DEPENDANCES OF THE OUTPUT CURRENT FOR SERIES RESONANT INVERTER IN DC-DC CONVERTERS

Radoslav IIvanov Trendafilov, Rumen Dimitrov Karov

Electrotechniques and Electronics, TU Sofia – branch Plovdiv, "Sankt Peterburg" blvd. Nr. 61, Postal Code 4000 Plovdiv, Bulgaria, phone: +35932659713, e-mail: radotrend@yahoo.com, r_karov@mail.bg

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Few publications in the area of resonant inverters are made which contains analysis of the output current and the regimes of work. Using high switching frequencies and proper design of the resonance circuit can be achieved useful in practice parameters. In the current paper series resonant inverter with a simple circuit has been analyzed. Few methods of control are listed, and each of them has its own particularity. The dependence for the output current is investigated – this is done theoretically, by means of simulation and practical comparison with results from a real scheme. As the high frequencies are used, the theoretical results differ from the ones taken from the practice. The presented paper helps the differences to be estimated.

At the end theoretical and graphical results are presented, so that a practical DC-DC converter with useful features can be designed, considering the high switching frequencies.

1. ANALYSIS

A short methodology for series resonant circuit should be reviewed below. It starts with the equivalent scheme (fig. 2.) of the inverter (fig. 1.). The methodology is for set regime of the scheme. The active resistance R represents the losses in the elements (active resistances of wires, capacitive and inductive loss, voltage drop over diodes, load resistance and so on) and voltage source $\frac{Uc_L}{p}$ shows voltage over the load filter capacitor. The value of this capacitor is great enough to consider that the voltage do not alter its value during the switching process when analysis is made. If there is no capacitor (or rectifier at all) then the value of R includes the value of the load.

Then the equivalent equation for equivalent scheme (fig. 2.) is:

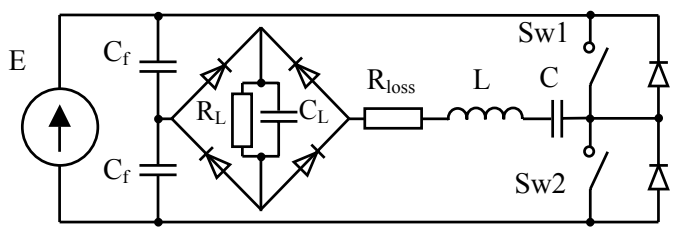

Fig. 1.

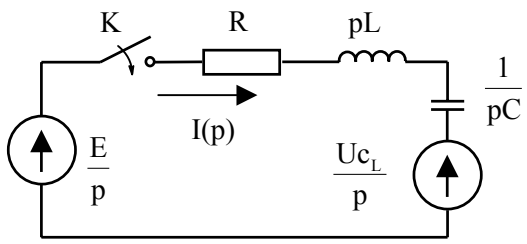

Fig. 2.

(1) $$I(p)=\frac{\frac{E-U_{c_L}}{L}}{p^2+\frac{R}{L}p+\frac{1}{LC}}$$

After transformation the expression of the current is:

(2) $$i(t)=\frac{E-U_{c_L}}{\omega L}e^{-\delta t}\sin(\omega t),$$

where $\omega=\sqrt{\frac{1}{LC}-\delta^2}$ and $\delta=\frac{R}{2L}$

For the average value of the output current for time periods $t=n\times\frac{\pi}{\omega}$ (n=0,1,2…), can be written:

(3) $$I_{n\_av}=\frac{1}{\pi}I_m\int_n^{n+1}e^{-\delta\frac{\alpha}{\omega}}\sin(\alpha)d\alpha,$$

where $I_m=\frac{E-U_{C_L}}{\omega L}$.

The average value of the current for any time period can be described with the expression:

(4) $$I_{out}=\frac{\sum_{n=0}^{m-1}\sqrt{\left[\frac{1}{\pi}I_m\int_{n\pi}^{(n+1)\pi}e^{-\delta\frac{\alpha}{\omega}}\sin(\alpha)d\alpha\right]^2}+\sqrt{\left[\frac{1}{\pi}I_m\int_{m\pi}^{(m+a)\pi}e^{-\delta\frac{\alpha}{\omega}}\sin(\alpha)d\alpha\right]^2}}{m+a},$$

where m is integer part of the correlation between resonant and control frequency, and b is the fraction part:

(5) $$\frac{f_{rez}}{f_{ctrl}}=m+a$$

Then the output voltage will be:

(6) $U_{out}=RI_{out}$

For the right choice of the switching element the maximum value of the current during the half-period after switching, has to be known. It is determinate by the equation:

(6) $$I_{1\max}=\frac{E-U_{C_L}}{\omega L}e^{-\delta t_m}\sin(\omega t_m),$$

where the moment t_m is:

(7) $$t_m=\frac{1}{\omega}\mathrm{arctg}\left(\frac{\omega}{\delta}\right)$$

2. METHODS OF CONTROL AND OTHER CONSIDERATIONS

Below, results taken from the methodology when using MathCAD (fig. 3.) and simulation software PSpice (fig. 3.) are shown. The results are very similar, when considering that R_{DS}=0,55Ω of the used MOSFET switching elements.

For best performance of the circuit few observation should be made. The idea of this type of control is to regulate the timing between resonant current pulses. This can be made with regulating the control frequency, dead time between switching the power switches and so on /1, 2/. When a switching element is turned on a positive resonant current pulse (considering the direction of the element) will go through the element, followed by negative resonant current pulse, which will go through the reverse diode (fig. 1.). If the switching element is still "on" new positive pulse will go and thus the process will run till the current goes to zero due to the losses and load. The time for this process can be controlled by the value of the elements of the resonance group – R,L,C, and in common – by their correlation (fig. 5.). When

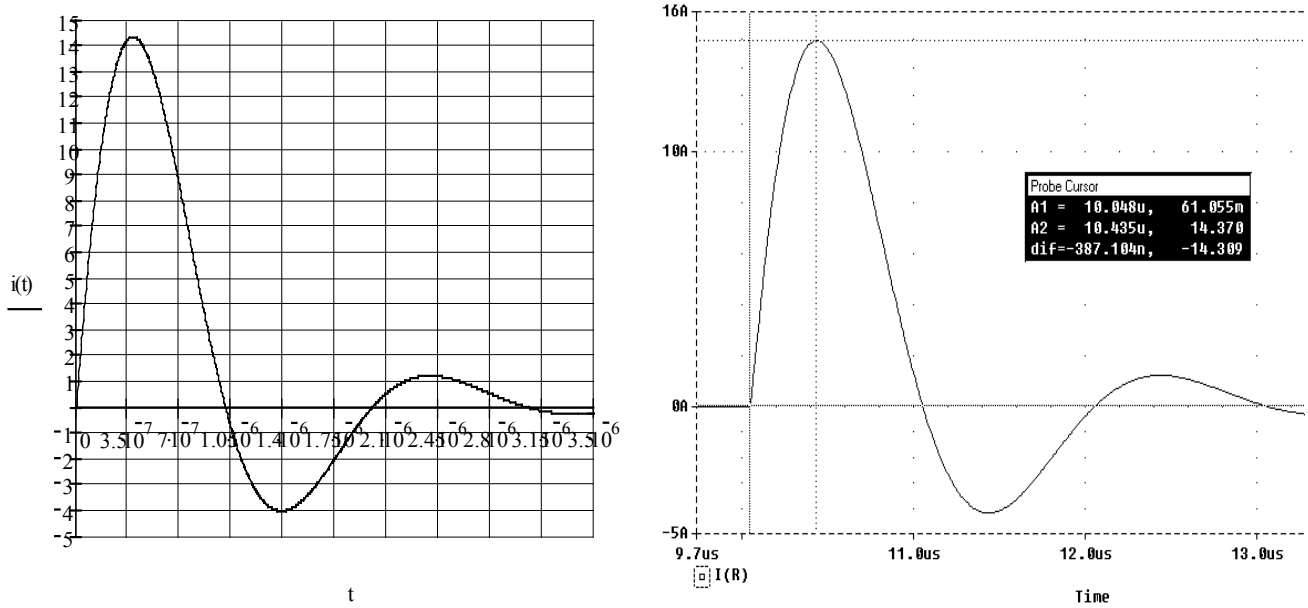

Fig. 3. Resonant current through R, L, C elements (R=10 Ohm; L=4uH; C=22nF) taken with calculation and simulation:

a) Calculations: t_{m1}=380,4nS; I_{m1}=14,29A

b) Simulation: T_{m1}=387,104nS; I_{m1}=14,309A

switching on, the current rise slowly due to the inductance L. This way "zero current switching" is made. A "pseudo zero cross switching" can be made when the switching off is done after few half-periods when the resonant current varies between zero and the maximum of the current half-period, which is at a low value (for example – below 10% of the maximum of the first resonant current pulse). This way the losses will be at a very low value.

If a switching of the second element is done considering the above, and the current is not zero, the initial conditions for the scheme from fig.2 are not zero, so the expression (1) and (2) will be changed. But these conditions can be ignored if they do not have influence on the final results. To reduce the influence and to make the

switching process as close as possible to real zero cross, a proper values for the resonant elements should be made. This way the methodology given above was entered in MathCAD software and graphics for determination the R,L,C values are established.

A coefficient of attenuation is entered:

$$(8) \qquad A = \frac{i_{m(1)}}{i_{m(2)}} = \frac{i_{m(2)}}{i_{m(3)}} = \cdots = \frac{i_{m(n-1)}}{i_{m(n)}},$$

where $I_{m(1)} \ldots I_{m(n)}$ are maximums of every half-period of the current.

When using high range variable loads it is important a scheme for controlling the gate pulses parameters to be provided. It can be seen from fig.4. that even when the load resistor R varies in a small area of values, the output voltage stays stable within limits. To make it stable in larger area of values it is necessary to regulate the timing between the "packages of pulses" and if necessary – the number of pulses together with timing. If the second method is needed to be realized the output voltage will depend on the correlation between the "package of pulses" timing and dead time for the switching transistors:

$$(9) \qquad U_{out} = RI_{out}D$$

where D is:

$$(10) \qquad D = \frac{t_{i\_on}}{t_{on} + t_{off}}$$

Here t_{i_on} and t_{off} is the time when there is current through R, L, C elements and time when switches are off respectively. It must be said that t_{i_on} can be different than "on" period t_{on} for the transistors.

The method which use switching off before current goes to zero is with low

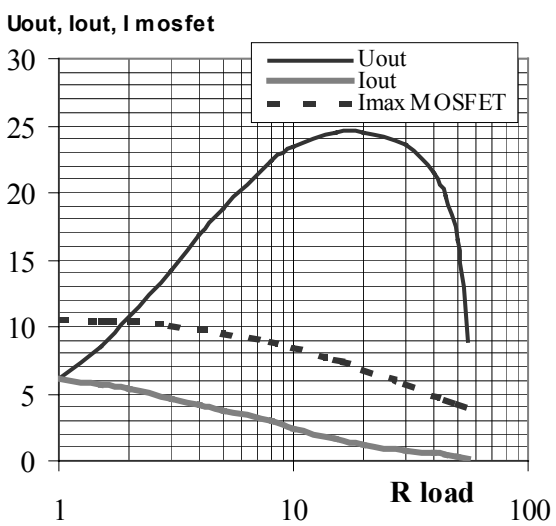

Fig. 4. Dependencies between output voltage, output current, max current through switching element and value of the load resistor.

L=8uH; C=10nF; f_{rez}=500kHz; f_{ctrl}=100kHz

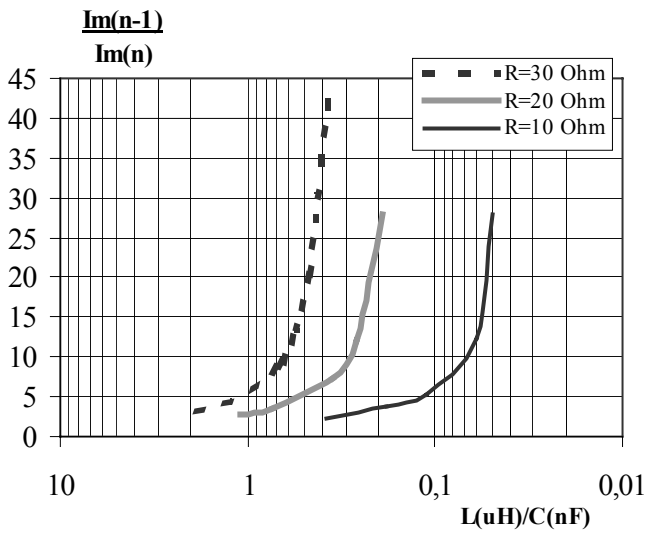

Fig. 5. Dependencies between R,L,C elements and correlation of the values of the max output currents during the half-periods.

U_R=24V; f_{rez}=500kHz; f_{ctrl}=100kHz

energy efficiency when using high output currents and switching before attenuation of the current to low values (the switching element will have to switch at a higher current value) and the correlation between L and C should be optimized according to fig.5.

3. PRACTICAL RESULTS

In practice the inverter works different than the theoretical and in simulation. Few things have to be considered – the switching always is for time different from zero, and voltage and current spikes persist during this process. Another difference is non-ideal parameters of the R, L, and C elements. Their parasitic parameters help a difference to occur in the performance of the scheme and finally – to decrease the efficiency.

Output voltages and current (reduced values) are shown with fig.6 and fig.7. On fig. 6 can be seen the moment when the switch breaks the resonant current. The result is a current spike during the 5th half-period. The value of this spike is too small, but it

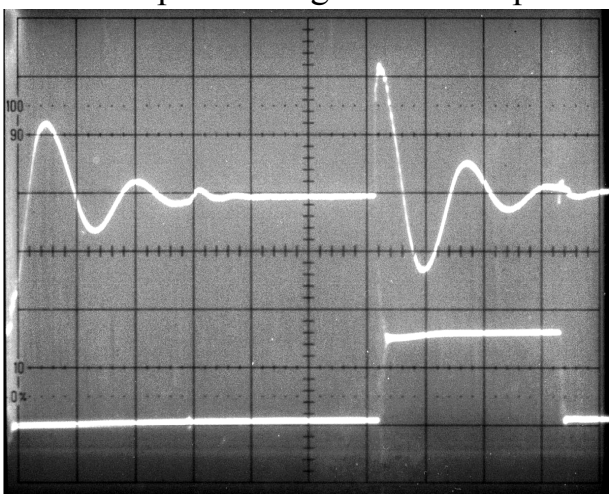

Fig. 6.Output current of the inverter and control pulse for one of the switching MOSFET.
2us/div; Ch up – 0,5A/div; Ch down – 10 V/div

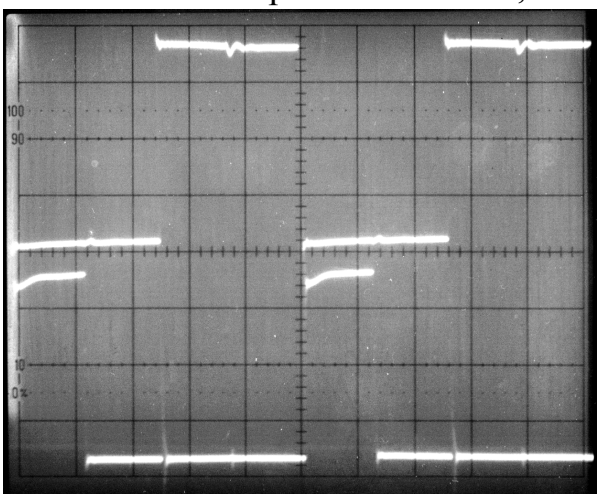

Fig. 7.Output voltage (voltage drop on MOSFET) and control pulse for one of the switching MOSFET.
5us/div; Ch up – 15V/div; Ch down – 5 V/div

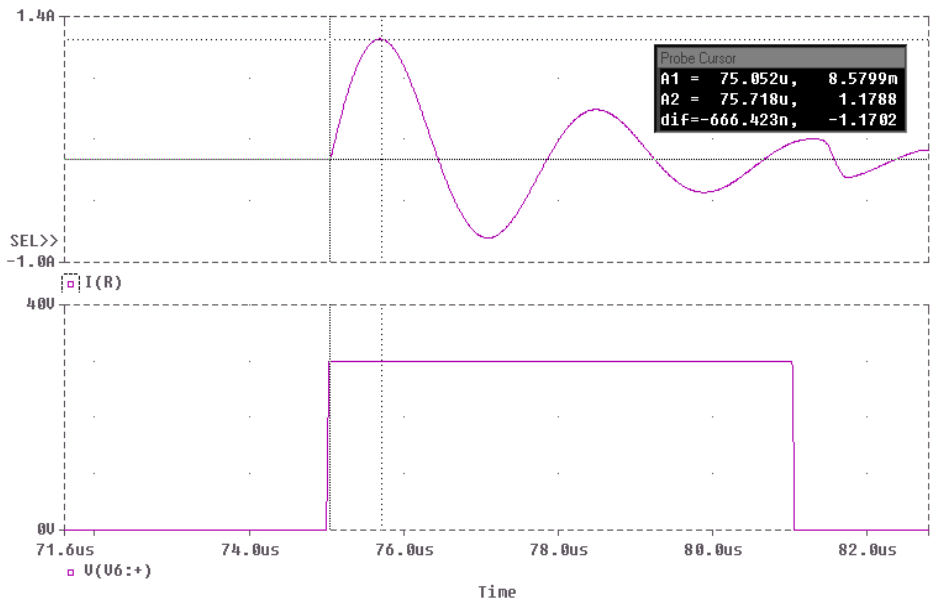

Fig. 8. Simulation with interrupting the resonant current before attenuating to zero. Below – control pulse.

must be considered that if the "on" time for the transistor decrease, the spikes may rise together with looses due to insufficient attenuation of the resonant current for this moment. In fact the value of "spike" is not so great due to the comparatively low current. However the simulation with the same values of the elements in the scheme does not show these problems (fig.8). For low power looses during switching on the real inductance must be with low parasitic parameters. Other way a high frequency swing of the resonant current may occur.

4. APPLICATION IN DC-DC CONVERTERS

Till now all the considerations were for resistive load. In practice it is needed the output current to be rectified and filtered for DC-DC applications. A bridge rectifier with fast recovery schotkky diodes can be used for this purpose. In this case, the voltage drop over the rectifier during every half period of the output swing of the current must be considered. If LC filter is used (no capacitor at the output) then the initial conditions will be changed (then load will act like RL). Infact the influence of the type of load at the output of the recifier is insignificant in practice as the converter is used as step down. With this scheme and method of control great correlation between supply and output voltage can be achieved, when output power is few hundred wats.

5. CONCLUSION

A resonant inverter is presented which is capable to drive high current, together with high resonant frequencies, when the switching elements work with low switching frequencies. The output characteristics of the inverter (with just one resonance frequency) help to be designed easy to control scheme. It is possible to use large range of control frequencies and this helps a proper working frequency area to be chosen.

6. REFERENCES

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