concept. Microcontroller is used to generate PWM signals for T-Source inverter switches. TSI boosted output voltage is applied to the induction heating load. The proposed High Efficiency T-Source inverter is shown in Figure-3. T shaped impedance network will be connected in front of single phase inverter circuit, So it is called T-source inverter. In this impedance network consist of coupled inductors L1, L2 and capacitor C1. Impedance network is mainly used to perform shoot through operation for boosting the voltage. Output voltage of TSI is given to the induction heating coil. Measured output voltage and

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current are given to the Microcontroller. Based on the feedback signal sinusoidal PWM Gate pulses is generated and given to the inverter switches through the gate driver unit.

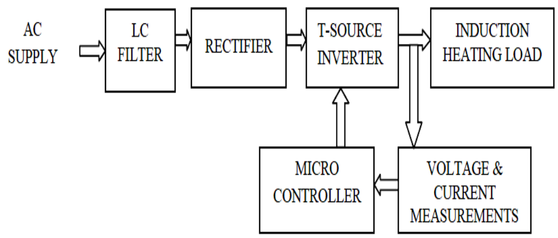

Figure-2. Block diagram of induction heating system.

2. WORKING PRINCIPLE OF INDUCTION HEATING

A source of high frequency electricity is used to drive a large alternating current through a coil. This coil is known as the work coil. The passage of current through this coil generates a very intense and rapidly changing magnetic field in the space within the work coil. The work piece to be heated remains placed within this intense alternating magnetic field. The alternating magnetic field induces a current flow in the conductive work piece. The arrangement of the work coil and the work piece can be thought of as an electrical transformer. The work coil is like the primary where electrical energy is fed in, and the work piece is like a single turn secondary that is short-circuited.

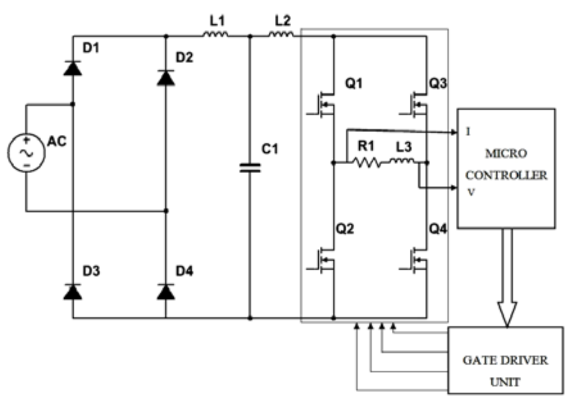

Figure-3. Proposed T-source inverter.

This causes tremendous eddy current to flow through the work piece. In addition to this, the high frequency used in induction heating applications gives increase to a phenomenon called skin effect. This skin effect forces the alternating current to flow in a thin layer towards the surface of the work piece. The skin effect increases the effective resistance of the metal to the passage of the large current. Therefore it greatly increases the heating effect caused by the current induced in the work piece [1, 4].

a) Proposed T-Source inverter topology

The T-source inverter overcomes the limitation of traditional voltage source inverter and current source inverter [2, 3, 5]. Inversion and boost function are accomplished in a single stage by TSI. It has smaller amount of components. Due to these reasons, the efficiency substantially increases. Contrasting the traditional inverter, TSI utilizes an exclusive impedance network that relatives the inverter main circuit to the DC source. The passive element of inductor and capacitor is reduced in T-source inverter. The two inductors are building together and it forms a couple inductors and it has low leakage inductance. The impedance network output is functional to the inverter circuit and the inverter circuit consists of four switches.

Boosting capability is achieved by using shoot through mode of switches operation. This operation performed by turning on the both switches simultaneously. During the shoot through mode the energy is transferred from capacitor to inductor. At the time, the voltage boosting capability achieved [11, 12, 14]. The DC voltage is fed as input to the impedance network of TSI which helps to achieve voltage buck and boost properties. The T-network is used instead of the LC-network for boosting the output voltage by inserting shoot through states in the PWM. TSI operate in two modes: a) Shoot through mode b) Non shoot through mode.

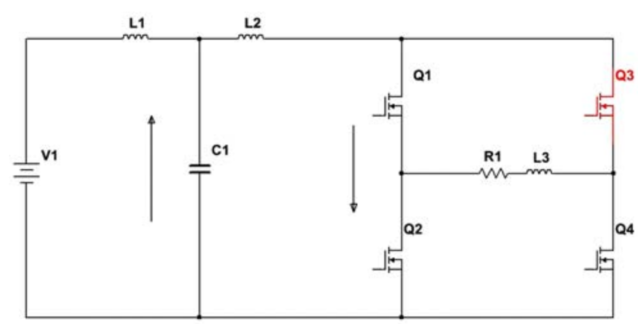

Figure-4. Shoot-through mode.

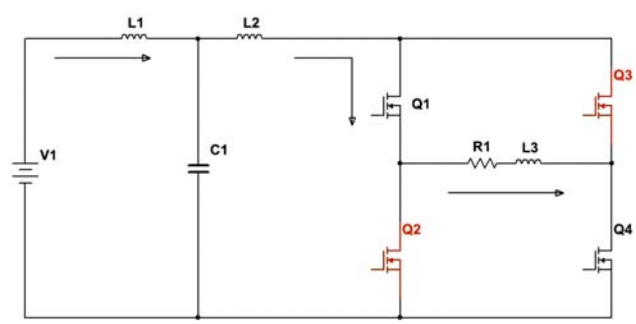

Figure-5. Non Shoot-through mode.

The equivalent circuit of T-Source Inverter in Shoot through mode of operation was shown in Figure-4. This shoot through zero state prohibited in traditional voltage source inverter. It can be obtained in three

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different ways such as shoot through via any one phase leg or combination of two phase leg. During this state capacitor C1 get charged. The equivalent circuit of TSI in non shoot-through mode of operation is shown in Figure-5. In this mode, the inverter bridge operates in one of traditional active states, thus acting as a current source when viewed from T-source circuit. During this state, voltage is impressed across the load. The diodes conduct and carry current difference between the inductor current and input DC current. Note that both the inductors have an identical current because of coupled inductors. During the design of TSI the most challenging is the estimation of values of the reactive components used in impedance network. The component values should be evaluated for the minimum input voltage of the converter, where the boost factor and the current stresses of the components become maximal.

b) Design of the T-Source inverter

The TSI governing equations can be developed for the Figure-5 using Kirchhoff's laws and voltage averaging. The average voltage through the inductances should be equal to zero for the switching time period T.

$$V_L = \overline{V}_L = \frac{\left[T_0 V_C + T_1 \frac{(V_{IN} - V_C)}{n}\right]}{T} = 0 \quad (1)$$

Both capacitor voltage V_C and output voltage V_{out} are functions of the shoot-through coefficient $D=T_0/T$.

$$\frac{V_C}{V_{IN}} = \frac{T_1}{(T_1 - n \cdot T_0)} = \frac{(1 - D)}{[1 - (n+1) \cdot D]} \quad (2)$$

where D satisfies a condition D < (1/ (n+1)), hence the maximum value of *D* for TSI *n>1* is smaller than for the conventional Z-source inverter (ZSI). This is the advantage of the TSI with *n>1* in comparison with ZSI because the same output voltage can be obtained with achieved smaller time period of short-circuits current. Using equation (2) the amplitude of voltage v_{dc} in non-shoot through states can obtain from:

$$V_{DC} = V_C + \frac{(V_C - V_{IN})}{n} = \frac{V_{IN}}{[1 - (n+1) \cdot D]} \quad (3)$$

In practice, the influence of leakage on inductance of the transformer is very important. The performance of TSI depends on the precision of the transformer design. Calculation of the average current of an inductor can be found as,

$$I_L = \frac{P}{V_{DC}} \quad (4)$$

The maximum current through the inductor occurs when the maximum shoot-through happens, which causes maximum ripple current. In our design, 60% peak-to-peak current ripple through the T-source inductor during maximum power operation was chosen. The boost factor of the input voltage is:

$$B = \frac{1}{1 - 2D_z} \quad (5)$$

where, D_Z is the shoot-through duty cycle as given below.

$$D_z = \frac{B - 1}{2B} \quad (6)$$

The calculation of required inductance of T-source inductors:

$$L = \frac{T_o V_c}{\Delta I_L} \quad (7)$$

where, T_0- is the shoot-through period per switching cycle.

3. SINUSOIDAL PULSE WIDTH MODULATION

The Sinusoidal Pulse Width Modulation (SPWM) is widely used in power electronics to digitize the power so that a sequence of voltage pulses can be generated by the on and off of the power switches [5, 16]. SPWM circuit is simple and rugged control scheme. That is why pulse width modulation inverter has been the main choice in power electronic. SPWM technique is characterized by constant amplitude pulses with different duty cycle for each period. The width of this pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content.

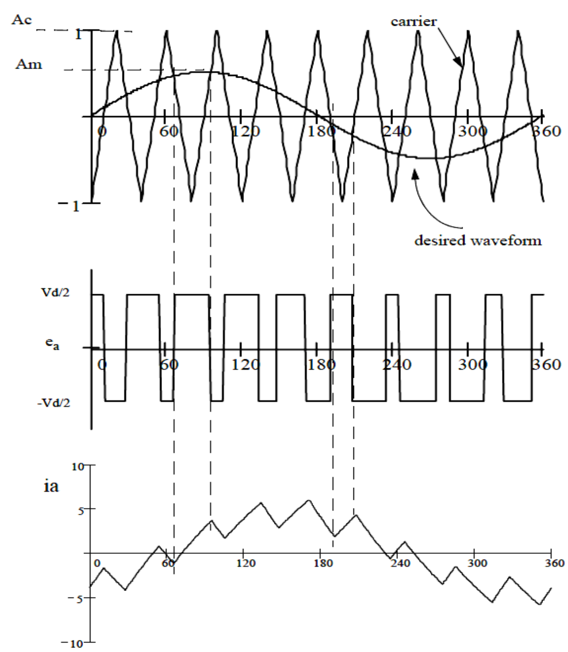

Figure-6. PWM input and output signals.

The Sinusoidal pulse width modulation is mostly used in inverter application. In this development a unipolar and bipolar SPWM voltage modulation type is selected because this method offers the advantage of effectively doubling the switching frequency of the inverter voltage, thus making the output filter smaller, cheaper and easier to implement. Normally, to generate this signal, triangle wave as a carrier signal is compared with the sinusoidal

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wave, whose frequency is the desired frequency. The switches in the voltage source inverter can be turned on and off as required. In the simplest approach, the top switch is turned on if turned on and off only once in each cycle, a square waveform results as shown in fig.6. However, if turned on several times in a cycle an improved harmonic profile may be achieved. In the most straightforward implementation, generation of the desired output voltage is achieved by comparing the desired reference waveform (modulating signal) with a high-frequency triangular carrier wave as depicted schematically. Depending on whether the signal voltage is larger or smaller than the carrier waveform, either the positive or negative DC bus voltage is applied at the output. Note that over the period of one triangle wave, the average voltage applied to the load is proportional to the amplitude of the signal (assumed constant) during this period.

The resultant chopped square waveform contains a model of the desired waveform in its low frequency components, with the higher frequency components being at frequencies of a close to the carrier frequency [6]. Notice that the root mean square value of the AC voltage waveform is still equal to the DC bus voltage, and hence the total harmonic distortion is not affected by the PWM process. The harmonic components are purely shifted into the higher frequency range and are automatically filtered due to inductances in the AC system. When the modulating signal is a sinusoid of amplitude Am, and the amplitude of the triangular carrier is Ac, the ratio m=Am/Ac is known as the modulation index. Note that controlling the modulation index therefore controls the amplitude of the applied output voltage.

4. ADVANCED FUZZY LOGIC CONTROLLER TECHNIQUE

The Fuzzy logic control is a heuristic approach that easily embeds the knowledge and key elements of human thinking in the design of nonlinear controllers. Structure of fuzzy controller is shown in Figure-7. Qualitative and heuristic considerations, which cannot be handled by conventional control theory, can be used for control purposes in a systematic form by applying fuzzy control concepts [13, 15, 17]. Fuzzy logic control does not need an accurate mathematical model, can work with imprecise inputs, can handle nonlinearity, and can present disturbance insensitivity greater than most nonlinear controllers. Fuzzy control is based on fuzzy logic theory, but there is no systematic design procedure in fuzzy control. The important advantage of fuzzy control design is that a mathematical model of the system is not required. Fuzzy controllers are rule-based controllers. The rules are given in the “if–then” format. The “if-side” is called condition and the “then-side” is called conclusion.

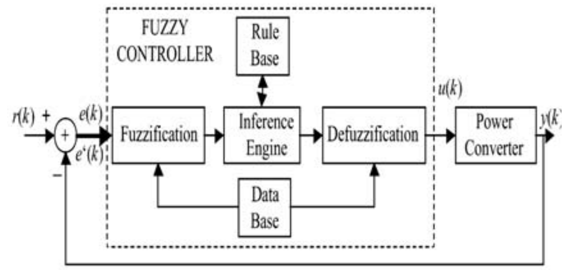

Figure-7. Structure of Fuzzy controllers.

The rules may use some variables both in condition and conclusion of the rules. Therefore, the fuzzy controllers can be applied to nonlinear multi input–multi output (MIMO) systems such as power electronic systems. Fuzzy logic controllers usually better other controllers in complex, nonlinear, or undefined systems for which a good practical knowledge exists. Fuzzy logic controllers are based on fuzzy sets, i.e., classes of objects in which the transition from membership to non-membership is smooth rather than abrupt.

Therefore, boundaries of fuzzy sets can be vague and ambiguous, making them useful for approximation systems. The first step in the fuzzy controller synthesis procedure is to define the input and output variables of the fuzzy controller. This is done accordingly with the expected function of the controller. There are not any general rules to select those variables, although typically the variables chosen are the states of the controlled system, their errors, error variation, and=or error accumulation. In power converters, the fuzzy controller input variables are commonly the output voltage or current error, and=or the variation or accumulation of this error. The output variables u (k) of the fuzzy controller can define the converter duty cycle, or a reference current to be applied in an inner current mode PI or sliding-mode controller.

5. SIMULATION RESULT

Simulation studies are carried out in MATLAB/Simulink to validate the proposed sinusoidal PWM based T-source inverter for induction heating.

Table-1. Simulation parameter.

S. No.	Parameter	Value
1	Input AC Voltage (Vin)	230 V
2	Output AC Voltage (Vout)	290 V
3	Topology Inductance (L)	0.0045 mH
4	Topology Capacitance (C)	0.001 nF
5	Modulation Index (M)	1
6	Switching Frequency (f_s)	25 kHz
7	Load Resistance (R_0)	100 kΩ
8	Load Inductance (L_0)	0.045mH

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The parameters of the proposed system are given in Table-1. The branch voltage of T-Source inverter is shown in Figure-8. The Figure-9 shows the output voltage and current of the proposed T-Source inverter. It represents the improved voltage level of TSI. The harmonic spectra of proposed T-source inverter was shown in Figure-10. It represents the reduced third order harmonic of IH system. The comparisons of conventional and proposed induction heating systems are shown in Table-2.

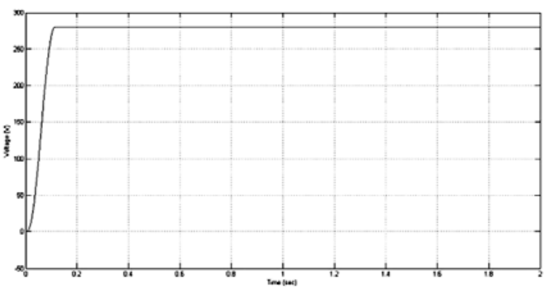

Figure-8. Branch voltage of T-source network.

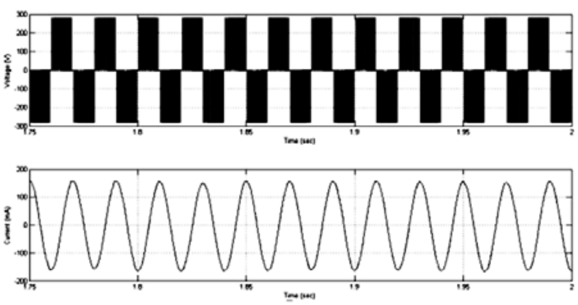

Figure-9. Output voltage and current of T-source inverter.

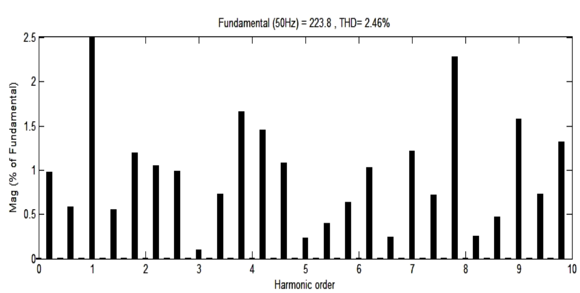

Figure-10. Harmonic spectra of T-Source inverter.

Table-2. THD Comparison of Induction Heating systems.

S. No.	System	THD	Efficiency
1	Existing series resonant inverter based Induction Heating system	3.35%	84.21%
2	Proposed T-Source inverter based induction heating system	2.46%	92.43%

6. CONCLUSIONS

This paper approaches the voltage boost T-source inverter with reduced THD and higher efficiency. It mainly focuses on the implementation of sinusoidal PWM based T-Source inverter for induction heating system. The theoretical values have been calculated and the simulation results were gained through Matlab simulations. The simulation results were almost similar to the calculated value of the output voltages. The output voltage can be increased depends on the requirement of the induction heating load. Though the system uses the Fuzzy logic controller based switching technique, it is easy to deal with the accurate temperature requirements like Steel factories, Food processing, Bio-medical applications and etc. From the results and progress throughout the proposed method, the T-Source inverter has overcome the barrier of traditional inverters and it achieves higher efficiency (92.43%) compared to the conventional induction heating system. Since the proposed topology needs some improvement as it makes higher voltage stresses. By implementing advanced soft switching techniques, the voltage stresses can be reduced fairly.

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