Minimization of the switching losses in high power induction furnaces using an analog state feedback controller

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***Abstract*— Due to the high efficiency and low switching losses of resonant power convertors in comparison with switching convertors, nowadays there is a growing trend towards these convertors. However, because of the high frequency of switching in such convertors, it is quite difficult to present an efficient control method. In this paper, based on the state feedback method and using pole placement technique a control strategy is developed which controlling delay time in the converter's switching to minimize losses in the induction and hardening furnaces. In the propose method, the input voltage is isolated from output load. Moreover, fewer number of elements are employed in the control circuit which will be caused lower costs and small dimensions for control system. As a result, the proposed controller is more economical in comparison with the conventional ones. To show the effectiveness of propose controller, simulation circuits using PSIM software and an experimental setup are provided and the results are reported**

***Index Terms*— Switching losses minimization; Induction furnace; State feedback; SRC converter.**

SRC	Series Resonant Converter
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
DCM	Discontinuous Current Mode
CCM	Continuous Current Mode
F	Magnetomotive Force (MMF)
N	Turns Ratio
$\Re$	Load Reluctance
φ	Magnetic Flux
g	Air Gap
μ_0	Air Gap's Permeability
μ_r	Magnetic Material's Permeability
A_c	Cross-Sectional Area
E	Input Voltage Magnitude
V_o	Output Voltage Magnitude
R_l	Load Resistance
R_o	Characteristic Resistance
ω_o	Resonant Frequency
Q	Quality Factor
L_m	Transformer Magnetization Inductance
C	Series Capacitor
L_{ls1}	Primary Leakage Inductance
L_{ls2}	Secondary Leakage Inductance

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1. INTRODUCTION

In conventional converters usually switching occurs in non-zero voltages or currents which cause some losses. Switching losses will reduce efficiency of converters and switches life time [1].

Since resonant power convertors inherently create the possibility of ZVS and ZCS, they reduce the switching losses.

In comparison with linear power regulators and PWM convertors, resonant power convertors have a lot of benefits such as low switching losses, less switch stress and low EMI. Although the high switching frequency, will caused hard controlling of resonant converters, but it will caused a reduction in dimensions of passive elements and as a result converters volume.

Series resonant power convertors (SRCs) are composed of two energy storage elements type: a capacitor with high time's constant in output filter and resonant elements with low time's constants in comparison with output filter's ones. SRC is controlled by mean of the ratio of switching frequency to resonance frequency. In the past, elements with higher time's constant, were used for SRC controlling propose[2]. Nowadays experts have come to the conclusion that using resonant elements will made control system faster. In[3]the analysis of the state space of resonant power convertors has been conducted and a number of controlling methods for these convertors have been examined in [4].

In [5, 6] a method based on state feedbacks for reducing the switching losses has been offered. According to [6] this method is independent from load variations and can reduce switching losses to desired value. The reason for employing the current feedback for controlling the convertor, is the simplicity of control circuits and the making control system responsibility faster. The overall strategy of this paper is focused on the function of the circuit at two energy levels. The state flow diagram to achieve these two energy levels has been illustrated in reference [3]. When the switches are turned on, the energy level of the circuit increases and after the switches are turned off, due to the current flow through the anti-parallel diodes of IGBTs, some of the charge returns to the source and energy level will be reduced. A problem associated with this method is the delay time related to IGBT's drive, which will be caused the circuit does not work at the full resonance, and this leads to raise the switching losses.

In [7], utilizing linearization and computing linear relationships between the input and output of the convertor, a method based on linear control procedures had been developed. In [8] a SRC was analyzed with phase shift control and difference situation has been studied. According to [8] phase shift not only has a direct relation with resonant tank's gain but also can play an important role in ZCS or ZVS switching. In [9] a traditional control system was explained. This method involved two control loop that make SRC converter able to operate always in resonant frequency for all load situations. According to [10], it can be said that in DCM operation's mode, ZCS in turn off mode can be achieved and due to the SRC's inherent properties, ZVS in turn on mode can be achieved easily. Because of ZCS turn off and ZVS turn on, switching losses can be decreased to almost zero and efficiency can reach to the desired value.

In [11] a new topology of SRC was introduced. In this topology two power switches are used instead of rectifier's bridge, the switches are controlled such that secondary current be in phase with resonant tank current. Input switches operated in constant frequency and output regulated by means of output switches.

In [12], a time domain model of SRC was presented. This model can be used to study the static and dynamic behavior of SRC converters. In [13], series resonant converter was controlled based on frequency control and phase shift control strategies. In [14], a control method has been introduced that tracking resonant frequency in the inductive load with minimum loss, minimum heat and the highest conversion efficiency. In [15], a duty-cycle based control was proposed for robust controlling of series resonant converters.

In [16] a SRC for wide input variation has been proposed. In [17] a digital control of resonant converters at ultra-high frequency has been proposed, this type of SRCs can use in powering microprocessors. In [18] an optimal designing of SRC based on Lagrange's method was introduced. In [19] for proper power management propose a microprocessor based SRC has been introduced. In [20], a variable inductance was used to control and regulate the dc output voltage in SRCs. In that method the switching frequency was constant.

In recent years, using the microcontrollers and so on, various methods have been provided, e.g. the circuit used in [21]. The high number of elements utilized in control circuit is remarkable in this paper.

SRCs have many application like in [22] which an induction furnace with SRC was studied and an automatics resonant frequency tracking has been introduced. Because of high output frequency and near sine wave current, SRC can be used in laser power supply. Because of this properties in SRCs, they can be used in induction cooker. According to [23], high output frequency can induct eddy current and a hybrid series-parallel for induction cooker is proposed in [24].

In [25], utilizing SRCs in contact less charger for electrical vehicles is investigated. According to [26], series resonant converters can be used as a voltage regulator in notebooks, desktops, and servers. SRCs have one resonant frequency. In resonant frequency, SRCs have no sensitivity to load changes.

In this paper we proposed an application of SRCs in induction furnace. The converter has been controlled by getting feedbacks from the inductor current and capacitor voltage. The reason for the use of these two state feedbacks is to achieve the minimum time's constant through the placement of the poles at the desired locations. Initially, the states equations of the system have been written and then, they have been normalized. To overcome nonlinearity of equations of the system states, operation's time of the converter is divided into two areas and then equations are solved. Based on the results, feedbacks gain have been obtained. Using these gains we operate SRC in resonance frequency, which cause resonant capacitor's voltage and resonant tank's current become approximately sine wave. Using proposed technique have been attempted to eliminate losses and stabilize the output.

The rest of paper is organized as follows: in second 2 state equations of system are derived, in section 3 proposed control technique will be introduced to minimize losses, in section 4 and 5 simulation and experimental result are provided, finally in section 6 conclusion and remarks are given.

2. Problem Statement And Preliminaries

Induction heaters and furnace have different topology such as half bridge ZVS-PWM high frequency inverter [27], multi inverter [28]. The converter used in this paper is shown in Figure 1. In this circuit, $Q1$ and $Q2$ are IGBT switches with a duty cycle of 50% which are located in a half bridge topology. Four diodes placed at the output are used to rectifying the voltage. The loads used in this converter is resistive type and lies in the category of reluctance loads. Converter's terminal is always shorted by a coil and it can be said that short circuit is always seen from the diode output of the convertor.

In the reluctance loads, Eq. (1) and Eq. (2) are governing; in addition, these relations help to justify the change in the output's current:

$$F = N.I = \Re.\varphi \tag{1}$$

$$\Re = \frac{g}{\mu_0.\mu_r.A_c} \tag{2}$$

(2)According to Eq. (1) and Eq. (2), if load's reluctance has a change, output current and MMF will be change. Changes in bobbin core's dimensions and materials will result in reluctance changes.

It should be noted that since we know from the characteristic curve that the gain has no significant changes nearby resonant frequency point therefore, variations of coil reluctance from no load to full load can be neglected. Therefore the status of the convertor has been studied under no-load conditions which can justify the full load conditions at reasonable approximation.

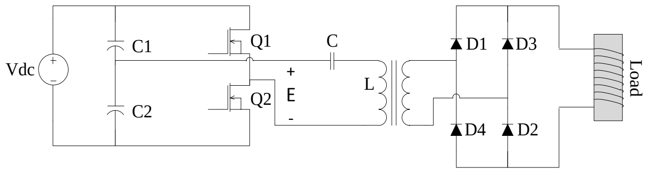

Figure 1: Schematic of circuit

According to Figure 1, we can write Eq. (3) and Eq. (4) as follows:

$$L\frac{di}{dt} = -v + E(t) \tag{3}$$

$$C\frac{dv}{dt} = i + abs\left(\frac{v_o}{R_L}\right) \tag{4}$$

To normalize Eq. (3) and Eq. (4), the variables Z_1, Z_2, Z_3 are defined as it follows:

$$z_1 = \frac{I_L}{I_{base}} = \frac{i}{\left(\frac{E}{R_o}\right)} \tag{5}$$

$$z_2 = \frac{v}{E} \tag{6}$$

$$z_3 = \frac{v_o}{E} \tag{7}$$

where Z_1 is the normalized inductor current, Z_2 the normalized voltage of the capacitor at resonance, and Z_3 is output's normalized voltage. Characteristic impedance and the frequency of the resonance can be defined according to Eq. (8) and Eq. (9).

$$R_o = \sqrt{\frac{L}{C}} \tag{8}$$

$$\omega_o = \frac{1}{\sqrt{LC}} \tag{9}$$

As it can be seen, with any changes in the impedance and capacitance values of the resonant tank, the characteristic impedance and the frequency of the resonance will change. Considering the Eq. (8) and Eq. (9), according to Eq. (10) by means of resonant frequency a new time's constant can be defined. According to Eq. (8) and Eq. (9) and load's value, resonant element value and quality factor can be defined such as below:

$$\tau = \omega_o t \tag{10}$$

$$L = \frac{R_o}{\omega_o}, C = \frac{1}{R_o.\omega_o}, Q = \frac{R_o}{R_L} \tag{11}$$

The aim is to find characteristic equation which used to find feedback's gain such that force converter to work at resonance frequency. The variables of state equations are capacitor's voltage and inductor's current and the input is resulted square waveform of switches (E). Substituting Eq. (10) and Eq. (11) in the Eq. (3) and Eq. (4) yields that:

$$\dot{z}_1 = -z_2 + u \tag{12}$$

$$\dot{z}_2 = z_1 + \frac{R_o}{R_L} abs(z_3) \tag{13}$$

As it can be seen, Eq. (13) is a non-linear equation and it cannot be solved easily. This non-linear effect is resulted from square waveform which is produced by switches. To linearize the equations, the following conditions are applied:

$$if \quad z_3 > 0:$$
$$\dot{z}_1 = -z_2 + u \ , \ \dot{z}_2 = z_1 + Q.z_3 \tag{14}$$

$$if \quad z_3 < 0:$$
$$\dot{z}_1 = -z_2 + u \ , \ \dot{z}_2 = z_1 - Q.z_3 \tag{15}$$

Considering the Eq. (14) and Eq. (15), since in this type of SRC because of shorted terminal of converter variable Z_3 can be neglected, therefore, we have:

$$\dot{z}_1 = -z_2 + u \tag{16}$$

$$\dot{z}_2 = z_1 \tag{17}$$

Eq. (16) and Eq. (17) can be written in matrix form (18):

$$\dot{z} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} z + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u \tag{18}$$

If the state feedback is considered as below:

$$u = \begin{bmatrix} -k_1' & -k_2' \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \tag{19}$$

where coefficient k_1' represents feedback's gain of the resonant inductor's current and coefficient k_2' expresses the feedback's gain of the resonant capacitor's voltage.

Because of the difficulty in changing current's feedback's gain, the value of coefficient k_1' is assumed to be 1. The coefficient k_2' is computed with respect to the aim of controlling the convertor. Substituting Eq. (19) in (18) yields that:

$$\dot{z} = \begin{bmatrix} -k_1' & -1-k_2' \\ 1 & 0 \end{bmatrix} z \tag{20}$$

The characteristic equation will be second order equation which named A(s). In general, regarding to the roots location, there are three types of answers: Over-damping, Under-damping and Critical damping. Our aim is computing the quickest response in order to minimize the time delay existing in control circuit, which is followed by minimizing the losses. Since the overshoot in the output can increasing stress on the switches, critical damping option is taken into account. Thus the coefficient k'_2 is obtained as follows:

$$A(s) = s^2 + (k'_1)s + (1 + k'_2) = 0 \;, k'_1 = 1 \tag{21}$$

$$\Delta = 0 \quad \rightarrow \quad k'_2 = 0.250 \tag{22}$$

Assuming the fact that equations have been normalized, the computed values above have been derived. To calculate the actual values, we have the following equations:

$$u = \begin{bmatrix} -k'_1 & -k'_2 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} -k'_1 & -k'_2 \end{bmatrix} \begin{bmatrix} \dfrac{i}{\left(\dfrac{E}{R_o}\right)} \\ \dfrac{v}{E} \end{bmatrix} \tag{23}$$

$$k_1 = \frac{k'_1}{\left(\dfrac{E}{R_o}\right)} \quad , \quad k_2 = \frac{k'_2}{E} \tag{24}$$

3. Control methods for the convertor

In this section, various methods for controlling the convector are being considered and the advantages and disadvantages of each of these controlling methods are stated. First of all, the control circuits are being presented for each method.

A. Feedback form transformer current

The circuit concerning this method is illustrated in

Figure 2.

In this control method, the transformer current —which is the capacitor C current—has been used as the feedback and this current is being compared with zero. Each time the current reaches zero, 50% duty cycle occur and Q1 and Q2 act reverse of each other. In this state, the switching frequency is equated with the resonant frequency of the capacitor and the transformer inductor.

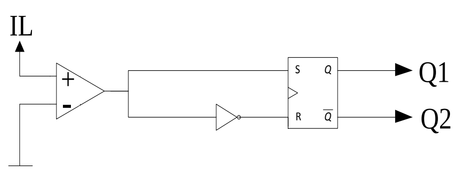

Figure 2: The schematic representation of the control circuit of the current feedback

But the problem of this method is the time delay present in the control circuit (this time delay includes: IGBT drive and logic gates that exist in the control circuit). These delays do not allow to get full resonance. It results in making switching losses, because the switches at the non-zero voltage and/or current turn on or off.

This delay time which is mostly caused by the delay time of IGBT drive can be resolved by exchanging the drive. However, this solution does not appear possible because time delay help Q1 and Q2 do not turn on with each other.

B. Feedback from the transformer current and capacitor voltage

The circuit in question is displayed in

Figure **3**.

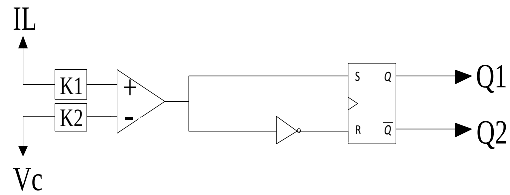

Figure 3: The schematic representation of the control circuit of the current and voltage feedback

In this control method, the control action can be done by comparing a coefficient of the capacitor's voltage with a coefficient of the transformer inductor's current. In this method, the switching frequency is proportionate to the resonance frequency of the inductor and capacitor. Difference between this method and previous method is that by accurate setting the k_1 and k_2 coefficients, delay time will be zero in the control system. These two coefficients are calculated in section 2.

4. Simulation

In this section, with regard to the control methods stated in section 3 and applying PSIM software, the system has been simulated. The purpose of this section is to indicate the benefits and drawbacks of the control methods.

The features of the simulated circuit are displayed in the table below:

Table 1: The features of the simulated circuit

Parameter	Value
E	250 V
L_m	2 mH
L_{ls1}	0.1 mH
L_{ls2}	1 nH
N	10
C	5 µF

Given the table above and using the control circuit of

Figure **2**, the waveform of the resonant circuit current in proportion to the voltage of the set of the inductor and capacitor resembles

Figure 4. In the graph above, the red sine form is related to the current of the set at resonance and the blue square waveform concerns the voltage of the set of the inductor and capacitor.

As it can be seen in the figure, by using this control system, the circuit does not completely enter the resonance and there is a delay time of 20 µs in the current.

Utilizing the Eq. (24), figuring out the values of k1 and k2 as well as using the control circuit of

Figure **3**, the waveform of the resonant current and the voltage of the set of the inductor and capacitor is indicated in

Figure 5. The values of k1 and k2 in this control are 0.031 and 0.001 respectively.

Considering
Figure 5, it can be observed that the problem of time delay has been solved and the circuit has really entered the resonance. This issue can be understood from the peak of the current at two states. Now in
Figure 6, a comparison of waveforms which have been compared in control systems will be made. 20 μs delay time is compensated in second control method.
Comparing these two simulations above proves the advantage of the control circuit of
Figure **3**.

Comparing
Figure 6 helps us realize that comparing the capacitor voltage with that of the inductor results in leading in the signal applied to transistors' gate. It also leads to in phasing of the waveform of the current and the voltage of the set at resonance

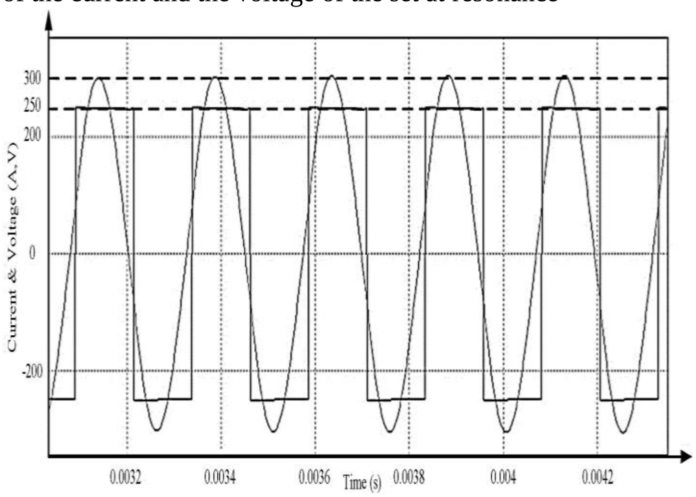

Figure 4: The waveform of the voltage and current in the presence of the control of the current feedback

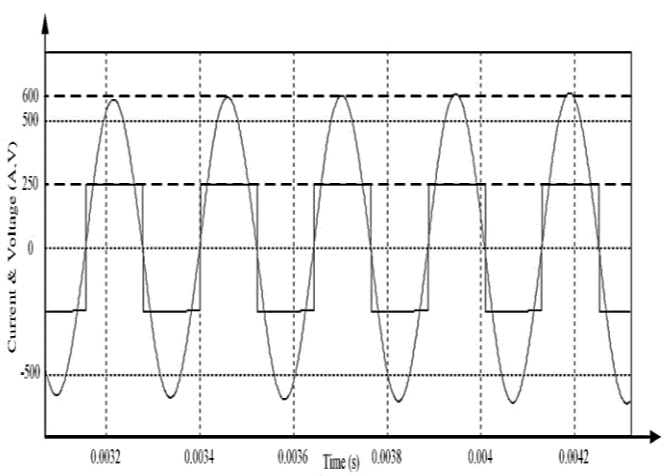

Figure 5: The waveform of the voltage and current in presence of the feedback control of voltage and current

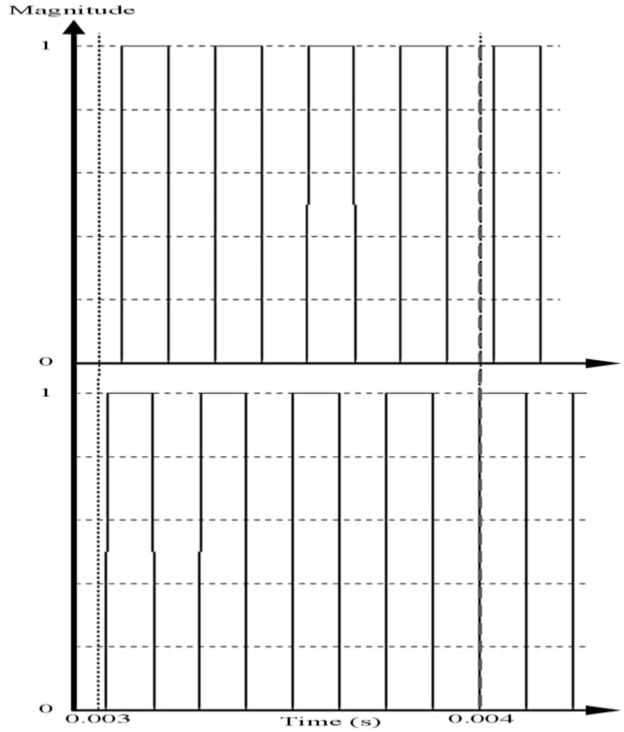

Figure 6: (a) The waveform of output compared with the current feedback (b) The waveform of output compared with the feedback of voltage and current

5. EXPERIMENTAL RESULT

Figure 7 displays an overview of experimental setup and

Figure **8** concerns the control circuit of this convertor.

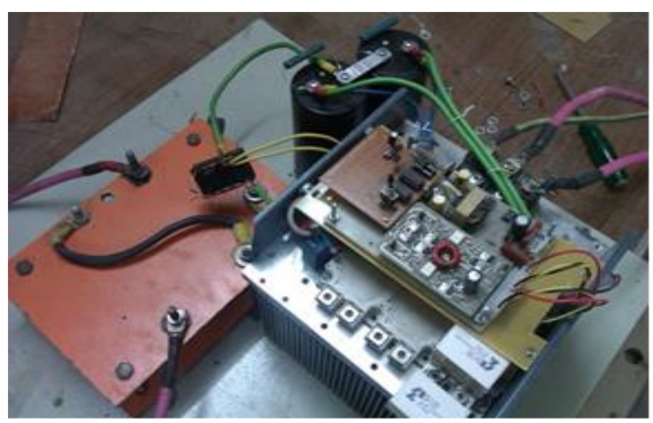

Figure 7: An overview of the circuit

In
Figure 9, time scale is 200μs and current scale is 20A and voltage scale is 100V. The resonant current and the input voltage waveforms for inductor and capacitor set resemble in
Figure 9. As it can be seen, at the moment that the square waveform has approached zero, the sine current has also reached zero. It indicates that these two waves are in phase and

the anti-parallel diodes of the switches do not turn on. In this case, the losses of switching have been minimized.

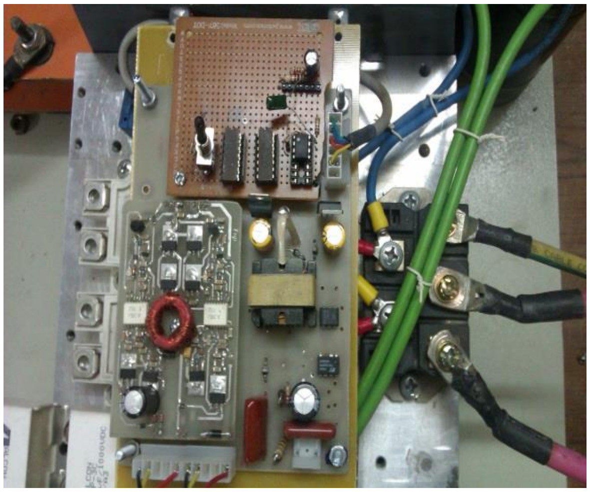

Figure 8: The view of the control circuit

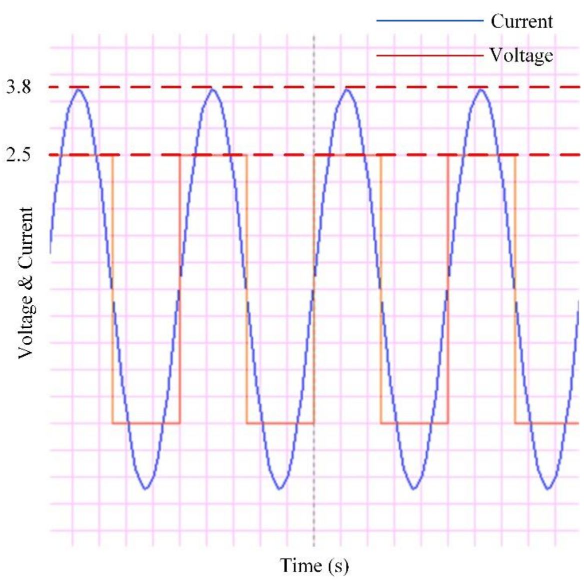

Figure 9: The waveform of the voltage and current using the control of the feedback of the current and voltage extracted from experimental setup

6. CONCLUSION

As mentioned in previous part, because of ZCS and ZVS ability, the switching loss can be decreased to desired value in SRC converter. However, because of the high frequency of switching in such convertors, controlling is difficult in this type converter. In this paper, a control method based on the state feedback for minimizing losses has been presented. By minimizing losses efficiency has been improved, and because of fewer elements in control system cost and volume is decreased significantly. According to experimental results, accuracy of proposed control system has been validated and the effectiveness of using the proposed control system in SRC converter has been confirmed.

The future work can be focused on the robust and adaptive controller design.

7. REFERENCES

[1] M. H. Rashid, Power Electronics Handbook. USA: Butterworth-Heinemann, 2011.

[2] M. G. Kim, D. S. Lee, and M. J. Youn, "A new state feedback control of resonant converters," *IEEE Transactions on Industrial Electronics*, vol. 38, pp. 173-179, 1991.

[3] R. Oruganti and F. C. Lee, "Resonant Power Processors, Part I---State Plane Analysis," *IEEE Transactions on Industry Applications*, vol. IA-21, pp. 1453-1460, 1985.

[4] R. Oruganti and F. C. Lee, "Resonant Power Processors, Part II-Methods of Control," *IEEE Transactions on Industry Applications*, vol. IA-21, pp. 1461-1471, 1985.

[5] L. Rossetto, "A simple control technique for series resonant converters," *23rd Annual* IEEE *Power Electronics Specialists Conference PESC 92*, 1992, pp. 787-792.

[6] L. Rossetto, "A simple control technique for series resonant converters," *IEEE Transactions on Power Electronics*, vol. 11, pp. 554-560, 1996.

[7] H. Sira-Ramírez and R. Silva-Ortigoza, "On the Control of the Resonant Converter: A Hybrid-Flatness Approach," *Fifteenth International Symposium on Mathematical Theory of Networks and Systems* Indiana, 2002, pp. 1-5.

[8] A. A. Aboushady, K. H. Ahmed, S. J. Finney, and B. W. Williams, "Steady-state analysis of full-bridge series resonant converter with phase-shift and frequency control," *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*, 2010, pp. 1-6.

[9] I. Khan, J. Tapson, and I. De Vries, "Automatic frequency control of an induction furnace," *IEEE* in Africon, 1999, pp. 913-916 vol.2.

[10] F. M. Ibanez, J. Vadillo, J. M. Echeverria, and L. Fontan, "Anomalous step-up behavior in discontinuous series resonant converters," *IEEE 15th Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2014, pp. 1-6.

[11] D. J. Tschirhart and P. K. Jain, "Secondary-side control of a constant frequency series resonant converter using dual-edge PWM," *Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2010, pp. 544-549.

[12] M. M. Peretz and S. Ben-Yaakov, "Digital Control of Resonant Converters: Frequency Limit Cycles Conditions," *Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition* (APEC 2009), 2009, pp. 1704-1708.

[13] P. Ranstad, H. P. Nee, and J. Linner, "A novel control strategy applied to the series loaded resonant converter," in Power Electronics and Applications, 2005 European Conference on, 2005, pp. 10 pp.-P.10.

[14] J. Tu, "Study and Implementation on Intelligence Frequency Tracking Model of Resonant Converter," *1st International Conference on Information Science and Engineering (ICISE 2009)*, 2009, pp. 404-408.

[15] A. Mohammadpour, H. Mokhtari, and M. R. Zolghadri, "Control of series resonant converter with robust performance against load and power circuit components uncertainties," *1st Power Electronic & Drive Systems & Technologies Conference (PEDSTC 2010)*, 2010, pp. 122-128.

[16] C. Je-Hyung, P. Ki-Bum, M. Gun-Woo, and Y. Myung-Joong, "A Hybrid PWM Resonant Converter Suitable for Wide Input Variation," *Applied Power Electronics Conference and Exposition (APEC 2009)*, 2009. Twenty-Fourth Annual IEEE, 2009, pp. 1504-1510.

[17] D. J. Tschirhart and P. K. Jain, "Digital control of resonant converters at ultrahigh frequency," *32nd International Telecommunications Energy Conference (INTELEC)*, 2010, pp. 1-6.

[18] A. Kiyoumarsi, R. o. A. Houshmand, R. Ali-Zargar, and M. r. Hassanzadeh, "Closed loop power control of an induction furnace,", *18th International Conference on Electrical Machines.(ICEM 2008)*, 2008, pp. 1-6.

[19] O. Jimenez, O. Lucia, I. Urriza, L. A. Barragan, and D. Navarro, "Power Measurement for Resonant Power Converters Applied to Induction Heating Applications," *IEEE Transactions on Power Electronics*, vol. 29, pp. 6779-6788, 2014.

[20] J. M. Alonso, Perdiga, x, M. S. o, D. G. Vaquero, A. J. Calleja, et al., "Analysis, Design, and Experimentation on Constant-Frequency DC-DC Resonant Converters With Magnetic Control," *IEEE Transactions on Power Electronics,* vol. 27, pp. 1369-1382, 2012.

[21] D. Milcevski, G. Stefanov, and L. Karadzinov, "Microcontroller Based Phase Control Circuit for Resonant Power Converters," *International Symposium on Power Electronics*, Republic Of Serbia, 2011, pp. 1-5.

[22] T. Phanom, "An induction furnace employing with half bridge series resonant inverter," 11th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON 2014), 2014, pp. 1-3.

[23] Y. Lu, K. W. E. Cheng, K. W. Chan, Z. G. Sun, and S. W. Zhao, "Development of a commercial induction cooker," *3rd International Conference on Power Electronics Systems and Applications,(PESA 200).*, 2009, pp. 1-3.

[24] P. K. Sadhu, D. Sinha, N. Paul, and A. Bandyopadhyay, "Energy efficient induction heated cooking - range using MCT based hybrid resonant converter," *2nd International Conference on Computer and Automation Engineering (ICCAE 2010)*, 2010, pp. 637-641.

[25] S. Valtchev and S. Valtchev, "Experimental study of the energy portions control in Series Resonant Converters," *13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM 2012)*, 2012, pp. 827-832.

[26] D. J. Tschirhart and P. K. Jain, "Variable frequency pulse density modulation for efficient high frequency operation of series resonant converters operating as voltage regulators," *Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC 2010)*, 2010, pp. 1334-1339. H. Sugimura, B. Saha, K. Soon-Kurl, S. Hideki, S. Sumiyoshi, H. Omori, et al., "A single stage induction heating high frequency series load resonant ZVS-PWM inverter with active filtering pfc rectifier operating at one diode conduction and ZCS commutation," *6th International Power Electronics and Motion Control IEEE Conference, (IPEMC 2009)* , 2009, pp. 689-695.

[27] Luci, x, O. a, Burdi, x, J. M. o, et al., "Series-Resonant Multiinverter for Multiple Induction Heaters," *IEEE Transactions on Power Electronics,* vol. 25, pp. 2860-2868, 2010.

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