Multiresonant ZVS Boost Converter

Elżbieta SZYCHTA
Technical University of Radom, Poland

Summary: The article presents properties of multiresonant voltage-increasing converter to be applied in DC voltage supply systems. The configuration of the system elements enables application of the technique of zero voltage switching (ZVS) of semi-conductor elements, which yields high operating frequencies of the system while maintaining high energy efficiency and reliability of operation. Results of simulation tests of the converter, based on Simploter, are discussed. Regulation characteristics are presented and the converter’s efficiency is determined.

1. INTRODUCTION

In energy-saving resonant power processing systems, switching of semi-conductor power elements occurs at high frequency and zero voltage (ZVS) or zero current (ZCS) [1]. Energy efficiency of such converters depends, to a large extent, on the transistor and diode switching processes. Power losses at turn on and off result from the current in the switched system multiplied by the voltage in switched semi-conductor elements.

What is characteristic of quasi-resonant ZCS converters is their ability to switch off the transistor at zero value of the current [8]. The transistor is switched on at the supply voltage of the converter. Losses due to impact of the transistor’s parasitic capacitance called occur then (switching Miller effect) [4]. Rectifying diode is switched off at zero current. Maximum operating frequency of quasi-resonant ZCS converters is limited above all by the losses connected to transistor turn-on, and is up to 2 MHz [15].

What is characteristic of quasi-resonant ZVS converters is their ability to switch off the transistor at zero value of the voltage [14]. Voltage stresses occur when the rectifying diode is switched, causing parasitic oscillations between the diode’s parasitic capacitance and resonant inductance. These oscillations cause losses at high switching frequencies and adversely affect the system’s stability. The conditions of semi-conductor element switching enable operation of quasi-resonant ZVS converter at operating frequencies up to 10 MHz [15].

ZCS and ZVS quasi-resonant converters allow for switching at zero value of current or voltage of the transistor or diode, but not of both the elements at the same time. These systems experience undesirable oscillations of resonant current caused by parasitic capacitances of semi-conductor elements and inductances of connections. This limits the potential for application of quasi-resonant converters to power processing at high switching frequency [14].

Further research into analysis of properties of resonant system structures where all semi-conductor elements would be switched at soft commutation of voltages or currents led to development of multiresonant converters [1,2,5,7,14]. Design of these converters features controlled switches, including MOSFET transistor, rectifying diode and resonant circuit overloading at two different frequencies. Load resistance of the converter is an element of the resonant circuit. Parasitic capacitances of the transistor and diode, leakage inductance of transformer, and connection inductances are all parts of the resonant circuit. Semi-conductor elements are switched at zero voltage (ZVS) or zero current (ZCS).

Designs of multiresonant converters operating at zero voltage of the transistor and diode (ZVS) should be characterized by the following properties (Fig. 1):

1. Resonant capacitance $C_S$ is located parallel with the transistor T. When the transistor conducts, capacitance $C_S$ is not a part of the system’s operation. When the transistor does not conduct, capacitance $C_S$ and parasitic capacitance of the transistor $C_{TS}$ in parallel, conduct resonant current of the converter.

2. Resonant capacitance $C_D$ is located parallel with the rectifying diode D. When the diode conducts, capacitance $C_D$ is not a part of the system’s operation. When the diode does not conduct, capacitance $C_D$ and parasitic capacitance of the diode $C_{DB}$ in parallel connection, conduct resonant current of the converter.

3. Resonant inductance $L$ is part of the circuit including the transistor and diode D. The circuit can also comprise a voltage source and filter capacitances and inductances.

Application of ZVS method in multiresonant converters produces high operating frequencies of such systems, enables elimination of parasitic oscillations of the current in resonant circuit, restricts dynamics of voltage and current stresses, and minimizes power losses [1]. Multiresonant ZVS converters can be applied in systems supplying DC voltage electricity, where high energy efficiency is a requirement.

Basic designs of multiresonant converters are presented in references [15, 17]. Results of tests of forward converter are discussed in [17]. Buck converter is analysed in [11,14].

![Fig. 1. Multiresonant ZVS boost converter](image-url)
Interesting properties of the other converter designs require detailed analysis. This article discusses multiresonant ZVS boost converter.

2. TOPOLOGY OF MULTIRESONANT ZVS BOOST CONVERTER

Multiresonant ZVS boost converter is shown in Figure 1. A high inductance $L_F$ choke, in series with a voltage source $E$, supplies the converter with current. Transistor MOSFET $T$, with resistance $R_T$ when conducting and output capacitance $C_{OS}$, is switched at frequency $f$. Diode $D_S$ is an integral part of the transistor and enables two-way conduction of current $i_T$ in a transistor leg. The rectifying diode $D$ contains parasitic output capacitance $C_{OD}$. The converter’s resonant circuit includes the following elements: choke with inductance $L$, capacitance $C_S$ in parallel with the transistor, and capacitance $C_D$, in parallel with the diode $D$. Elements of the resonant circuit cooperate with the system’s parasitic reactances, that is, inductance $L$ ‘absorbs’ leak reactance of the transformer, and capacitances $C_S$ and $C_D$ in parallel connections ‘absorb’ parasitic capacitances $C_{OS}$, $C_{OD}$. The value of capacitance $C_S$ should be much greater than that of the parasitic capacitance $C_{OS}$ in order for the capacitance $C_S$ to take over most part of the resonant current. Choice of a transistor of the lowest possible output capacitance $C_{OS}$ contributes to greater efficiency of the system [1]. Configuration of the system elements allows for application of zero voltage switching of both the transistor and the diode. Capacitance $C_F$ is a low-pass filter that limits pulsa­tion of output voltage.

When the transistor is conducting, the capacitance $C_S$ is not involved in conduction of resonant current. At high quality factor of the system, frequency of oscillations $f_D$ of the resonant circuit $R$, $L$, $C_D$, $C_{OD}$ is:

$$f_D = \frac{1}{2\pi \sqrt{L(C_D + C_{OD})}}$$

(1)

When the diode $D$ is conducting, the capacitance $C_D$ is not involved in conduction of resonant current. At high quality factor of the system, frequency of oscillations $f_S$ of the resonant circuit $R$, $L$, $C_S$, $C_{OS}$ is:

$$f_S = \frac{1}{2\pi \sqrt{L(C_S + C_{OS})}}$$

(2)

3. DESCRIPTION OF THE SYSTEM'S OPERATION

In a boost system (Fig. 1), an operating cycle is divided into five time intervals. Current and voltage waveforms, in relative units, during the cycle are illustrated in Figure 2. Resonant circuits for particular intervals are shown in Figure 3.

In the first time interval ($t_0 \leq t \leq t_1$) (Fig. 2), at the moment $t = t_0$, the transistor is switched on to operate. The equation: $i = i_t + i_s$ obtains for node 1 (Fig. 3a). The value of resonant current $i_s$ is larger than that of the supply current $I$. Current $I$ is constant, thus the difference of currents $i_s - I$ is conducted by the diode $D_S$ of the transistor. Energy occurring in the choke $L$ at $t = t_0$ is passed on to the capacitance $C_F$ in the circuit: $L$, $D$, $C_F$, $D_S$. When the current $i_s$ reaches the value $I$, diode $D_S$ stops conducting and the system moves on to the second operating range, and voltages of the drain – source transistor $u_{CS}$ and of the diode $u_{CD}$ equal zero.

In the second time interval ($t_1 \leq t \leq t_2$) (Fig. 2), at $t = t_1$, the current $i_t = I$, the current $i_s = 0$ and the transistor begins to conduct (Fig. 3b). Energy stored in the choke $L$ at $t = t_1$ continues to be transferred to the capacitance $C_F$ in the circuit: $L$, $D$, $C_F$, $I$. At $t = t_2$, the current $i_t = 0$, the current $i_s$
In the third time interval \((t_3 \leq t \leq t_4)\) (Fig. 2), the output voltage \(U_0\) is greater than that of the transistor \(u_{CS}\) and a resonant circuit arises: \(R_P, C_P, (C_D + C_{0D}), L\). Current of the transistor \(i_L = I - I_1\). At \(t = t_3\) the transistor is switched off (at zero voltage \(u_{CS}\)).

In the fourth time interval \((t_4 \leq t \leq t_5)\) (Fig. 2), the transistor and the diode \(D\) are not conducting (Fig. 3d). The capacitance \(C_S\) and parasitic capacitance \(C_{0S}\) and the capacitance \(C_D\) and parasitic capacitance \(C_{0D}\) overlap with the resonant current \(I_L\). The equation: \(I = I_1 + i_{CS}\) obtains for node 1 (Fig. 3d). The process of oscillatory overlap of the current \(I_L\) continues until \(t = t_4\), when \(u_{CD} = 0\).

In the fifth time interval \((t_5 \leq t \leq t_6)\) (Fig. 2), at \(t = t_4\), the diode \(D\) begins to conduct (Fig. 3e). The capacitance \(C_S\) and parasitic capacitance \(C_{0S}\) are conducting the current \(i_{CS}\) till \(t = t_5\), when \(u_{CS} = 0\). The transistor is ready to be turned on in the following cycle of the converter’s operation.

Multiresonant ZVS converter is characterised by the following properties:

\[ f_N = \frac{f}{f_S} \]

\[ C_N = \frac{C_D + C_{0D}}{C_S + C_{0S}} \]

\[ M = \frac{U_0}{E} \]

\[ R_N = \frac{R}{Z_S} \]

\[ Z_S = \sqrt{\frac{L}{C_S + C_{0S}}} \]

where:

\(f\) — operating frequency of the converter,

\(f_N\) — operating frequency, relative units,

\(C_N\) — capacitance factor,

\(M\) — voltage conversion factor (output voltage, relative units),

\(U_0\) — output voltage of the converter,

\(R_N\) — load resistance, relative units,

\(Z_S\) — characteristic impedance [1].

The power \(P_{we}\) received by the converter is:

\[ P_{we} = I \cdot E \]

(4)

where:

\(I\) — mean value of converter supply current.

Power \(P_{wy}\) released in load resistance \(R\) of the converter is:

\[ P_{wy} = \frac{U_0^2}{R} \]

(5)

Efficiency of the converter \(\eta\) is:

\[ \eta = \frac{P_{wy}}{P_{we}} \]

(6)

The magnitudes represented in the system of equations (3) are necessary to determine regulating characteristics of the converter. In view of complex mathematical apparatus, these characteristics can be determined using simulation tests.

4. SIMULATION TESTS

Multiresonant ZVS converter (Fig. 4) was subjected to Simplerker-based simulation tests. The simulation system comprised a MOSFET transistor IRFP460 (output capacitance \(C_{0S} = 870\text{pF}\)), and an ultrafast diode HFA25TB60 (output capacitance \(C_{0D} = 100\text{pF}\)) of International Rectifier. The resonant circuit contains the following element values: \(L = 7\mu\text{H}, C_S = 7\text{nF}, C_P = 23\text{nF}, L_P = 600\text{pH}, C_P = 10\text{mF}, R = \text{var}\) on the basis of equations (1) and (2), resonant frequencies are: \(f_S = 678\text{kHz}, f_D = 396\text{kHz}\). Supply voltage \(E = 50\text{V}\).
The range of operating frequencies $f$ which ensures ZVS switching in the converter at $C_N = 2.9$, $R = 30\Omega$ is $338kHz \leq f \leq 535kHz$. Frequency $f$ can be increased through reduction of the transistor’s conducting time. Minimum frequency $f_{min} = 338kHz$ obtains at the transistor’s conducting time $t_{max} = 2.2\mu s$ and depends on the value of capacitance factor $C_N$. Figure 5 shows current and voltage waveforms during converter’s steady operation at frequency $f = 338kHz$. Current and voltage waveforms in the steady condition are stable in nature. The waveform of transistor current $i_g$ displays slight oscillations related to presence of the output capacitance $C_{DS}$. Transistor switching occurs at zero value of voltage $u_{CS}$.

Full of frequency $f$ below $f_{min} = 338kHz$ at $C_N = 2.9$ causes the system to become unstable, i.e. the converter is no longer capable of ZVS switching. The case of the loss of system stability is illustrated in Figure 6. Maximum frequency $f_{max} = 535kHz$ occurs at transistor’s conducting time $t_{min} = 1\mu s$ and depends on the value of the transistor’s parasitic capacitance. At frequencies $f$ over the value $f_{max} = 535kHz$, major impact of parasitic capacitances on the system’s operation becomes noticeable (Fig. 8). Within the range of operating frequencies $338kHz \leq f \leq 535kHz$, output voltage $U_0$ changes within the range $130,6V \geq U_0 \geq 59,7V$, supply current $13,1A \geq I \geq 2,6A$. Values of maximum voltages in the transistor and the diode occur within the ranges: $326V \geq U_{CSmax} \geq 185V$ and $246V \geq U_{CDSmax} \geq 42V$.

Figure 8 shows selected regulating characteristics obtained as a result of simulation tests: $M = \frac{f}{f_N}$, $I_{Smax}/I_0 = \frac{f}{f_N}$, $U_{CSmax}/E = \frac{f}{f_N}$, $U_{CDSmax}/E = \frac{f}{f_N}$. Each characteristic is presented for the range of operating frequency $f_{min} \leq f_T \leq f_{max}$ which guarantees ZVS switching. The range of operating frequency $f_T$ is variable and dependent upon load resistance $R_L$. Drop of frequency $f_T$ below $f_{min}$ causes the system to lose its stability (Fig. 6). At values of frequency $f_T$ over $f_{max}$ parasitic capacitances have significant influence on the system’s operation and increase of switching losses (Fig. 7).
Rise of relative frequency $f_N$ causes reduction of the values of factor $M$, maximum voltages in the transistor $U_{CSmax}/E$ and the diode $U_{CDmax}/E$ as well as maximum transistor’s current $I_{Smax}/I_0$ (Fig. 8). Growth of resistance $R_N$ leads to increase in values of factor $M$, maximum voltages in the transistor $U_{CSmax}/E$ and the diode $U_{CDmax}/E$ as well as maximum transistor’s current $I_{Smax}/I_0$, with increased value of relative frequency $f_N$ and reduced range $f_N$ that ensures zero voltage switching.

Figure 8 indicates that at $C_N = 2.9$, $R_N = 1$, in the frequency range $0.50 \leq f_N \leq 0.79$ (338kHz $\leq f \leq 535$kHz), conversion factor of the converter $M$ fits into the range: $2.6 \geq M \geq 1.2$, maximum voltage values in the transistor $U_{CSmax}/E$ are within the range: $6.5 \geq U_{CSmax}/E \geq 3.7$, maximum voltage values in the diode $U_{CDmax}/E$ are within the range: $4.9 \geq U_{CDmax}/E \geq 1.8$, maximum current values of the transistor fit in the range: $4.6 \geq I_{Smax}/I_0 \geq 2.6$.

Simulation testing confirms impact of parasitic capacitances of the transistor and of the diode, and of the value of factor $C_N$ on the converter’s stability. Value of capacitance factor $C_N$ increases through growth of capacitance $C_D$ (bearing in mind the existence of parasitic capacitance $C_{Q0}$). Simulation tests of the transistor’s conducting time $t_{max} = 2.1\mu s$, $R = 30\Omega$, $C_D = \text{var}$ showed that the converter’s operation is stable if $2.6 \leq C_N \leq 6.4$.

When the value $C_N$ increases, load voltage varies in the range $128V \geq U_0 \geq 78V$, supply current $I$ changes within the range $12.4A \geq I \geq 4.7A$. The system’s efficiency fits into the range $0.88 \geq \eta \geq 0.86$.

The higher the factor $C_N$ the lower the maximum value of resonant current $i_L$ in the inductance $L$, the higher the conductance losses, and thus the lower the system’s efficiency $\eta$. Growth of factor $C_N$ leads to reduction of maximum voltage value $U_{CSmax}$ in the diode. Major impact of changes of factor $C_N$ on variation of operating frequency and maximum voltage values $U_{CSmax}$ in the transistor is not observed.

Simulation testing of the impact of load fluctuations on the system’s operation demonstrates, that reduction in value of resistance $R$ causes reduced frequency $f$, lower value of current $I$ and of voltage $U_0$. The higher the value of resistance $R$, the higher the maximum voltage values in the transistor $U_{CSmax}$ and the diode $U_{CDmax}$ and the higher the maximum current values of the transistor $I_{Smax}$. At $C_N = 2.9$, $t_{max} = 2.1\mu s$, when values of resistance vary in the range $10\Omega \leq R \leq 30\Omega$, frequency $f$ changes in the range $343$kHz $\leq f \leq 358$kHz, voltage $U_0$ fluctuates in the range $55V \leq U_0 \leq 120V$, voltage $I$ changes in the range $6.54A \leq I \leq 10.9A$, the system’s efficiency is within the range $0.92 \geq \eta \geq 0.88$.

Figure 9 illustrates efficiency of the converter $\zeta$ in function of relative frequency $f_N$ in the range of operating frequency which ensures ZVS switching. Figure 9 shows, that efficiency $\zeta$ of the system declines as relative resistance $R_N$ grows at
Fig. 7. Current and voltage waveforms in the converter obtained during simulation, $C_N = 2.9$, $f = 535$Hz, $R = 30\Omega$

Fig. 8. Regulation characteristics for voltage boost converter, relative units, $C_N = 2.9$, a) conversion factor $M$, b) maximum transistor currents $I_{\text{Smax}}/I_0$, c) maximum voltages in the transistor $U_{\text{CSmax}}/E$, d) maximum voltages in the diode $U_{\text{CDSmax}}/E$
5. CONCLUSION

Simulation testing of the analysed system yields the following conclusions:

1. Multiresonant ZVS boost converter provides good zero-voltage switching conditions for both the transistor and the diode. Parastatic capacitances of the transistor and the diode, parasitic inductions of connections, and leakage inducance of transformer are all part of the resonant circuit.

2. Switching of the transistor and the rectifying diode at zero voltage in the converter enables high operating frequency of the system while high energy efficiency is maintained.

3. The range of the converter’s operating frequency in which ZVS switching is assured, determined on the basis of simulation testing, is variable and dependent on the load resistance.

4. Stability of the converter, defined as the ability to switch semi-conductor elements in cooperation with the resonant circuit, is maintained in the range of operating frequencies determined in regulation characteristics. Drop of the frequency below values within the system’s operating range causes the system to lose its stability. A choice of resonant capacitances suited to conditions of the system’s power supply and load, influences stability of the system.

5. Increase of operating frequencies above values within the system’s operating range, shown in regulating characteristics, intensifies influence of parasitic capacitance on the system’s efficiency.

6. Multiresonant ZVS boost converter generates DC voltage and can be applied in power supply systems where high energy efficiency is required.

7. Maximum voltage values in the transistor and the diode grow small, as the system’s operating frequency rises or the value of load resistance falls.

8. Tests should continue using a real model in order to verify and confirm simulation results at the conditions of the converter’s power supply and load.

REFERENCES


Elżbieta Szychta

Graduated from the Electrical Faculty of Warsaw Polytechnic in 1981. Obtained a degree of doctor of engineering from the Electrical Faculty of Warsaw Polytechnic in 1988. Since 1981 she has worked for the Transport Faculty Kazimierz Pulaski at the Technical University of Radom. An assistant professor in the Department of Electrical Machinery and Equipment. Interested in industrial power electronics.

Address: Politechnika Radomska, Wydział Transportu, 26-600 Radom, ul. Małczewskiego 29; tel: (048) 361 77 00, e-mail: eszychta@pr.radom.pl