Operating Modes of a Series-Parallel Resonant DC/DC converter

Nikolay Dimitrov Bankov, Alexandar Stoyanov Vuchev and Georgi Petrov Terziyski

Abstract – **A qualitative description of the operating modes of a series-parallel resonant DC/DC converter is made. The conditions for the operating modes are indicated. These operating modes are presented in the phase plane, which makes them easier to study. The locations of the various operating modes within the plane of the output characteristics of the converter are shown.**

Keywords – **series-parallel DC/DC converter, phase plane, operating modes**

I. INTRODUCTION

The series-parallel DC/DC converter is gaining increasing popularity as a power source for various electro-technologies. It is studied in details in a number of publications [1÷5]. With this converter there are many modes of action, which depend on both the operating frequency and the load current.

The purpose of this work is merely to provide qualitative description of the basic operating modes of the converter, assuming that the semiconductor switches are ones of soft commutation. These either are switches with forced (controlled) turn-on and automatic turn-off switching at zero current (ZCS), or switches with forced turn-off and automatic turn-on switching at zero voltage (ZVS).

II. OPERATING MODES

Fig.1 shows the primary electrical circuit diagram of the examined DC/DC converter. It consists of an inverter (semiconductor switches $S_1 \div S_4$ with anti-parallel diodes $D_1 \div D_4$), a resonant circuit (L и C), a coordinate transformer (Tr), an uncontrolled rectifier ($D_5 \div D_8$), an inductive filter (L_F) and a load resistor (R_0). It is assumed that all elements of this circuit are ideal, the commutations are momentary, and the ripples of the input voltage U_d and the output current I_0 are ignored.

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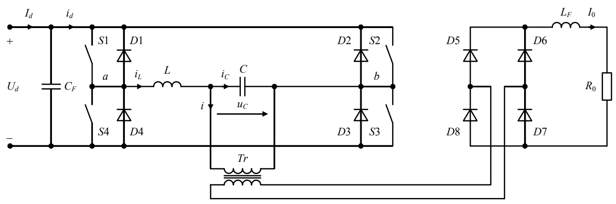


Fig.1. Circuit diagram of the converter

For the purposes of studying this series-parallel resonant DC/DC converter the following assumptions are accepted:

- the coordinate transformer is ideal with a transform coefficient of one unit;
- all semiconductor switches are ideal. Their commutations are momentary, and the voltage through them is inadmissibly low;
- the effect of the damping circuits of the semiconductor switches is ignored;
- the reactive elements are at no loss;
- the input voltage ripples U_d and the output current ripples I_0 are inadmissibly low.

Under these assumptions, the study of the suggested converter comprises analysis of a series-parallel L - C circuit with resonant frequency f_0. This circuit is activated on one side by the voltage u_{ab}, provided through the inverter, and on the other side by the current i through the primary coil of the transformer. Voltage u_{ab} is expressed in rectangular form, amplitude $\pm U_d$ and frequency f. Current i is also expressed in rectangular form, amplitude $\pm I_0$ and in phase with the capacitor voltage C.

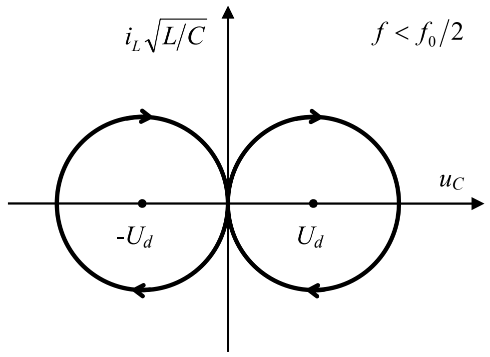
The various operating modes with the examined converter depend on both the operating frequency f, and on the intensity of the load current I_0. These operating modes can be presented in the phase plane $\left(x = u_C / U_d;\ y = i_L \sqrt{L/C} / U_d\right)$ with purpose to make them easier to study.

A. No-load modes $(I_0 = 0)$.

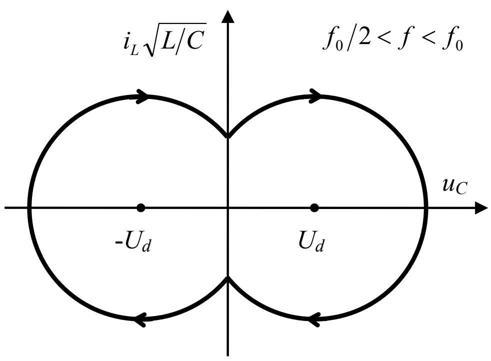
The no-load mode of the series-parallel DC/DC converter is absolutely analogous to the short-circuit mode of the series resonant circuit converter. There are three possible mode cases, depending on the operating frequency rate f, compared to the resonant frequency rate f_0. Fig.2a ÷ 2в presents these three modes in the phase plane.

In case that $f < f_0/2$, the converter is operating in discontinuous current mode. Each pair of semiconductor switches and their matching anti-parallel diodes conduct together for a full-period ripple cycle, and then the current i_L resets back to zero and remains at zero rate, until the next pair of switches turns on (fig. 2a). The continuous current mode operates at $f_0/2 < f < f_0$ (fig.2b). In both cases the operating frequency is lower than the resonant frequency, which requires using the ZCS type switches.

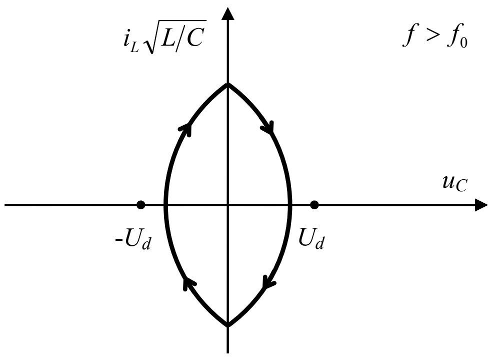
With $f > f_0$ it is required to use type ZVS switches. Then the current i_L is always continuous (fig.2c).



a)



b)



c)

Fig.2. No-load converter modes

B. Short-circuit mode $(U_0 = 0)$.

In this operating mode, capacitor voltage C is always zero. Therefore I_0 the current circulation is carried out by the diodes of the rectifier, while they are all on at the same time. The inductance voltage L is u_{ab}, and the current i_L running through it is expressed in triangular form and amplitude $U_d/4Lf$. The current intensity I_0 is also $U_d/4Lf$. Regardless the rate of the operating frequency, the soft commutation of the inverter is possible only with switches with forced turn-off switching, i.e. ZVS type switches.

C. Loading modes at $I_0 < U_d/\sqrt{L/C}$.

Examinations starts with no-load and discontinuous current mode (fig.2a), having the load current I_0 increase to a rate, lower than $U_d/\sqrt{L/C}$.

During the current pause i_L, corresponding to p. 0 from fig.3, the current I_0 is turned off through the load and all the diodes of the rectifier turns off. The controlled turn-on switching of the one pair of switches (ZCS) causes the current to linearly increase i_L in the inductance L, until it reaches $i_L = \pm I_0$. Then the conduction carries through the inverter switches and their anti-parallel diodes, until i_L resets back to zero (p. M_1 or p. M_2). After the anti-parallel diodes of the inverter have turned off, the capacitor C starts discharging at continuous current, and then the current I_0 flow is turned off again through the load and all the diodes of the rectifier (p. 0). In this *first* operating mode (fig.3), after each half-period the ripple cycle turns back to a state, identical to the baseline state.

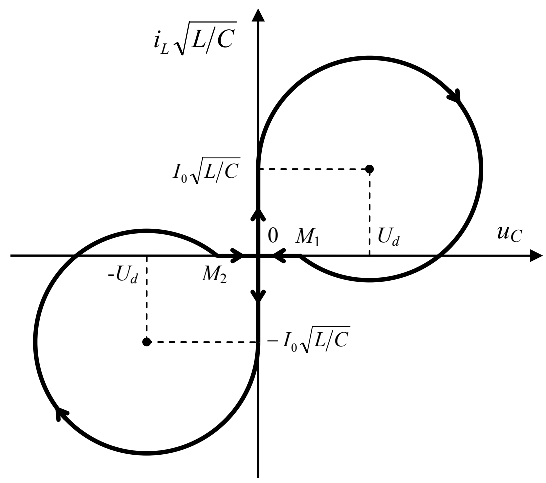


Fig.3. First loading operating mode

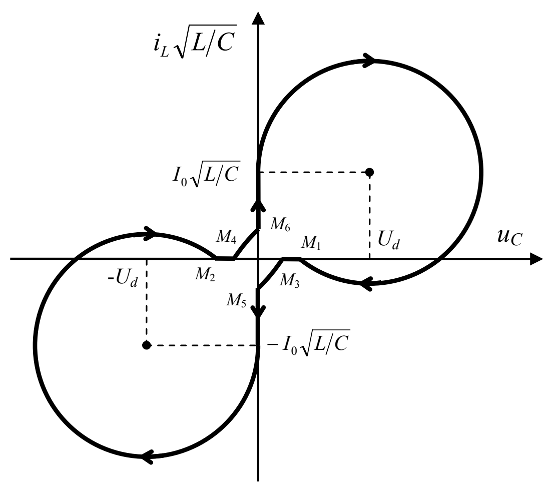


Fig.4. Second mode

When the operating frequency increases, a *second* operating mode is achieved (fig.4), very similar to the first one. The difference between the two modes comprises in the fact, that the inverter switches turn-on at time points, corresponding to p. M_3 or p. M_4 respectively, before the full discharging of the capacitor C at continuous current I_0 takes place.

In both cases, there is no actual commutation between the switches of the inverter because the current flow i_L is still discontinued. The continuous current mode becomes possible with the increase in the operating frequency over a critical point, where turning on the switches takes place at the same time the current is reset i_L back to zero. Then p. M_1 or M_2 from fig.4 correspond to p. M_3 or M_4, respectively. Fig. presents this *third* operating mode in the phase plane. 5. When the converter operates at frequency, equal to the critical frequency, the point draws a trajectory, as shown in fig. 5 with a dashed line.

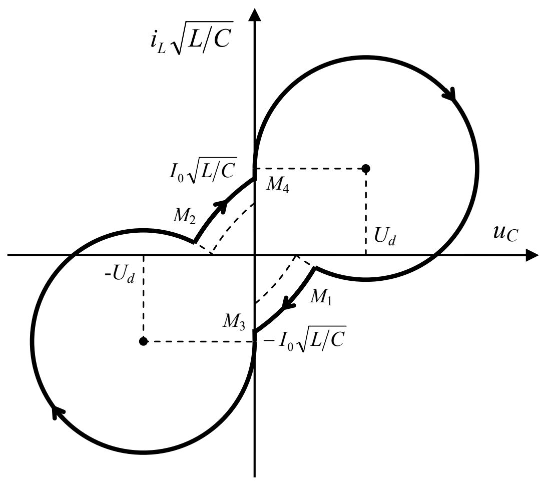


Fig.5. Third mode

So far, in all three load modes we studied above, there has been one current circulation phase I_0 through the load and the diodes of the capacitor, during which the current i_L increased linearly. This phase is completed, when i_L becomes $i_L = \pm I_0$. If the current I_0, is maintained at constant rate, a new increase in the operating frequency will cause this phase to disappear and the capacitor commutations become momentary. These conditions can bring up two more operating modes, majorly different from one another in their mechanisms of capacitor commutation:

- *Fourth* mode (fig.6) - capacitor switches are with controlled turn-on switching (ZCS). In this case the operating frequency has to be lower than the resonant frequency, while the ordinate of p. M_1 is negative.
- *Fifth* mode (fig.7) - capacitor switches are with controlled turn-off switching (ZVS). In this case the operating frequency has to be higher than the resonant frequency, and the ordinate of p. M_1 is positive.

From the latter, fifth mode, if the operating frequency continues increasing, a *sixth* operating mode is achieved, as illustrated in fig.8. In this mode, the phase of current circulation I_0 through the diodes of the capacitor, during which the current i_L increases linearly, appears again. The sixth mode is characterized by decrease in the output voltage and it is contiguous with the short-circuit mode of the converter.

D. Loading modes at $I_0 > U_d/\sqrt{L/C}$.

When the loading current I_0 is higher than $U_d/\sqrt{L/C}$, the inverter switches have to be with controlled turn-off and automatic turn-on switching at zero voltage (ZVS). Presentation in the phase plane is similar to the one, shown in fig.7 (fifth mode) or fig.8 (sixth mode).

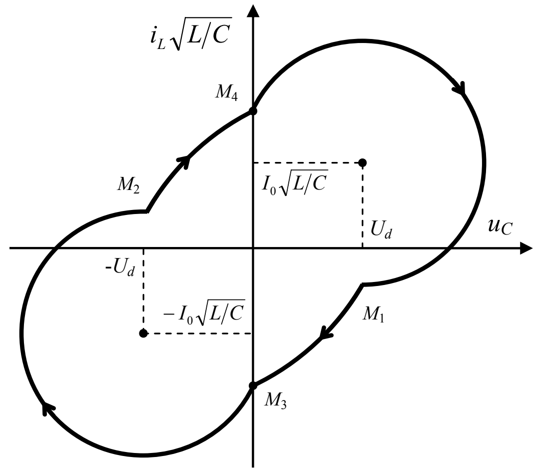


Fig.6. Fourth mode

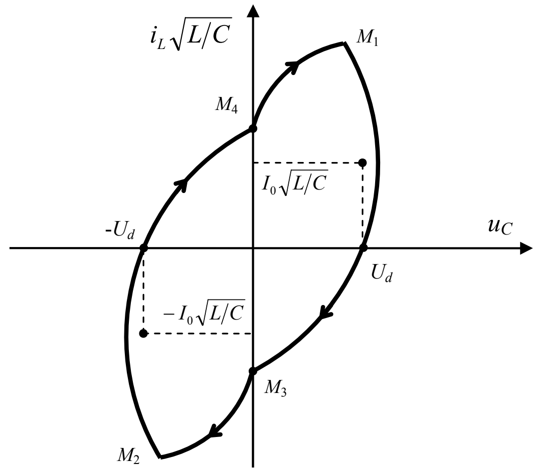


Fig.7. Fifth mode

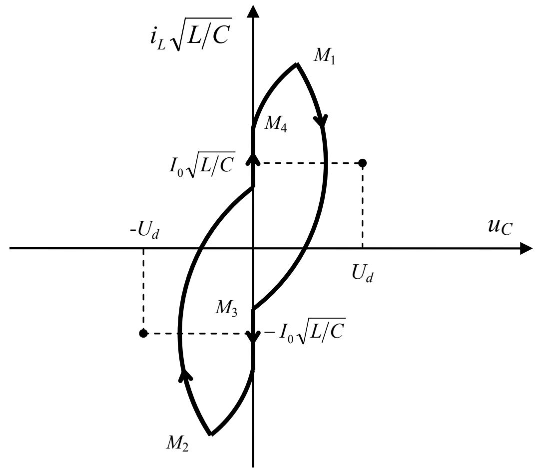


Fig.8. Sixth mode

III. OUTPUT CHARACTERISTICS

Fig.9 and fig.10 show the output characteristics of the series-parallel DC/DC converter at frequencies, respectively, lower or higher than the resonant frequency. These characteristics are obtained, using the analysis of the converter, performed in [1, 2]. Controlling parameter for the output voltage is resonant cycle distraction $\nu = f/f_0$. The locations of the various operating regiments are indicated in the output characteristics plane.

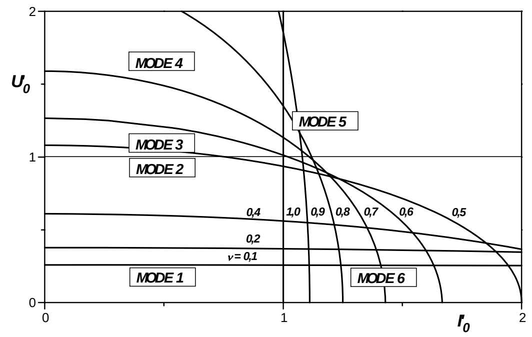


Fig.9. Output characteristics at frequencies, lower than the resonant frequency

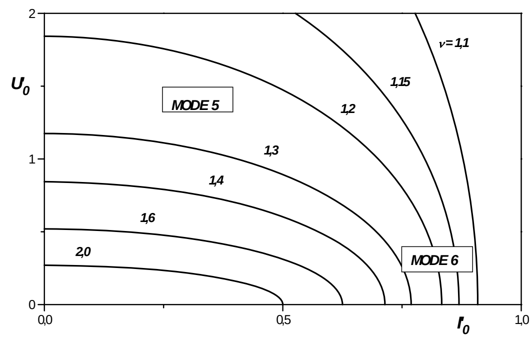


Fig.10. Output characteristics at frequencies, higher than the resonant frequency

Modes 1, 2, 3 and 4 are achieved, when the current flow I_0 is lower than $U_d/\sqrt{L/C}$ $\left(I_0' = \dfrac{I_0}{U_d/\sqrt{L/C}} < 1\right)$, the inverter switches are with controlled turn-on switching (ZCS), and the operating frequency is lower than the resonant frequency (fig.9). In this application the converter has output characteristics of a "voltage source" type, and the output voltage control requires slight adjustment in the operating frequency.

And vice versa, when the frequency is higher than the resonant frequency (fig.10), and the inverter switches are with controlled turn-off switching (ZVS), modes 5 and 6 take place. Then the converter operates more as a power source. Controlling this current power requires significant alteration in the operating frequency. In addition, the converter operation in conditions, close to the short-circuit mode, arises certain problems.

Modes 5 and 6 take place when $I_0 > U_d/\sqrt{L/C}$, the inverter switches are with controlled turn-off switching (ZVS), and the operating frequency is lower than the resonant frequency (fig.9). In this application the converter exploitation is difficult to carry out and has practical use.

IV. CONCLUSION

The possible operating modes of the series-parallel DC/DC converter have been examined. These operating modes have been presented in the phase plane, with purpose to perform precise analysis of the converter. The converter operation has shown to be of special interest at:

- operating frequencies, lower than the resonant frequency and ZCS commutation of the power switches. The converter has shown characteristics as a voltage source.
- operating frequencies, higher than the resonant frequency and ZVS commutation of the power switches. The converter has shown characteristics as a power source.

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