International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 18, Issue 3 (May.-June. 2022), PP. 65-71

Design and Control of Dual Frequency Full-Bridge Inverter for Induction Hardening

Dr. P. Sharath Kumar*[1], P. Aniketh*[2], B. Anil Kumar*[3], Y. Pranav Sai Reddy*[4],
J. Aravind Reddy*[5]
**Department of Electrical & Electronics Engineering, Sreenidhi Institute of Science and Technology, Yamnampet, Ghatkesar, Hyderabad, Telangana, INDIA*

ABSTRACT
This paper presents design and control aspects related to dual frequency full-bridge inverter are used for induction gear hardening application. Single dual frequency full-bridge inverter configuration for dual frequency operation is considered. Zero voltage switching aspects related to this configuration are explained. Performance of this proposed inverter configuration is presented with simulation waveforms in MATLAB/Simulink.

Key words: *Full-bridge resonant inverter, Induction hardening, Dual frequency inverter, Asymmetric duty cycle control, ZVS*

Date of Submission: 13-06-2022 Date of Acceptance: 27-06-2022

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. 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 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 [11].

Okudaira et al have proposed in [10]-[14] 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. Esteve et al have introduced inverter topologies with dual frequency outputs in [15]-[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. Bill Diong et al have proposed multilevel inverter configuration for dual frequency induction heating power supply in [17]-[18]. Cascaded H-bridge multilevel inverter circuit is used.

This paper presents design and control aspects related to dual frequency full-bridge inverter for induction hardening. A single full-bridge inverter configuration is considered for this application. Design and ZVS aspects of this configuration are explained. Simulation 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 [19]-[20]. 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. 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.

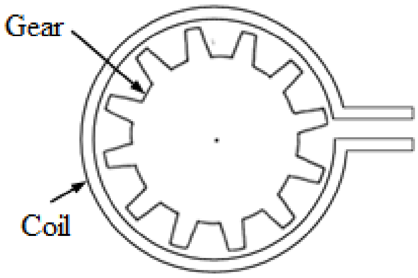


Fig. 1(a). Gear and coil arrangement

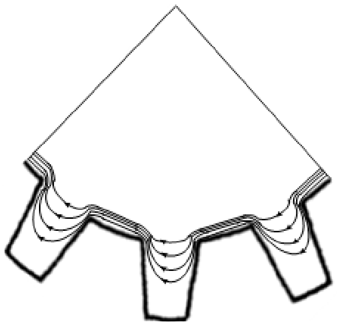


Fig. 1 (b). Current distribution in gear with low frequency supply

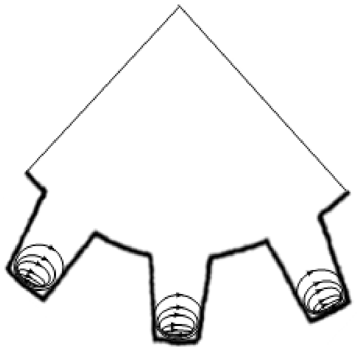


Fig. 1 (c). Current distribution in gear with high frequency supply

Fig. 1. Induction surface hardening of gear

III. INVERTER FOR INDUCTION GEAR 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.

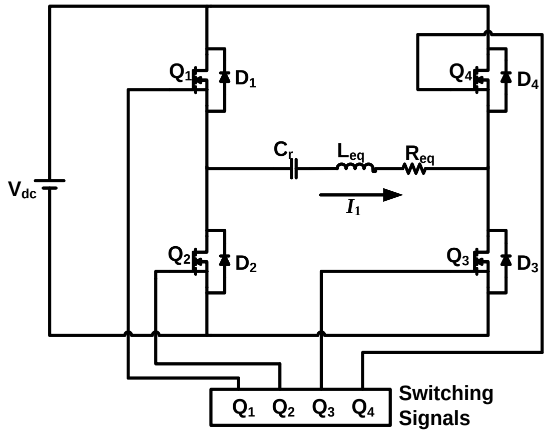


Fig. 2. Full-bridge series resonant inverter

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. In the recent past, other methods of power control such as, asymmetric duty cycle control and asymmetric voltage cancellation control have also become popular. These two techniques help in overcoming the limitations of phase modulation technique in the aspect of ZVS operating range.

IV. DUAL FREQUENCY FULL-BRIDGE INVERTER CONFIGURATION

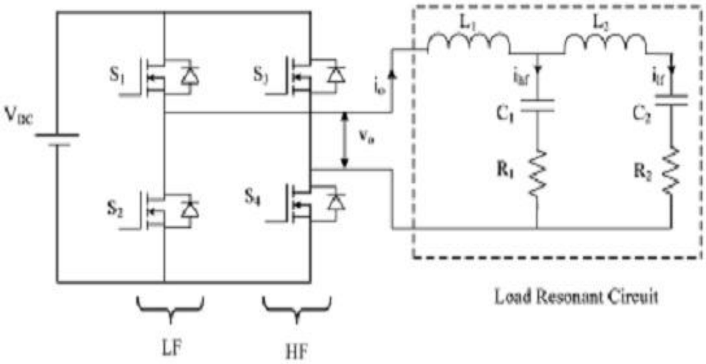


Fig. 3. Dual frequency inverter configurations for induction hardening

Dual frequency full-bridge inverter configuration for induction hardening application is shown in Fig.3. It consists of single full-bridge series resonant inverter whose output is v_0. The 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 asymmetric duty cycle control technique.

V. DESIGN ASPECTS OF DUAL FREQUENCY FULL-BRIDGE 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

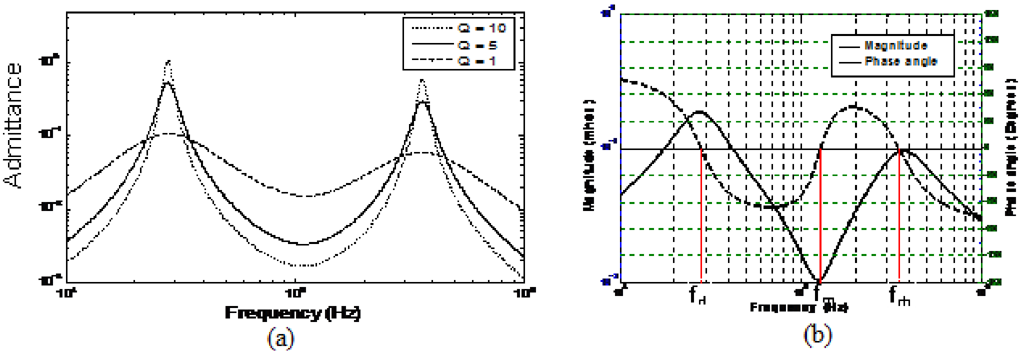
$$Q_h = \frac{1}{R_1}\sqrt{\frac{L_1}{C_1}} \tag{1}$$

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

$$f_{rh} = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{3}$$

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

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).



(a)
(b)

Fig. 4. Admittance characteristics
(a) for different Q (b) for gear load

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

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

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.

TABLE - I
Parameters of the Proposed Dual Frequency Inverter Configuration

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
DC source voltage (V_{DC})	50V

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 5% to 10% below their switching frequencies. This helps in achieving zero voltage switching (ZVS) of the devices in the inverter. 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.

VI. SIMULATION RESULTS OF DUAL FREQUENCY FULL-BRIDGE INVERTER

Figs. 5 to 8, shows the output voltage of full-bridge inverter v_0 and output current i_0 for $D_l = D_h = 1$, and $D_l = 0.3$, $D_h = 1$, $D_l = 0.3$, $D_h = 1$, and $D_l = D_h = 0.3$ respectively.

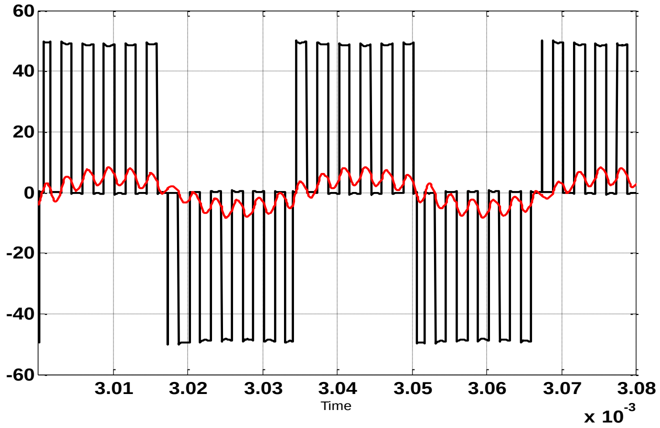


Fig. 5. V_0 and output current i_0 for $D_l = D_h = 1$

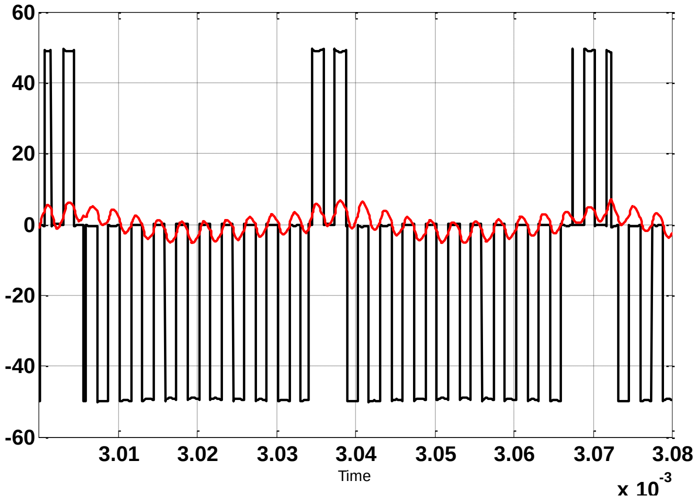


Fig. 6. V_0 and output current i_0 for D_l =0.3, D_h =1

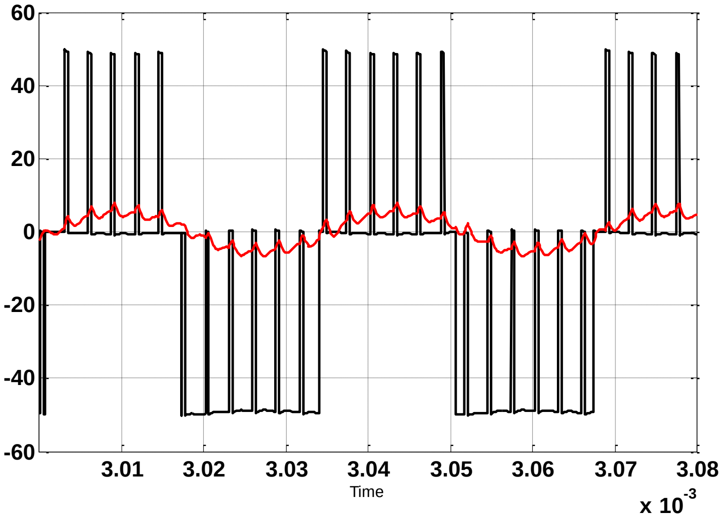


Fig. 7. V_0 and output current i_0 for D_l =1, D_h =0.3

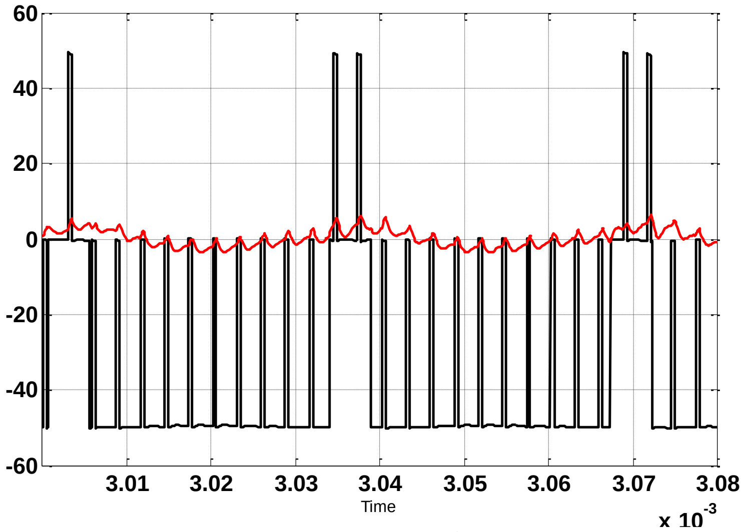


Fig. 7. V_0 and output current i_0 for D_l=0.3, D_h=0.3

The low frequency and high frequency currents at different duty-ratios are tabulated in Table – II. These currents are independently controlled by varying their respective leg duty-ratios.

TABLE – II
Current magnitudes with different duty-ratios

D_l	D_h	Simulation	
		I_{lf}	I_{hf}
1	1	10.6	6.36
0.6	1	6.2	6.36
0.3	1	4.1	6.36
1	0.6	10.6	3.8
1	0.3	10.6	2.4
0.6	0.6	6.2	3.8
0.3	0.3	4.1	2.4

ZVS operation of the proposed configuration is explained using simulation waveforms shown in Figs. 5 to 8. In Fig. 5, 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 full-bridge inverter. This is due to the reason that i_o is a combination of low and high frequency currents which are flowing through the devices of both legs of the inverter.

VII. CONCLUSIONS

Control and design aspects of the dual frequency full-bridge inverter are highlighted. Simultaneous and independent control of dual frequency currents is presented. Design of the proposed inverter configuration is explained. ZVS aspects for the dual frequency inverter are presented. High power applications are possible due to the presence of full-bridge inverter configuration.

REFERENCES

[1] Wolfgang R. Schwenk, “Simultaneous dual-frequency induction hardening”, Heat Treating Progress, Volume 3, pp. 35-38, April 2003.

[2] Fabio Biasutti, Christian Krause and Sergio Lupi, “Induction hardening of complex geometry and geared parts”, Heat Processing 3-2012, pp. 60-70.

[3] Electroheat Technologies, “Simultaneous dual-frequency gear hardening” [Online]. Available: http://www.electroheat-technologies.com/SDF%20Article. pdf

[4] Wolfgang Schwenk and Hans-Joachim Peter, “Surface hardening using the simultaneous dual frequency method”, Metallurgia, March 2003, pp. 8-9.

[5] Valery Rudnev, “ Induction Hardening of gears and critical components Part II”, Gear Technology, Nov/Dec 2008, pp 47-53.

[6] S.Okudaira, K.Nomura and K. Matsuse, “New quasi resonant inverter for induction heating”, in conference record of PCC-Yokohama, 1993, pp. 117-122.

[7] S.Okudaira and K. Matsuse, “Adjustable frequency quasi resonant inverter and basic characteristics”, Trans. Inst. Elect. Engg. Japan, 1994, vol. D-114, no.10, pp. 67-76.

[8] S.Okudaira and K. Matsuse, “Frequency and power control of induction heaterwith adjustable frequency quasi resonant inverter”, Trans. Inst. Elect. Engg. Japan, 1998, vol. D-118, no. 3, 1998, pp. 377-384.

[9] Shizumasa Okudaira and Kouki Matsuse, “Power control of an adjustable frequency quasi resonant inverter for dual frequency induction heating”, Proceeding of IPEMC-2000, S-34-2, pp. 968-973.

[10] Shizumasa Okudaira and Kouki Matsuse, “Adjustable frequency quasi-resonant inverter circuits having short-circuit switch across resonant capacitor”, IEEE Transactions on Power Electronics, Vol.23, No.4, pp.1830-1838, July 2008.

[11] Yusuke Ishimaru , Kazuo Oka, Kazuki Sasou, Kouki Matsuse and Masayoshi Tsukahara, “Dual high frequency quasi-resonant inverter circuit by using power MOSFET for induction heating”, IPEMC-2009, pp. 2545-2550.

[12] Shizumasa Okudaira and Kouki Matsuse, “A new quasi-resonant inverter with two-way short-circuit switch across a resonant capacitor”, in Proc. PCC Conf., Osaka, Japan, 2002, D17-7, pp. 1496-1501.

[13] S.Okudaira and K. Matsuse, “New quasi resonant inverter with short circuit switches across the resonant capacitor and its operating characteristics”, Trans. Inst. Elect. Engg. Japan, 2005, vol. D-125, no. 8, pp. 793-799.

[14] Shizumasa Okudaira and Kouki Matsuse, “Dual frequency output quasi-resonant inverter for induction heating”, Transactions of the Institute of Electrical Engineers of Japan. D”, 2001,Volume 121-D, No.5, pp. 563-568.

[15] V.Esteve, J.Pardo, J.Jordan, E.J.Dede, E.Sanchis-Kilders and E.Maset, “High power resonant inverter with simultaneous dual-frequency output”, Proc. 36th Annu. IEEE (PESC’05), 2005, pp. 1278-1281.

[16] V.Esteve, J.Jordan, E.J.Dede, E.Sanchis-Kilders and E.Maset, “Induction heating inverter with simultaneous dual frequency output”, Proceedings of Applied Power Electronics Conference and Exposition, March 2006, pp. 1505-1509.

[17] B.Diong, K. Corzine, S. Basireddy, and S.Lu, “Multilevel inverters based dual-frequency power supply”, IEEE Power Electron. Lett., Volume 1, No. 4, pp. 115-119,Dec.2003.

[18] B. Diong, S. Basireddy, K. Corzine, and Y. Familiant, “Multilevel inverters with equal or unequal sources for dual-frequency induction heating”, in Proc. 19th Annu. IEEE (APEC’04), vol. 2, 2004, pp. 825–831.

[19] L.Grajales, J.A.Sabate, K.R.Wang, W.A.Tabisz and F.C.Lee, “Design of a 10kW, 500kHz phase shift controlled series resonant inverter for induction heating”, IEEE, pp.843-849, 1993.

[20] L.Grajales and F.C.Lee, “Control system design and small signal analysis of a phase-shift controlled series resonant inverter for induction heating”, IEEE-PESC ’95, vol.1, pp.450-456, 1995.