Transformerless Step Up Alternating Voltage Regulators With Sinusoidal Currents

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***Abstract* – A new transformerless AC voltage regulators with a sinusoidal input and output currents and ability of voltage increasing are considered. The regulators can be used as the soft-starting devices for asynchronous motors. Results of mathematical modeling and analytical calculation of RMS values by fundamentals of the currents and voltage are given.**

***Index Terms* – Transformerless step-up-step-down AC voltage regulator, analytical calculation, mathematical model.**

I. INTRODUCTION

THE MOST COMMONLY used devices for the soft start of an asynchronous motor, containing the back-to-parallel thyristors in each phase are characterized by two general drawbacks [1]. First one is the low energy quality performance during the starting time, which is, particularly, reflected in unsinusoidality of the output voltages and output and input currents, as well as phase shift between input voltage and current fundamentals. The second one considers the conversion factor that is limited by unity. This drawback makes it impossible to maintain the output voltage at its nominal value when the input voltage decreases.

The multizone thyristor regulators of AC voltage (RAV) were proposed in [2, 3] as converters that allow to illuminate some disadvantages of those conventional regulators. The new regulators, in particular, allow improving the energy quality performance, but also have the conversion factor of voltage limited by unity.

II. TRANSFORMERLESS STEP UP RAV

The new transformerless alternating voltage regulators which are free from the specified restrictions are considered in this paper. They are characterized by sinusoidal input and output currents waveforms and ability of voltage increasing. The new regulators can be used to improve the energy quality of soft-start devices for asynchronous motors.

The scheme of a suggested basic three-phase transistor regulator of AC voltage is presented in Fig. 1. A bidirectional switch for alternating current used in the regulator is depicted in Fig 2. The vector diagram explaining the principle of operation of the regulator is shown in Fig. 3. Fig. 4 shows simulation results obtained by the PSIM program for the basic RAV. The input voltage and current, control signals for the bidirectional switch of capacitor branch and the output voltage with current are shown as well.

The regulator operates as follows. The control pulses of the switches S_1 and S_2 turn on them alternately, thereby connecting and breaking circuit containing either inductor L_1 or capacitor C_1. Switching between vectors of the voltages' fundamentals V_{1C} and V_{1L}, occurs. These vectors characterize the load voltage when the branch with capacitor C_1 or inductor L_1 is enabled. It becomes possible to obtain the required load voltage V_1, as a resultant vector of the output voltage will be characterized by a sum of qV_{1C} and $(1–q) V_{1L}$ vectors and depend on relative time q of their switching durations. Capacitor C_2 is required to receive the energy stored in the inductor during breaking the respective branch.

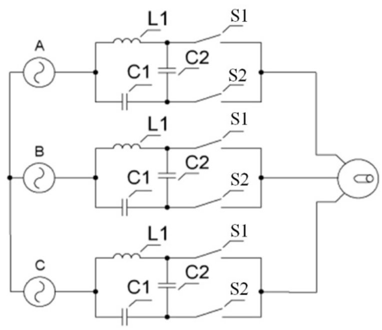

Fig. 1. A basic three-phase transistor regulator of alternating voltage.

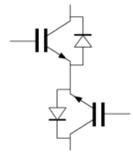

Fig. 2. Bidirectional switch.

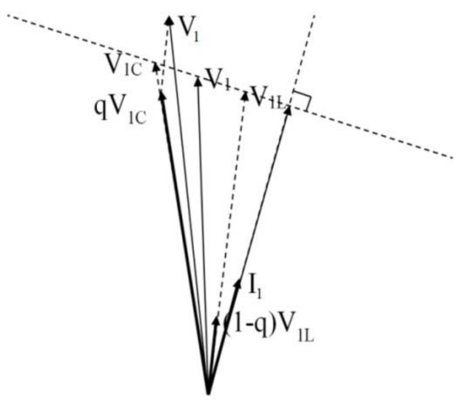

Fig. 3. Phasor diagram.

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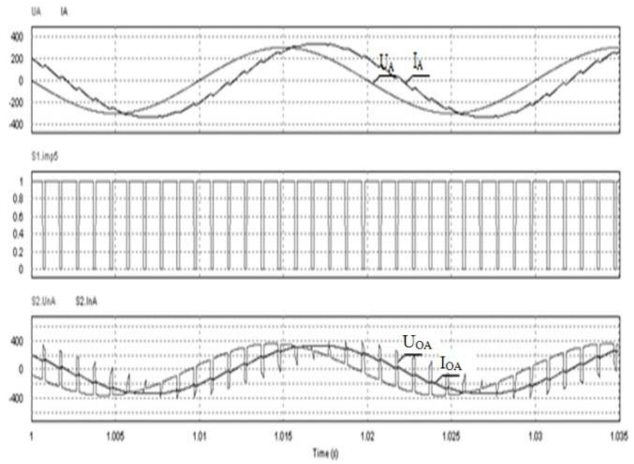

Fig. 4. Waveforms of the currents and voltages of a basic regulator (U_O – output voltage).

A simplified regulator with halving number of switches is shown in Fig. 5. Waveforms of its currents and voltages are shown in Fig. 6. Resistor R_1 is required for damping.

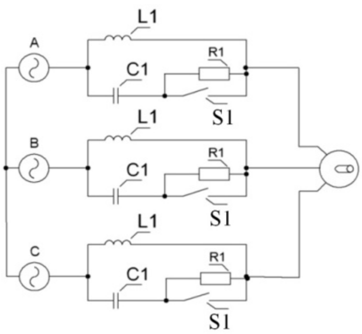

Fig. 5. Simplified three-phase transistor-based AC voltage regulator

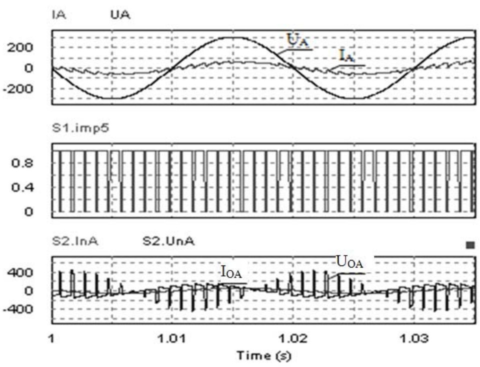

Fig. 6. Diagrams of currents and voltages for the simplified regulator.

Further decreasing the number of switches in the regulator can be achieved in a regulator, where ability of connection to both terminals of the power source phases that may occur in an autonomous power-supply system. The scheme of a simple regulator for this case is shown in Fig. 7 and the same waveforms are shown in Fig. 8. Switching on transistor T_1 serially with the power source and the load makes capacitors C_1 be switched through the diodes of three-phase bridge M_1, while switching on transistor T_2 serially with a power source and a load makes inductors L_1 get switched through diodes of three-phase bridge M_2. Thus, the mode of operation of this circuit is similar to the operation mode of regulator in Fig. 1, but this scheme has only two transistors instead of twelve in the first circuit with the same number of diodes in both topologies i.e. also twelve.

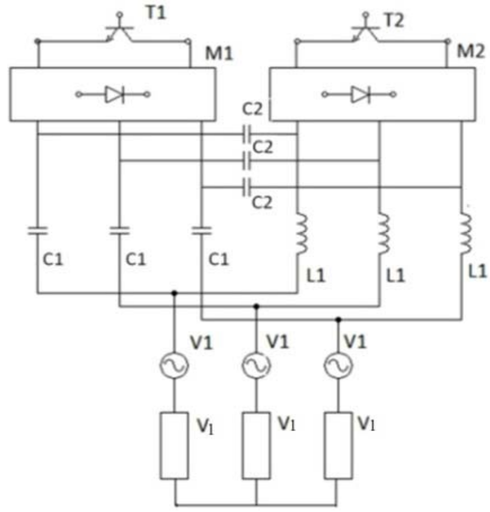

Fig. 7. Simple three-phase transistor AC voltage regulator (V_l – V_{load}).

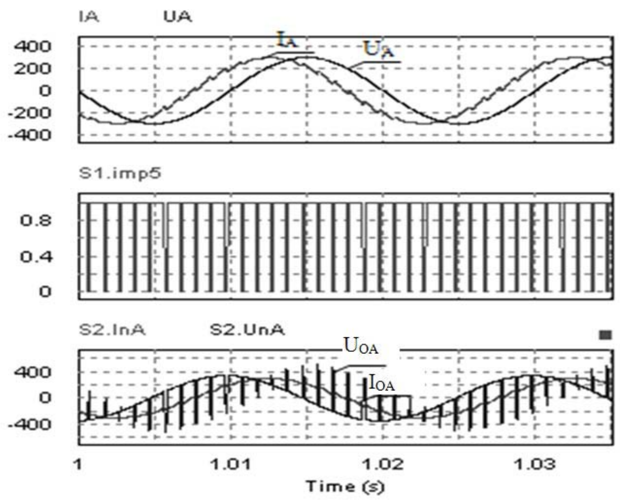

Fig. 8. Diagrams of currents and voltages for the simplified regulator with reduced number of transistors

The nature of transient process in the regulator with the linear increase of the load voltage is shown in Fig. 9 (load is asynchronous motor A02-52-4 with P_1=10kW, η=88,5%, n=1450rpm and cosφ=0,87), where: a) fundamentals of load current and voltages RMS values, b) load voltages and motor speed.

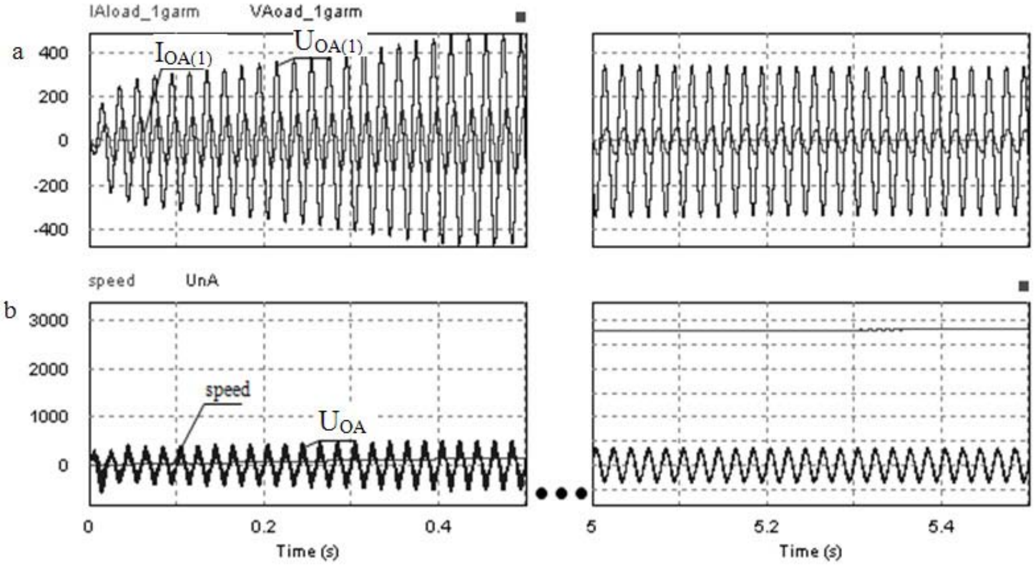

Fig. 9. Diagrams of a currents and voltages of the basic three-phase transistor alternating voltage regulator soft-starting.

III. ANALYTICAL CALCULATION AND RESULTS

The direct method of calculation (ADE2) [4] is used for the construction of the regulator mathematical model on a smooth component (fundamental). The equivalent circuit of one phase of regulator is shown in Fig. 10.

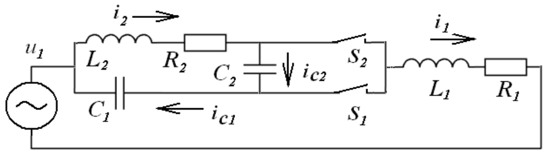

Fig. 10. Equivalent circuit of one phase of transformless step up AC voltage regulator.

Differential equations of the circuit for both its states can be written as:

$$L_1 \frac{di_1}{dt} + R_1 i_1 - u_{c1} - (1-\Psi)u_{c2} = e_1 \tag{1}$$

$$L_2 \frac{di_2}{dt} + R_2 i_2 + u_{c1} + u_{c2} = 0 \tag{2}$$

$$C_1 \frac{du_{c1}}{dt} + i_1 - i_2 = 0 \tag{3}$$

$$C_2 \frac{du_{c2}}{dt} + (1-\Psi)i_1 - i_2 = 0 \tag{4}$$

where ψ – is the switching function, equal to unity when the switch S_1 is switched on and equal to zero when the switch S_2 is switched on.

The following system of equations for the sine and cosine components of the fundamentals of the variables prepared to write in the matrix form is obtained as a result of this system of equations algebraization by the ADE2 approach:

$$\begin{vmatrix} R_1 & \omega L_1 & -1 & -M & 0 & 0 & 0 & 0 \\ R_2 & \omega L_2 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & \omega C_1 & 0 & 0 & 0 & 0 \\ M & -1 & \omega C_2 & 0 & 0 & 0 & 0 & 0 \\ \omega L_1 & 0 & 0 & 0 & -R_1 & 0 & 1 & M \\ 0 & \omega L_2 & 0 & 0 & 0 & -R_2 & -1 & -1 \\ 0 & 0 & \omega C_1 & 0 & -1 & -1 & 0 & 0 \\ 0 & 0 & 0 & \omega C_2 & -M & 1 & 0 & 0 \end{vmatrix} \cdot \begin{vmatrix} I_{1(1)a} \\ I_{2(1)a} \\ U_{C1(1)a} \\ U_{C1(1)p} \\ I_{1(1)p} \\ I_{2(1)p} \\ U_{C2(1)a} \\ U_{C2(1)p} \end{vmatrix} = \begin{vmatrix} E_{1(1)a} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$$

The adjusting and external characteristics of the regulator are plotted, Fig. 11, Fig. 12, by the solutions of these equations, which presented simultaneously with the corresponding characteristics obtained in the model of the PSIM program. For small values of modulation index M the error of simulations results with theoretical appears indicating the necessity in the sequel to adjust the calculation subject to higher harmonics of switching function.

It is significant that the conversion factor of the voltage directly depends on a relative value of the load current.

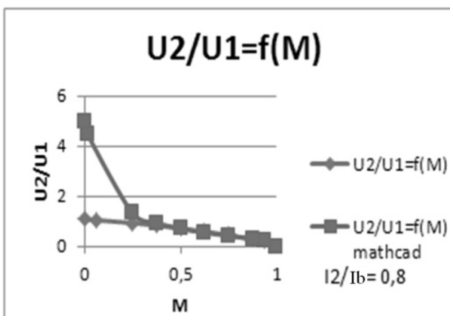

Fig. 11. Adjusting characteristic.

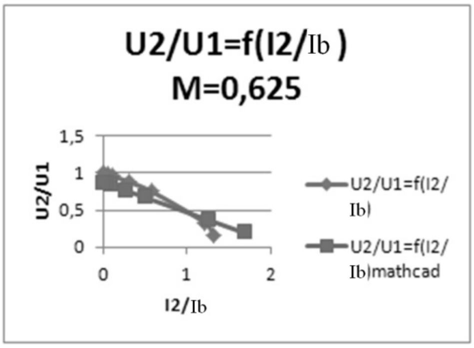

Fig. 12. External characteristic.

IV. CONCLUSION

Thus, the expansion of the calculation direct method of the energy quality performance based on the model with variable parameters leading to differential equations with the periodical discontinuous coefficients is constructed. The accounting of first terms in the expansion of variable coefficients in a Fourier series allowed obtaining the analytical solutions in a closed form for all state variables and output variables fundamentals. This in turn led to the analytical expressions for all regulator general characteristics: external, adjusting and energy. Further development of the direct method for systems with variable parameters will occur in the direction of construction of analytical solutions subject to effect of variables higher harmonics.

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