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# The Integral Parameters of the Mode of a Single-Phase Controlled Compensating Device

***Abstract***. *We analyzed the electrical processes in the circuit, in particular, the modulations of the current and voltage on the network side of the device and on the side of the reservoir capacitor. We determined that, in spite of the sign-constant voltage of the reservoir capacitor, the current in the circuit is alternating, complex-nature, due to the processes of energy transmission at the frequency of the network and the frequency of modulation. We analytically substantiated the integral expressions for the determination of the currents and voltages in the elements of the circuit of the single-phase controlled compensating device.*

***Streszczenie.*** *Analizowano układ jednofazowego kompensatora mocy biernej , a szczególnie zjawiska modulacji prądu I napięcia po dołączeniu układu do sieci I do pojemnościowego zasobnika energii. Dołączenie zasobnika energii wyraźnie wpływa na prąd badanego układu.* ***Analiza pracy jednofazoego kompensatora mocy biernej***

**Keywords:** power controlled compensating device, modulation, energy storage, transistor current operating value.
**Słowa kluczowe:** jednofazowy kompensator mocy biernej, pojemnościowyzasobnik energii

## Introduction

Electrical loads of an asymmetric or (and) nonlinear nature are widely used in electrical engineering complexes. It makes researchers look for the methods and ways of the compensation for such loads influence on the network and the indices of the electric energy quality [1, 2]. A certain place among the filtering and compensating devices belongs to the condenser and reactor elements; filters created by the combination of the series, parallel and series-parallel connection of the said elements. Some researchers [3, 4] unite the said devices into a filter-compensating devices group by the physical processes in them. A variable mode characterizes a certain category of electric energy consumers during the operation. It cases the alteration of the energy consumption indices and poses the problem of control of the filtering and compensating modes [2]. Taking the above said into account, one introduces the static thyristor compensators for the reactive power and discretely controlled compensating devices.

## The analysis of the previous research

There are power converting devices and corresponding systems of their control [2], providing the improvement of the quality of the electricity in the electrical network. The authors of papers [1, 3, 5−10] focus their attention at the problems of the synthesis of the optimal system of control of the compensating convertor with the provision of high energy indices of its operation mode [3]. However, they do not touch upon some problems of the distribution of the electric energy in the power part of the convertor and semiconductor elements. Therefore, there arises a task for the analysis of the electrical processes of the distribution of the energy in the power elements of the convertor of the compensating device to determine their integral indices [11].

## The purpose of the paper

The determination of the integral indices of the energy storage elements and semiconductor elements of the single-phase compensating device.

## The material of the research

The modern control devices used for the reduction of the reactive power consumption and the improvement of the quality of electricity usually base on the autonomous voltage invertor structure [2, 4, 10]. According to the performed analysis, we examine a single-phase device circuit shown in Fig. 1. The power circuit is based on the structure of the autonomous voltage invertor. This circuit is meant for the reduction of the inactive component of the load current, the decrease of the reactive power consumption due to the organization of the energy flow in the storage device because of the impulse control of the invertor transistors, depending on the present value of the current and voltage of the consumer.

In the considered case the power supply ( $v_{gr}$ ) is connected to the load with equivalent resistive impedance ($R_{Ld}$) and inductive reactance ($L_{Ld}$). The circuit of the convertor power part consists of input buffer reactor ($L_b$), four transistors with diodes oppositely connected by a bridge joint.

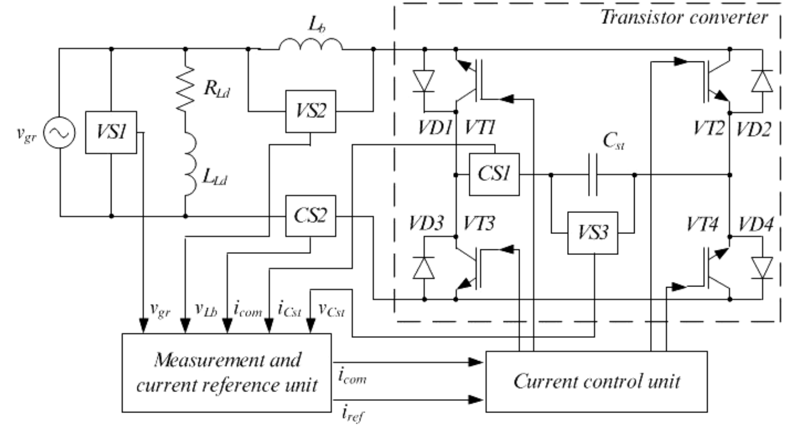

Fig.1. The circuit of the researched model

Reservoir capacitor ($C_{st}$) is joined in the bridge diagonal and is used as energy storage device. The circuit includes elements measuring certain parameters: alternating current supply voltage sensor (VS1); voltage sensor (*VS2*) of buffer inductance, voltage sensor (*VS3*) of reservoir capacitor; reservoir capacitor current sensor (*CS1*); buffer inductance current sensor (*CS2*). The signals from the sensors pass to the measurement and current reference unit of the compensating device. The resistive impedance and inductive reactance load ($L_{Ld}$; $R_{Ld}$), connected to the supply voltage $v_{gr} = V_{gr.m} \sin\left(\omega_{gr} t\right)$, is assumed constant for the calculation. The semiconductor elements are idealized. The mode of the transistor control unit, the parameters of buffer inductance $L_b$ and reservoir capacitor $C_{st}$ are chosen in accordance with recommendations given in [12] and are presented in Table 1.

Table 1. The numerical values of the mode parameters and the circuit parameters

| Parameter | Unit | Value | Parameter | Unit | Value |
|---|---|---|---|---|---|
| $V_{gr.m}$ | $V$ | 311.12 | $L_{Ld}$ | $Hn$ | 0.058 |
| $\omega_{gr}$ | $rad/s$ | 314.159 | $R_{Ld}$ | $Ohm$ | 10.4 |
| $I_{ref.m}$ | $A$ | 100 | $L_b$ | $Hn$ | 0.0054 |
| $\omega_i$ | $rad/s$ | 314.159 | $C_{st}$ | $F$ | 0.002 |
| $\psi_i$ | $rad$ | $\pi/2$ | $V_{Cst.0}$ | $V$ | 810 |

It provides the generation of current with operating value $I_{gr.RMS}$ that exceeds the network voltage in phase by angle $\pi/2$. The transistor control unit provides the generation of the control impulses due to which the set error between the reference ($i_{ref}$) and present ($i_{com}$) current of the compensating device is worked out. In the considered case, the error of current regulation does not exceed 10 % of its amplitude.

Using the data of Table 1, we simulated the process of current generation:

$$i_{ref} = I_{ref.m} \sin\left(\omega_i t - \psi_i\right) \tag{1}$$

where $I_{ref.m}$ − the current amplitude; $\omega_i$ − the current angular frequency; $\psi_i$ − the current initial phase. The results of the mode simulation are presented in the form of time diagrams: the voltage and current of the buffer inductance (the current of the compensating device) – Fig. 2. a, b; the voltage and current of the reservoir capacitor − Fig 2. c, d; the voltage and current of the semiconductors − Fig 2. e, f.

Paper [2] properly describes the principle of operation of the device. One should mention certain special features of the processes in the convertor power circuits. The voltage of the network reactor $L_b$ (Fig. 2, buffer inductance voltage) has two components.

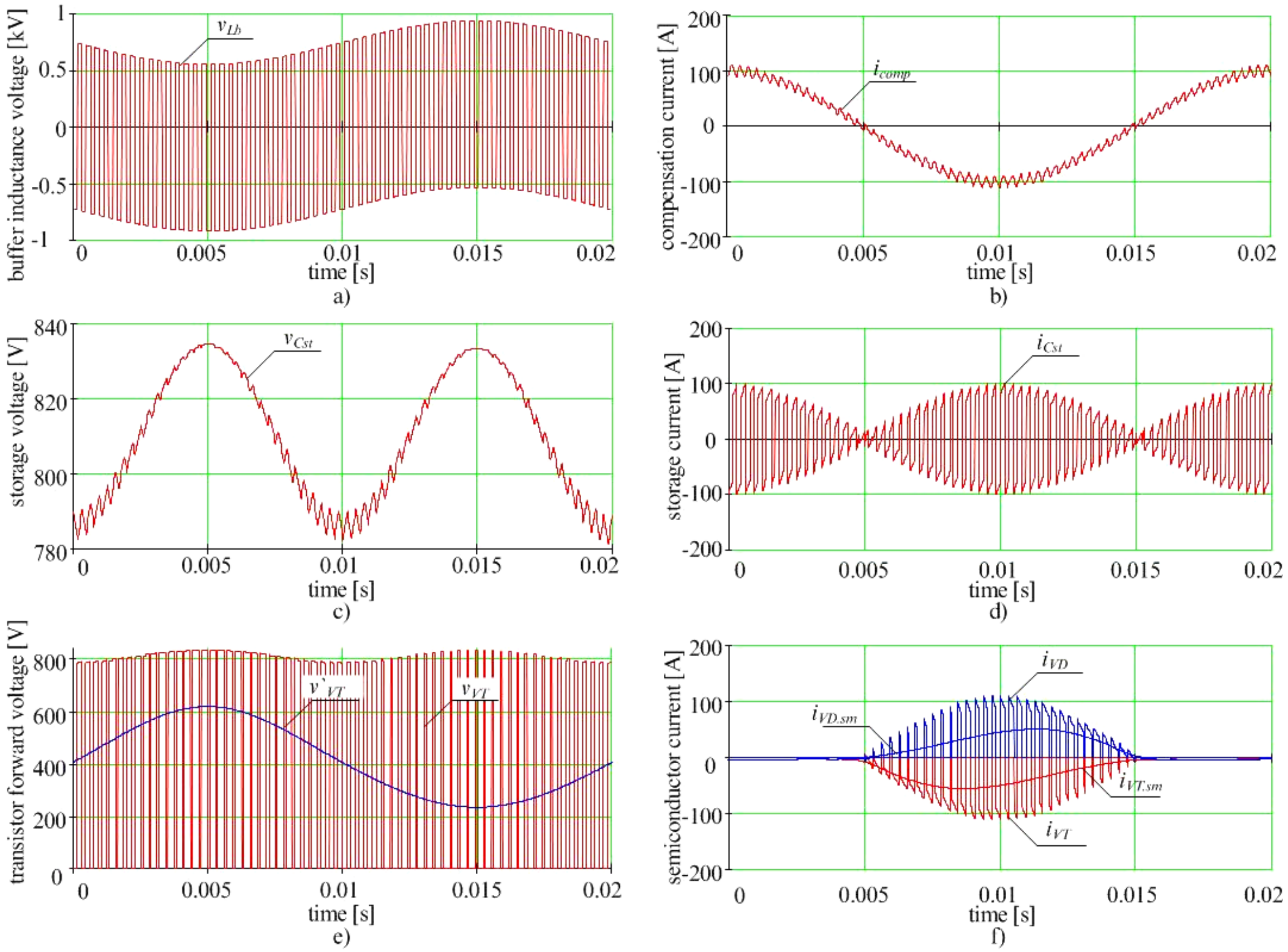

Fig.2. The parameters of the mode of the circuit shown in Fig. 1

The first component depends on the change of the network voltage; the second component – on the mode of the transistor convertor control:

(2) $$v_{Lb} = V_{Lb.1.} \sin\left(\omega_{gr} t\right) + v_{Lb.mod}$$

where $V_{Lb.1.}$ – the amplitude of the fundamental harmonic of the buffer reactor; $v_{Lb.mod}$ – the voltage depending on the commutation of the convertor semiconductor elements, besides, the second component, due to the specific current modulation caused by the law of impulse control, also includes a harmonic, changing with the network frequency, and having the amplitude $V_{Lb.1.}$. Thus, the voltage of the buffer reactor equals:

(3) $$\begin{aligned} v_{Lb} &= V_{Lb.1.} \sin\left(\omega_{gr} t\right) + \\ &+ V_{Lb.mod.1} \sin\left(\omega_{gr} t + \phi\right) + v_{Lb.mod.h}\,. \end{aligned}$$

The reservoir capacitor voltage $C_{stor}$ includes three components: the first one is constant and depends on the initial charge of the capacitor; the second one is variable, it depends on the network voltage (the fundamental harmonic of the current of the compensating device); the third one is variable high-frequency and depends on the current pulsations. In this case, in the equivalent network circuit of the convertor, by the second Kirchhoff's law – $u_{Gr} + u_{Lb} \pm u_{Cstor} = 0$. Sign "$\pm$" of the last component is determined by the commutation of capacitor $C_{stor}$, by semiconductor valves set along/opposing the circuit made by the network supply and the reactor $L_b$. This mode makes it possible to simultaneously generate the low-frequency component of the current and support the capacitor voltage.

The current of the reservoir capacitor $C_{stor}$ (Fig. 2 storage current) is of a complex nature and depends on two processes – the control of the transistors and the uncontrolled operation of the diodes. The current of the reservoir capacitor and the network current are related to each other and the currents of the semiconductor elements as follows:

(4) $$\begin{cases} i_{VD} + i_{VT} = i_{Cst}; \\ i_{VD} - i_{VT} = i_{gr} \ \text{if} \ \dfrac{du_{gr}}{dt} > 0; \\ i_{VT} - i_{VD} = i_{gr} \ \text{if} \ \dfrac{du_{gr}}{dt} < 0. \end{cases}$$

Transistor commutation functions $\psi_1, \psi_2, \psi_3, \psi_4$, acquire values "0" or "1", depending on the control algorithm, but they are always distributed in the following way:

(5) $$\psi_1 + \psi_3 = 1,\ \psi_2 + \psi_4 = 1\,,$$

with the use of the symmetric law of control:

(6) $$\psi_1 = \psi_4,\ \psi_2 = \psi_3\,.$$

It results in the generation of the voltage of the network part of the transistor convertor:

(7) $$u_{in} = (2\psi_1 - 1) u_{Cst} = (1 - 2\psi_3) u_{Cst}\,,$$

where $u_{Cst}(t)$ – the voltage of the reservoir capacitor.

One can determine the capacitor current based on the balance of the instantaneous power at the input and output of the convertor:

(8) $$u_{Cstor} i_{Cstor} = u_{in} i_{in}\,,$$

or taking into account (7):

(9) $$i_{Cst} = (2\psi_1 - 1) i_{in}\,.$$

To determine the currents in the transistor and the bridge key diode we take into consideration the unilateral conductivity of these elements. Using the commutation function, according to [13], we take into account that the growing component of the current curve closes with the help of the transistor and the falling one – with the help of the diode [14]. Then, for transistor *VT1* the following expression is true:

(10) $$i_{VT1} = \frac{1}{2}\left(i_{in}\psi_1 + \left|i_{in}\right|\psi_1\right) = \frac{\psi_1}{2}\left(i_{in} + \left|i_{in}\right|\right).$$

Then the current of the inverse-parallel diode equals:

(11) $$i_{VD1} = \frac{\psi_1}{2}\left(\left|i_{in}\right| - i_{in}\right).$$

Using the two latter relations, one can calculate the load of the valves by the average and operating values of the current in the function of the convertor current on the side of the network and the adopted algorithm of the circuit valves commutation, which determines the commutation function.

It is possible to obtain the calculation relations for the average and operating values of the currents [13, 14] if we assume that there is an infinitely high multiplicity of the valves switch frequency as to the network current frequency. Then, the current impulses in the valve can be approximated by a continuous function according to the average value during the period of the commutation of the current impulse function ($i_{VT.sm}$, $i_{VD.sm}$). The valve current impulses are subject to double modulation: the amplitude modulation – by the law of the module of the input current and the pulse-width modulation – by the law of the change of the commutation function (modulation signal) $\vartheta_{p.a.} = \frac{1}{2}\left[1 + m \sin\left(\omega_{gr} t\right)\right]$, where $m$ – modulation depth ($m = 0...1$). The average value of the transistor current during the period of the network current ($T = 0.02,\ t_1 = 0.005,\ t_2 = 0.015$):

(12) $$I_{VT.a} = \frac{1}{T}\int_{t_1}^{t_2} \vartheta_{p.a.} I_m \sin\left(\omega_{gr} t + \frac{\pi}{2}\right) dt = -\frac{I_m}{2\pi}\,.$$

The sum of the diode and transistor current is the current of the reservoir capacitor and their difference – the network current (reactor). The average value of the diode current is determined as the integral of the difference between the network current and the transistor current:

(13) $$\begin{aligned} I_{VD.a} &= \frac{1}{T}\int_{t_1}^{t_2} \left[ I_m \sin\left(\omega_{gr} t + \frac{\pi}{2}\right) - \right. \\ &\left. - \vartheta_{p.a.} I_m \sin\left(\omega_{gr} t + \frac{\pi}{2}\right) \right] dt = \frac{I_m}{2\pi}. \end{aligned}$$

The operating values of the transistor and diode current are determined analogously.

(14) $$\begin{aligned} & I_{VT.rms} = I_{VD.rms.} = \\ &= \sqrt{\frac{1}{T}\int_{t_1}^{t_2} \vartheta_{p.a.} {I_m}^2 \sin^2\left(\omega_{gr} t + \frac{\pi}{2}\right) dt} = \sqrt{\frac{I_m^2}{8}} = \frac{I_m}{2\sqrt{2}}. \end{aligned}$$

One can determine the voltage applied to the transistor power circuits (Fig. 2, transistor forward voltage), by the capacitor voltage, neglecting the higher harmonics, which are very small in comparison with the fundamental harmonic:

(15) $$v_{Cst} = V_{Cst.0} - V_{m2}\cos\left(2\omega_{gr}t\right)$$

and the relative duration of the valve current impulse $\vartheta_{p.a.}$:

(16) $$v`_{VT} = \vartheta_{p.a.}v_{Cst} = \frac{1}{2}\Big[V_{Cst.0} + V_{Cst.0}m\sin\left(\omega_{gr}t\right) - \\ -V_{m2}\cos\left(2\omega_{gr}t\right) - \frac{V_{m2}m}{2}\sin\left(3\omega_{gr}t\right)\Big].$$

Thus, the maximal value of the voltage applied to the valve (Fig. 2, transistor forward voltage), is:

$$V_{VT.\max} = V_{Cstor.0} + V_{m2},$$

and the average value of the voltage is:

$$V_{VT.a} = \frac{1}{T}\int_{t_1}^{t_2} v`_{VT}\,dt = \frac{V_{Cst.0}}{2}.$$

The results of the calculation for the mode parameters given in Table 1 are presented in Table 2.

Table 2. The results of the calculations by the output data of Table 1.

| Parameter | Unit | Value |
|---|---|---|
| Semiconductor average current, $I_{VT.a} = -I_{VD.a}$ | A | 15.91 |
| Semiconductor RMS current, $I_{VT.RMS} = I_{VD.RMS}$ | A | 35.46 |
| Storage average voltage, $V_{Cst.a}$ | V | 810 |
| Semiconductor maximum voltage, $V_{VT.\max} = V_{VD.\max}$ | V | 842.9 |
| Semiconductor average voltage, $V_{VT.a}$ | V | 405 |

## Conclusions

1. The alteration of the reservoir capacitor current and voltage, having another harmonic, accompanies the operation of the compensating device, which corresponds to the action of a single-phase bridge rectifier. The transistor control impulses modulate the current of the capacitor and the voltage at the rectifier input, which corresponds to the operating modes of an autonomous invertor.
2. The order of the calculation of the parameters of the semiconductor element mode is analogous to the calculation of the corresponding parameters for rectifiers, but it is necessary to take into account the increase of the capacitor voltage during the calculation of the parameters by the voltage.
3. In the operating mode of the controlled compensating device, the current of the transistor and the inverse-parallel diode is of the operating value that is half as high as the operating value of the compensating current.

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## REFERENCES

[1] Popescu M., Bitoleanu A., Dobriceanu M., Suru V., Optimum control strategy of three-phase shunt active filter system, *World Academy of Science, Engineering and Technology*, Roumunia, no. 58, pp. 441–446, 2009.

[2] Bialobrzeski O. V., Vlasenco R. V., Interrelation of electric-power parameters of the single-phase active power filter mode with parameters of the stores attached, *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, Issue 4, pp. 79–84, 2015. (in Russian)

[3] Yang Z., Sun J., Zha X., Tang Y., Power Decoupling Control for Capacitance Reduction in Cascaded H-Bridge Converter-based Regenerative Motor Drive Systems. *IEEE Transactions on Power Electronics*, no. 10, p. 1, 2018, doi: 10.1109/TPEL.2018.2818719

[4] Zhujkov V. J., Mikolayetz D. A., Features of modes work filtering compensating devices, *Tekhnichna elektrodynamika*, no. 1, pp. 24–29, 2011. (in Russian)

[5] Zagirnyak M., Kalinov A., Maliakova M., Analysis of instantaneous power components of electric circuit with a semiconductor element, *Archives of Electrical Engineering*, vol. 62, no. 3, pp. 473−486, 2013, doi: 10.2478/aee-2013-0038

[6] Zagirnyak M., Maliakova M., Kalinov A., Analysis of electric circuits with semiconductor converters with the use of a small parameter method in frequency domain, *COMPEL – The international journal for computation and mathematics in electrical and electronic engineering*, vol. 34, no. 3, pp. 808-823, 2015, doi: 10.1108/COMPEL-10-2014-0260

[7] Zagirnyak M., Kalinov A., Maliakova M., An algorithm for electric circuits calculation based on instantaneous power component balance, *Przeglad Elektrotechniczny,* vol. 87, no. 12 B, pp. 212-215, 2011.

[8] Zagirnyak M., Maliakova M., Kalinov A., Analysis of operation of power components compensation systems at harmonic distortions of mains supply voltage, *Joint International Conference – ACEMP 2015: Aegean Conference on Electrical Machines and Power Electronics, OPTIM 2015: Optimization of Electrical and Electronic Equipment and ELECTROMOTION 2015: International Symposium on Advanced Electromechanical Motion Systems*, pp. 355-362, 2016, doi: 10.1109/OPTIM.2015.7426958

[9] Zagirnyak M., Maliakova M., Kalinov A., Compensation of higher current harmonics at harmonic distortions of mains supply voltage, *2015 16th International Conference on Computational Problems of Electrical Engineering (CPEE)*, Lviv, 2015, pp. 245-248, doi: 10.1109/CPEE.2015.7333388.

[10] Leon M. Tolbert., William A. Peterson, Cliff P. White a.m., A bi-directional DC-DC converter with minimum energy storage elements, *IEEE Transactions on power electronics*, vol. 22, no. 2, pp. 284-391, 2002.

[11] Qawaqzeh M., Bialobrzheskyi O., Zagirnyak M., Identification of distribution features of the instantaneous power components of the electric energy of the circuit with polyharmonic current, *Eastern-European Journal of Enterprise Technologies*, vol. 2, no. 8, pp. 6-13, 2019, doi: 10.15587/1729-4061.2019.160513.

[12] Bialobrzheskyi O., Rod'kin D., Gladyr A., Power components of electric energy for technical and commercial electricity metering, *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, no. 2, pp. 70−79, 2018, doi: 10.29202/nvngu/2018-2/10

[13] Muhammad Rashid, *Power Electronics Handbook*, Butterworth-Heinemann, 1522 pp., 2017.

[14] Tchaplygin E. E., Nguen Hoang, An Spectral models of switching converters with variable switching frequency, *Electrichestvo*, no. 4, pp. 41−49, 2006. (in Russian)