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multiresonant converter,
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MULTIRESONANT CONVERTER TO BE APPLIED IN POWER SUPPLY SYSTEMS OF TELEMATICS EQUIPMENT

The article presents properties of ZVS buck multiresonant converter in power supply systems of telecommunications equipment. Configuration of system elements enables application of the technique of switching semiconductor elements at zero voltage (ZVS). Zero-voltage switching allows for high frequencies of the system operation while maintaining a high energy efficiency and operating reliability. Results of simulation testing of the converter, based on Simplorer software, are presented.

MULTIREZONANSOWY PRZEKSZTAŁTNIK DO ZASTOSOWANIA W SYSTEMACH ZASILANIA URZĄDZEŃ TELEMATYKI

Artykuł przedstawia własności przekształtnika multirezonansowego ZVS obniżającego napięcie DC do zastosowania w systemach zasilania urządzeń telematyki. Konfiguracja elementów układu umożliwia zastosowanie techniki przełączania elementów półprzewodnikowych przy zerowym napięciu (ZVS), co pozwala na uzyskanie wysokich częstotliwości pracy układu przy zachowaniu wysokiej sprawności energetycznej oraz niezawodności działania. Przedstawiono wyniki badań symulacyjnych przekształtnika w oparciu o program Simplorer.

1. INTRODUCTION

Demand for high-frequency power processing has led to development of research into quasi-resonant converters, where semi-conductor power elements are switched at zero voltage (ZVS QRC) or zero current (ZCS QRC) [1].

Energy efficiency and operating reliability of the converters depend to a large extent, on the conditions of transistor and diode switching processes. Power losses occur during turn-on and turn-off, which are a result of current in the switched circuit multiplied by voltage in the switched semi-conductor elements. At high frequencies, parasitic inductances of connections and transistor and diode capacitances form resonant circuits which generate parasitic electromagnetic oscillations. Parasitic impact of diode capacitance occurs in the state of transistor conductance, while parasitic impact of transistor capacitance upon the circuit's operation obtains in the condition of diode conductance.

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ZCS and ZVS quasi-resonant converters provide good switching conditions for either the transistor or the diode, but not for both the elements at the same time. Undesirable oscillations, caused by parasitic capacitances of semi-conductor elements and parasitic inductance of connections, as well as occurrence of hard commutation of currents or voltages limit the possibilities of applying quasi-resonant converters to power processing at high-frequency switching [7].

Research into resonant systems where switching of all semi-conductor elements occurs in advantageous conditions, i.e. at soft commutation of currents or voltages, has led to development of multiresonant converters [1,4]. The converters may be applicable in power supplies for transport telematics equipment, where supply of constant voltage and precise value is required at high energy efficiency and operating reliability.

2. TOPOLOGY OF ZVS BUCK MULTIRESONANT CONVERTER

ZVS buck multiresonant converter is shown in Fig.1.

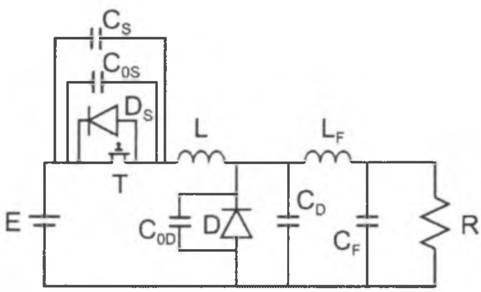

Fig.1. ZVS buck multiresonant converter

The circuit is supplied with voltage *E*. Transistor MOSFET *T* of output capacitance C_{OS} is switched at the frequency *f*. Antiparallel diode D_S represents the body diode of a MOSFET. The rectifying diode *D* is characterised by a parasitic output capacitance C_{OD}. The converter's resonant circuit comprises passive elements: resonant inductance L, resonant capacitance C_S in parallel with the transistor *T*, and the capacitance C_D in parallel with the diode *D*. Elements of the resonant circuit operate with the circuit's parasitic reactances, that is, inductance *L* "absorbs" the leakage inductance of the transformer and the capacitances C_S and C_D in parallel connections "absorb" parasitic capacitances C_{OS}, C_{OD}. Configuration of the elements allows for application of the zero voltage switching technique of both the transistor and the rectifying diode. Capacitance C_F and inductance L_F are filter components.

3. OPERATION OF THE BUCK MULTIRESONANT CONVERTER

During the switching cycle, the buck ZVS (Fig.1) operates in four topological stages as shown in Fig. 2. The high filter inductance L_F lets the load be presented as a current source I_0. The control method should ensure switching of the transistor *T* at zero voltage.

In the first operating stage (Fig.2a), the transistor T conducts, and the resonant current i_L is lower than the load current I_0. The current source I_0 forces the rectifying diode D to conduct the current difference $I_0 - i_L$. Voltage of the drain - source transistor u_{CS} is zero and the diode's voltage is u_{CD}. When the resonant current i_L reaches the value I_0, the diode D is turned off, the process of commutation begins, and the circuit enters the second operating interval.

In the second operating stage (Fig.2b) rectifying diode D is off, and the resonant current i_L is conducted by: the transistor T, inductance L, capacitances C_D and C_{0D}. Voltage of the drain - source transistor u_{CS} is zero. The process of charging capacitance C_D and the parasitic capacitance C_{0D} of the diode D with resonant current i_L begins. The second operating range ends when the transistor is turned off (at zero voltage u_{CS}).

In the third operating stage (Fig.2c) transistor T and diode D do not conduct. Capacitance C_S and the parasitic capacitance C_{0S} of the transistor, capacitance C_D and the parasitic capacitance C_{0D} of the diode overload with the resonant current i_L. If the voltage u_{CD} of capacitance C_D and capacitance C_{0D} reaches zero, and the voltage u_{CS} of capacitance C_S and capacitance C_{0S} is still positive, the third operating stage finishes, and the diode D turns on. In the fourth operating stage (Fig.2d) capacitance C_S and the parasitic capacitance C_{0S} of the transistor T discharge with the resonant current i_L when the rectifying diode D conducts. The fourth stage ends when the transistor voltage u_{CS} reaches zero. Transistor T is ready to turn on in the next cycle of converter operation.

If, in the end of the third operating stage, the voltage u_{CS} of capacitance C_S and capacitance C_{0S} reaches zero, and the voltage u_{CD} of capacitance C_D and capacitance C_{0D} is still positive, then, in the fourth operating stage (Fig.2e), capacitance C_D and parasitic capacitance C_{0D} of the diode D discharge with the resonant current i_L while the antiparallel diode D_S is conducting. The fourth stage ends when the voltage u_{CD} of the diode D reaches zero. Transistor T is ready to turn on in the next operating cycle of the converter.

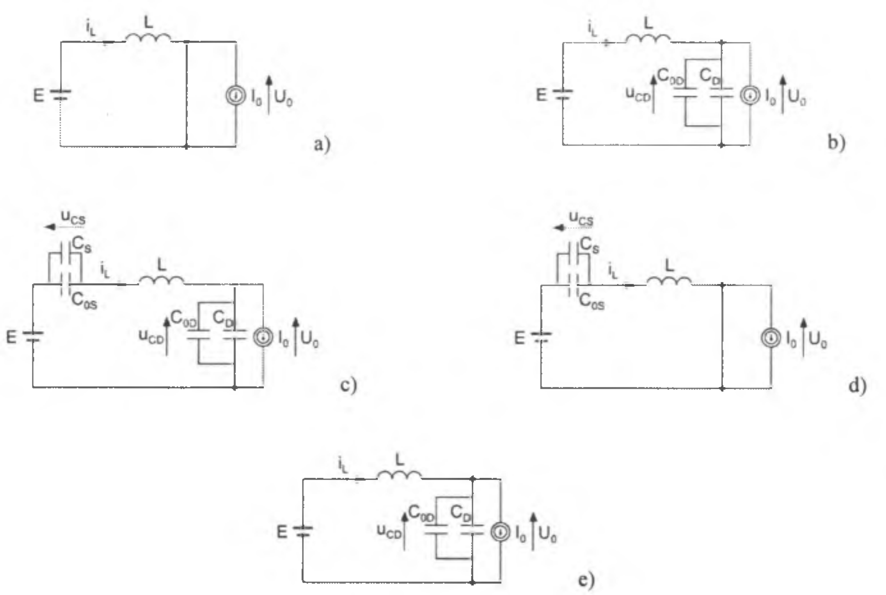

Fig.2. Resonant circuit a) in the first stage, b) in the second stage, c) in the third stage, d) in the fourth stage if capacitance C_D and capacitance C_{0D} discharged earlier; e) in the fourth stage if capacitance C_S and capacitance C_{0S} discharged earlier

The method of control allows the transistor to turn on at the moment when the resonant current i_L reaches zero. Within the range of the transistor's conduction, the current i_L is:

$$i_L = \sqrt{\frac{C_D + C_{0D}}{L}} \cdot E \cdot \sin\left(\frac{1}{\sqrt{L(C_D + C_{0D})}} t\right) \tag{1}$$

Maximum time t_{max} by which the transistor must be turned off is defined for the value of current i_L equal to the load current I_0, that is:

$$t_{\max} = \frac{\pi - \arcsin(\lambda)}{\dfrac{1}{\sqrt{L(C_D + C_{0D})}}} \tag{2}$$

where:

$$\lambda = \frac{I_0}{E \cdot \sqrt{\dfrac{C_D + C_{0D}}{L}}} \tag{3}$$

where: λ – normalized load current.

Multiresonant ZVS converter is characterised by the following parameters:

$$f_S = \frac{1}{2p\sqrt{L(C_S + C_{0S})}};\ f_D = \frac{1}{2p\sqrt{L(C_D + C_{0D})}};\ f_N = \frac{f}{f_S};\ C_N = \frac{C_D + C_{0D}}{C_S + C_{0S}};\ M = \frac{U_0}{E} \tag{4}$$

where: f - switching frequency,
f_S, f_D - resonant frequencies,
f_N - normalized switching frequency,
C_N - ratio of capacitance,
M – conversion ratio (relative input voltage).

Parameters M and λ are necessary to design the converter's circuit [1]. On the basis of a family of control characteristic curves $M = f(f_N)$ for C_N = var, in consideration of the changes of maximum transistor voltage in function of normalized switching frequency f_N for C_N = var, the circuit's operation area at zero-voltage switching is defined that ensures stable course of characteristic curves in the full rage of voltage and load and at minimum possible value of ratio C_N.

4. SIMULATION TESTS

Multiresonant converter ZVS was subject to simulation testing with the aid of Simplorer. The simulation testing was carried out for the model shown in Fig.3. The simulation model uses a transistor MOSFET IRFP460 (output capacitance C_{0S}=870pF) and an ultrafast diode HFA25TB60 (output capacitance C_{0D}=100pF) of International Rectifier.

The resonant circuit includes elements of the following values: $L = 7\mu H$, $C_S = 10nF$, $C_D = var$. Resonant frequency $f_S = 577kHz$. Supply voltage $E = 200V$, load current $I = 10A$. Based on observation of voltage and current waveforms resulting from the simulation, a range of switching frequency was selected where ZVS switching for the target value of load current is ensured. For the presented circuit parameters, where $C_N = 2,3$, the range is $625kHz \leq f \leq 909kHz$.

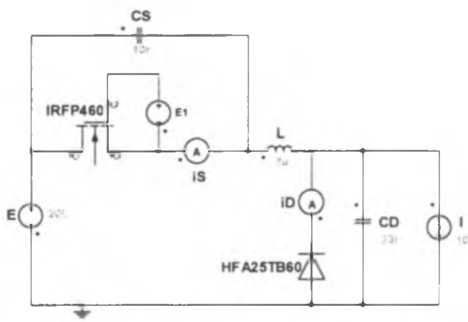

Fig.3. Simulation model of buck ZVS MRC

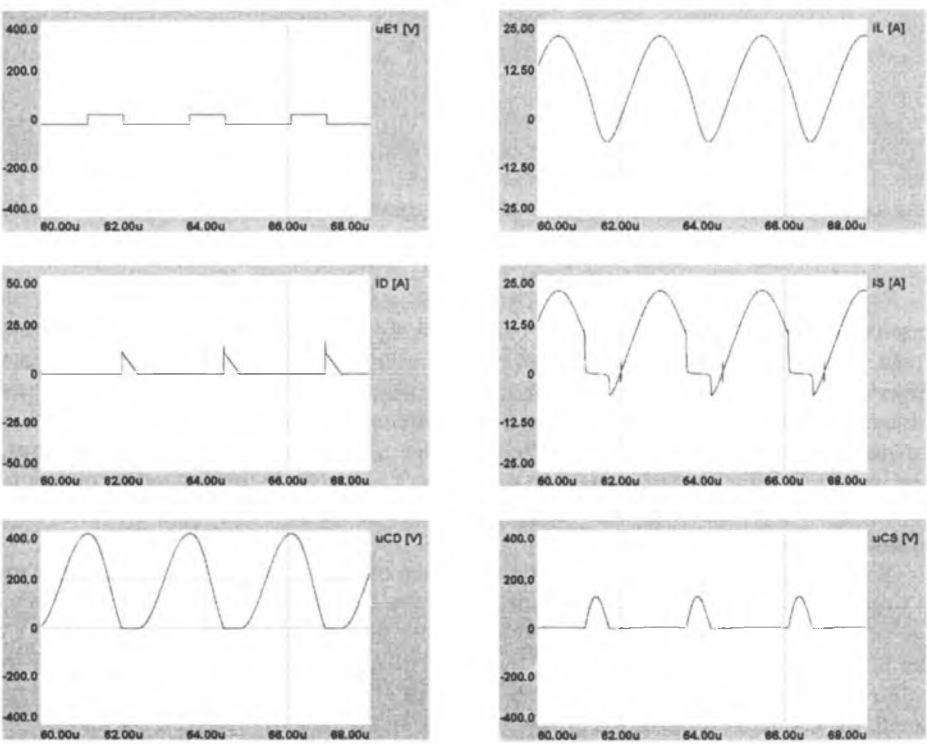

Fig.4. Current and voltage waveforms of buck ZVS MRC, obtained as a result of simulation, $C_N = 2,3$, $f = 625kHz$

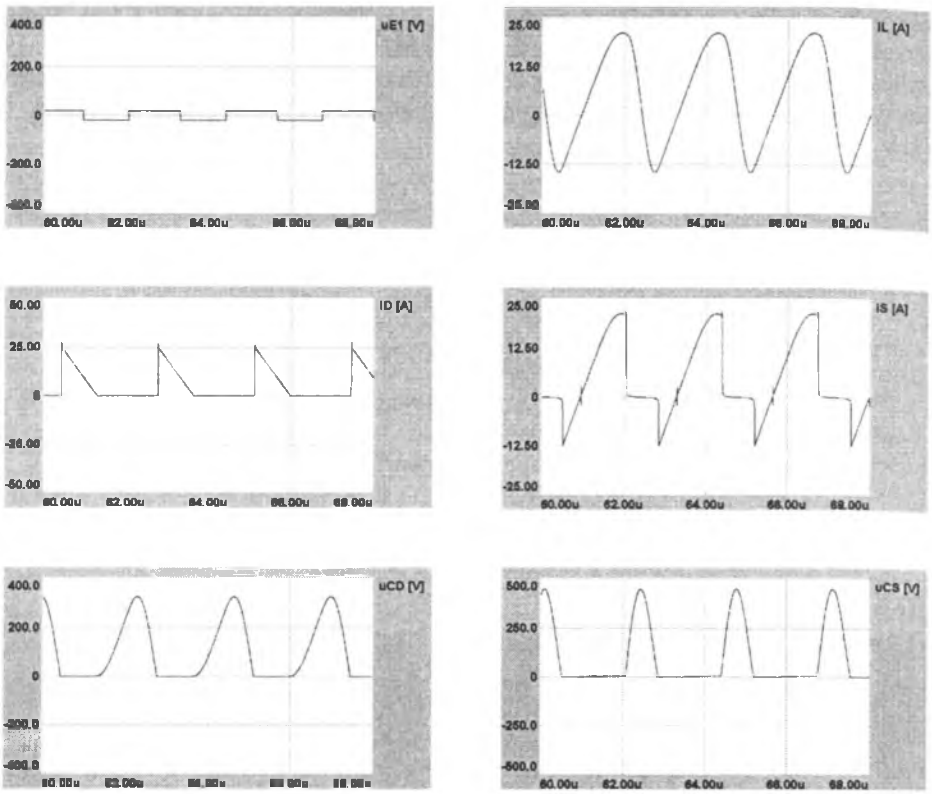

Fig.5. Current and voltage waveforms of buck ZVS MRC, obtained as a result of simulation, $C_N = 2{,}3$, $f = 909$kHz

Fig.4 and 5 show current and voltage waveforms of the converter during steady operation for the values of frequency $f = 625$kHz and $f = 909$kHz, when $C_N = 2{,}3$. Current and voltage waveforms in the steady state are stable in nature. When $f = 625$kHz, the transistor voltage u_{CS} does not exceed the value of voltage E, and the diode voltage u_{CD} does not exceed double the value of voltage E. The increase of switching frequency f influences growth of the transistor voltage u_{CS} and drop of the diode voltage u_{CD}, and reduces losses in the transistor, as the impact of parasitic capacitance on the circuit's operation increases in the circumstances. Parameters of the transistor and the diode limit the range of the converter's switching frequency.

Simulation tests have confirmed the influence of transistor and diode parameter values, and values of elements of the resonant circuit, on the converter's stability and efficiency. The value of capacitance C_S should be markedly higher than that of parasitic capacitance C_{0S}, in order to take over a dominant share of resonant current. Choice of a transistor of the lowest possible output capacitance C_{0S}, results in increased efficiency of the converter. If the ratio C_N is small, the converter's operation proves unstable. In the case of presented circuit parameters, the converter's operation is stable if $C_N \geq 2{,}2$. The value of capacitance ratio C_N is increased by choice of the capacitance C_D values (while keeping in mind the presence of parasitic capacitance C_{0D}).

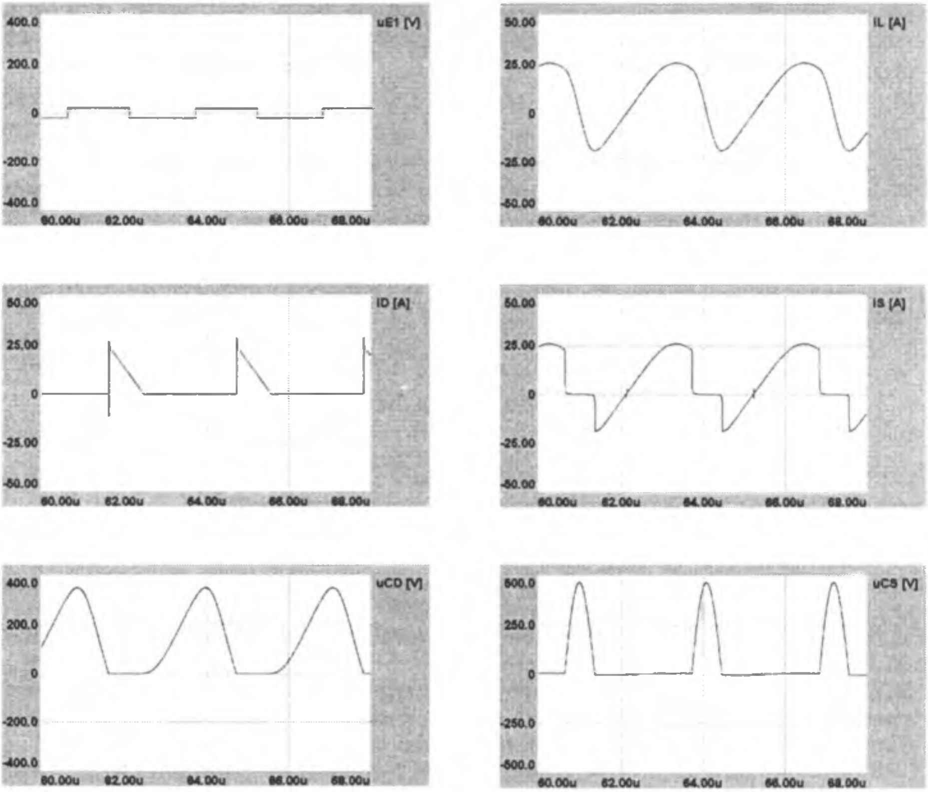

Fig.6. Current and voltage waveforms of buck ZVS MRC, obtained as a result of simulation, $C_N = 4{,}6$, f = 195kHz

Fig.6 shows current and voltage waveforms of the converter during stable operation when $C_N = 4{,}6$. The higher the ratio C_N is, the higher the maximum value of resonant current in the inductance L and the conducting losses, thus the lower the circuit's efficiency. Growth of the ratio C_N lowers the switching frequency, raises the transistor voltage u_{CS}, and reduces the diode voltage u_{CD}.

5. CONCLUSION

Simulation testing of the converter under analysis leads to the following conclusions:

1. Switching of the transistor and the rectifying diode at zero voltage in resonant converters (ZVS) enables to obtain high operating frequencies of the converter while maintaining high energy efficiency and operating reliability, since parasitic capacitances of the transistor and the diode, parasitic inductances of connections and the leakage inductance of the transformer are involved in the resonant circuit.

2. Zero-voltage-switching multiresonant converters provide advantageous conditions for zero-voltage switching of both the transistor and the diode. The transistor and the diode voltage levels, and magnitudes of parasitic capacitance currents can be reduced by choice of parallel resonant capacitances.
3. Multiresonant buck ZVS converter generates DC voltage within a range of frequency in the area of stable operation and can be used in power supplies for transport telematics equipment, where high energy efficiency and operating reliability are required.
4. Research should continue on real models to verify and confirm results of simulation testing under conditions of the converter's power supply and load. Actual tests should determine permissible ranges of operating frequency, where electromagnetic compatibility of telecommunications, control and monitoring equipment used in transport telematics is obtained.

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