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

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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 \( S_1 \sim S_8 \) with anti-parallel diodes \( D_1 \sim D_8 \)), a resonant circuit \( (L \sim C) \), a coordinate transformer \( (Tr) \), an uncontrolled rectifier \( (D_9 \sim D_{10}) \), 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.

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

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 \( i_f \) through the primary coil of the transformer. Voltage \( u_{ab} \) is expressed in rectangular form, amplitude \( \pm U_d \) and frequency \( f \). Current \( i_f \) is also expressed in rectangular form, amplitude \( \pm I_f \) 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 \( (\varepsilon = u_c/|U_d|, \; y = i_f\sqrt{L/C}/U_d) \) with purpose to make them easier to study.

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 + 2a 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 \( i_f \) resets back to zero and remains at zero rate, until the next pair of switches turns on (fig. 2a). The continuous current

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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).

\[ \begin{align*}
\text{Fig.2. No-load converter modes} \\
(i) & \quad f < f_0/2 \\
(ii) & \quad f_0/2 < f < f_0 \\
(iii) & \quad f > f_0
\end{align*} \]

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.

\[ \begin{align*}
\text{Fig.3. First loading operating mode} \\
\text{Fig.4. Second mode}
\end{align*} \]

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.

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

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).
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 \( v = f / f_0 \).

The locations of the various operating regiments are indicated in the output characteristics plane.

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.

REFERENCES