The International Conference on Electronics
& Oil: From Theory to Applications
March 05-06, 2013, Ouargla, Algeria

Frequency Duty Cycle Closed Loop Control of PWM-LLC Resonant Inverter for Induction Heating Applications

M.HELAIMI[1], M. BENGHANEM[2], B. BELMADANI[3]
(1,3) Dept. of electrical engineering, university of Hassiba Ben Bouali- Chlef, Algeria
(2) Dep. of Automatic Control, university of Mohamed Boudhiaf-Oran, Algeria
halimi1976@yahoo.fr

***Abstract*—This paper presents the frequency duty cycle closed loop control of PWM-LLC resonant inverter suitable for induction heating applications. The complete closed loop control is obtained using small signal analysis. The validity of proposed control is verified by simulation results.**

Key-Words— **PWM-LLC resonant inverter, frequency/duty cycle control, induction heating**

I. Introduction

Nowadays, resonant topologies are used in a number of industrial applications, including power supplies for induction heating systems. PWM-LLC is being a more popular topology because it has the desirable characteristics of the series and parallel ones [1]-[5].

In control practice, PI controllers have been successfully applied to a wide variety of engineering problems, including power converters [6]-[7].

In this paper, we propose an effective control system for PWM-LLC resonant inverter which uses variable frequency and variable duty cycle. The output power of the proposed inverter has to be controlled by adjusting the duty cycle of the switches using power loop circuit based on PI controller. A PLL is used as frequency tracking control. In this case, the complete closed loop control is obtained using small signal analysis [8]-[9].

The organization of this paper is as follows: the proposed inverter circuit configuration is given in Sections II. Closed loop system design and parameter tuning of the proposed PI controller are presented in Sections III. Section IV provides the corresponding verification results. Conclusion is given in Section V.

II. Circuit description

A number of induction-heating resonant inverters have been reported in literature. However, they all employ the basic conversion process of AC-DC rectification of the phase source and followed by a single phase higher frequency stage. Figure **1** show the proposed configuration used in this work:

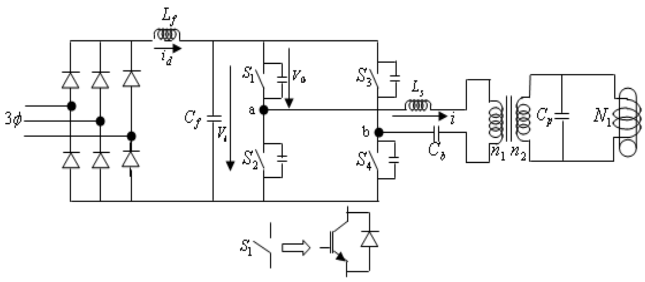

Fig.1: The proposed PWM-LLC resonant inverter

It consists of four IGBT transistors with anti-parallel diodes and the resonant tank LLC. The transistors S1 and S4 conduct alternately to S2 and S3 with a duty of 50%. The induction heating load constitutes a **50 CrV4** carbon steel billet placed inside a N1-turns cooper coil at specific air gap. Figures **2** and **3** show the measured characteristics of the **50 CrV4** work piece:

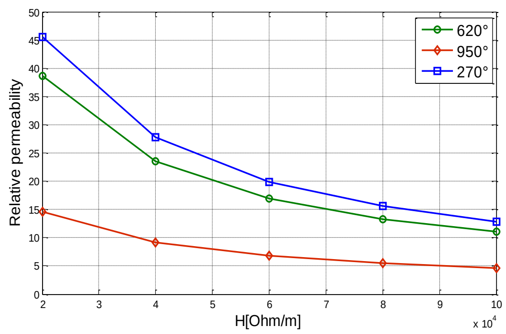

Fig.2. relative permeability of **50CrV4** versus H at different temperature

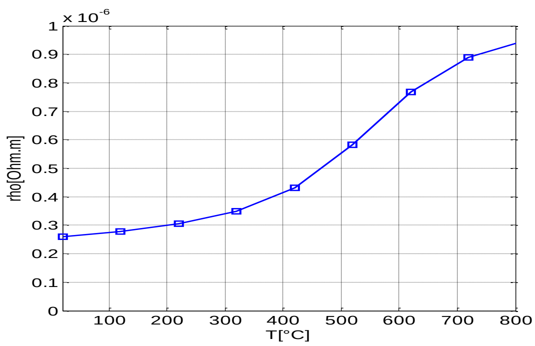

Fig.3. resistivity of **50CrV4** versus the temperature

During the heating cycle these parameters vary especially when the work piece reaches the Curie temperature $T_c = 750°C$.

The induction heating load can be modelled by means of a series combination of its equivalent resistance R_{eq} and equivalent inductance L_{eq} [10]-[11].

III. Proposed control system

Figure 4 describes detailed complete closed loop system architecture:

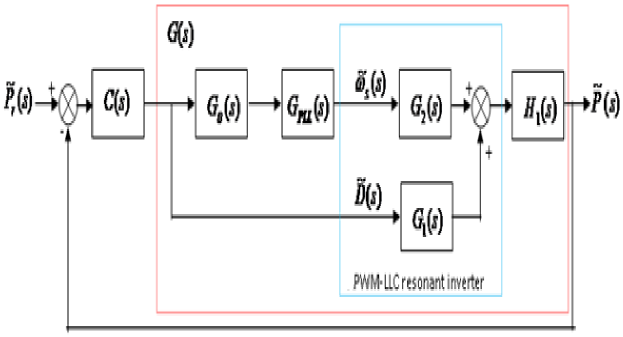

Fig.4: Detailed closed loop system architecture

$C(s)$ is the controller to implement,

$$C(s) = K_p.(1+\frac{1}{T_i.s})$$

$G(s)$ is the plant to be controlled,

$$G(s) = (G_\theta(s).G_{PLL}(s).G_2(s)+G_1(s)).H_1(s)$$

where,

$$G_1(s) = \frac{a_3.s^3+a_2.s^2+a_1.s+a_0}{b_6.s^6+b_5.s^5+b_4.s^4+b_3.s^3+b_2.s^2+b_1.s+b_0}$$

$$G_2(s) = \frac{a_6.s^2+a_5.s+a_4}{b_6.s^6+b_5.s^5+b_4.s^4+b_3.s^3+b_2.s^2+b_1.s+b_0}$$

$$G_{PLL}(s) = \frac{a_8.s+a_7}{b_9.s^2+b_8.s+b_7}$$

$$H(s) = \frac{1}{\tau.s+1}$$

$$G_\theta(s) = K_\theta$$

The pole of $G(s)$ are found to be:

$p_{1,2} = (-0.0657 \pm 1.64.i).10^6$,

$p_{3,4} = (-0.0789 \pm 0.7653.i).10^6$

$p_{5,6} = (-0.0657 \pm 1.64.i).10^6$,

$p_{7,8} = (-0.0789 \pm 0.7653.i).10^6$,

$p_{9,10} = (-0.0657 \pm 0.1094.i).10^6$,

$p_{11,12} = (-0.0036 \pm 0.0027.i).10^6$

$p_{13,14} = (-0.0657 \pm 0.1094.i).10^6$,

$p_{15} = -0.7653.10^6$

Notice that all the real parts of the poles are negatives, thus, the system is found stable.

The first order reduced model of the above system, $G(s)$, is given by,

$$G_r(s) = \frac{a}{s+b}$$

The closed loop system under unity feedback for this system is found to be,

$$\frac{\tilde{P}(s)}{\tilde{P}_r(s)} = \frac{K_p.a.(1+T_i.s)}{T_i.s^2+(T_i.b+a.K_p.T_i).s+K_p.a}$$

The characteristic polynomial is given by,

$$s^2+(b+a.K_p).s+\frac{a.K_p}{T_i}$$

Matching this with the standard polynomial form, to give,

$$s^2+2.\xi.\omega_n.s+\omega_n^2$$

$$\begin{cases} K_p = \frac{1}{a}.(2.\xi.\omega_n - b) \\ T_i = \frac{a.K_p}{\omega_n^2} \end{cases}$$

ω_n is the natural system frequency,

ξ is the damping factor,

IV. COMPARISON AND DISCUSSION

In this section, we evaluate, through computer simulation performed in **MATLAB/SIMULINK**, the ability of the proposed controller to regulate the output power of the system.

The control objectives are:

1. To heat steel metal from $20°C$ to $240°C$ in $15s$.
2. To regulate the output power.
3. To maintain power factor near unity

Figure 5 shows the Bode plot of the open loop transfer function $L(s) = C(s).G(s)$ with the conventional PI controller:

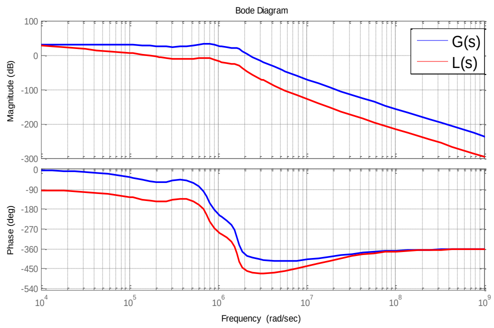

Fig.5: Bode plot of the open loop transfer function

Figures 6-9 show the output power response for step change in reference signal from $12.07w$ to $14.92w$ and the corresponding output waveforms $i_{Ls}(t)$, $i_{load}(t)$ and $v_c(t)$ of the PWM-LLC resonant inverter:

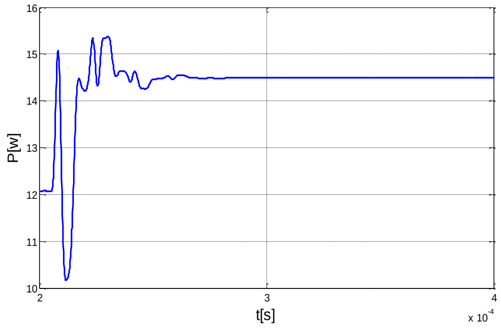

Fig.6: Output power

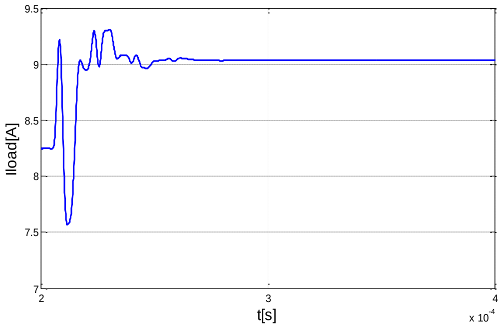

Fig.7: Output current $i_{load}(t)$

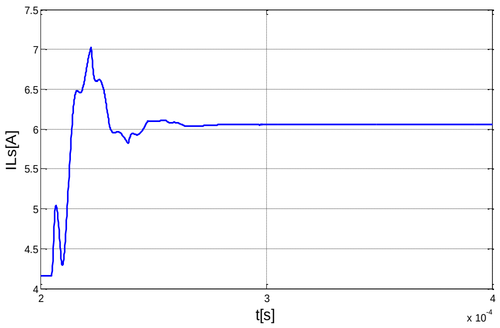

Fig.8: Output current $i_{Ls}(t)$

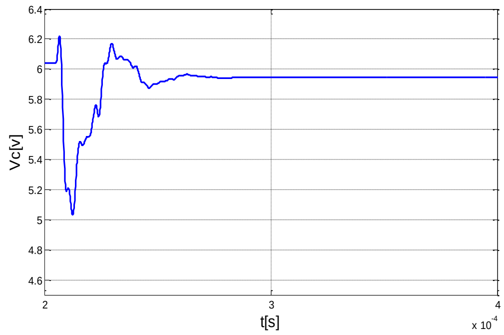

Fig.9: Output voltage $v_c(t)$

Some performance characteristics for the feedback control system with the proposed controller are summarized in the Table I:

Table I. Some performance characteristics

	Phase margin [°]	I_{1max} [A]	Overshoot [%]
G(s)	145.62	-	-
PI	39.46	12.993	27.03

By examine those results, it can said that when the control parameters of the PI controller are chosen for achieving fast response, the overshoot is relatively large (27.03%).

V. Conclusion

The design and implementation of PI controller for the closed loop power regulation of PWM-LLC resonant inverter suitable for induction heating applications is discussed in this paper. The effectiveness of the proposed controller is verified by simulation results. The closed loop response is improved by tuning the parameters of PI controller.

References

[1] S. Chudjuarjeen, A. Sangswang, and C. Koompai, "An Improved LLC Resonant Inverter for Induction-Heating Applications with Asymmetrical Control", IEEE Transactions on Industrial Electronics, vol 58, N°7, pp 2915-2925, Jully 2011.

[2] S. Chudjuarjeen and V. Hathairatsiri “Series and Parallel Resonant Inverter for Induction Heating application", International Conference on Science, Technology and Innovation for Sustainable Well-Being (STISWB), 23-24 July 2009, Mahasarakham University, Thailand.

[3] A. Kelemen and N. Kutasi “Lyaponov-based frequency shift power control of induction heating converters with hybrid resonant load” Acta Universitatis Sepientiae, 2009, pp 41-52.

[4] J. Epsi, E. Dede, R. G. Gil and J. C. Moreno “Design of the L-LC resonant inverter for induction heating based on its equivalent SRI”, IEEE Transactions on Industrial Electronics, vol 54, N°6, pp 3178-3187, December 2007.

[5] S. Chudjuarjeen, A. Sangswang, and C. Koompai, “LLC resonant inverter for induction heating with asymmetrical voltage-cancellation control,”in Proc. IEEE Int. Symp. Circuits Syst., Taipei, Taiwan, May 2009, pp. 2874–2877.

[6] D. K. Nayak and S. R. Reddy, "Closed loop controlled synchronous rectified push-pull converter", European journal of scientific journal, Vol.49, N°3 pp. 377-386, 2011.

[7] M. Gopinath and S. Ramareddy, "Closed loop control of an efficient Ac-DC step up converter", International journal of electrical engineering, vol. 5, N°.1, pp.1–6, 2012.

[8] J. Tian, J. Petzoldt and T. Riemann, M. Scherf and G. Berger, "Control system analysis and design of a resonant inverter with the varaiable frequency variable duty cycle" , European Conference on Power Electronics and Applications (EPE), 2005, Dresden, Germany.

[9] L. Grajales and F.C. Lee "Control system design and small signal analysis of a phase shift controlled series resonant inverter for induction heating", in PESC Record- IEEE Power Electronics Specialists Conference, 1995, pp 450-456.

[10] Nabil A. Ahmed, "Three-phase High frequency AC conversion circuit with dual mode PWM/PDM control strategy for high power IH applications", PWASET Vol.35, pp 371-377, Novembre 2008.

[11] O. Lucía, J. M. Burdio, I. Millán, J. Acero, and D. Puyal, "Load-adaptive algorithm of half-bridge series resonant inverter for domestic induction heating," IEEE Trans. Ind. Electron., vol. 56, N°. 8, pp. 3106–3116, Aug. 2009.