LOAD CHARACTERISTICS OF PULSE WIDTH MODULATE CONTROLLED SERIES RESONANT DC-DC CONVERTER

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A series resonant DC-DC converter is examined at pulse width modulated control. The operation modes are presented. Based on an existing analysis of the converter are built the functional dependencies for the basic quantities as a function of the output current. A comparison is made between the calculated load characteristics and those, received from the simulation with PSpice.

Keywords: Series Resonant DC-DC Converter, PWM Control

1. INTRODUCTION

Pulse width modulated control (PWMC) of series resonant DC-DC converters at constant operation frequency above resonant secures wide range of their output power change. However, some peculiarities, connected with the modes of energy exchange between the power supply source, resonant circuit and the load are observed under it [1]. They are defined mainly from the loading of the converter. Together with this, in order to preserve the conditions for soft commutation, it is necessary that, in the different modes, the power switches have different commutation mechanisms. As a result of the analyses and the models in [2], [3] and [4] the dependencies for the basic quantities of the converter at operation above the resonant frequency were obtained.

The purpose of the present work is to create the dependencies of all converter quantities on the loading based on the existing mathematic expressions, proposed in [4]. As a fidelity test, the load characteristics have to be compared with those received through simulation with PSpice.

2. OPERATION MODES

The examined converter (Fig.1) consists of a bridge inverter ($S_1 \div S_4$, $D_1 \div D_4$), a series resonant circuit (L, C), an uncontrollable bridge rectifier ($D_5 \div D_8$), a filter capacitor C_0 and a load resistor R_0.

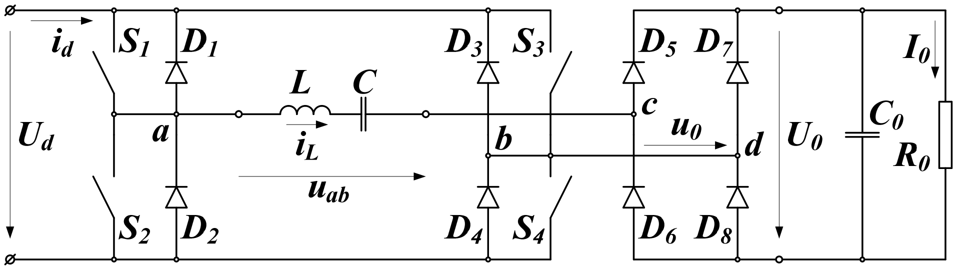

Fig.1. Circuits of the series resonant DC-DC converter

It is proposed in [1] that the operation of the examined converter be analyzed on three separate modes, defined by the loading. Wave forms of the normalized inverter voltage $\boldsymbol{u_{ab}}$ and current $\boldsymbol{i_L}$ through the resonant circuit for the three cases are shown on Fig. 2. Furthermore, there are presented the sequences of conducting of the inverter power devices for one half-cycle.

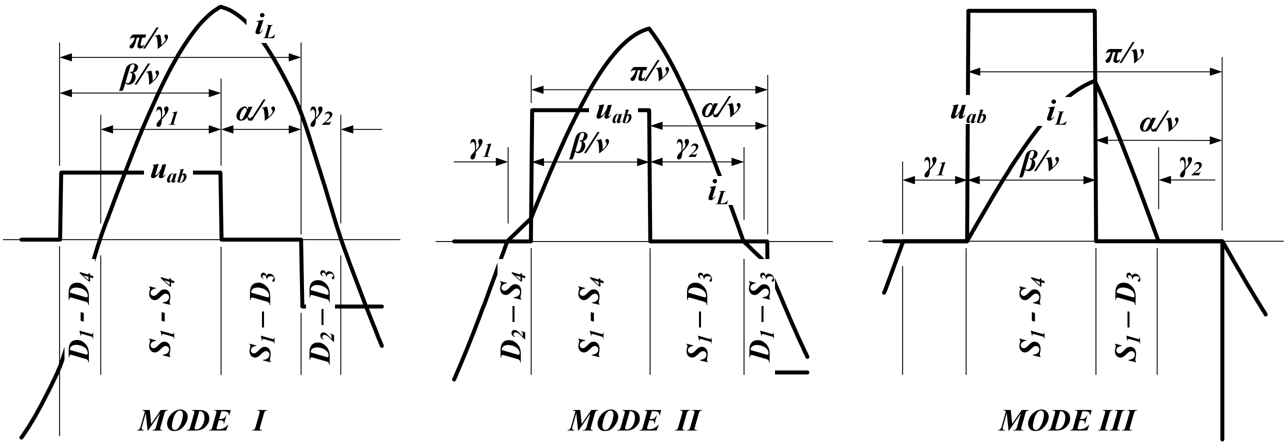

Fig.2. Wave forms of inverter voltage $\boldsymbol{u_{ab}}$ and resonant tank current $\boldsymbol{i_L}$ at the alternative operating modes

The inverter conditionally can be divided into two circuit sections. The first one consists of switches $\boldsymbol{S_1}$, $\boldsymbol{S_2}$ and their anti-parallel diodes $\boldsymbol{D_1}$ and $\boldsymbol{D_2}$, and the second one respectively of $\boldsymbol{S_3}$, $\boldsymbol{S_4}$ and $\boldsymbol{D_3}$, $\boldsymbol{D_4}$. The duty ratio of the inverter voltage $\boldsymbol{u_{ab}}$ is defined by the phase shift between the control signals of switch couples $\boldsymbol{S_1}$, $\boldsymbol{S_2}$ and $\boldsymbol{S_3}$, $\boldsymbol{S_4}$. In this case the phase shift is called a control angle and on Fig.2 it is marked with $\boldsymbol{\alpha}$. The angle of the half-cycle for the operation frequency $\boldsymbol{\omega_S}$ is marked with $\boldsymbol{\pi}$ respectively, and with $\boldsymbol{\beta}$ – the angle, corresponding to the interval, in which the energy exchange with the power supply source is achieved. The three angles are reduced to resonant frequency $\boldsymbol{\omega_0}$ of the tank circuit through frequency distraction $\boldsymbol{\nu = \omega_S / \omega_0}$ [4].

In order to secure conditions for soft commutation in the first mode (***MODE I***), it is necessary that all power switches ($\boldsymbol{S_1 \div S_4}$) have one and the same commutation mechanisms – spontaneous switching on at zero voltage and forced switching off. Only in this case energy can return towards the power supply source (in the interval γ_2).

For the realization of soft commutation on the second (***MODE II***) and the third (***MODE III***) mode it is necessary that the $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ switch on forcibly some time after the zeroing of the resonant current and switch off by zero current. Switches $\boldsymbol{S_3}$ and S_4 have the same commutation mechanism as in the first case (***MODE I***). At these two modes no energy is returned to the power supply source. Even more, in the third mode (***MODE III***) in the operation of the resonant circuit, there appear discontinued current pauses.

It is clear from the wave forms on Fig. 2 that independent of the operation mode, the switches $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ conduct bigger part of time in comparison to $\boldsymbol{S_3}$ and $\boldsymbol{S_4}$. This suggests that the loading of the power devices is not the same.

3. LOAD CHARACTERISTICS

In [4] the mathematic expressions for the basic converter quantities at operation above the resonant frequency were received. Based on them their functional dependencies on the loading at frequency distraction ***ν=1,15*** are built below. With purpose to obtain generalized results, all quantities are presented in relative units.

The dependencies of the output voltage on the output current by different values of the controlling angle ***α*** are shown on Fig. 3. The boundaries between the three operation modes are shown with dotted line. At the first mode (***MODE I***) the characteristics are soft, because of the significant voltage-drop across the resonant circuit. The converter operates with low power factor.

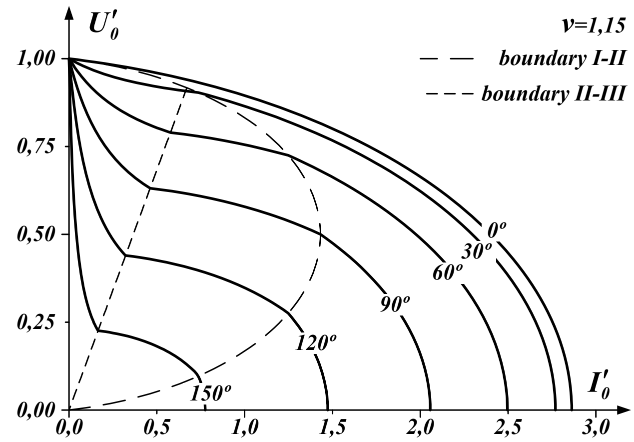

Fig.3. Dependence of output voltage on the output current

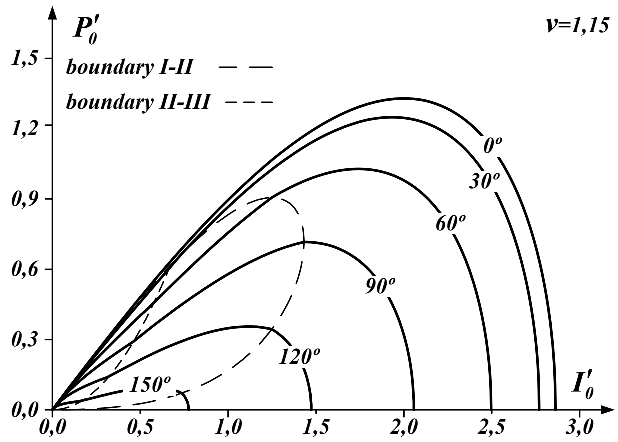

Fig.4. Dependence of output power on the output current

At the second mode (***MODE II***) characteristics are steady and the power factor is high. Now the voltage-drop across the resonant circuit is approximately equal to the output voltage $\boldsymbol{U_0}$. At the third mode (***MODE III***) characteristics become soft again because of the discontinued character of the current through the resonant circuit.

The dependencies of the output power on the output current are shown on Fig. 4. It seems that approximately for half the control range ($0 \leq \alpha \leq 90^o$) the maximum of the power is received in ***MODE I***. For the other half the maximum is in ***MODE II***.

As mentioned, the different operation modes define different requirements towards the elements, constructing the converter circuit. With purpose to clarify these requirements, there are some of the basic characteristics, received at control angle $\alpha = 90^o$ presented below. On Fig. 5 and Fig. 6 there are shown the dependencies of the average and root-mean-square values of the currents through the converter power devices on the output current. It becomes clear from them, that as it has been assumed, the loading of the switches (thick lines) and diodes (dotted lines) is not the same. For all modes the currents I'_{S12_AVR} and I'_{S12_RMS} through switches S_1 and S_2 of the first inverter circuit section are bigger that those (I'_{D12_AVR}, I'_{D12_RMS}) through their anti-parallel diodes (D_1, D_2). Thus the circuit section operates in inverter mode.

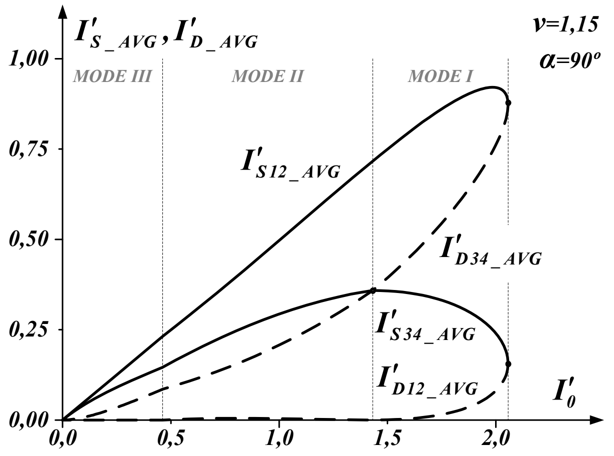

Fig.5. Dependencies of average values of currents, running through the inverter switches and diodes on the output current

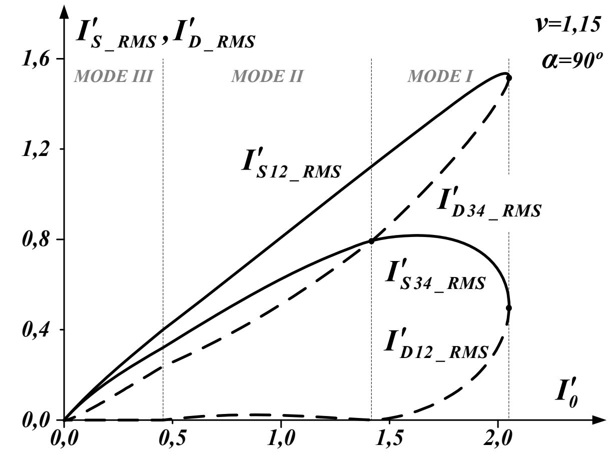

Fig.6. Dependencies of root-mean-square values of currents, running through the inverter switches and diodes on the output current

At the first mode (***MODE I***) the currents I'_{S34_AVR} and I'_{S34_RMS} through switches S_3 and S_4 are smaller than those (I'_{D34_AVR}, I'_{D34_RMS}) through the diodes (D_3, D_4). This means that the circuit section operates in rectifier mode. For the other two modes the currents through the switches become bigger of those through the diodes and the second circuit section like the first operates in inverter mode.

Generally, the loading of switches S_1 and S_2 of the first circuit section is bigger than that the one of switches S_3 and S_4 of the second circuit section. With the diodes it is opposite –D_3 and D_4 are more loaded. Even more, in the mode of discontinued current (***MODE III***) diodes D_1 and D_2 do not conduct at all.

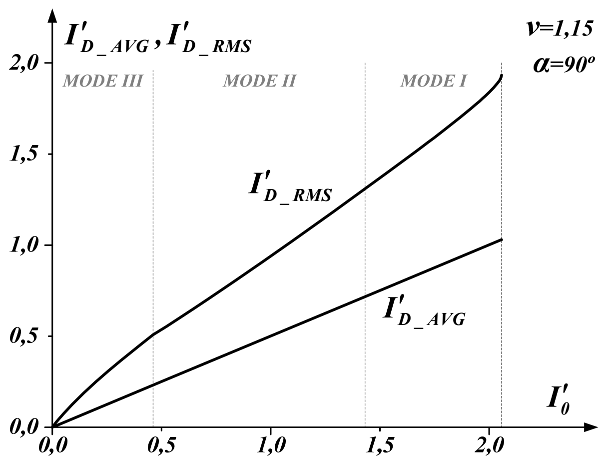

Fig.7. Dependencies of average and root-mean-square values of currents, running through the rectifier diodes on the output current

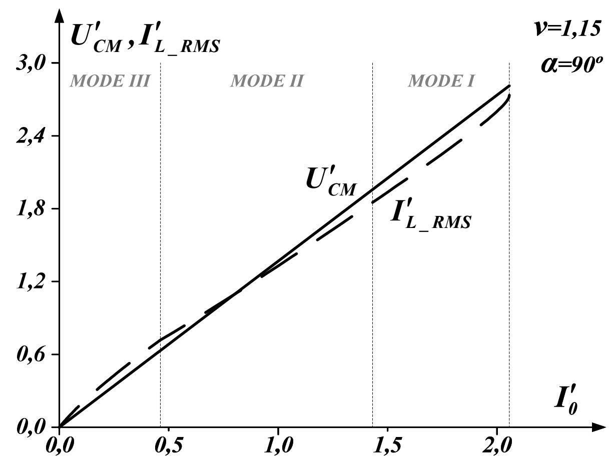

Fig.8. Dependencies for resonant tank circuit of root-mean-square value of current, running through inductance ***L*** and peak value of voltage across capacitor ***C*** on the output current

On Fig. 7 there are shown the dependencies of the average and root-mean-square values I'_{D_AVR} and I'_{D_RMS} of the currents through the diodes of the rectifier. ($D_5 \div D_8$). Since the characteristics are smooth, almost straight lines, this means that the loading of these diodes is proportional to the output current. The same can be expressed for the loading of the elements of the resonant circuit as well. On Fig. 8 there are shown the dependencies of the root-mean-square values of the current I'_{L_RMS} through the inductance (dotted line) and the peak value of the voltage U'_{CM} across the capacitor, that are also smooth, almost straight lines.

4. Comparison of Results

With purpose to test the obtained results a simulation is made with the help of PSpice. The simulation example uses the following basic parameters: U_d=150V; L=240μH; C=56nF; f_S=50kHz; α=π/2rad. On Fig. 9 there are presented in relative units the dependencies of the output voltage and power as function of the output current. The characteristics, received from the expressions, given in [4] are shown with thick lines. The values of the output voltage (triangles) and the output power (rhombs), received through simulation are presented with symbols.

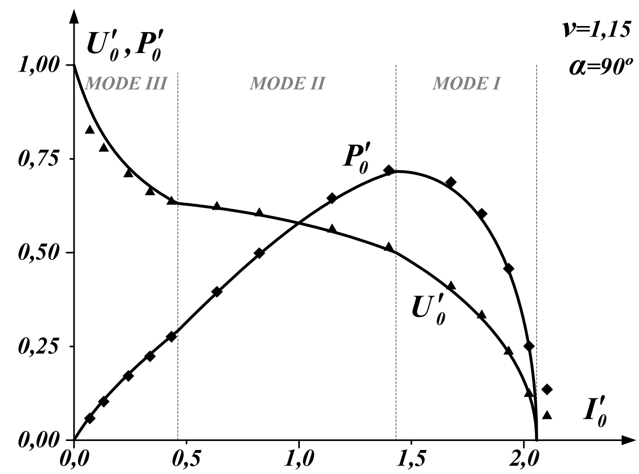

Fig.9. Dependencies of output voltage and power on the output current

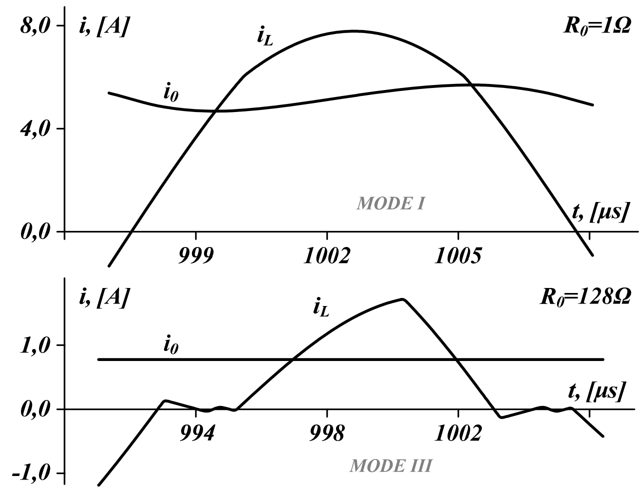

Fig.10. Wave forms of resonant current and output current ***MODE I*** and ***MODE III***

The comparison shows that for two of the cases, the results of simulation with PSpice differ from those, obtained through the above-described way. The first case is observed at modes very close to the short circuit, on the low limit of ***MODE I***. All observations up to this point accept output current I_0 and voltage U_0 as ideally smoothened. But in the given case this is not valid. With the increase of the output current, the constant-time of the output circuit $T_0=R_0C_0$ decreases and the filtering cannot be accepted as ideal.

The second case of differences in the results is obtained at the discontinued circuit mode (***MODE III***). Due to impossible sharp zeroing of the current through the rectifier diodes, in reality ideal current pauses are not obtained. When restoring the diodes that have been operated, there starts a long transition in the rectifier, during which the resonant current has small absolute nonzero value.

The wave forms of the resonant i_L and output i_0 current, shown on Fig. 10, illustrate the examined case of deviation of the results.

5. CONCLUSION

On the basis of the existing mathematic expressions the load characteristics of series resonant DC-DC converter, operating above its resonant frequency, at pulse width modulated control are created. The possible operation modes of the converter are commented, their boundaries are shown in graphics.

It is determined that the power devices of the inverter are always loaded differently. Besides that at certain conditions one of its circuit sections operates in rectifying mode. The currents through the power devices are function of the controlling angle and the output current.

It is determined that the loading of the elements of the resonant circuit and the diodes of the rectifier are proportional to the loading of the converter.

The comparison of the obtained results to those received by the simulation with PSpice show some differences. They are due mainly to some assumptions, made with regards to the expressions, received for the corresponding quantities of the converter. However, in general the results have good coincidence, which shows the high correctness of the applied mathematic models and dependences.

The obtained characteristics can help design this type of converter and chose of its operation mode as well.

6. REFERENCES

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