Design and Control of Two-Inverter Dual Frequency Induction Hardening

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***Abstract*—Dual frequency inverters are used for induction gear hardening. Two inverter topology for dual frequency operation is considered. Design and control aspects related to dual frequency inverters are presented in this paper. Zero voltage switching aspects related to this configuration are explained. Performance of this inverter is presented along with simulation and experimental waveforms.**

Keywords— Induction hardening; Resonant inverter; ZVS.

I. INTRODUCTION

Induction heating technique plays a major role in industrial heating applications. It is a non-contact heating process and the heat is generated in the material itself. There is no open flame and hence this process is safe and there are no heat losses due to conduction. This process is clean and environment friendly since no ash and smoke are produced. Easier control, maintenance and good efficiency are the additional advantages. Induction heating technique is rapidly replacing the conventional heating techniques used in domestic cooking and industrial heat processes like welding, annealing, melting, surface hardening etc.

When high frequency currents are passed through a coil wound over an electrically conductive work piece, heat is generated in the work piece due to eddy currents induced in it. Currents are induced on the surface of work piece with penetration depth δ, which depends on frequency of the induced currents. Penetration depth is expressed as $\delta=\sqrt{\rho/\pi\mu f}$. μ and ρ are the magnetic permeability and electrical resistivity of the work piece respectively. Heat is transferred to rest of the work piece by conduction from the surface. Resonant converters are used to supply the high frequency currents to the load coil.

Induction surface hardening is one of the applications of induction heating. Hardening is a heat treatment process in which the surface of the material is heated to its normalizing temperature and then cooled rapidly with a suitable fluid. It results in a hard and wear resistant surface while the inner core remains relatively soft. Mechanical parts such as gears, sprockets, springs, shafts, etc. are subjected to surface hardening to increase the wear resistance without affecting the interior of the part. Carburizing, nitriding, flame hardening and hard chromium plating are some of the traditional methods used for surface hardening. Today induction surface hardening is widely used over these traditional techniques due to its advantages like shorter heating time, minimum surface decarburizing and oxidation etc.

Effective and uniform surface hardening is possible when the surface profile of the work piece is uniform. Thus metal slabs and cylindrical objects like shafts and rods can be uniformly surface hardened using this technique with single frequency current [1]-[2]. But it does not provide uniform surface hardening in complex surfaced work pieces like gears and sprockets. Here, a low frequency (LF) current results in good fatigue strength at the root of the work piece and abrasion resistance at the tip [3]-[4]. But the tooth is through hardened and it affects the ductility of the core. If high frequency (HF) alone is used, the tooth face is hardened but the root cannot be hardened without through hardening of the tooth. This problem can be solved with simultaneous dual frequency heating where the low and high frequency currents are simultaneously applied to the coil. Actual frequencies to be used mainly depend on the desired depth of hardening. Typical low and high frequencies used for this application are 10-30 kHz and 100-400 kHz respectively. Certain methods are suggested in the literature to produce dual frequency currents.

Valery Rudnev has explained in [5] about the conventional techniques used in industries for induction hardening of gear loads. In conventional single frequency pulse method, single frequency pulse is applied at a desired power level and then the gear is subjected to quenching and tempering. This technique can be used for gears with small and medium teeth. Most of the times the tips of teeth are through hardened and it is difficult to heat the gear root. In single frequency pulsing method the sequence of processes involved is preheating, application of high power density pulse, quenching and tempering. Dual frequency pulsing method has been introduced later. In this method, the gear is heated with two different frequency pulses one after the other. But this process needs two different power supplies and a fast mechanism to change the position of gear [4]. In order to overcome these difficulties simultaneous dual frequency power supplies are preferred.

Okudaira et al in [6]-[10] introduced a quasi-resonant inverter with adjustable output frequency. The load is modeled as equivalent inductance and equivalent resistance in series with matching transformer. This inverter consists of two resonant capacitors and a one way short circuiting switch across the second resonant capacitor. By manipulating the on-time of the switch the fundamental frequency of the output is

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controlled. Thus this circuit can produce dual frequency i.e. low and high frequency output currents. But these currents are not available simultaneously to the load. The operating frequency range is not wide. An indirect output power control method has also been proposed. The same circuit has been realized in [11] with Power MOSFETs instead of IGBTs in order to increase the operating frequency to 100 kHz or more.

Okudaira et al have proposed in [10]-[12] and [13] another type of inverter circuit which has one resonant capacitor and a two way short circuit switch across the capacitor. The output frequency is controlled by manipulating the switching interval of two way switch. In this circuit the range of output frequency becomes very wide. But the output current is not a sine wave. Simultaneous application of dual frequency currents is still not possible. An indirect output power control method has also been proposed.

Okudaira et al have proposed in [14], an inverter circuit which is slightly modified from the circuit proposed in [10]. The load is fed through a polarity providing circuit. The operating frequency range is 10 to 20 kHz. This circuit is designed to provide control over fundamental and third order harmonic current by manipulating the shorting time of second resonant capacitor thus making simultaneous application of dual frequency currents possible. The fundamental frequency is also adjustable. But the possible ratio of high to low frequency is fixed at three only. MOSFETs are used as switching devices. Number of switching devices used is more.

Esteve et al have introduced inverter topologies with dual frequency outputs in [15] and [16]. Dual frequency currents are obtained by means of medium frequency PWM modulation of the high frequency signal. Dual output frequencies are obtained with single inverter. Medium frequency output power regulation is obtained by changing the amplitude of medium frequency control signal. High frequency output power is controlled by adjusting the frequency of the high frequency signal. The output resonant circuit described in this paper is modified and used in this thesis.

Bill Diong et al have proposed multilevel inverter configuration for dual frequency induction heating power supply in [17] and [18]. Cascaded H-bridge multilevel inverter circuit is used. Dual frequencies of first through seventh harmonics and their independent control are possible. Two-cell H-bridge inverter with both equal and unequal sources have been analyzed for this application. But the control is more involved and digital control technique is required.

This paper presents design and control aspects related to dual frequency inverter for induction hardening. A two inverter configuration is considered for this application. Requirements of this application are mentioned. Design and ZVS aspects of this configuration are explained. Simulation and experimental results are presented.

II. REQUIREMENTS FOR INDUCTION GEAR HARDENING

Effective and uniform surface hardening is possible when the surface profile of the work piece is uniform. It is possible to control the depth of the heated layer and its hardness by choosing suitable values of frequency, heating time and power density. Thus metal slabs and cylindrical objects like shafts and rods can be uniformly surface hardened using this technique with single frequency current [1]. But it does not provide uniform surface hardening in complex surfaced work pieces like gears and sprockets. A gear and induction heating coil arrangement is shown in Fig. 1(a). The distribution of induced currents in the gear when a low frequency current alone is supplied to the coil is shown in Fig. 1(b). Here, a low frequency (LF) current alone results in good fatigue strength at the root of the work piece and abrasion resistance at the tip [3]-[4]. But the tooth is through hardened and it affects the ductility of the core. If high frequency (HF) alone is used it results in a current distribution as shown in Fig.1(c) in the gear. Now the tooth face of the gear is hardened but the root cannot be hardened without through hardening of the tooth. This problem can be solved with simultaneous dual frequency heating where the low and high frequency currents are simultaneously applied to the induction coil. Actual frequencies to be used mainly depend on the desired depth of hardening. Typical low and high frequencies used for this application are 10-30 kHz and 100-400 kHz respectively. Typical proportions of low frequency and high frequency power requirement is 70% and 30% respectively.

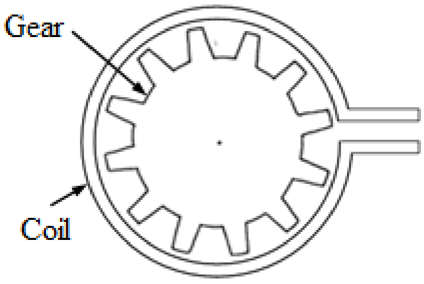


Fig. 1(a). Gear and coil arrangement

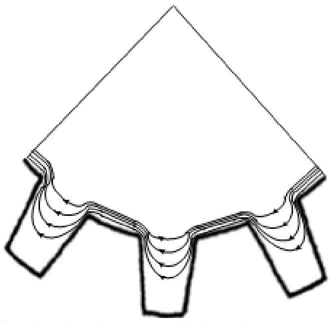


Fig. 1 (b). Current distribution in gear with low frequency supply

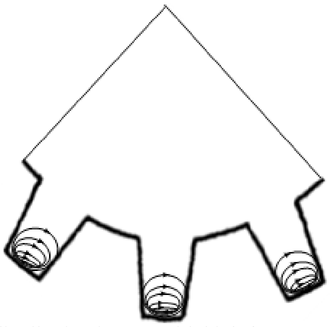


Fig. 1 (c). Current distribution in gear with high frequency supply
Fig. 1. Induction surface hardening of gear

III. INVERTER FOR INDUCTION HARDENING AND CONTROL TECHNIQUES

Induction heating load has inherently poor p. f. (typically, 0.1 to 0.3 lagging). For this reason, load is resonated to compensate for the reactive power demanded by the load. Resonant inverters are used for supplying the required power at required frequency to the induction heating system. The devices used may be MOSFETs or IGBTs based on the power rating. Resonant inverters are helpful in increasing efficiency and reducing EMI problems. High efficiency is obtained with zero voltage switching (ZVS) operation of the inverter. Commonly used inverter for this application is series resonant inverter shown in fig.2. It is due to its simplicity and better performance characteristics over others. Symbols used in this figure have their usual meaning.

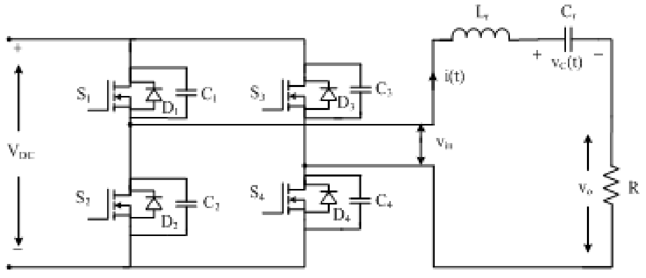


Fig. 2. Series resonant inverter

From the aspect of control, variable frequency or constant frequency control may be used. Use of variable frequency control is limited due to the disadvantages associated with it. In constant frequency control, duty cycle is varied to control the output power. This method is also known as phase shift or phase modulation technique [19],[20]. In certain applications, variable frequency with duty cycle control is also used. In the recent past, other methods of power control such as, asymmetric duty cycle control [21] and asymmetric voltage cancellation control [22] have also become popular. These two techniques help in overcoming the limitations of phase modulation technique in the aspect of ZVS operating range.

IV. TWO INVERTER CONFIGURATION

A two inverter configuration for dual frequency induction hardening application is shown in fig.3. It consists of two series resonant inverters whose outputs are added together ($v_0 = v_{01}+v_{02}$). The combined output is applied to a load resonant circuit which is again a combination of two series resonant circuits. L_1, C_1, R_1 form high frequency resonant circuit and (L_1+L_2), C_2, R_2 form low frequency resonant circuit. L_1 is the actual load coil through which dual frequency current is supposed to flow. L_2 is the additional inductance and not part of the load coil. C_1 and C_2 are resonant capacitors. R1 and R_2 correspond to equivalent resistances referred to the load coil for high and low frequency current paths of the gear. High frequency current flows through L_1, C_1, R_1 and low frequency current flows through (L_1+L_2), C_2, R_2 respectively. High and low frequencies of the inverter are 350 kHz and 30 kHz respectively. Current and power control in the load coil is done using duty cycle control of the two inverters. Simulation and experimental waveforms of output voltage and load currents along with their FFTs are shown in fig.4 and 5 for $D_l=1$, $D_h=1$ and $D_l=1$, $D_h= 0.4$ respectively.

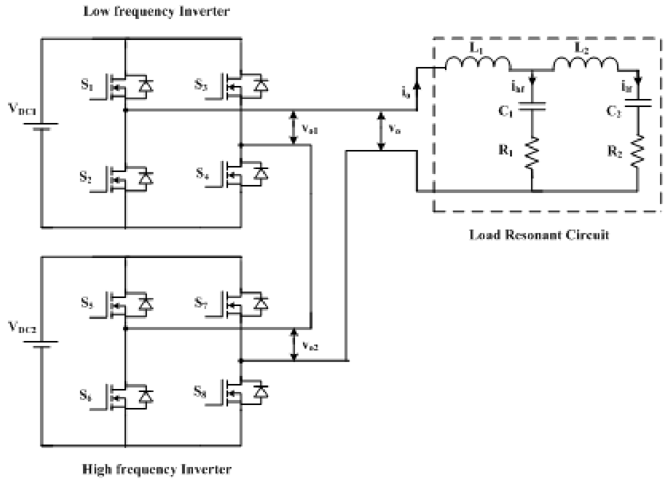
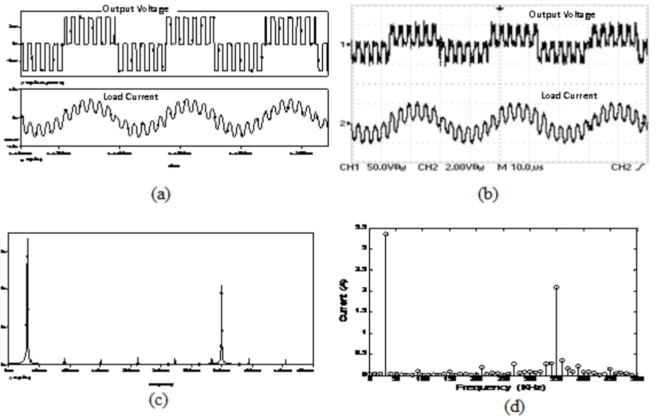


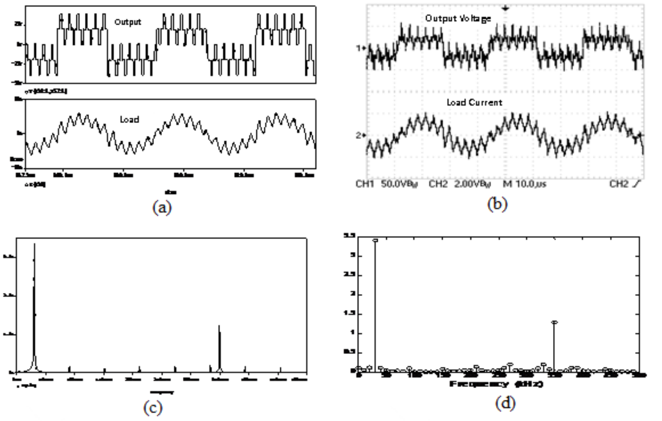
Fig. 3. Two Inverter configurations for dual frequency induction hardening



(a) (b)

(c) (d)

Fig. 4. Simulation and experimental results of v_0, i_0 and FFTs of output current (a) Simulation waveforms of v_0 and i_0 (b) Experimental waveforms of v_0 and i_0 (c) FFT of simulated waveform of i_0 (d) FFT of experimental waveform of i_0



(a) (b)

(c) (d)

Fig. 5. Simulation and experimental results of v_0, i_0 and FFTs of output current (a) Simulation waveforms of v_0 and i_0 (b) Experimental waveforms of v_0 and i_0 (c) FFT of simulated waveform of i_0 (d) FFT of experimental waveform of i_0

V. DESIGN ASPECTS OF DUAL FREQUENCY INVERTER

The admittance characteristic of this load resonant circuit is shown in Fig. 6(a) for different quality factors. The quality factors and resonant frequencies of the high and low frequency resonant circuits are expressed as

$$Q_h = \frac{1}{R_1}\sqrt{\frac{L_1}{C_1}} \tag{1}$$

$$Q_l = \frac{1}{R_2}\sqrt{\frac{(L_1+L_2)}{C_2}} \tag{2}$$

$$f_{rh} = \frac{1}{2\pi\sqrt{L_1C_1}} \tag{3}$$

$$f_{rl} = \frac{1}{2\pi\sqrt{(L_1+L_2)C_2}} \tag{4}$$

If Q_l and Q_h are high, low and high frequency components of load current will have negligible harmonics and will be very close to sine wave. The admittance characteristic shown in Fig. 6(a) justifies this. In this figure, quality factors of both resonant circuits are assumed to be equal. But in practice, these values need not be same. Magnitude and phase characteristics of practical load admittance are shown in Fig. 6(b).

In addition to two series resonances, a parallel resonance also exists at a frequency f_{rp}, given by

$$f_{rp} = \frac{1}{2\pi\sqrt{\left(\frac{C_1C_2}{C_1+C_2}\right)L_2}} \tag{5}$$

At f_{rp}, the circuit offers low admittance. This parallel resonance does not influence the performance of the load resonant circuit. Parameters of the proposed load resonant circuit of Fig. 3 are shown in Table-1.

In practice, for the design of complete load resonant circuit, low and high switching frequencies are to be selected based on depth of hardening required. Low and high resonant frequencies may be selected up to 10% below their switching frequencies. This helps in achieving zero voltage switching (ZVS) of the devices in the inverters. L_1 and L_2 are calculated for selected values of C_1, C_2, and the two resonant frequencies. L_1 is formed by winding the coil around the gear with suitable wire size. As mentioned earlier, L_2 is additional inductance used. It is not part of the load coil L_1. For calculation of the power, R_1 and R_2 need to be measured in the actual gear.

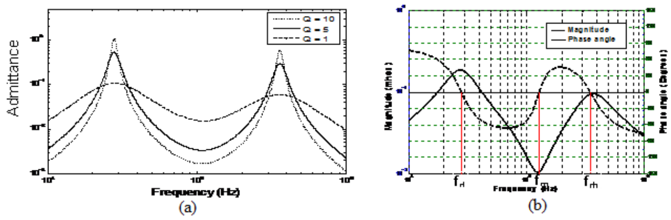


Fig. 6. Admittance characteristics (a) for different Q (b) for practical load

TABLE I. PARAMETERS OF THE PROPOSED DUAL FREQUENCY INVERTER

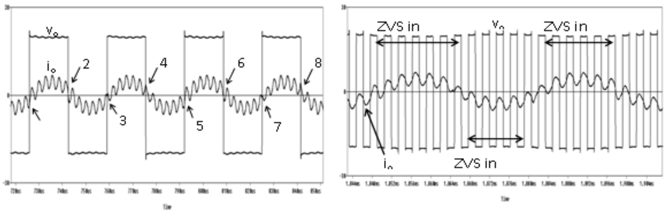
Item	Symbol	Value
Equivalent inductance of the load coil	L_1	6.09 μH
High frequency resonant capacitor	C_1	0.036 μF
High frequency equivalent resistance	R_1	8.2 Ω
Low frequency resonant inductor	L_2	47.63 μH
Low frequency resonant capacitor	C_2	0.604 μF
Low frequency equivalent resistance	R_2	5.39 Ω
Low switching frequency	f_l	30 kHz
High switching frequency	f_h	350 kHz
Q-factor of low frequency resonant circuit	Q_l	1.586
Q-factor of high frequency resonant circuit	Q_h	1.749

VI. ZVS ASPECTS FOR THE DUAL FREQUENCY INVERTER

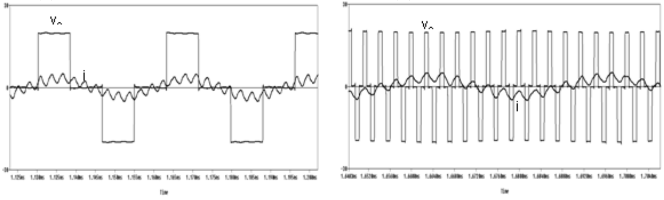
ZVS operation of the proposed configuration is explained using simulation waveforms shown in Figs. 7(a) to 7(d). Figs. 7(a) and (c) show the output voltage of LF inverter v_{01} and output current i_0 for $D_l = D_h = 1$ and $D_l = D_h = 0.5$ respectively. Figs. 7(b) and (d) show the output voltage of HF inverter v_{02} and output current i_0 for $D_l = D_h = 1$ and $D_l = D_h = 0.5$ respectively. In Fig. 7(a), instants 1, 3, 5, and 7 correspond to switching of lagging leg (right-leg) devices and instants 2, 4, 6 and 8 correspond to switching of leading-leg (left-leg) devices of LF inverter. At instants 1 and 5 there is possibility of ZVS for lagging leg devices but ZVS is not possible at instants 3 and 7. Similarly for leading leg, at instants 4 and 8, ZVS is possible and at instants 2 and 6, ZVS is not possible. Hence ZVS is ensured only at certain instants but not always for LF inverter.

In Fig. 7(b), it can be observed that for certain cycles, ZVS for leading leg devices only is possible. During this zone, ZVS for lagging leg devices is not possible and vice-versa. Hence ZVS is not ensured in every cycle for both leading and lagging leg devices of HF inverter. This is due to the reason that i_0 is a combination of low and high frequency currents which are flowing through the devices of both the inverters.

Similarly, these effects can be observed in Figs. 7(c) for v_{01} and i_0 and 7(d) for v_{02} and i_0 for LF and HF inverters respectively for $D_l = D_h = 0.5$.



(a) v_{01} and i_0 for $D_l = D_h = 1$ (b) v_{02} and i_0 for $D_l = D_h = 1$



(c) v_{01} and i_0 for $D_l = D_h = 0.5$ (d) v_{02} and i_0 for $D_l = D_h = 0.5$

Fig. 7. v_{01}, v_{02} and i_0 for different duty ratio combinations

ZVS operation of LF inverter is not significant due to low switching frequency and hence low switching losses. In HF inverter there is difficulty in achieving ZVS for both legs simultaneously in every cycle as explained above. An auxiliary circuit can be used to overcome this problem in high power applications. In HF inverter of the proposed configuration, the power handled is small. Hence it does not influence the overall efficiency significantly.

VII. OUTPUT POWER CONTROL AND OVERALL EFFICIENCY

In the proposed dual frequency inverter, power control is achieved through phase modulation control of corresponding inverters. Low and high frequency output powers are dependent on the corresponding current components. The useful power which generates heat in the gear is calculated as the power dissipation in the equivalent resistances of the gear i.e., $I_{lf}^2R_2$ and $I_{hf}^2R_1$. I_{lf} and I_{hf} are rms values of low and high frequency currents.

Low and high frequency currents with varying D_l and constant D_h (= 1) are shown in Fig. 8(a). It can be observed that while low frequency current is varying with its duty cycle, high frequency current remains almost constant. Similarly, Fig 8(b) shows low and high frequency currents with varying D_h and constant D_l (=1). It can be observed that high frequency current varies with its duty cycle whereas, low frequency current remains constant. Hence independent control of low and high frequency currents is possible. This is true for any other values of D_l and D_h. Experimental and simulation results shown in these figures are found to be in good agreement with each other.

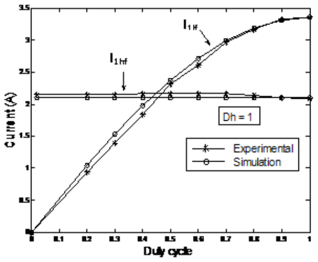


Fig. 8. (a) I_{1lf} and I_{1hf} vs D_l

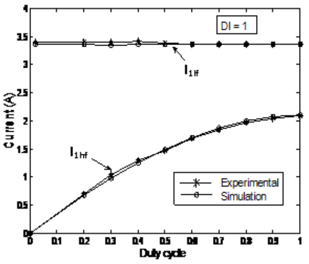


Fig. 8(b) I_{1lf} and I_{1hf} vs D_h

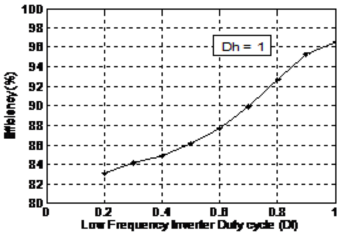


Fig. 9(a) Overall efficiency vs D_l

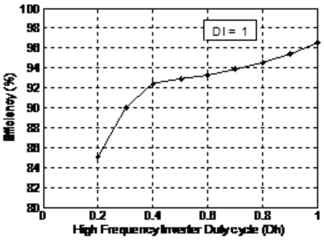


Fig. 9(b) Overall efficiency vs D_h

Overall efficiency curves of the proposed inverter are shown in Figs. 9(a) and (b). In Fig. 9(a), low frequency output power is varied while high frequency output power is kept constant. In fig. 9(b), high frequency output power is varied while low frequency output power is kept constant. It can be observed that the overall efficiency remains considerably high for wide variation of duty cycle under both situations.

VIII. CONCLUSIONS

Control and design aspects of the dual frequency inverter are highlighted. Simultaneous and independent control of dual frequency currents is presented. Design of the proposed inverter is explained. ZVS aspects for the dual frequency inverter are presented. As the power handled by high frequency inverter is small, overall efficiency is not affected significantly. Overall efficiency mainly depends on the efficiency of low frequency inverter. The proposed topology gives high overall efficiency (>95%). High power applications are possible due to the presence of two full-bridge inverters.

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