BEHAVIORAL MODELING OF A CONTROL SYSTEM OF A TRANSISTOR RESONANT INVERTER OPERATED ABOVE RESONANT FREQUENCY

Tsvetana Grigorova[1], Nikolay D. Bankov[2]

[1]Department of Electronics, Technical University –Sofia, Branch Plovdiv, blvd. Sankt Petersburg 61, 4000 Plovdiv, Bulgaria, phone: +359 32 659721, e-mail: c_grigorova@abv.bg
[2]University of Food Technologies, 26 Marital Blvd., 4002 Plovdiv, Bulgaria, phone: +359 32 603791, e-mail: nikolay_bankov@yahoo.com

Keywords: transistor resonant inverter, control system, methods for deep regulation

The paper presents behavioral modeling of a control system of the transistor resonant inverter, operated above the resonant frequency. The self-oscillating control system allows deeply control of the inverters output power, by varying the transistor turn-on time. Inverter analysis is made by means of the new coefficients K_U and K_θ, which are the transistors and diodes conduction angles function. These quantities directly correspond with the consideration modern methods for deep regulation of the transistor inverter output power. Their using ensures the calculating quickness and convenience. They allow evaluating the behaviour of the mentioned resonance inverter when the load is changed during the time of a real technological process.

In the control system, the switches operate with suitable dead time between the driving commands, ensuring zero voltage turn-on (ZVS). The transistors current limiting system is introduced. The control system allows improving resonant inverters stability and response time by sudden large changing of the load, power supply or the driving commands. The computer simulation of the induction melting transistor inverter confirms the analysis results.

1. INTRODUCTION

Resonant converters have many favorable advantages. They can be designed for zero-voltage switching (ZVS), zero-current switching (ZCS) in either current fed or voltage fed topologies. Indeed, they were shown to be useful in multitude of applications ranging from dc-dc converters [1], active power factor correction circuits, to capacitor charges [2], and electronic welders [3], [4]. In most cases the output power of the resonant inverters changes a lot as the size and character of the load as well as the supply voltage changes. Therefore a measure should be output power according to a certain rule. There are modern methods for deep regulation of the output power inside the resonant inverter [5]-[7]. At the same time the input DC source can be uncontrolled. A method for output power control of resonant inverters, belonging to this group of methods, which has not been thoroughly studied, is based on the change in the transistors turn-on time [8].

2. CIRCUIT ANALYSIS AND MAIN STEADY STATE EQUATIONS

Fig.1 shows the full-bridge transistor resonant inverter. The power switches used in the circuit are MOSFET transistors. Assuming that the switches, transistors and diodes are ideal.

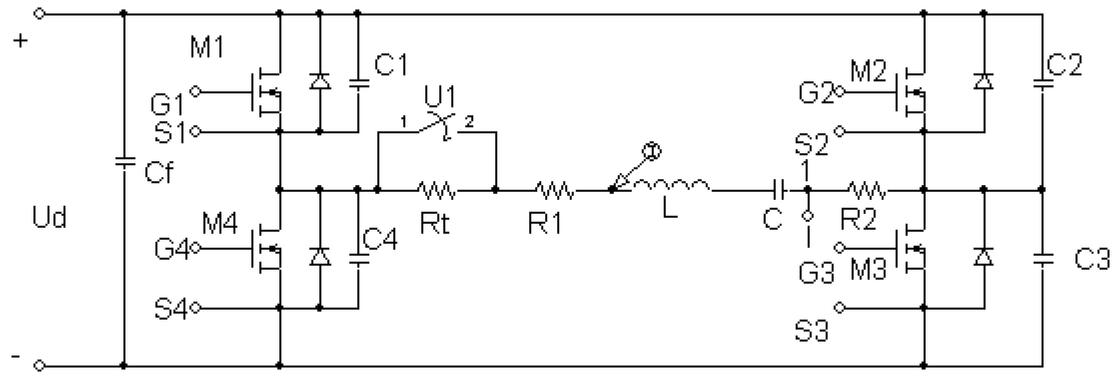

Fig.1 Full-bridge resonant inverter

The inverter operates in continuous current mode as $\omega_S > \omega_0$. The electromagnetic processes investigation in the inverter at the rated mode is made on the basis of the offered analysis in [9] for the transistor resonant inverter, operated above resonant frequency. The necessary results for the inverter design are shown in table 1, where the following common symbols are used:

- $\omega_0 = 1/\sqrt{LC}$ - resonant frequency; ω_S - switching frequency;
- $\nu = \omega/\omega_0$ - frequency coefficient; $\delta = \dfrac{R}{2L}$ - resonant link damping factor;
- I_{L0}, U_{C0} - initial values of the resonant link current and voltage across series capacitor for each stage of the converter operation - eqns. (7) and (9);
- $\theta_{VT} = \omega_0 \cdot t_{VT}$ - transistors conduction angle; $\theta_{VD} = \omega_0 \cdot t_{VD}$ - diodes conduction angle.

Table 1
Results from analysis

Quantity	Expression	
$\theta_{VT} + \theta_{VD}$	π/ν	(1)
θ_{VD}	$arctg \dfrac{\sin \pi/\nu}{e^{\frac{\delta}{\omega_0}\cdot\frac{\pi}{\nu}} + \cos \pi/\nu}$	(2)
θ_{VT}	$\dfrac{\pi}{\nu} - arctg \dfrac{\sin \pi/\nu}{e^{\frac{\delta}{\omega_0}\cdot\frac{\pi}{\nu}} + \cos \pi/\nu}$	(3)
α	$\dfrac{tg\theta_{VD}}{1 - \dfrac{\delta}{\omega_0} tg\theta_{VD}}$	(4)

K_U	$\dfrac{tg\theta_{VD}}{e^{-\frac{\delta}{\omega_0}\theta_{VT}} sin\theta_{VT}\left(1-\dfrac{\delta}{\omega_0}tg\theta_{VD}\right)}$	(5)
K_θ	$\dfrac{tg\theta_{VT}-\dfrac{\delta}{\omega_0}tg\theta_{VT}tg\theta_{VD}}{tg\theta_{VT}+tg\theta_{VD}}$	(6)
U_{C0}	$U_d(2K_\theta-1)$	(7)
U_{Cm}	$U_d(2K_U K_\theta-1)$	(8)
I_{L0}	$\dfrac{2\alpha K_\theta U_d}{\omega_0 L}$	(9)
I_{VTav}	$\omega C U_d \dfrac{(1+K_U)K_\theta-1}{\pi}$	(10)
I_{VDav}	$\omega C U_d \dfrac{(1-K_U)K_\theta}{\pi}$	(11)
I_d	$2(I_{VTav}+I_{VDav})=2\omega C U_d(2K_\theta-1)/\pi$	(12)

Inverter analysis is made by means of the new coefficients K_U and K_θ, which are the transistors and diodes conduction angles function. These quantities directly correspond with the consideration modern methods for deep regulation of the transistor inverter output power. Their using ensures the calculating quickness and convenience. They allow evaluating the behaviour of the mentioned resonance inverter when the load is changed during the time of a real technological process.

3. CONTROL SYSTEM OF THE INVERTER

The operation of the control system (CS) fig.2 is synchronized with the current **i** in the resonant circuit. The control system is described using Analog Behavioral Modeling (ABM) [10]. In the control system, the switches operate with suitable dead time between the driving commands, ensuring zero voltage turn-on (ZVS).

The resistor R2 senses the current through the resonant link (fig.1). This information is delivered of the voltage-controlled switches (S2, S3), realizing input synchronized device, which tracks the resonant current zero crossing. The shaped pulses start the sawtooth voltage generator (SVG) (fig. 2), formed by the capacitor C8, current source I1 and controlled voltage source E6. The voltage increasing time is equal to the transistors turn-on time - t_{VT}. The voltage-control switch S1 output shaped pulses are used to zeroing SVG at the same time, are fed to the flip-flop trigger U1. The pulse distributor U1 forms two channels of the control pulses, dephased at 180^0. The dependent voltage sources E3÷E6 provide the required power, amplitudes and galvanic separation of the control signals.

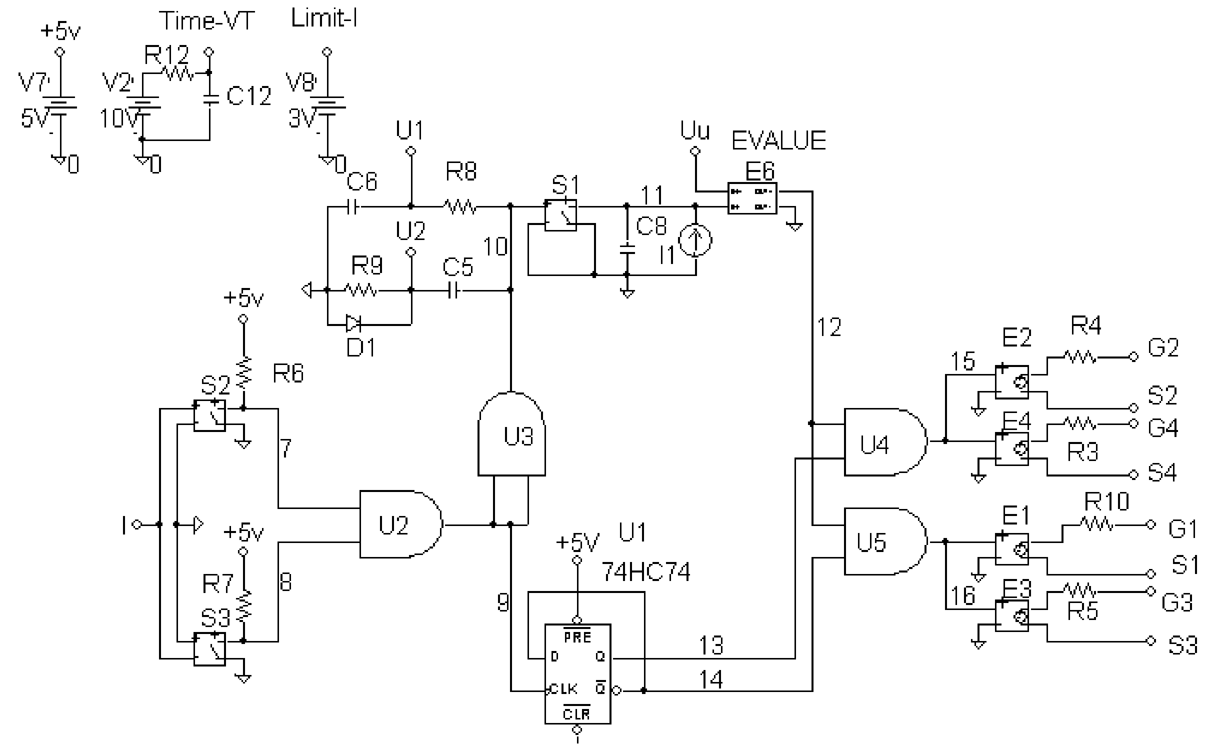

Fig.2 Inverter control system

The turn-on time of the transistors is achieved through V_2, R_{12} and C_{12} - signal Time-VT. The inverter current limitation level is fixed through V_8 (signal – Limit-I).

Fig.3 circuit realizes the peak current limit of the inverter, which is fixed through V3 (signal Limit-I), in an advance specified level.

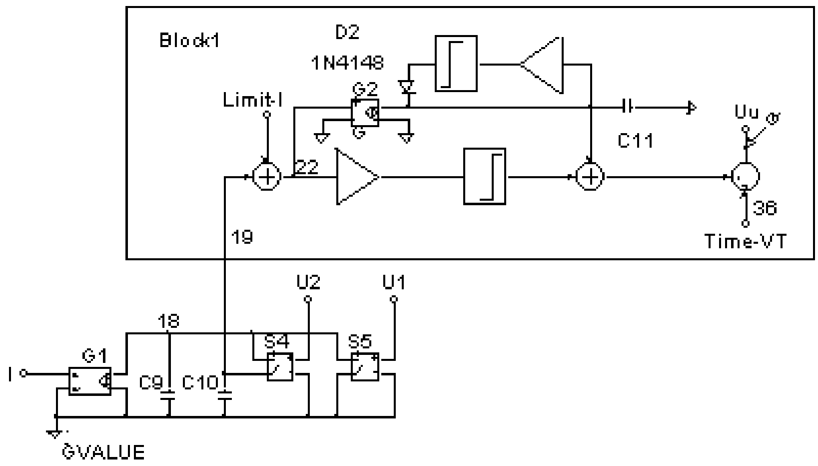

Fig.3 Peak current limited circuit of the inverter

For the purpose feedback circuit by current controlled source G_1, voltage-controlled switches S_4 and S_5, and capacitors C_9, C_{10} is realized. The voltage of the capacitor C10 is compared to the signal Li by means of the Block1 circuit) changes control signal Uu, thus the transistors turn-on time is decreased. The signal Uu is equal to the signal Time-VT, if the peak current is smaller than the previously specified value.

4. SIMULATION RESULTS

By means of proposed design method is designed transistor resonant inverter by following input evidence: P = 2,5kW; f = 100kHz; U_d = 300V. ω' = 1,15 is chosen. The resonant circuit elements values are: C =35nF, L =96μH and R = 14,5Ω.

The following quantities values are received: k = 2.87; ν = 1.16; α = 0,84; θ_{VD} = 0,64rad; θ_{VT} = 2.06rad; K_U = 1,28; K_θ = 1,49; U_{C0} = 593,4V; U_{Cm} = 840V; I_{L0} = 14,5A; I_{VTav} = 5,02A; I_{VDav} = 0.87A; θ_m = 1,43rad; I_{VTmax} =17,8 A; I_d = 8,3A. MOSFET transistors, type IRFP450 have been used. During the simulation snubbers value is 1nF. Fig. 4 shows the OrCad PSpice computer simulation results, which confirm these from the analysis - U_{Cm} = 839.758V, I_{VTmax} =17,817A.

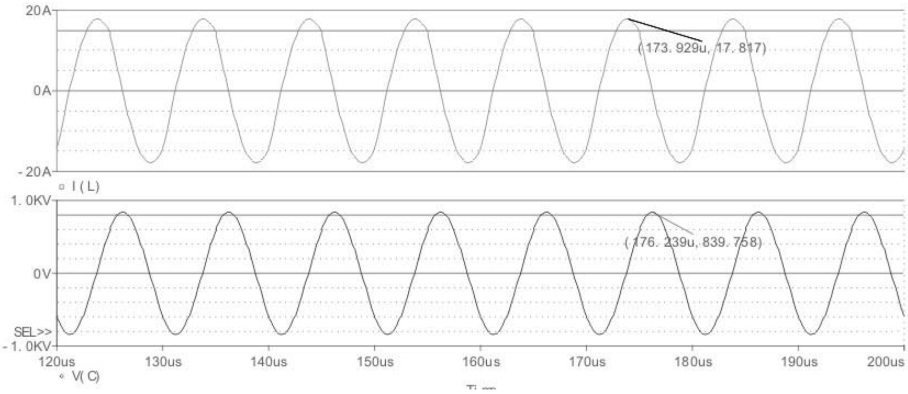

Fig.4 Resonant link current and voltage across series capacitor

The peak current limited circuit operation is illustrated, as in the inverter from fig.1 the short circuit mode is simulated by switch U2. Fig.5 shows the waveforms, explaining these processes.

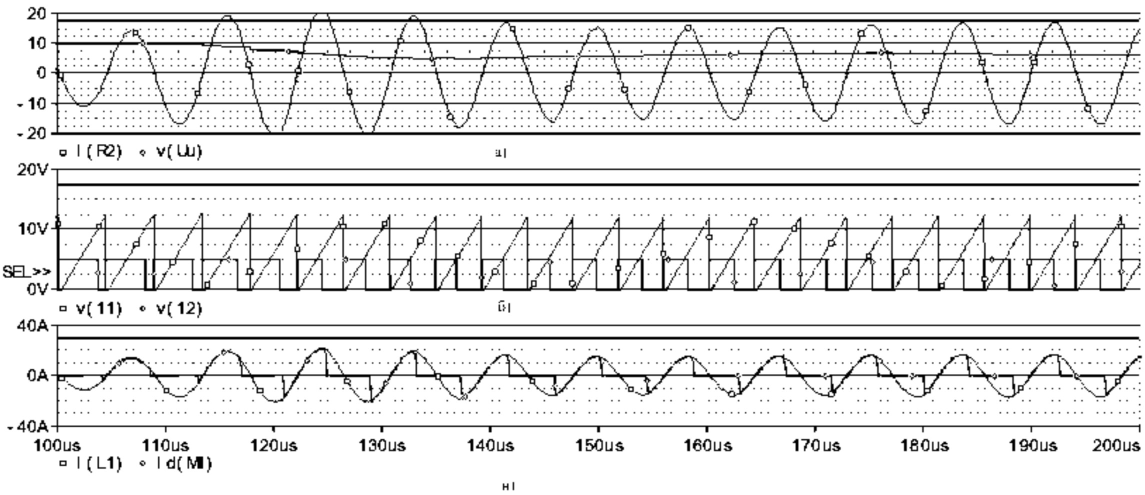

Fig.5 Transistor resonant inverter and control system waveforms in short circuit mode

From the waveforms are seen that the transistors turn-on time is decreased automatically (fig.5a), after the failure mode has occurred. This is the reason for the limitation of the resonant current.

5. CONCLUSIONS

The behavioral modeling of the proposed control system for induction heating transistor inverter is simulated using OrCad PSpice. In the control system, the switches operate with suitable dead time between the driving commands, ensuring zero voltage turn-on (ZVS). The transistors current limiting system is introduced. The control system allows improving resonant inverters stability and response time by sudden large changing of the load, power supply or the driving commands.

REFERENCES

[1] Steigervald R. L., *High frequency resonant transistor DC-DC converters*, IEEE Trans. Ind. Electron., vol. IE-31, pp.181-191, 1984.

[2] Lippincott A., R. Nelms, *A capacitor-charging power supply using series-resonant topology, constant on time/variable frequency control, and zero-current switching*, IEEE Trans. Power. Electron., vol. -38, pp.438-447, 1991.

[3] Bottari S., L. Melassani, P. Teni, *High frequency 200kHz inverter for induction heating applications,* IEEE Ind. Applicat. Soc. Conf. Rec., pp. 308-316, 1995.

[4] Kamli M., S. Yamamoto and M. Abe, *A 50-150 kHz half-bridge inverter for induction heating applications,* IEEE Trans. on Industrial Electronics, Vol. 43, № 1, pp. 163-171, 1996.

[5] Cheron Y., H. Foch, J. Roux*, Power transfer control methods in high frequency resonant converters*, PCI Proceedings, Munich, pp. 92-103, 1986.

[6] Bankov N., V. Kostova*, A Method for Power Control of Transistor Resonant Inverter,* XXXVII International Scientific Conference on Information, Communication and Energy Systems and Technologies "ICEST2002", Nis, Yugoslavia, Proceedings of Papers, Volume 1, pp. 389-392, 2002.

[7] Bankov, N., S. Tabakov, C. Gavrovski, *Analisis of a transistor series-resonant inverter operating at frequencies higher than the resonance,* Proceedings, Faculty of Electrical Engineering, Skopje, Vol. 21, № 1-2, December, pp.37-43, 2001.

[8] Bankov N., Ts. Grigorova, *Modeling of a Control System of a Transistor Resonant Inverter,* XXXIX International Scientific Conference on Information, Communication and Energy Systems and Technologies "ICEST2004", Bitola, Macedonia, 2004, in the press.

[9] Bankov N., Ts. Grigorova, *Control methods and analysis of a transistor resonant inverter, operated above resonant frequency*, E+E'2004, in the press.

[10] *OrCAD PSpice A/D User's Guide*, OrCAD Inc., USA, 1999.