AC Voltage Regulator on the Basis of the Consecutive Voltage Regulator with PWM

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Abstract – **In this paper construction of a system with the stabilization of the current value of the variable voltage and frequency based on variable voltage regulator with voltage boost with PWM control is proposed. A mathematical model of the system is constructed. Basic energy relationships and dependencies of the system are analyzed.**

Index Terms – **stabilization of AC voltage, regulation of AC voltage, step-up voltage, pulse-width modulation, PWM**

I. INTRODUCTION

THE MOST common way to stabilize the AC voltage in autonomous objects is double-conversion on the structure back-to-back. In addition to stabilized voltage at the load the consumer also receives a fixed frequency in this structure.

The use of electrolytic capacitors in the DC link has main problems:

- Limited operating temperature range.
- High mass and dimensions (also associated with the smoothing reactor to the rectifier output).

In the recent trend of building such systems, in which a value of the effective AC output voltage is stable and a frequency can be varied depending on the frequency generated by the primary source. The load is shared to a load is not sensitive to frequency and frequency sensitivity (in this case requires an additional inverter). In this case, there is no serious emergency operation of the DC. Also temperature range of the whole device is expanded.

Known solution system which is based on parallel semiconductor voltage source inverter which is used as the inactive power compensator and stabilizes the effective voltage on the load [1,2]. The disadvantage of this system is the large reactive currents compensator. Currents compensator is required to stabilize effective value AC voltage.

II. PROBLEM DEFINITION

In this paper relationships are established and analyzed to determine the parameters of the boost voltage regulator with PWM. Only an effective value of output voltage of the generator is stabilized while frequency is variable. Mathematical model of the system is based on the direct methods of analysis of energy processes in the systems. The major energy relations analyzed analyzed.

III. THEORY

In this paper AC voltage regulator is used for regulation and stabilization RMS AC voltage (Fig. 1.) with voltage boost, with AC transistor, with pulse-width modulation (PWM). Voltage boost is introduced by means of high-frequency transformer. Transformer is operating for high frequency. Frequency of the transformer is much higher than the frequency of the power supply.

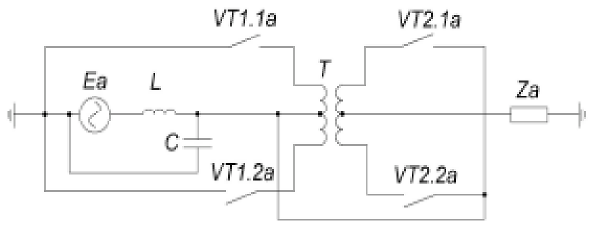

Fig. 1. One-phase AC voltage regulator.

Where E_a - input voltage, *VT1.1a-VT2.1a* – AC transistor, *T* - transformer, *Za* – impedance of load.

Three-phase voltage regulation is obtained by parallel connecting of regulators. The neutral is used for independent operation of the unbalanced phase load.

The device operates as follows. When the effective value the power supply is equal to one (in p.u.), it repeats itself and the load. In this situation the output voltage of the regulator is zero.

Let the supply voltage is three-quarters of the current generated voltage (Fig. 2.). On the key elements of the control fed rectangular pulses. The voltage on the load will be the sum of two vectors – input voltage and voltage boost (fig. 3). On the key VT2.1-VT-2.2 fed the control pulses so that to create a pause in the zero voltage in each phase of the control pulses overlap each other at the required time. It creates the effect of freewheeling diode [4]. Input current Ia will be pulsed component. Effect of the freewheeling diode voltage is necessary to flow in the secondary winding of transformer. To improve the quality of the input current is required appropriate LC filter at the output of each phase voltage source.

The pulsed nature of the input current is a feature of the AC voltage regulator with PWM (Fig. 2). Waveform of output current at the output of the regulator will be substantially sinusoidal at multiple pulse-width control method and a switching frequency of a few kHz (Fig. 3).

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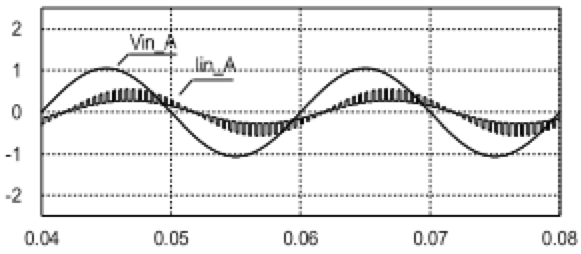

Fig. 2 Waveforms of input voltage and input current of the regulator.

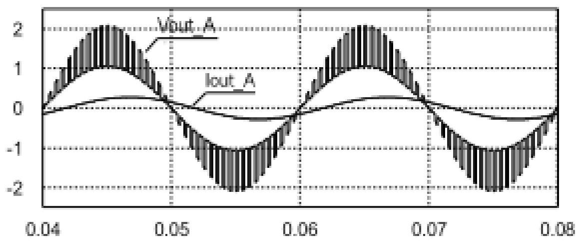

Fig. 3 Waveforms of output voltage and output current regulator.

Where Vin_A is input voltage of regulator, Iin_A is input current of regulator (fig. 2) and Vout_A is output voltage of regulator, Iout_A is output current of regulator (fig. 3).

IV. MATHEMATICAL MODEL OF THE SYSTEM

Fig. 5 shows a block diagram of the system. Where VS – is voltage source, RVV – regulator variable voltage, L – active-inductive load.

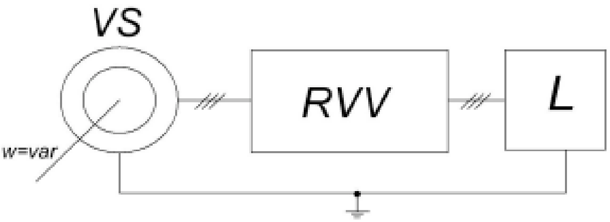

Fig. 5 Block diagram of the system.

The quality of the input current is estimated. Direct methods of calculation is used (ADE – Algebraization Differential Equations) [3]. The parameters for the THD current is calculated: I_{hh} - effective value of current of higher harmonic and $I_{(1)}$ - effective value current fundamental harmonic, On fig. 6 shows the equivalent circuit of one phase of the system, to evaluate the quality of the input current.

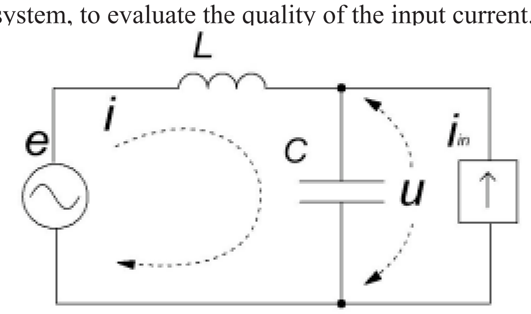

Fig. 6. Equivalent input circuit of one phase of the system.

In Fig. 6 e – input voltage source, L and C input filters, i_{in} – input current of regulator.

We write the system of differential equations, obtain:

$$\begin{cases} L \cdot \dfrac{di}{dt} + u = e \\ i = C \cdot \dfrac{du}{dt} + i_{in} \end{cases} \tag{1}$$

Than we transform the system of equations (1) relative source voltage, obtain:

$$\frac{di^2}{dt} + \frac{i}{LC} = \frac{1}{L} \cdot \frac{de}{dt} + \frac{i_{in}}{LC} \tag{2}$$

Let do algebraization of equation (2). Carry out the calculation of the equation 2 by higher harmonics. We express the result obtained through the integral THD second order $ITHD_I 2$ (Fig. 7):

$$I_{hh} = \frac{1}{LC} \cdot \frac{I_{in(1)}}{w^2} \cdot ITHD_I 2 \tag{3}$$

Where I_{hh} - the input current higher harmonics, which should be defined, $I_{in(1)}$ - the first harmonic of the input current, w – cyclic frequency, $ITHD_I 2$ - integral THD current second order:

$$ITHD_I q = \sqrt{\sum_{k=2}^{\infty} [\frac{I_{(k)}}{k^q \cdot I_{(1)}}]^2}$$

The mathematical model is simulated using the program package MathCAD. For a given signal spectrum is calculated. Then $ITHD_I 2$ is calculated. The dependence of the $ITHD_I 2$ of the duty cycle D is shown on Fig. 7.

Let do algebraization of equation 2. Carry out the calculation of the equation 2 by fundamental harmonics:

$$I_{(1)} = \sqrt{\frac{K_2 \cdot E_{(1)} + K_3 \cdot I_{in(1)}^2 - K_4 \cdot E_{(1)} \cdot I_{in(1)}}{K_1}}, \tag{4}$$

where $K_1 = 1 + \dfrac{1}{w^4 (LC)^2} - \dfrac{2}{w^2 \cdot LC}$, $K_2 = \dfrac{E_{(1)}^2}{w^2 L^2}$,

$K_3 = \dfrac{I_{in(1)}^2}{w^4 (LC)^2}$, $K_4 = \dfrac{2 \cdot \sin\alpha}{w^3 L^2 C}$

Equation 5 based on 3 and 4 is calculated:

$$THD_I = \frac{I_{hh}}{I_{(1)}} \tag{5}$$

The value of the harmonic current at a given duty cycle *D* is obtained. THD_I depends on the input *LC* filter and on integrated THD second-order (3). The dependence of the THD_I of the duty cycle *D* is shown on fig. 7.

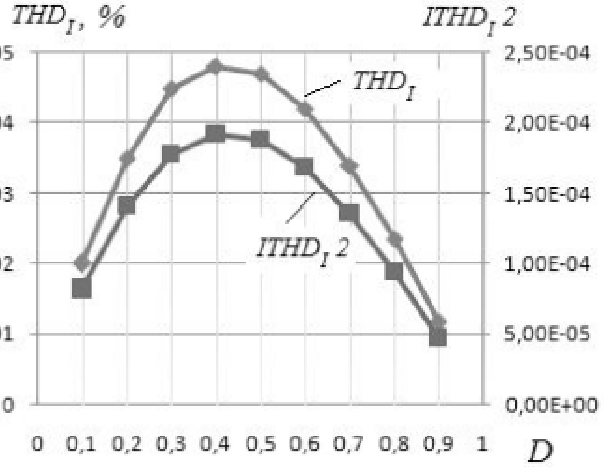

Fig. 7. Dependencies THD_I, $ITHD_I 2$.

The greatest impact of the higher harmonics occurs when duty cycle $D = 0.4 \div 0.5$ (fig. 7). LC filters provide $ITHD_I$ distortion of input current not exceeding 5%.

Equivalent output circuit of one phase of the system is present.

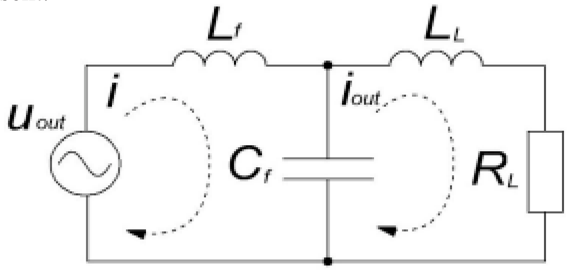

Fig. 8. Equivalent output circuit of one phase of the system.

We write the system of differential equations, obtain:

$$\begin{cases} L_f \dfrac{di}{dt} = u_{out} - u_c \\ u_c = i_{out} R_L + L_L \dfrac{di_{out}}{dt} \\ i = C_f \dfrac{du}{dt} + i_{out} \end{cases} \tag{6}$$

Than we transform the system of equations (6) relative output current, obtain:

$$L_f \frac{d^3 i_{out}}{dt^3} + R_L \frac{d^2 i_{out}}{dt^2} + \frac{2}{C_f} \frac{di_{out}}{dt} + \frac{R_L}{L_f C_f} i_{out} = = \frac{1}{L_f C_f} u_{out} \tag{7}$$

The next step is integration equation 7, obtain:

$$L_f i_{out} + R_L \overline{i_{out}} + \frac{2}{C_f} \overline{\overline{i_{out}}} + \frac{R_L}{L_f C_f} \overline{\overline{\overline{i_{out}}}} = \frac{1}{L_f C_f} \overline{\overline{\overline{u_{out}}}} \tag{8}$$

Calculation on the higher harmonics. We have high frequency of PWM, solution $\overline{i_{out}}, \overline{\overline{i_{out}}}, \overline{\overline{\overline{i_{out}}}} = 0$.

So the equation (8) becomes:

$$L_f i_{out(hh)} = \frac{1}{L_f C_f} \overline{\overline{\overline{u}}}_{out(hh)} \tag{9}$$

Let do algebraization of equation 9:

$$I^2_{out(hh)} = \frac{(\frac{1}{L_f C_f})^2 \cdot (\overline{\overline{\overline{U}}}_{out(hh)})^2}{L_f^{\,2}}$$

Integral third order of output voltage [3]:

$$\overline{\overline{\overline{U}}}_{out(hh)} = ITHD_U 3 \cdot \frac{U_{out(1)}}{w_{out}^2}$$

Where $ITHD_U 3$ is integral total harmonic distortion voltage third order.

According to the direct method of calculation ADE [4]:

$$ITHD_U q = \sqrt{\sum_{k=2}^{\infty} [\frac{U_{(k)}}{k^q \cdot U_{(1)}}]^2},$$

where *q* –order of *ITHD* , *k* – number of harmonic.

Solution for the high harmonics:

$$I_{out(hh)} = \frac{1}{w_{out}^2 L_f C_f} \frac{U_{out(1)}}{w_{out} L_L} \cdot ITHD_U 3 \tag{11}$$

Calculation on the fundamental harmonics. Equivalent output circuit of one phase of the system for fundamental harmonic is present.

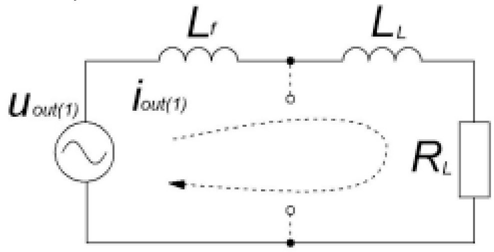

Fig. 9. Equivalent output circuit of one phase of the system for fundamental harmonic.

We have high frequency of PWM, fundamental harmonic capacity can be ignored.

Solution for the fundamental harmonic:

$$I_{out(1)} = \frac{U_{out(1)}}{\sqrt{w_{out}^2 (L_f + L_L)^2 + R_L^2}} \quad (12)$$

Equations (13) includes equations (11) and (12):

$$THD_{Iout} = \frac{ITHD_U 3}{w_{out}^2 L_f C_f} \sqrt{(\frac{L_f + L_L}{L_L})^2 + (\frac{R_L}{w_{out} L_L})^2} \quad (13)$$

THD_{Iout} (Fig. 10) depends on the output $L_f C_f$ filter and parameter of the load and on integrated $ITHD_U 3$ of voltage third order (fig. 10).

We evaluate the quality of the output voltage using a method ADE. A mathematical model of the system is constructed using the software MathCAD and checked by means of software PSIM. The equation that describes the output voltage:

$$U_{out} = \left[\frac{2}{\pi} \cdot \sum_{k=1}^{500} (\cos(kw_i t) \cdot \frac{\sin(\frac{kw_i t_i}{2})}{k}) + D \right] \cdot \sin(wt) + \sin(wt)$$

Where U_{out} - output voltage on the load, k – harmonic number, t_i - pulse width, D – duty cycle.

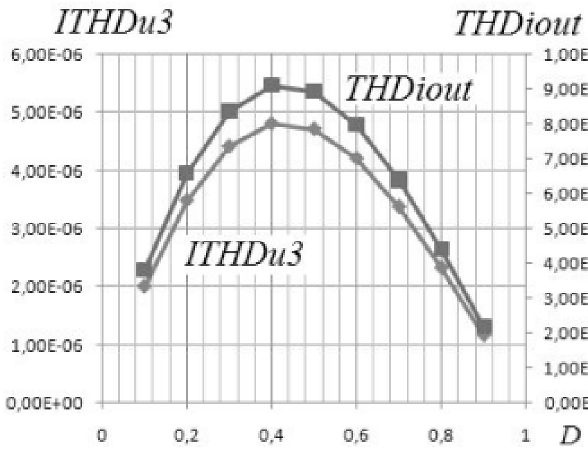

Fig. 10. Dependencies $ITHD_U 3$, THD_{Iout}.

Thus the quality output current can be estimated when the load parameters is unknown. Knowing the law according to which changes the integral total harmonic distortion of voltage q-order, we can predict the quality of the output current, not calculating the current itself. This is the main advantage of the ADE method.

V. EXPERIMENTAL RESULTS

To find the relation between the first harmonic of the output voltage control and the duty cycle, calculation of the corresponding coefficient of the Fourier series is needed [3]:

$$U_{out(1)} = 2 \cdot E \cdot [D + \frac{1}{2\pi} \cdot \sin 2\pi D]$$

In p.u.

$$C_p = \frac{U_{out(1)}}{E} = 2 \cdot (D + \frac{\sin 2\pi D}{2\pi})$$

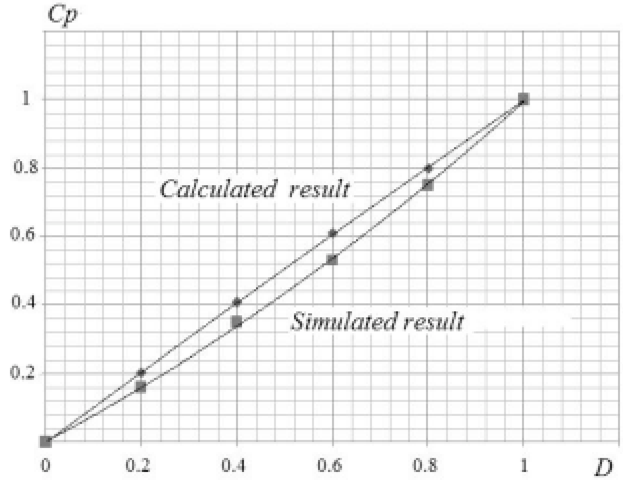

Fig. 11. Control characteristics.

Since there is a leakage inductance L_s, simulated and calculated results are different. How we can look control characteristics (Fig. 11), this regulator provides a wide control range.

Fig. 12 shows a family of load characteristics of the converter at different duty cycle of regulation. Load characteristic shows the relation effective value fundamental harmonic output voltage $U_{out(1)}$ on the effective value fundamental harmonic output current $I_{out(1)}$.

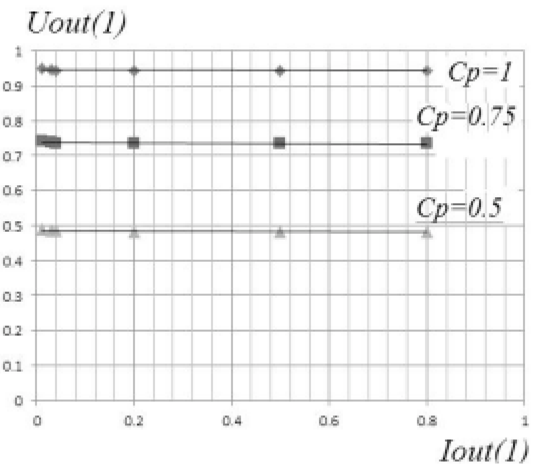

Fig. 12. Family of the load characteristics.

Relation of fundamental harmonic of output voltage on parameters of the circuit is used the method ADE1 [3]:

$$U_{out(1)} = \frac{(\frac{1}{w^4C^2L^2} + A^2) \cdot CpU_{in(1)}}{1 + (\frac{R_{in}}{wL_{in}})^2 + B^2 + A^2 - 2B - 2\frac{R_{in}^2}{w^4L_{in}^2LC}}$$

where $A = \frac{R_{in}}{w^3CLL_{in}}$, $B = \frac{L_{in} + L}{w^2L_{in}LC}$.

Calculation formula for finding the load characteristics:

$$I_{out(1)} = \frac{U_{out(1)}}{Z_L},$$

where Z_L - impedance.

$$Z_L = \sqrt{R_L^2 + (w_{out}^2 L_L)^2}$$

Load characteristics are linear. The calculated and modeled results of the external characteristics are the same.

VI. CONCLUSION

Thus, the output voltage in the considered system is increased compared with the input voltage. It is used for stabilization and regulation of the load voltage when the input voltage is below nominal.

Mathematical model of the system was built. The main energy characteristics were analyzed. LC filters provide THD of input current not exceeding 5%. Used the regulator wide adjust the output voltage at the supply voltage control range to 2x is allows. Load characteristics are linear. The calculated and simulated results of the load characteristics are the same.

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