2014 Power and Energy Systems: Towards Sustainable Energy (PESTSE 2014)

Comparison of Control Methods for High Frequency IH Cooking Applications

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***Abstract*—This paper presents the comparison of different fixed frequency control strategies for Induction Heating (IH) applications. Phase shift control method (PSM), Asymmetrical duty cycle control (ADC) method, and Asymmetrical voltage cancellation (AVC) methods are used to control the output voltage in IH applications. The performance analysis of the control methods is discussed in this paper. The MATLAB simulation results are given to validate the control schemes.**

Keywords—Induction Heating; phase shift control method;asymmetrical duty cycle control; asymmetrical voltage cancellation method; etc.

I. INTRODUCTION

In recent years the metal heat treatment applications such as surface hardening, brazing, forging, annealing, tube welding, tempering, melting and soldering with the help of induction heater [1], [2] have special interest in industrial electromagnetic heat processing plants due to its much more excellent characteristics such as cleanness, safety, quick warming, high temperature heating, maintainability, controllability, high efficiency, high reliability, and low cost [3], [4]. The operation of IH is based on Faraday's law of electromagnetic induction. When the induction coil is energized with high frequency power supply it generates alternating magnetic flux in the coil with the same frequency of the current. When the magnetic flux links with the metal piece, the eddy currents are developed on the surface of a metal piece [5] -[8]. Mainly the heat producing factors in IH applications depend upon the frequency and magnetic field intensity. The requirements of IH appliance are high switching frequency, power factor nearly equal to one, high efficiency, low cost, wide power range, and reliability [9], [10].

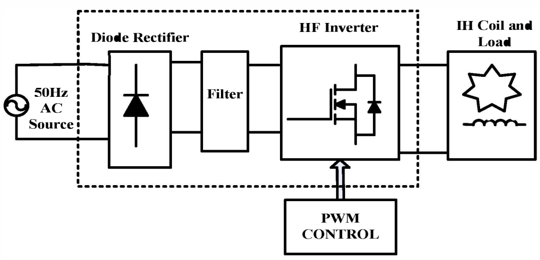

Fig.1.Typical arrangement for IH application

The typical arrangement of IH is shown in fig. 1. The available AC supply is converted into DC with suitable rectifier, and then DC is converted into a high frequency power supply, it is fed into the IH coil [7], [11].

In IH applications inverters play a major role in delivering power to the load. Here inverter is operating with a high switching frequency. But due to higher switching frequency switching loss also increase, which leads to decreased efficiency of the inverter. So, by reducing the voltage across the switch to zero during turn on and off transition, the switching loss can be minimized, which can be achieved by using resonant inverter.

When switching frequency is less than resonant frequency load acts as capacitive load and there is more turn on switching loss due to

- Reverse recovery effect
- Miller's effect
- Discharging of internal capacitance

When switching frequency is equal to resonant frequency, its power factor is unity, and inverter switching loss becomes zero. But this case is not occurring in practical conditions. For obtaining high efficiency, the inverter is to be operated at switching frequency greater than the resonant frequency,resulting in zero voltage state during the switching on and off transitions [12], [13].

For control over the output voltage or power in inverter application frequency is the traditional factor. By the variable frequency operation, the inverter has the several disadvantages such as a wide noise spectrum, which creates problems during control of electromagnetic interference (EMI) and it becomes more complex while filtering of the output-voltage ripple [14] -[17].

The variable frequency operation disadvantages can overcome by fixed frequency operation. In the process of operation, the inverter is to be operated with a fixed frequency.

To control the output voltage in fixed frequency operation in IH applications the following control techniques are applied. Those are phase shift control (PSC), asymmetrical duty cycle (ADC) method and asymmetrical voltage cancellation (AVC) method. In spite of the advantages of the fixed frequency control strategy, it has some disadvantages also. There may be

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loss of soft switching operation during large variation of load or output power [18], [19]. So operation within a narrow frequency range is preferred.

This paper presents the analysis and comparison of different control strategies to obtain the optimum ZVS control for reducing switching losses in the switches of the inverter for obtaining high efficiency.

II. OUTPUT VOLTAGE CONTROL USING DIFFERENT CONTROL METHOD

The full bridge inverter (FBI) is offering more control possibilities [11], due to that in this paper FBI is considered. The load is consisting of IH equivalent load parameters. Where R, L, and C are load equivalent resistance, inductance, and resonant capacitor. Fig.2 (a), (b) shows the FBI, and its uncontrolled output voltage and current.

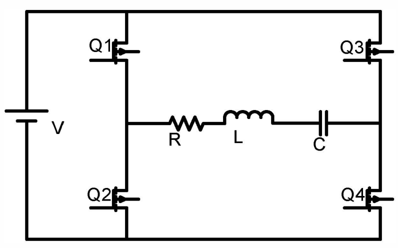


Fig.2.(a). Full bridge series resonant inverter.

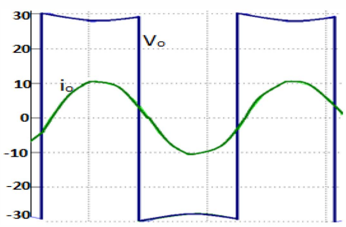


Fig .2.(b). Uncontrolled output voltage

The controlled output voltage can be achieved using the following control techniques. Those are PSC, ADC, and AVC. The output voltage can be controlled by varying the: α^+, α^-, and β control angels.

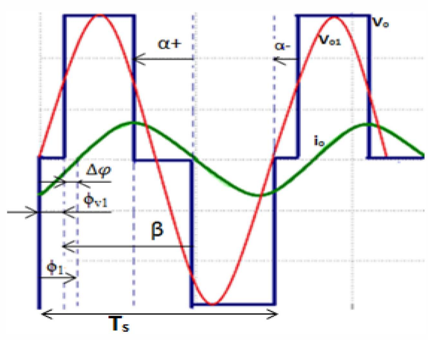


Fig.3.Output voltage and current with controlled variables

The quasi square output voltage and load current waveforms are shown in fig .3. The quasi-square wave voltage is applied to the IH equivalent load circuit.

The output voltage is represented with the help of Fourier analysis. Where V_{oh} is amplitude and $\emptyset_{vh}$ is phase of h_{th} harmonics.

$$V_{oh}=\frac{V}{h\pi}\sqrt{a_h^2+b_h^2} \quad (1)$$

$$\emptyset_{vh}=tan^{-1}\frac{a_h}{b_h} \quad (2)$$

Where V is DC input voltage.

$$a_h=\sinh(\beta-\alpha^+)+\sinh\beta+\sinh\alpha^- \quad (3)$$

$$b_h=1-\cosh(\beta-\alpha^+)-\cosh(\beta)+\cosh\alpha^- \quad (4)$$

The THD is obtaining as

$$\%THD=100\sqrt{\frac{\sum_{h=2}^{\infty}(a_h^2+b_h^2)}{(a_1^2+b_1^2)}} \quad (5)$$

The average output power Pout determined as

$$P_{out}=\sum_{h=1}^{\infty}\frac{R}{2}*\frac{V_{oh}^2}{R^2+\left(h\omega_s L-\frac{1}{h\omega_s C}\right)^2}$$

$$=\sum_{h=1}^{\infty}\frac{1}{2R}\frac{V_{oh}^2}{\left[1+Q^2\left(h\omega_n-\frac{1}{h\omega_n}\right)^2\right]} \quad (6)$$

Where $Q=\frac{\sqrt{\frac{L}{C}}}{R}$ is quality factor,

V_{oh} = output voltage.

$\omega_n=\frac{\omega_s}{\omega_0}$ normalised switching frequency .

ω_s = angular switching frequency

$\omega_0=\frac{1}{\sqrt{LC}}$ angular resonant frequency

The high frequency harmonics are neglected, assuming that filtering is provided by the resonant tank. So the output power

$$P_{out}\cong\frac{V_{o1}^2}{2R\left[1+Q^2\left(\omega_n-\frac{1}{\omega_n}\right)^2\right]} \quad (7)$$

The phase lag $\emptyset_1$ between a fundamental component of output voltage V_{o1} and output current i_0 is

$$\emptyset_1=\tan^{-1}\left(\frac{\omega_s L-\frac{1}{\omega_s C}}{R}\right)=\tan^{-1}\left(Q\left(\omega_n-\frac{1}{\omega_n}\right)\right) \quad (8)$$

Normalized voltage amplitude V_{o1n}

$$V_{o1n} = \frac{V_{o1}}{V_{o1(max)}} \quad (9)$$

Normalized output power

$$P_n = \frac{P}{P_{max}} = \frac{\frac{V_{o1}^2}{2R\left[1+Q^2\left(\omega_n-\frac{1}{\omega_n}\right)^2\right]}}{P_{max}} = (V_{o1n})^2 \quad (9)$$

Where V_{o1} (max) and P_{max} are corresponding maximum magnitude obtained with $\alpha^+,\alpha^- = 0^0$, and $\beta = 180^0$.

$$V_{o1(max)} = \frac{4V}{\pi} \quad (10)$$

$$P_{max} \cong \frac{V_{o1(max)}^2}{2R\left[1+Q^2\left(\omega_n-\frac{1}{\omega_n}\right)^2\right]} \quad (11)$$

The output current expressed as

$$i_o = I_o \sin(\omega_s t - \Delta\varphi) \quad (12)$$

Where I_o is the amplitude of output current

$$\Delta\varphi = \emptyset_1 - \emptyset_{v1} \quad (13)$$

ZVS can be achieved at

$\Delta\varphi > 0$ as presented in [19] (14)

The $\Delta\varphi$ can be increased by two ways. One is by increasing $\emptyset_1$ or by reducing $\emptyset_{v1}$. The traditional approach of increasing $\emptyset_1$ is by increasing switching frequency. But increase of $\emptyset_1$ leads to low power factor, so for same power appliances more current circulates in circuit which results in an increase of conduction losses and turn off switch losses. So increasing $\emptyset_1$ is not a suitable option and better approach is to reduce $\emptyset_{v1}$ which depends upon control angels α^+, α^-, and β.

$$\Phi_{v1} = \tan^{-1}\left(\frac{\sin(\beta-\alpha^+)+\sin\beta+\sin\alpha^-}{1-\cos(\beta-\alpha^+)-\cos\beta+\cos\alpha^-}\right) \quad (15)$$

The optimum control strategy is that one which gives required output voltage and power with minimum $\emptyset_{v1}$. The variation of voltage with minimum $\emptyset_{v1}$ can be achieved by varying individual control angles α^+ or α^- and maintaining $\beta = 180^0$[19].

The different control strategies are defined as below.

A. *Phase shift control method*

In PSC method [20]-[23] control variable is sigma (σ) it varies between 0-180°. Where $\sigma = (180° - \alpha^+)$, $\beta = 180°$ and $\alpha^+ = \alpha^- = \alpha$. The amplitude and phase of the fundamental voltage V_{o1} are respectively.

$$V_{o1} = \frac{4V}{\pi}\cos\frac{\alpha}{2} \quad (16)$$

$$\Phi_{v1} = \frac{\alpha}{2} \quad (17)$$

where V is DC input voltage.

Fig.4 shows the output voltage and current waveform obtained by PSC voltage control strategy.

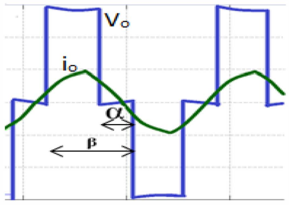


Fig.4.output voltage and current in PSC control method

B. *Asymmetrical duty cycle control method*

In ADC method β is the control variable [20],[23]-[25]. It varies between 0-180°. In addition, the following condition is also used: $\alpha^+ = \alpha^- = 0°$. The output voltage and current is obtained by ADC method is shown in fig.5.

The amplitude and phase of the voltage V_o are respectively.

$$V_{o1} = \frac{4V}{\pi}\cos\frac{\alpha}{2} \quad (18)$$

$$\Phi_{v1} = \frac{\alpha}{2} \quad (19)$$

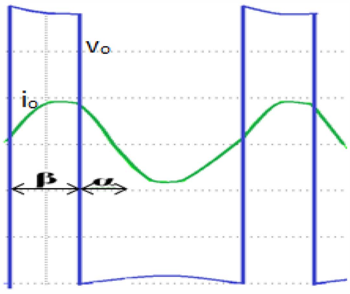


Fig .5.Output voltage and current in ADC control method

C. *Asymmetrical voltage cancellation control method*

The AVC control strategy [19],[20],[23],[26] offers more control possibilities with minimum losses as compared to PSC and ADC, as it uses three control variables α^+, α^-, and β. The control variables α^+, α^-, and β are vary between 0-180°, and always $\alpha^+ < \beta$. The output voltage and current waveforms obtained by AVC method is given in fig. 6. The amplitude and phase of the voltage V_o are respectively.

$$V_{o1} = \frac{V}{\pi}\sqrt{10 + 6\cos\alpha} \quad (20)$$

$$\Phi_{v1}=\tan^{-1}\left(\frac{\sin\alpha}{3+\cos\alpha}\right) \quad (21)$$

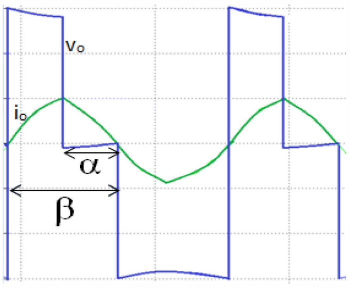


Fig.6.output voltage and current in AVC control method

III. COMPARISONS OF CONTROL METHODS FOR LOW POWER IH APPLICATIONS

In this section comparison of control strategies is made such that, which strategy is having the best performance in the form of less switching losses and % THD.

In all control strategies voltage is controlled such that ZVS must be achieved. For getting ZVS operation it is essential to operate at a frequency greater than resonant frequency. Thus, the main objective is to find out the optimum control strategy such that it controls the voltage within narrow frequency range with ZVS operation, by considering the load variation. From the equations (18), (20) and (22) it is observed that all the control strategies cannot maintain ZVS operation in the same way.

A. *First comparison:*

By substituting (8), (18),(20), and (22) in the condition (15) produces:

$$\frac{\omega_n^2-1}{\omega_n} > \frac{\tan\frac{\alpha}{2}}{Q} \quad (22)$$

For PS and ADC controls, and

$$\frac{\omega_n^2-1}{\omega_n} > \frac{\frac{\sin\alpha}{3+\cos\alpha}}{Q} \quad (23)$$

For AVC control,

Using the equations (23) and (24) the plot drawn between normalized switching frequency (ω_n) and control angle (α) for different Q-factors which is shown in fig.7. Minimum ω_n is required for the variation in the load for obtaining minimum losses. The AVC is having the minimum ω_n compared to the other PSC and ADC methods.

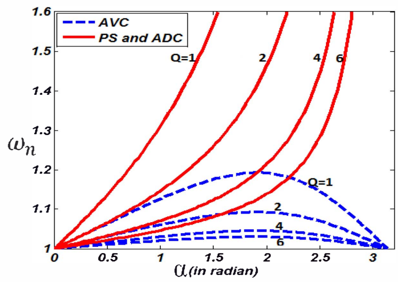


Fig.7.Plot between ω_n and α with different Q-factors

It is observed from the plot that for obtaining the same value of output voltage with ZVS, PSC and ADC requires higher normalized frequency, when compared with AVC. The AVC is having a minimum normalized frequency, so that conduction loss and turn off losses are also less in AVC method as compared with PSC and ADC [19], [23], [27].

B. *Second comparison*

By substituting the equation (17) and (19) in equation (10) normalized power (P_n) from PS and ADC method can be obtained as

$$P_n=\left(\cos\left(\frac{\alpha}{2}\right)\right)^2 \quad (24)$$

$$\frac{\alpha}{2}=\cos^{-1}\sqrt{P_n} \quad (25)$$

Substituting equation (26), in equation (23) normalized frequency for PS and ADC can be found at

$$\omega_n=\frac{(\tan(\cos^{-1}\sqrt{P_n}))+\sqrt{(\tan(\cos^{-1}\sqrt{P_n}))^2+4Q^2}}{2Q} \quad (26)$$

Similarly substituting the equation (21) in equation (10) normalized power (P_n) for AVC method can be obtained as

$$P_n=\frac{(5+(3*\cos\alpha))}{8} \quad (27)$$

$$\alpha=\cos^{-1}\frac{8P_n-5}{3} \quad (28)$$

Substituting (29) in equation (24) normalized frequency can be obtained as

$$\omega_n=\frac{\sqrt{9-(8P_n-5)^2}+\sqrt{9-(8P_n-5)^2+Q^2(8+16P_n)^2}}{Q(8+16P_n)} \quad (29)$$

Using the normalized switching frequency (ω_n) and normalized power (P_n) the plots is drawn for different Q-factors. Q-factor variation is represented for variation of the load. From the equation (28) the minimum normalized power is limited to 0.25 because the minimum normalized output voltage is limited 0.5.

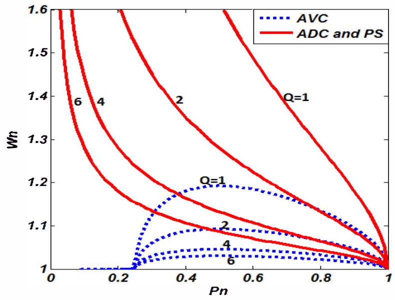
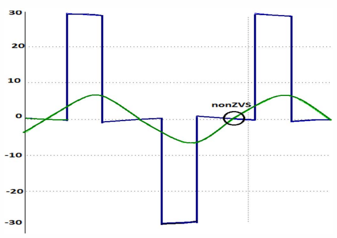


Fig.8.Plot between P_n and α with different Q-factors

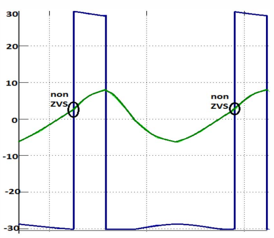
From fig (8) it is observed that for obtaining the same value of output power with ZVS, ADC and PS method requires more normalized frequency as compared to AVC method. In AVC method power control can be achieved within a narrow frequency range. Thus, with AVC method higher efficiency can be achieved reducing losses [19].

C. *Third comparison*

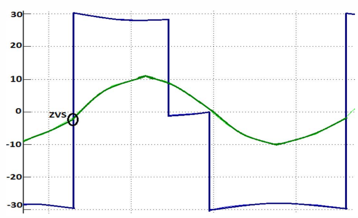
The ZVS is achieved when the switch current is negative while turning on the switch. The ZVS occurrence is compared in PSC, ADC, and AVC control methods with fixed frequency operation and under equal load conditions[19],[23] which is presented in fig.9. It is observed that for same frequency and load condition ZVS is attained by AVC method but it is not obtained in PS and ADC methods.



(a)



(b)



(c)

Fig.9.simulation waveforms of output voltage and current: (a) PSC method (ZVS is lost) ,(b) ADC method (ZVS is lost) ,(c) AVC method (ZVS maintained)

D. *Fourth comparison*

The fourth comparison is based on the total harmonic distortion (THD), which is a measure of closeness in shape between a waveform and its fundamental component. The purpose is to find, which control method causes less THD in output voltage. For this comparison substituting the equation (3),(4) in equation (5)

For PSC method (with $\alpha^{+}=\alpha^{-}=\alpha$ and $\beta=180^{0}$)

$$\%THD=100*\sqrt{\frac{\sum_{h=2}^{\infty}\left((\sin(h(180°-\alpha))+\sin(h\alpha))^2+\left(1-\cos(h(180°-\alpha))-\cos h180°+\cos h\alpha\right)^2\right)}{((2\sin(\alpha))^2+(2+2\cos(\alpha))^2)}} \quad (30)$$

For ADC method(with $\alpha^{+}=\alpha^{-}=0$ and $\alpha=180°-\beta$)

$$\%THD=100*\sqrt{\frac{\sum_{h=2}^{\infty}((2\sin(h(180°-\alpha)))^2+(2-2\cos(h(180°-\alpha)))^2)}{((2\sin(\alpha))^2+(2+2\cos(\alpha))^2)}} \quad (31)$$

For AVC method (with $\alpha^{+}=\alpha,\alpha^{-}=0$,$\beta=180^{0}$)

$$\%THD=100*\sqrt{\frac{\sum_{h=2}^{\infty}\left((\sin(h(180-\alpha)))^2+\left(2-\cos(h(180°-\alpha))-\cos(h180°)\right)^2\right)}{((\sin(\alpha))^2+(3+\cos(\alpha))^2)}} \quad (32)$$

%THD is a function of control angle α. Using the equations (31),(32) and (33) the plot between α and %THD is presented in fig.10 for different control strategies. It is observed from the fig. 10, the %THD increases as a control angel α increases. In PSC and ADC control method %THD increases more rapidly than the AVC method with increase of control angel. It can conclude that AVC is having less harmonic content in output voltage. Therefore, AVC is having the better performance in different operating conditions.

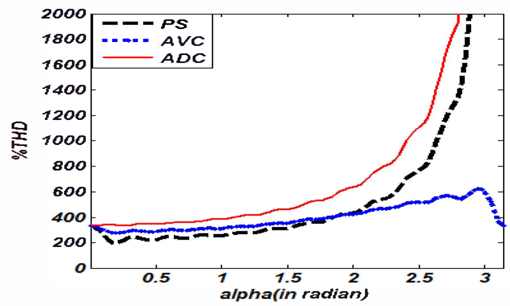


Fig.10.Comparison of %THD in output voltage

From the above four comparisons AVC is the better control method compared with the PSC and ADC.

IV. CONCLUSION

In this paper, three control methods are compared for IH applications; those are PSC, ADC, and AVC. The control methods are applied to the series resonant FBI. For the purpose of optimum control strategy four comparative measures are taken, the ZVS is considered in first three comparisons, %THD is considered in fourth comparison. The series resonant FBI is having higher performance, better control in output voltage without losing ZVS operation with AVC method only.

REFERENCES

[1] A. Okuno , H.Kawano, J.Sun, M.Kurokawa, A.Kojina and M.Nakaoka, " Feasible development of soft-switched SIT inverter with load-adaptive frequency-tracking control scheme for induction heating," IEEE transactions on industry applications, VOL. 34, NO. 4, pp. 713 – 718, JULY/AUGUST 1998

[2] S.Kleangsin, A.Sangsawang, S.Naetiladdanon, and C. Koompai, "Constant output power control of three-phase inverter for an induction heating system",in Proc. IEEEElectrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), pp. 1-6,MAY 2013

[3] Young-Sup Kwon, Sang-Bong Yoo, Dong-Seok Hyun, "Half-Bridge series resonant inverter for induction heating applications with load-adaptive PFM control strategy", in Proc. IEEE Power electronics conference and exposition(APEC), vol.1,pp. 575-581, March 1999.

[4] Henry W. Koertzent, Jacobus D. van Wyk and Jan A. Ferreira, "Design of the Half-Bridge, Series Resonant Converter for Induction Cooking "in Proc. IEEEPower Electronics Specialists Conf. (PESC), vol. 2, pp. 729–735, June.1995

[5] J.M.HQ, F.C.Juang, "A practical PWM inverter control circuitry for induction heating and studying of the performances under load variations", in Proc. IEEE Industrial Electronics(ISIE), vol.1,pp.294-299, July 1998

[6] J. M. HO, M.T. LEE, "A Novel PWM Inverter Control Circuitry for Induction Heating" in Proc. IEEE Power Electronics congress,pp. 113-119,Oct 1996

[7] Fairchild Semiconductor AN9012, " Induction heating system topology review" July 2000

[8] Qinghua Xiao, Jie Zhao, Mingfa Wang, "Research on frequency tracking capacitive PWM of induction heating power supply" Challenges in environmental science and computer engg.(CESCE), vol-2, pp. 377-380, March 2010

[9] M.Helaimi, M.Bettayeb, M. Benghanem, B. Belmadani, " Control system design and small signal analysis of APWM resonant inverter for induction heating",Electrical power and energy conversion system(EPECS), pp.1-6, Nov 2009

[10] Nam-Ju Park, Dong-Yun Lee, and Dong-Seok Hyun, Fellow, IEEE, " A power-control scheme with constant switching frequency in class-D inverter for induction-heating jar application", IEEE Transactions on industrial electronics, VOL. 54, NO. 3, pp.1252-160, JUNE 2007

[11] S. Llorente, F. Monterde, J.M. Burdío, and J. Acero, "A comparative study of resonant inverter topologies used in induction cookers", in in Proc. IEEE Power electronics conference and exposition(APEC), vol.2,pp. 1168-1174, March 2002

[12] M. K. Kazimierczuk and D. Czarkowski, " Resonant power converters.", New York: Wiley, 1995.

[13] Kunrong Wang, Fred C. Lee, Guichao Hua, and Dum Borojevic, "A comparativestudyofswitching losses of IGBTS under hardswitching,Zero voltage switching and zero current switching", in Proc. IEEEPower Electronics Specialists Conf. (PESC), vol. 2, pp. 1196-1204, June.1994

[14] J.Jittakortl, S.Chudjuarjeen2, S.Yachiangkam I, A.Sangswangl,S. Naetiladdanonl and C. Koompail, "An improved dual-series resonant inverter for induction cooking appliance with asymmetrical voltage-cancellation control and power loss analysis" in Proc. IEEEElectrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), pp. 1-4,MAY 2012

[15] J.Jittakort1, S. Chudjuarjeen2, A. Sangswang, S. Naetiladdanon, and C.Koompa, "A dual output series resonant inverter with improved asymmetrical voltage-cancellation control for induction cooking Appliance, in Proc. IEEE IECON,pp.2520-2525, Nov 2011

[16] L.A.Barragán, J.M.Burdío,J. I. Artigas, D. Navarro, J. Acero, and D.Puyal, "Efficiency optimization in ZVS seriesresonant inverters with asymmetrical voltage-cancellation control, IEEE transactions on power electronics, VOL. 20, NO. 5, september 2005

[17] S.H. Hosseini, A. Yazdanpanah Goharrizi and E. Karimi, "A multi-output series resonant inverter with asymmetrical voltage-cancellation control for induction-heating cooking appliances", in Proc. IEEE Power Electronics and motion control conference(IPEMC),vol.3,pp.1-6, Aug 2006

[18] Samart Yachiangkam1, Anawach Sangswang1, Sumate Naetiladdanon1,Chayant Koompai1, and Saichol Chudjuarjeen, "Resonant Inverter with a Variable-Frequency AsymmetricalVoltage-Cancellation Control for Low Q-Factor Loads in Induction Cooking", Power Electronics and Applications (EPE 2011)

[19] J. M. Burdío, L.A. Barragán, F. Monterde, D.Navarro, and J.Acero, "Asymmetrical voltage-cancellation control for full-bridge series resonant inverters" IEEE transactions on power electronics, VOL. 19, NO. 2, MARCH 2004

[20] B.Sharp, Hunter Wu, "Asymmetrical voltage-cancellation control for LCL resonant converters in inductive power transfer systems"in Proc. IEEE Power electronics conference and exposition(APEC), pp. 661-666, Feb 2012

[21] F. S. Tsai, P. Materu, and F. C. Lee, "Constant-frequency clamped-mode resonant converters", *IEEE Trans. Power Electron.*, vol. 3, no. 4, pp. 460–473, Oct. 1988

[22] J. A. Sabaté and F. C. Lee, "Off-line application of the fixed-frequency clamped-mode series resonant converter," *IEEE Trans. Power Electron.*,vol. 6, no. 1, pp. 39–47, Jan. 1991

[23] JosC M. Burdio', Francisco Canales2, Peter M. Barbosa2, and Fred C. Lee2, "A comparison study of fixed-frequency control strategies for ZVS DC/DC series resonant converters" in Proc. IEEEPower Electronics Specialists Conf. (PESC), vol. 1, pp. 427-432, June.2001

[24] P. Imbertson and N. Mohan, "Asymmetrical duty cyclepermits zero switching loss in PWM circuits with noconduction loss penalty," IEEE Trans. Ind. Appl., vol. 29,no. 1, pp. 121–125, 1993.

[25] P. Imbertson and N. Mohan, "New directions in dc-dc powerconversionbased on idealized concepts leading ultimately to theasymmetrical duty-cycle power converter," IEEE Trans. Circuits Syst.

[26] F. Monterde, Jose M. Burdio, "Unipolar voltage-cancellation control of resonant inverters for induction cooking appliances", in Proc. Industrial Electronic Society(IECON), Vol.2, pp.820-824, Sept 1998

[27] J.Jittakort1, S.Yachiangkam1, A.Sangswang1, S.Naetiladdanon1,C.Koompai1, and S.Chudjuarjeen, "A variable-frequency asymmetrical voltage- cancellation control of series resonant inverters in domestic induction cooking.", in Proc.IEEE Power electronics and ECCE Asia (ICPE & ECCE),pp.2320-2327, June 2011