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REGULATION OF THE OUTPUT POWER AT THE RESONANT CONVERTER

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Abstract

In this paper a method for regulating an alternating current voltage source with pair of IGBT transistor's modules, in a full bridge configuration with series resonant converter is given. With the developed method a solution is obtained which can regulate the phase difference between output voltage and current through the inductor, in order to maintain maximum output power. Control electronic via feedback signals regulates the energy transfer to the tank by changing the pulse width of signals which are used as inputs to the gates of the IGBTs. By increasing or decreasing the pulse width transmitted to the various gates of the IGBT the energy transfer to the tank is increased or decreased . PowerSim simulations program is used for development of controlling methodology. Developed method is practically implemented in a prototype of the device for phase control of resonant converter with variable the resonant load.

Key words: pulse width method, phase regulation , power converter.

1. INTRODUCTION

Power converter loaded by serial resonant load is very suitable for control of processes in which output load changes dynamically. The process in the induction heating is one of them. In such configuration maintaining maximum output power is an imperative [1], [7], [10]. In order to get the maximum output energy, operating frequency of power supply must track the resonant frequency of resonant tank. Commonly, the approach for regulation of the output power includes the control of duty cycle and switching frequency, [2], [3]. The frequency control scheme is one of the most popular control schemes. However, direct frequency control results in a number of disadvantages, including high sensitivity near resonance, strong dependence on the resonant tank, and requirement for additional control circuitry to detect operation below resonance in order to prevent non zero voltage switching (ZVS) conditions. Another control method which is becoming more popular is the regulation of the phase angle between the output voltage and the resonant inductor voltage or current, [3]. By regulating the inductor current or voltage phase angle, the switching frequency is regulated and hence, the operating point is controlled. Phase control provides advantages of self-tuning to the tank resonant frequency (insensitive to component variations), reduced sensitivity for improved control near resonance, and inherent protection against the operation below resonance to avoid non-ZVS conditions. When it is operated above resonance, the resonant inductor dominates at the resonant tank so the output impedance of the converter is inductive as presented in Fig. 1, and the inductor current lags (and hence, the inductor voltage leads) the output voltage from 0° to 90° as the switching frequency shifts away from resonance. The output power decreases as the phase angle varies from 0° to 90°. Thus, it is possible to control the output power by directly controlling the phase angle between the output voltage and inductor voltage or current. The switching frequency on this way is indirectly controlled through phase control.

By controlling the phase angle between the output voltage and the inductor current to be larger than 0, the system will be forced to operate above resonance, resulting in ZVS operation for appropriately designed resonant tanks. When the resonant frequency shifts due to variations of the tank elements and load, the phase controller will self-tune to the resonant frequency and the operating point will not be affected. Phase control can be performed by sensing either the inductor current or voltage. Current sensing gives accurate results since the current is nearly sinusoidal, but requires a current transformer (CT), which is not desired for some applications. The method of inductor voltage sensing results in more significant phase error due to the larger harmonic components in the inductor voltage, since the inductor is usually connected to the switching network.

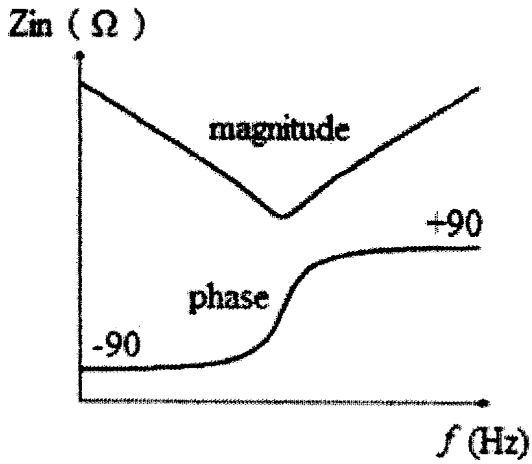


Fig. 1. Input impedance for a typical resonant tank

2. CONTROL OF THE OUTPUT POWER

During the heating process, the load resistance and inductance vary hugely. This variations change the resonant frequency of the resonant circuit since the load inductance and resistance are part of a resonant tank, Fig. 2, [6]. The process in the induction heating is dynamical process and its dynamic influences the resistance and inductance of the resonant tank.

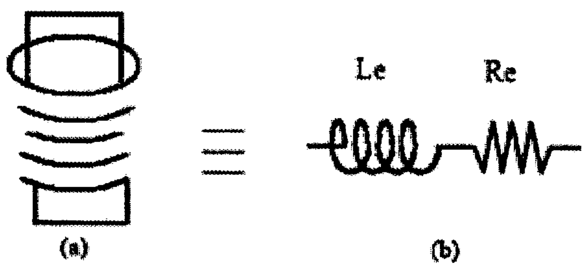


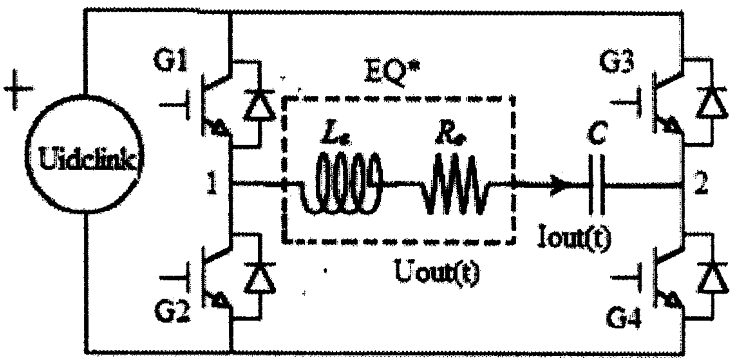
Fig. 2. (a) Inductor, (b) L-R equivalent circuit

In the Fig. 3 is given full bridge converter witch is load with equivalent Le, Re parameters from induction device. Parameters of the circuit are:

Rms value on the square wave Uout(t) in the case of power converter at no-load condition or loaded with dominant resistance load is given with equation (1), [9].

$$Uoutrms = Uidclink\sqrt{\frac{k}{2^{n-1}}} \quad (1)$$

Where n is number of bits which are processing signals in control electronic, and k is the number of the time intervals which equal to $T/2^n$. Constant k obtains values from 1 to 2^{n-1}.



EQ*-equivalent circuit from heating device

Fig. 3. Full bridge converter with equivalent resonant circuit

The switching frequency f_{sw} equal to resonant frequency f_0 of the resonant tank is calculated with equation (2):

$$f_{sw} = \frac{1}{2\pi\sqrt{L_e C}} \quad (2)$$

IGBT transistors are used as main switching elements.

In the Fig. 3 at connection points 1 and 2 output load is connected. The signals from the control unit over the driver circuit are controlling the gates of four transistors in the bridge. They are square pulses whose width changes in order to obtain voltage with effective value and frequency specified by the particular application on the output of the converter. The applications of the induction devices do not require strict criterion in terms of sinus form of the output voltage from the converter. So for such applications output voltage can deviate from the ideal sinus wave. The wave forms of the pulse signals on the gates of IGBT transistor and the output voltage is present Fig. 4.

The selected values of the components, DC link voltage and the output converter power for resonant frequency of 6 kHz are given in Table 1.

Table 1. Values of the parameters of the converter

Uidclink (V)	Poutmax (W)	values of components Re (Ω)	Le (μH)	C (μF)
75	9000	0.468	8.6	13

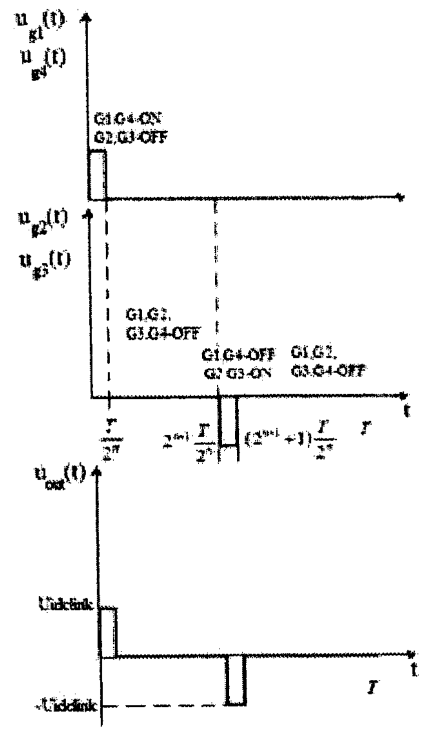
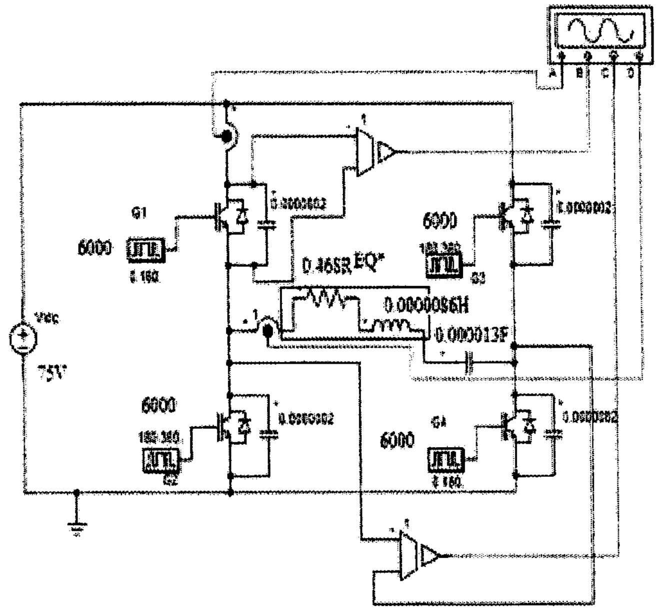


Fig. 4. The wave forms of the pulse signals on the gates of IGBT and the output voltage

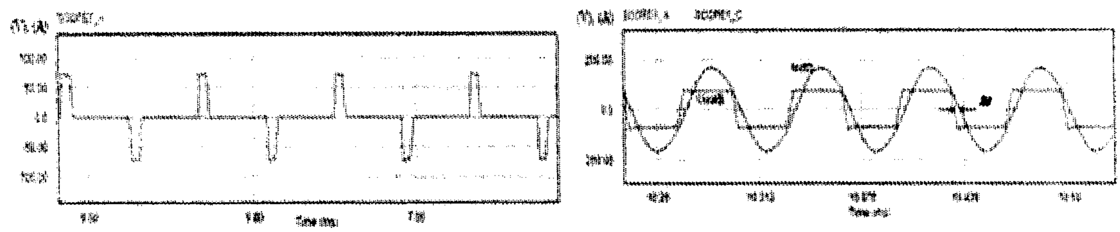
In Fig. 5. is presented simulation circuit for the full bridge converter with the series resonant circuit for above given values of the parameters , [4] .

In Fig. 6 are given wave forms of the output voltage for $k = 1$, $n = 4$ bits and the time interval $T/2^4 = T/16$, also the output voltage and current for $k = 2^{n-1}$, $n = 4$ bits which are obtained from simulation of the circuit from Fig. 3 in the PowerSim program, [4]. From the Fig. 5 it can be concluded, that when circuit operates close to the resonant frequency output inductor current lags behind output voltage for phase angle Δφ.



EQ* Equivalent circuit from heating device

Fig. 5. Simulation circuit for the full bridge converter with the series resonant circuit



a) b)

Fig. 6. Wave forms: (a) output voltage for $k = 1$, $n = 4$ bits, time interval $T/2^4 = T/16$, (b) the output current lags behind the output voltage

n Table 2 are given results of simulation of full bridge power converter when it operates with the series resonant load.

The results from Figs. 4, 5 and Table 2 show that the change on the pulse width on the gates for IGBT change phase angle between current and voltage as well as the output power. So, the change of the phase angle between the current and the output voltage of converter can regulate the output power of the converter.

Table 2. Values on the output power, current and phase difference in dependence of pulse width on the gates of IGBTs

G1 (°)	G2 (°)	G3 (°)	G4 (°)	Ioutrms (A)	Uoutrms (V)	Δφ (°)	Sout (VA)	Iout lag/lead
0-167	180-147	180-147	0-167	117	65	8.1	7605	lag
0-170	180-350	180-350	0-170	120.8	67.2	5.4	8117	lag
0-175	180-355	180-355	0-175	133.3	72	4.9	9598	lag
0-178	180-358	180-358	0-178	119	72	0.5	8568	lead
0-180	180-360	180-360	1-180	118	72	2.1	8496	lead

METHOD FOR PHASE CONTROL

The configuration of a full bridge series resonant converter with digital phase control by inductor current sensing is shown in Fig. 7, [9], [10]. Analysis is made in case when processing of signals is performed with n-bits and the controller determinates the value of binary signals at time intervals 2^n. The period of the output signal of the converter will be synthesized into time interval 2^n and each interval has duration of $T/2^n$.

The microprocessor controls the synthesized voltage on the output of the converter for $kT/2^n$ intervals, where k obtains values from 1 to 2^{n-1}.The wave forms in this closed loop system are presented in Fig. 8, [4]. The method begins with determination of the period by detecting the inductor zero current crossing, then computes the required time delays from the zero crossing in order to determine when to turn on/off the upper and down transistor in the appropriate IGBT module and to achieve the desired phase difference. Bellow is presented, the control equations for current sensing.

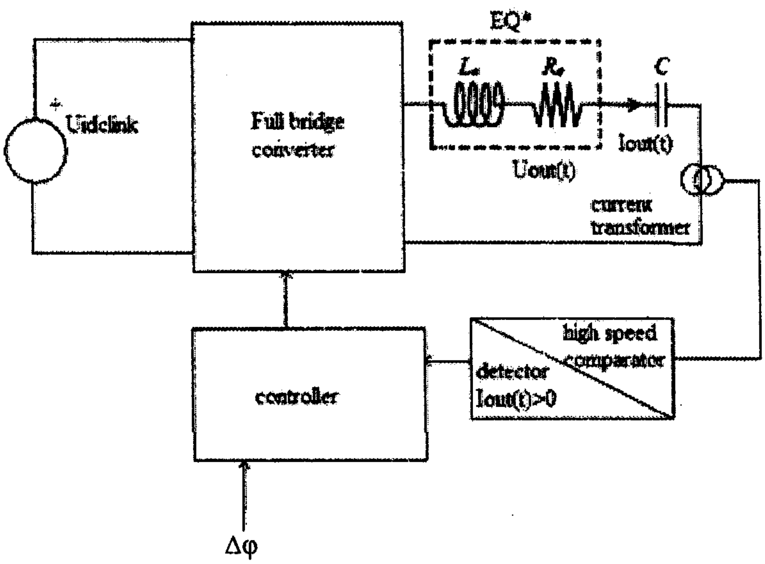


Fig. 7. Digitally controlled serial resonant converter with inductor current sensing

From Fig. 8, it can be derived:

$$T_{delay} = \frac{kT}{2^n} - \Delta t = \frac{kT}{2^n} - \Delta\varphi \frac{T}{360} \tag{3}$$

where Δt is time difference between output voltage and inductor current. $\Delta\varphi$ is phase command and T is a period. T_{delay} is a control variable and it can be computed from the phase command and the period. The methodology of phase control with sensing the inductor current is presented bellow in a consequent manner:

1. Detect the zero-crossing of the inductor current using a high-speed comparator.
2. Record T of the previous cycle, which is the time interval between two zero-crossing points.
3. Compute T_{delay} according (3).
4. Wait T_{delay}.
5. Turn off G1 and G4 (Fig. 4).
6. Wait $T_1 = \frac{T}{2}(1 - \frac{k}{2^{n-1}})$
7. Turn on G2 and G3 (Fig. 4).
8. Wait $k\frac{T}{2^n}$
9. Turn off G2 and G3.
10. Wait $T_1 = \frac{T}{2}(1 - \frac{k}{2^{n-1}})$
11. Turn on G1 and G3.
12. Wait for the next zero-crossing of the inductor current, then repeat this cycle.

Taking into consideration equation (3), for $\Delta\varphi/90° = \theta$, general form of equation for current sensing is derived as:

$$T_{delay}[i] = \frac{T[i-1]}{2^{n+2}}\left(4k - \theta[i]2^n\right) \tag{4}$$

where "i" is current cycles, and $0 \le \theta[i] \le 1$.

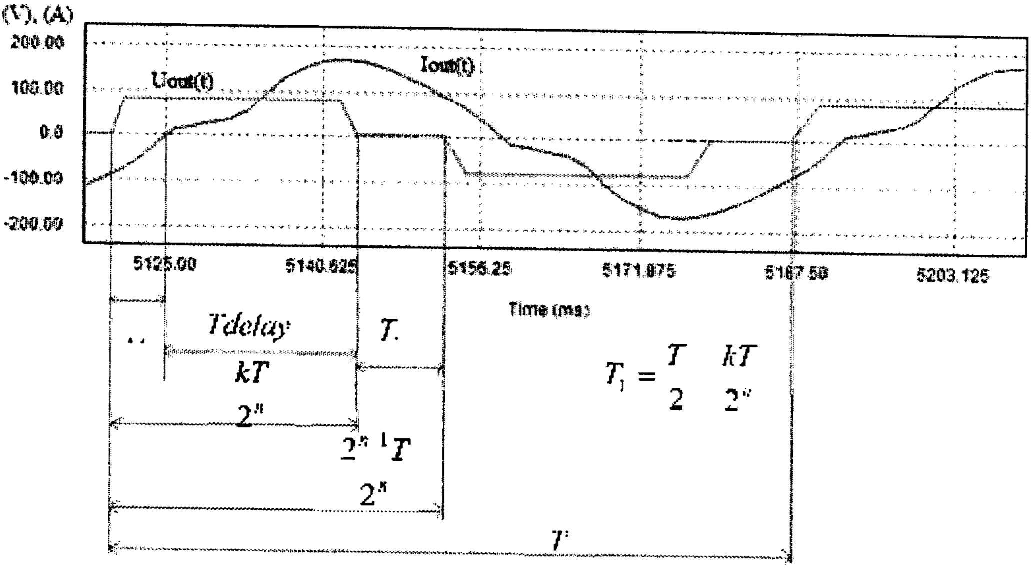


Fig. 8. Output current and output voltage in the full bridge serial resonant converter

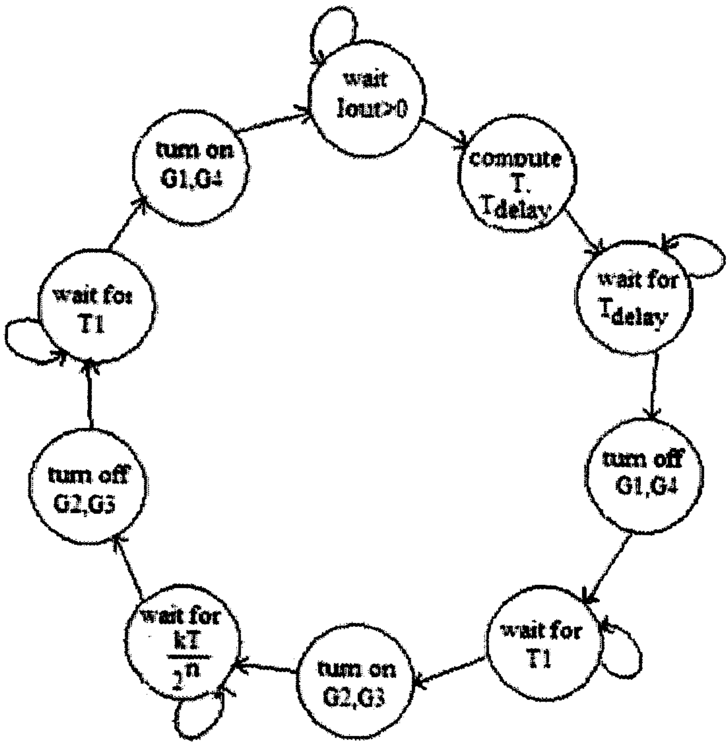


Fig. 9. State diagram of digital control algorithm by current sensing

From (4) we can see that the switching period of the previous cycle is used for delaying the computation of the current cycle.

The state diagram of the digital control algorithm is presented in the Fig. 9. The method can be easily realized using standard digital logic and by implementing it in CMOS digital control IC or programmable logic. It can also be implemented in a microcontroller or digital signal processor (DSP).

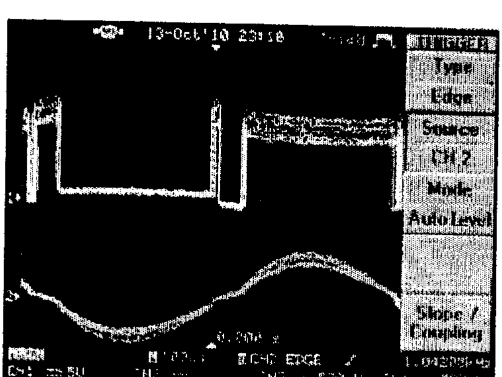
3. EXPERIMENTAL RESULTS

Based on research of digital phase control of resonant converter presented in this paper and authors previous work [10], we have realized a prototype of the device for phase control of resonant converter based on microprocessor Pic18F452. The work of the controller with installed program code is simulated in the simulation program PROTEUS. The device for phase control is tested in configuration of the half bridge serial resonant converter with changeable inductance of the resonant circuit for 22%. The results of measurements are given in Table 3 and Fig. 10.

Table 3. Shift of the switching frequency of the converter when inductance of the resonant circuit is changed

	$L(\mu H)$	$C(\mu F)$	$R(\Omega)$	$f_o(Hz)$	$I_{outrms}(A)$	$U_{DCLINK}(V)$
а)	423	55	0.5	1043	4.45	10
б)	485	55	0.5	976	3.3	10
в)	526	55	0.5	932	4.26	19.5
г)	542	55	0.5	922	3.3	20

Table 3 shows that the phase control circuit moves the switching frequency when inductance of the resonant circuit is changed.



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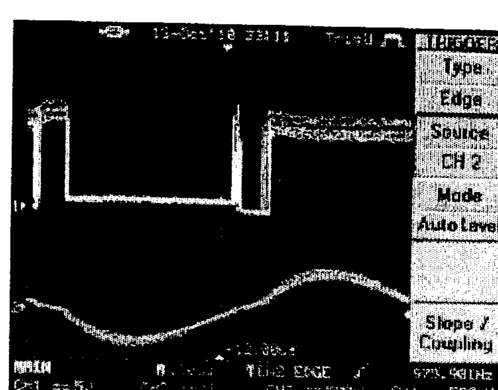

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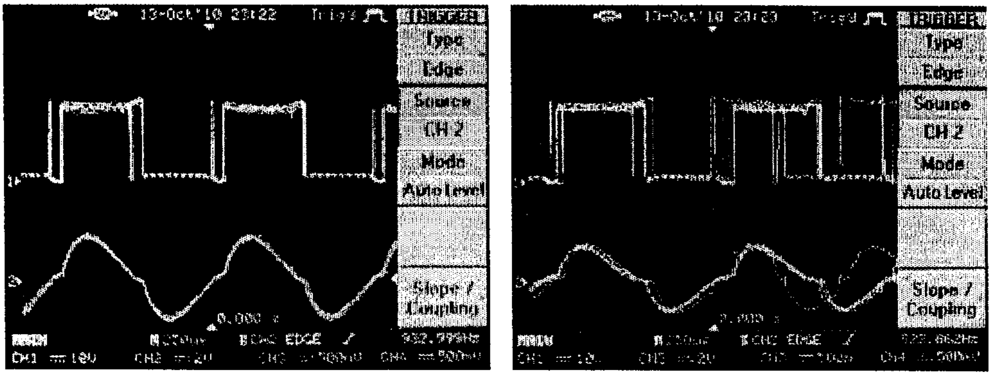

в) г)

Fig. 10. Wave forms of the output voltage and output current at phase controlled serial resonant converter

Performed simulations and experimental measurements proved that:

- The results of simulations and experiments showing satisfactory agreement.
- On the basis of the developed methodology for the device for phase control and by using the programming code and microprocessor support of 18F452 controller, phase difference (the indirect resonant frequency) between the output voltage and the output current is controlled and regulated.
- The value of the DC link voltage and the effective value of current is determined by the available technical possibilities which we had during the research.

4. CONCLUSION

This paper is a result of theoretical research of the authors regarding application of the resonant converters in a control of processes with variable dynamic. Method for regulation of alternating current voltage source with pair of IGBT transistor's modules, in a bridge configuration with serial resonant converter is developed and presented. Presented solution can be applied in the induction heating of metals. In the process of the induction heating the parameters of resonant circuit R and L are changing. As a consequence of their change the resonant frequency is also changed. Since the maximum power of the resonant converter is developed at resonance frequency, the shifting of the resonant frequency causes a change of the output power of the converter. By the aid of the developed method a theoretical solution for regulation of phase difference between output voltage and the current through the inductor is obtained. So the output power of the converter is maintained at maximum value. By regulation of the phase angle of the inductor current the operating point is controlled as well. Developed method is practically implemented in a prototype device for phase control of resonant converter with variable resonant load. Also, this method can be a good basis for control of processes with variable dynamic, realized by using standard CMOS logic, or digital signal processor (DSP). The research of authors is focused on development and promotion of software for microcontroller based on the methodology described in this paper.

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