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SADRŽAJ

ODREĐIVANJE IZLAZNIH KARAKTERISTIKA KVAZI-REZONANTNOG KONVERTORA POMOĆU KOMPJUTERSKIH SIMULACIJA
DETERMINATION OF OUTPUT CHARACTERISTICS OF QUASI-RESONANT POWER CONVERTER WITH COMPUTER SIMULATION

Goce Stefanov, Saso Gelev, Vlatko Cingoski,Vasilija Sarac and Roman Golubovski, *Faculty of Electrical Engeenering-Radovis, R.Macedonia*

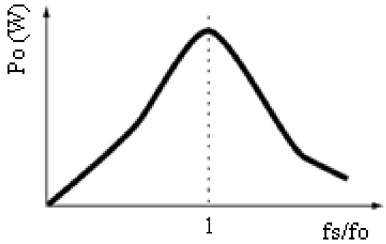
Sadržaj: *U ovaj rad je analiziran kvazi-rezonanten konvertor. Pomoću kompjuterskih simulacija u programu PowerSim, određene su izlazne karakteristike ovog konvertora, odnosno zavisnosti snage i energetske efikasnosti od otstupanja radne od rezonantne frekvencije.*
Abstract: *In this paper the quasi-resonant power converter is analyzed. By computer simulations in PowerSim program are determined its output characteristics, ie the output power and efficiency from deviation of the operating from resonant frequency*.

1. INTRODUCTION

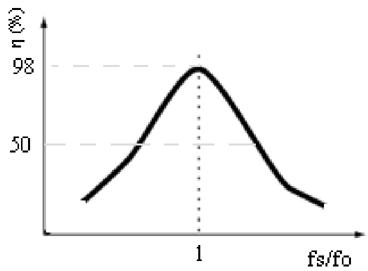
Generally, semiconductor switching devices operate in Hard Switch Mode in various types of PWM DC-DC converters and DC-AC inverter topology employed in a power system. In this mode, a specific current is turned on or off at a specific level of voltage whenever switching occurs, [1], [2], [3]. This process results in switching loss. The higher the frequency the more the switching loss, which obstructs efforts to raise the frequency. Switching also causes an EMI problem, because a large amount of di/dt and dv/dt is generated in the process.
Higher energy conversion efficiency at high frequency switching can be obtained by manipulating the voltage or current at the moment of switching to become zero. This is called "Soft Switching", which can be subcategorized into two methods: Zero-voltage switching and Zero-current switch-ing. Zero-voltage switching refers to eliminating the turn-on switching loss by having the voltage of the switching circuit set to zero right before the circuit is turned on. Zero-current switching is to avoid the turn-off switching loss by allowing no current to flow through the circuit right before turn-ing it off. The voltage or current administered to the switching circuit can be made zero by using the resonance created by an L-C resonant circuit. This topology is named a resonant converter [1], [2].
In power electronics, accordyng to the type of resonant circuit, mainly used three topologies of resonant converters, serial resonant converter, parallel resonant converter and quasi-resonant converter .
The resonat circular frequency ω_0, damping circular frequency ω_d and damping consant α of the resonat circuit with inductance L, resistance R and capacitance C, powered by converter is:

$$\omega_0 = \frac{1}{\sqrt{LC}},\ \alpha = \frac{R}{2L},\ \omega_d = \sqrt{\omega_0^2 - \alpha^2} \qquad (1)$$

In the serial and parallel resonant converter when switching frequency f_s of the converter is same by the resonate frequency f_0 of the resonant circuit, transferred energy from the converter to the load is maximum, Fig. 1 [1], [4]. In the Fig.1a can be seen that the output power P_o and efficiency η at serial and parallel resonat converter is greatest when switching frequency f_s is same with resonat frequency f_0, ie. $f_s = f_0$.



a)



b)

Fig.1 Output characteristics in power converter: a) depending on the output power P_o of the deviation of the switching f_s of the resonant frequency f_0 (normalized switching frequency f_s/f_0), b) depending on the efficiency η of the deviation of the switching f_s of the resonant frequency f_0

At quasi-resonant, although basic operating concept is similar to that of a series resonant converter, controlling the gate in the switching circuit is totally different. Purpose in this paper is for values of *RCL* elements obtained from the design of device for induction heating [4], to determine the power output and efficiency in this the topology of converter.

2. OPERATION MODE IN QUASI-RESONANT POWER CONVERTER

In the Fig. 2 is show equivalent circuit of the quasi-resonant power converter.

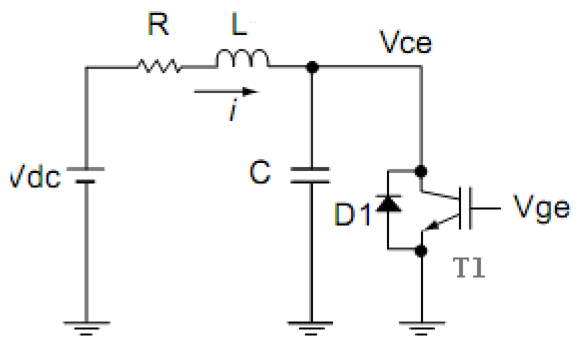


Fig. 2 Equivalent circuit of the quasi-resonant converter

In the Fig. 2, V_{dc} is voltage of DC-LINK circuit, *R*, *L*, and *C* are elements of the resonat circuit, *T*1 is IGBT transistor with his antiparallel diode *D*1, V_{ce} is voltage collector emitter and V_{ge} is voltage gate emiter of IGBT. In the Fig. 3 is shown waveforms of the current and voltage obtained with simulations on the circuit of Fig. 2 in PowerSim program [5].

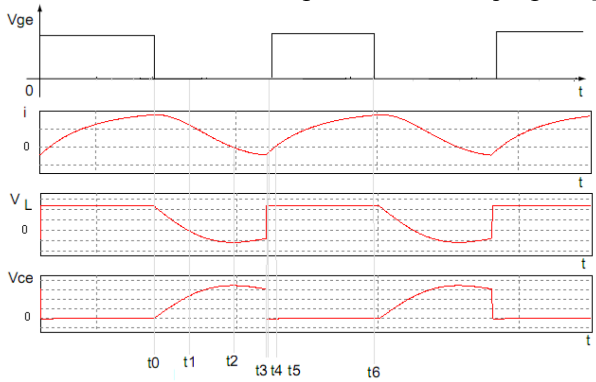


Fig. 3 Wave forms of the current and voltage in the circuit of Fig. 2.

Time interval *t*0-*t*1 (mode 1): As mentioned earlier, the switching circuit is turned off when the resonant current flowing through the circuit is at its peak, i.e. at *t*0. In this process, a turn-off switching loss occurs. The *V*ce level is rapidly increased by the capacitor (*C*r) to become DC-LINK (*V*dc) at *t*1. Even when the switch is turned off at *t*0, the current keeps incrementing to reach its peak at *t*1, when *V*ce becomes equal to *V*dc, as DC-LINK is higher than the resonant voltage. At this point, the energy stored in the inductor begins to be transferred to the capacitor.

Time interval *t*1-*t*4 (mode 2): As *V*dc is lower than *V*ce after *t*1, the current decreases to zero at *t*2, when the resonant voltage reaches its maximum. This is also the point where the transfer of the energy stored in the inductor to the capacitor is completed. The peak level of the resonant voltage has a direct relationship with the turn-on time of the switch (*t*5-*t*6). After *t*2, the capacitor starts discharging the energy to the inductor, which causes the voltage and the current flowing in inverse to decrement and reach its minimum level at *t*3, i.e. *V*ce=*V*dc, respectively. Passing *t*3, the resonant current increases as *V*ce<*V*dc and the discharge is com-pleted at *t*4.

Time interval *t*4-*t*5 (mode 3): After *t*4, the energy sent by the capacitor and stored in the inductor, is converted to DC-LINK as the D1 diode is forward biased. The resonant current is flowing through D1 during the time S1 is turned on.

Time interval *t*5-*t*6 (mode 1): As the switching circuit remains turned on while the current is freewheeling through D1, the current flows in the right direction through the circuit and the inductor starts to store the energy, which makes it possible to do a zero voltage turn-on switching.

In *t*6, the switching circuit is turned off, returning to time *t*0. The peak level of the voltage is in direct relationship with the duty cycle *D*. So by adding or reducing on duty cycle or change of the frequency can manipulate transfer of the output energy.

3. DETERMINATION OF OUTPUT CHARACTERISTICS

The parameters of the resonant circuit $L = 23.93$ µH, $R = 1.14\ \Omega$, $C = 10.6$ µF; switching frequency $f_s = 10000$ Hz and requirements power $P_o = 58$ kW are obtained with simulations of direct induction heatings on work piece iron in the computer program ELTA, product of the FluxControl [4]. In the Fig. 4 is show the circuit to simulation of quasi-resonant converter in the PowerSim program, which is used for determination of output characteristics [5].

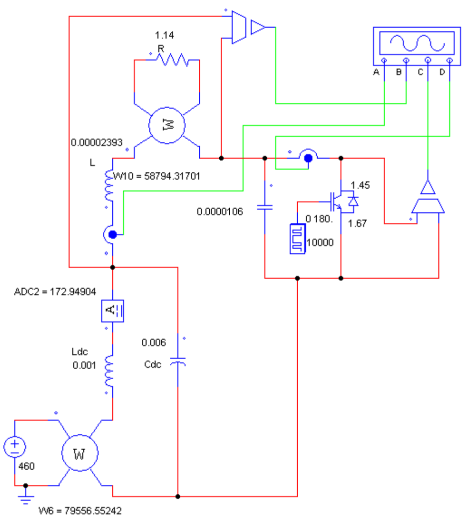


Fig. 4 Circuit to simulation of quasi-resonant converter in the PowerSim program, which is used for determination of output characteristics

In simulations is used model on IGBT transistor with voltage in conduct state $V_{ceSAST} = 1.67$ V and diode with forward voltage $V_F = 1.45$ V. The DC-LINK voltage V_{dc} is set on the beginning on value 460 V so as to output power of the converter is $P_o = 58$ kW at switching frequency $f_s = f_0 = 10000$ Hz.

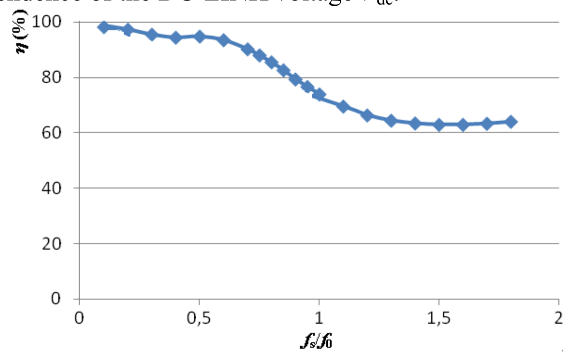
3.1 Operation of quasi-resonant converter with constant output power

In the Table 1 is given values of the voltage, current, power and efficiency on the circuit on Fig. 4, obtained with simulations in PowerSim program. Values in the Table 1 are obtained so that to different switching frequency, DC-LINK voltage V_{dc} is changes until the output power get value 58 kW. Duty cycle *D*, all the time in simulations are holding on the value 0.5.

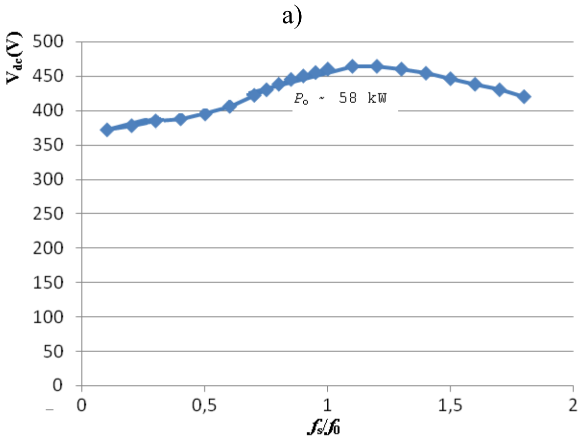
Table 1 Values of the voltage, current, power, efficiency, resonant and switching frequency obtained with simulations on the circuit on Fig. 4, when the output power of the converter is constant $P_o \approx 58$ kW.

U_{dc} (V)	I_{dc} (A)	P_{dc} (kW)	P_o (kW)	f_0 (kHz)	f_s (kHz)	η (%)
438	213	93.29	58.70	9.98	16.00	62.9
446	209	93.21	58.60	9.98	15.00	62.9
454	204	92.62	58.68	9.98	14.00	63.4
460	198	91.08	58.63	9.98	13.00	64.4
464	191	88.52	58.73	9.98	12.00	66.3
464	182	84.44	58.70	9.98	11.00	69.5
460	173	79.58	58.79	9.98	10.00	73.9
450	164	73.80	58.54	9.98	9.00	79.3
438	157	68.76	58.80	9.98	8.00	85.5
422	154	64.99	58.63	9.98	7.00	90.2
406	154	62.52	58.44	9.98	6.00	93.5
395	157	62.00	58.77	9.98	5.00	94.8
388	159	61.69	58.25	9.98	4.00	94.4
384	159	61.06	58.30	9.98	3.00	95.5
378	159	60.10	58.50	9.98	2.00	97.3
372	160	59.52	58.45	9.98	1.00	98.2

In the Fig. 5 is shown output characteristics in quasi-resonant converter depending on the deviation of the switching f_s of the resonant frequency f_0, ie normalized switching frequency f_s/f_0, when the output power of the converter is constant $P_o \approx 58$ kW. In the Fig. 5a is show dependence of the efficiency η and in the Fig. 5b is show dependence of the DC-LINK voltage V_{dc}.



a)



b)

Fig. 5 Output characteristics of the converter dependend from normalized switching frequency f_s/f_0 when the output power is constant $P_o \approx 58$ kW a) efficiency η and b) DC-LINK voltage V_{dc}

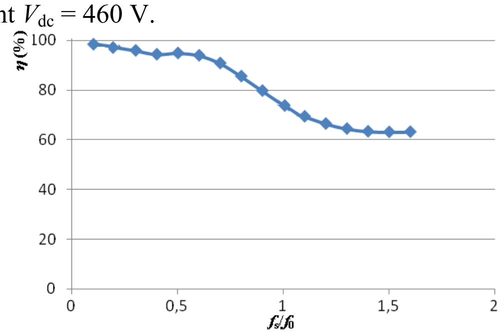
3.2 Operation of quasi-resonant converter with constant DC-LINK voltage

In the Table 2 is given values of the parameters obtained with simulations on the circuit on Fig. 4 on different switching frequency, but so that DC-LINK voltage V_{dc} is constant. And here, duty cycle D for all the time are holding on the value 0.5.

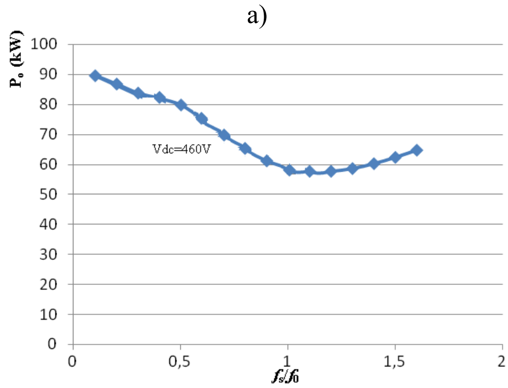
Table 2 Values of the voltage, current, power, efficiency resonant and switching frequency obtained with simulations on the circuit on Fig. 4 when DC-LINK voltage is constant $V_{dc} = 460$ V

U_{dc} (V)	I_{dc} (A)	P_{dc} (kW)	P_o (kW)	f_0 (kHz)	f_s (kHz)	η (%)
460	223	102.8	64.74	9.98	16.00	63.1
460	215	98.9	62.34	9.98	15.00	63.0
460	207	95.22	60.25	9.98	14.00	63.3
460	198	91.08	58.62	9.98	13.00	64.4
460	189	86.94	57.71	9.98	12.00	66.4
460	181	83.26	57.69	9.98	11.00	69.3
460	173	79.58	58.79	9.98	10.00	73.9
460	167	76.82	61.18	9.98	9.00	79.6
460	165	75.9	64.87	9.98	8.00	85.5
460	167	76.82	69.70	9.98	7.00	90.7
460	174	80.04	75.12	9.98	6.00	93.9
460	183	84.18	79.8	9.98	5.00	94.8
460	189	86.94	81.98	9.98	4.00	94.3
460	190	87.4	83.78	9.98	3.00	95.9
460	194	89.24	86.78	9.98	2.00	97.2
460	198	91.08	89.54	9.98	1.00	98.3

In the Fig. 6 is shown output characteristics in quasi-resonant converter in case when DC-LINK voltage is constant $V_{dc} = 460$ V.



a)



b)

Fig. 6 Output characteristics of the converter dependend from normalized switching frequency f_s/f_0 when DC-LINK voltage V_{dc} is constant a) efficiency η and b) the output power P_o

In the Fig. 6a is show dependence of the efficiency η of the deviation of the switching f_s of the resonant frequency f_0, ie normalized switching frequency f_s/f_0, and in the Fig. 6b is show dependence of the output power P_o of the converter (also of normalized switching frequency f_s/f_0).

In the Fig. 7 is shown waveforms of the current *i*(t), as and voltages V_L(t) and V_{ce}(t) when the switching frequency is same by resonant, ie $f_s = f_0$.

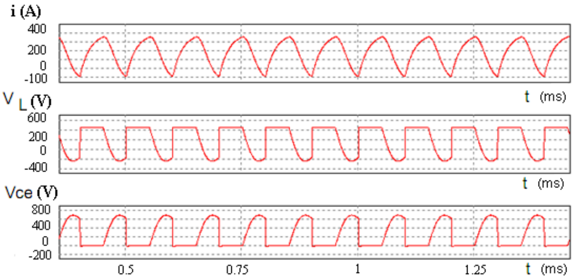


Fig. 7 Waveforms of the current *i*(t), as and voltages V_L(t) and V_{ce}(t) when the switching frequency is same by resonant, ie $f_s = f_0 = 9.98$ kHz.

In the Fig. 8 is shown waveforms of the current *i*(t), as and voltages V_L(t) and V_{ce}(t) when the switching frequency is greater from resonant, ie $f_s = 16$ kHz $> f_0 = 9.98$ kHz.

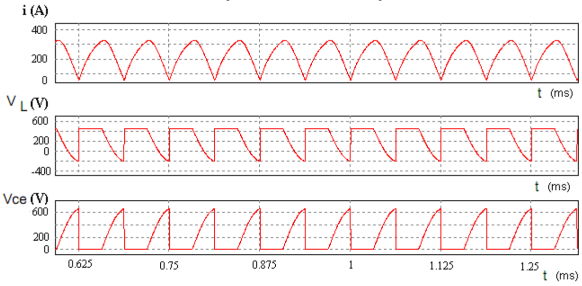


Fig. 8 Waveforms of the current *i*(t), as and voltages V_L(t) and V_{ce}(t) when the switching frequency is greater from resonant, ie $f_s = 16$ kHz $> f_0 = 9.98$ kHz.

In the Fig. 9 is show waveforms of the current *i*(t), as and voltages V_L(t) and V_{ce}(t) when the switching frequency is less from resonant, ie $f_s = 1$ kHz $< f_0 = 9.98$ kHz.

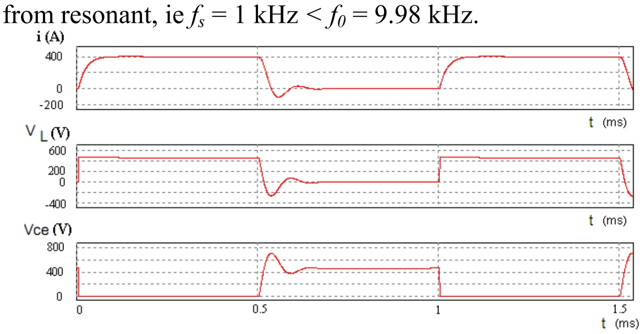


Fig. 9 Waveforms of the current *i*(t), as and voltages V_L(t) and V_{ce}(t) when the switching frequency is less from resonant, ie $f_s = 1$ kHz $< f_0 = 9.98$ kHz

3.3 Analysis of the results

From the table 1 and 2, as and the Fig. 5, 6, 7, 8 and 9 can be concluded:

1)At quasi-resonant converter the output power is not maximal on the resonant frequency as which is case in the serial and parallel converters.

2)The output power and the efficiency of the converter is greates to low switching frequency. In table 2, to frequency 1 kHz the output power is $P_o = 89.54$ kW, and efficiency is 98.3 %.

3)For high frequencies (13 kHz, 14 kHz, 15 kHz, 16 kHz), it can be considered that the converter operate with constant efficiency (though small).

4)For higher frequencies (11 kHz, 12 kHz, 13 kHz), but close to the resonant the converter operate with a constant output power $P_o \approx 58$ kW.

5)In the operation of the quasi-resonanat converter special attention should be paid IGBT transistor to turn on in conditions of ZVS, moment *t*4 in the Fig. 3. i.e. transistor turn on when the voltage collector-emitter is low. (diode is turn on in the time of inclusion of the transistor). This decrease switching losses and improves the efficiency of the converter.

6)In the Fig. 8, when the switching frequency is greater from resonant, can be seen that the IGBT transistor not turn on in conditions on ZVS, ie diode not is turn on when IGBT are turn on, and because in this time generate switching losses.

7)In the Fig. 9, when the switching frequency is less from resonant, can be seen that when IGBT is turn off and the voltage of coil passes through zero, appear oscillations by damping circular frequency ω_d. The appearance of these oscillations is limits lower frequency to what can be applied the quasi-resonat converter.

4. CONCLUSION

In the paper is analyzed the operation of the quasi-resonant converter. By the computer simulations in PowerSim program are determined output characteristics of this converter. Determined is frequencies band in which the converter operate with maximum power, frequencies band in which operate with constant power, as and frequencies band in which the converter operate with constant efficiency.

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