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Power Electronic Transformer Based AC Voltage Regulator for Industrial Applications

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Abstract – Power electronic transformers (PET) based on ac voltage regulator with pulse-width regulation, in various areas of their application are discussed. A research of a power electronic transformer based on an ac voltage regulator operating at high frequency with ability to support unity power factor by means of mathematical modeling is conducted. The major power characteristics are obtained using the output factors of electric energy quality of the device. A universal single-phase experimental mock-up is presented Problems linked with stabilization of AC voltage can be solved with the AC voltage regulators. It is known that regulators of AC voltage can be also used for stabilization of an ac voltage, regulation of reactive power, active filters. Besides similar converters do not contain electrolytic capacitors, unlike known "back-to-back" of converters that respectively prevents from emergency operation which can occur in their DC-link. In addition, power electronic transformers based on AC voltage regulators can be classified by power that respectively and allow to define area of their application, namely distributive systems, mobile/autonomous objects (system of power supply of responsible consumers), "smart" networks. The main advantage this PET on the basis of ac voltage regulator, is ability to support single entrance power factor.

***Index Terms* - Power electronic transformer, AC voltage regulator, Pulse width modulation**

I INTRODUCTION

Special attention to the AC-AC voltage regulators is caused by the following circumstances. One of criterion of technical development of country is the extent of electric energy transformation by a semiconductor converter before consumption. This value reaches 45-50% in the developed countries, including Russia. In the USA this value reaches 70%. First of all there are ac-dc converters for grid supply and power DC-applications. For example, traction supply of electric transport, DC transmission lines, regulated electric drives with DC motors, electrolysis bathtubs of nonferrous metallurgy, chemical electro technologies on a direct current, power supplies of the electronic equipment, system of lighting with light devices of a direct current.

The other mass type of consumer using the AC machines demands presence of power electronic converters (frequency converters) with the adjustable voltage and frequency for the regulated electric drive. Another class of consumers requires the high frequency converters for induction heating installations and for high-frequency AC-mains; for systems with a contactless electric energy pickup in mobile objects. Finally, actuality of these converters is expanded by the power conditioning applications. However, in the developed countries 30-50% of the produced electrical energy is consumed without the transformation and regulation.

Let us consider an example with oil treatment. For receiving the electric power it is necessary no just to burn the oil, but to make two more transformations of energy. The first transformation is thermal-to-mechanical. Then mechanical energy is converted to the electric energy. After this direct consumption of electric energy will become even more wasteful. Regulation and matching of its parameters with the consumer's demands becomes necessary. It will provide the considerable preservation of the electric power, increase of efficiency of its use sparing operating modes of the consumer and increase in its service life, improvement of quality of production released by the consumer of the electric power.

Therefore the problem of creation of power electronics branch is obvious. The one concerns the development and production of a new class of power converters. There are AC voltage regulators with the improved electromagnetic compatibility with AC grid and load. In case of need it is possible to use them to implement the power conditioning. AC voltage regulators have a wide scope of applications and their need constantly grows. They are used in systems of voltage regulation and stabilization, compensation of asymmetry and distortions, as devices of soft start-up of asynchronous and synchronous motors, etc.

Linear voltage regulators based on the autotransformers or transformers with a multi section winding are characterized with the high weight and dimensional factors, low speed and complexity of automation. Partially, these shortcomings are not applied in the voltage regulators based on electronic converters. Today among these regulators the most widely spread are the ones with a voltage boost (with phase or pulse-width regulation) [3] – [5] and transformer voltage stabilizers with multi section windings [6] – [8]. But the transformer presence in the power scheme considerably worsens mass-dimensional and cost indexes of the regulator.

Considering the power capacities, it is necessary to define the AC voltage regulator field of application. The most popular fields of application are smart-grid, distributed generation, autonomous objects, responsible consumers. Problems linked with stabilization of AC voltage can be solved with the AC voltage regulators as well [27]. It is known that AC voltage regulators can be also used for stabilization the AC voltage, regulation of reactive power, active filters. Besides this converters do not contain electrolytic capacitors, unlike well-known “back-to-back” converters. That respectively prevents it from emergency operation which can occur in a dc-link.

To all other, in the considered regulators it is possible to obtain the increased output voltage due to the electronic transformer in the high frequency link. This fact provides an additional advantage compared to the conventional matrix converters. In addition, power electronic transformers based on the AC voltage regulators can be classified by power. That allows one to define the area of their application. It can be applied in distributive systems, mobile/autonomous objects (system of power supply of responsible consumers), and smart grid.

II CLASSIFICATION

The traditional AC voltage regulators having the transformer in their structure operate at the power supply frequency that, respectively makes the system heavy. To improve the mass-dimensional indicators, the transformers working at frequency that considerably higher than the power supply frequency are used.

Power electronic transformers based on the AC voltage regulators can be classified as follows:

- the ones using the step-up [10,15] / step-down [22,25] transformer
- PET with a direct/bidirectional power flow.
- The ones with the power factor correction [7,24].
- Depending on the control strategy (pulse-width modulated (PWM) [13], pulse-width regulated (PWR) [10, 11, 15, 21, 22, 24, 26], hysteresis controlled [14], phase modulated [13]).
- With/without using the soft (For minimization of the switching losses). Schemes which provide implementation of the soft switching are presented in [7, 13].
- Presence or absence of a voltage boost. The most interesting option is the combined class of the AC voltage regulators with a voltage boost with pulse-width regulation implemented with fully controlled switches with an intermediate link of high frequency (the high frequency transformer – the power electronic transformer) [25, 24, 6, 21, 26].
- Depending on the primary winding side converter type, secondary winding converter type. Also, there are different PET types depending on the bidirectional switch implementation (quantity of active elements in a key of ac).

III THEORY

PET based on the AC voltage regulator is present on Fig.3.1.a). Operation at a high frequency allows one to reduce mass-dimensional indicators of the transformer and regulator significantly. Switches on the primary and secondary winding sides of the transformer can be implemented as half-bridge, as in fig.3.1.a) or full bridge topologies. To smooth the high frequency pulsations of the input and output currents and voltage of the regulators there are small input and output LC filters used?

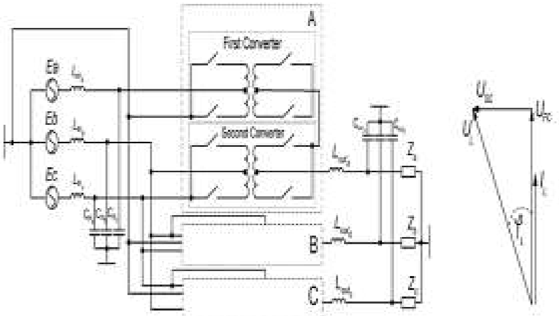

Fig 1 a) PET based on ac voltage regulator , b) Phasor diagram for the ideal regulator

Phasor diagram for the ideal regulator is depicted by Fig. 1.b). Voltage boost active component, U_{ak}, is injected in phase with the input voltage, Ea. Quadrature component of the voltage boost, U_{qk} is injected with 90 degrees shift. Values of these components are determined by the following two requirements: the first one is to provide the desired output voltage, U_{out}, and the second is zero phase-shift between input current, I_{out}, and source voltage, Ea.

For obtaining the main power characteristics of the regulator its mathematical model based on our ADE method of the analysis is created. This method allows us to receive formulas for all integral power quality factors using the coefficients of the initial differential equations. At the same time there is no need to solve the differential equations.

It is necessary to estimate quality of the input current. For this purpose in figure 2 the equivalent circuit of the three phase system is presented. The presented scheme, for simplified calculation, is reduced to one phase by delta-star transformation of the linear three-phase current sources [26]. The equivalent circuit of one phase of system's input is presented on figure 2. Having put the current sources together we will receive an equivalent circuit. The pulsed nature of the input current is a feature of the AC voltage regulator with PWM. 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.
The system's differential equations are as follows:

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

Let us rewrite the system (1) in relation to the desired variable i.e. current:

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

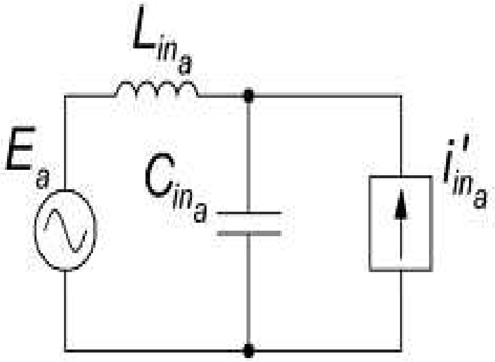

Fig 2 Equivalent input circuit of one phase of the system

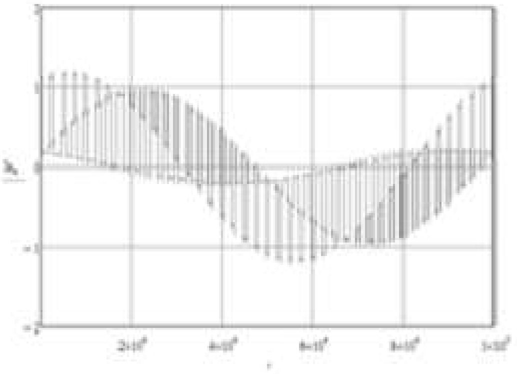

Fig 3 Diagram of current of the given current source

Let us apply the algebraization procedure to the equation (2). This procedure suggests writing the equation for the higher harmonic components and double integration. The result is obtained and expressed through the second order Weighted THD (WTHD) $WTHD_I 2$ (Fig.7):

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

(3)

Where I_{hh} is the higher harmonics components of the input current, which should be defined, $I_{in(1)}$ is the fundamental harmonic of the input current, w is the angular frequency, $WTHD_I$ 2 is the second order weighted THD of the current:

The mathematical model is simulated using the program package MathCAD. For a given signal, the spectrum is calculated. Then $WTHD_I$ $_2$ is obtained. The dependence of the $WTHD_I$ 2 .

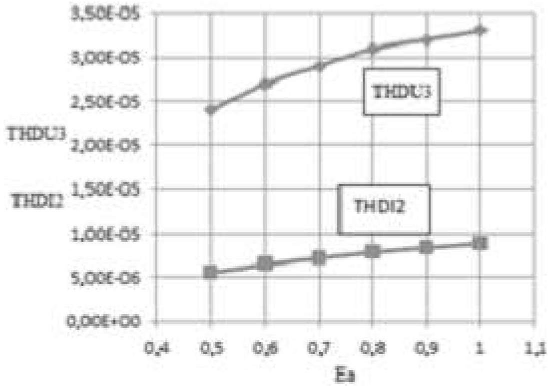

Fig 4 Energy quality

Let us apply algebraization of equation 2 and carry out the calculations of the equation 2 for fundamental harmonics:

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

(4)

$$K_1 = 1 + \frac{1}{w^4 (LC)^2} - \frac{2}{w^2 \cdot LC}, \quad K_2 = \frac{E^2_{(1)}}{w^2 L^2}$$

$$K_3 = \frac{I^2_{in(1)}}{w^4 (LC)^2}, \quad K_4 = \frac{2 \cdot \sin\alpha}{w^3 L^2 C}$$

Equation 3.5 using 3.3 and 3.4 is obtained:

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

(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 second-order weighted THD (3.3). The dependence of the I THD_I of the Ea is shown in Fig.4.

The equivalent circuit of system's output is presented in figure 5.

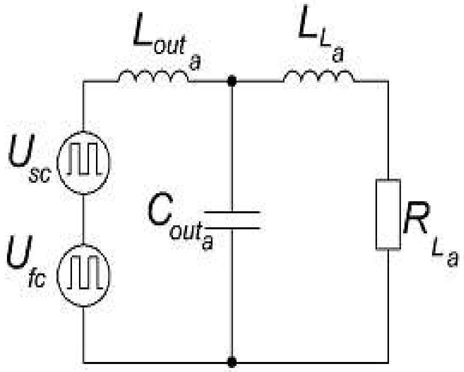

Fig 5 the equivalent circuit of the output

Considering that the voltage sources presented on fig 5 are included consistently, everything is reduced to a uniform source of voltage. The original equations are the following:

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

(6)

Solution for the higher harmonics:

$$I_{out(hh)} = \frac{1}{w^2_{out} L_f C_f} \frac{U_{out(1)}}{w_{out} L_L} \cdot \overset{\equiv}{THDU}$$

(3.7)

Where $WTHD_U$ 3 is third-order weighted total harmonic distortion of the voltage.

According to the direct method of calculation ADE

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

(3.8)

Where q is the order of WTHD, k is number of harmonic. Solution for the fundamental harmonic:

$$I_{out(1)} = \frac{U_{out(1)}}{\sqrt{w_{out}^2 (L_f + L_L)^2 + R_L^2}} \qquad (3.9)$$

Equations 3.10 is obtained from the equations 3.7 and 3.9:

$$THD_{Iout} = \frac{\overset{\equiv}{THDU}}{w_{out}^2 L_f C_f} \sqrt{\left(\frac{L_f + L_L}{L_L}\right)^2 + \left(\frac{R_L}{w_{out} L_L}\right)^2} \qquad (3.10)$$

Thus the output current quality (Fig.3.4) can be estimated when the load parameters are unknown. Knowing the law according to which voltage q-order weighted total harmonic distortion changes, we can predict the quality of the output current, without calculation of the current itself. This is the main advantage of the ADE method. Results of calculation of the voltage-boost components, U_{fc} and U_{sc} versus the input voltage Ea are shown on Fig.3.6.

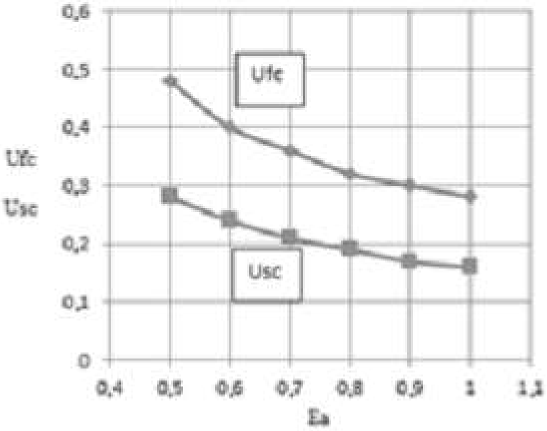

Fig 6 Results of calculation of the Udk and Uok

VI MATLAB/SIMULINK MODEL

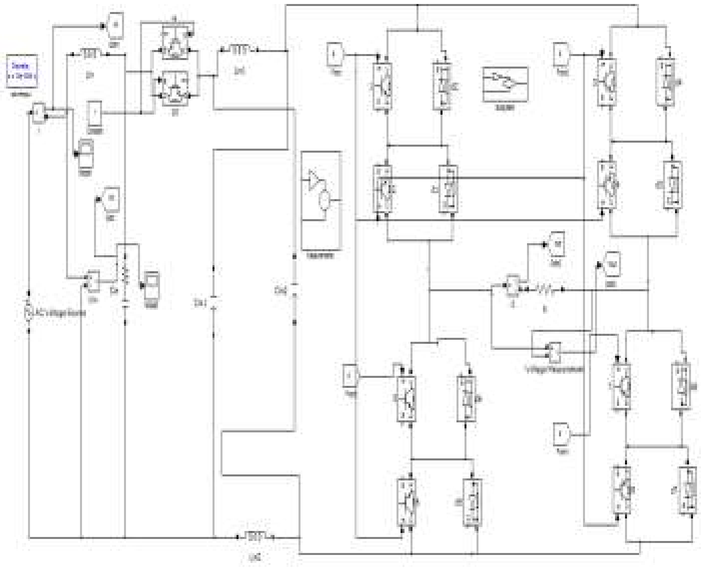

Fig. 7 Matlab/Simulink model PET based on ac voltage regulator

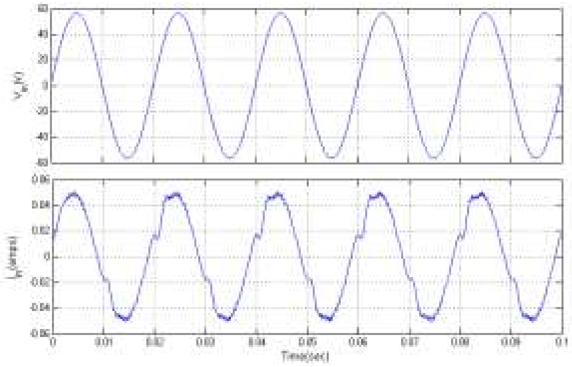

Fig.8 simulation wave form of Input Voltage and Currents Matrix converter R load 25 hz

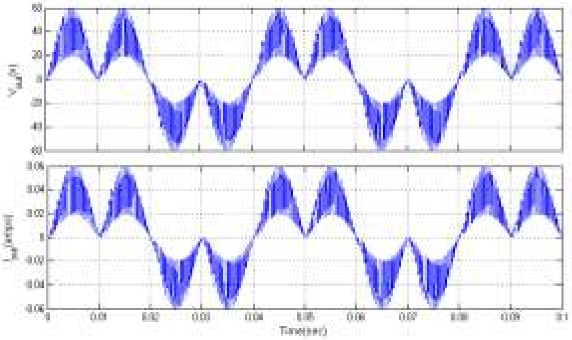

Fig.9 simulation wave form of Output Voltage and Currents

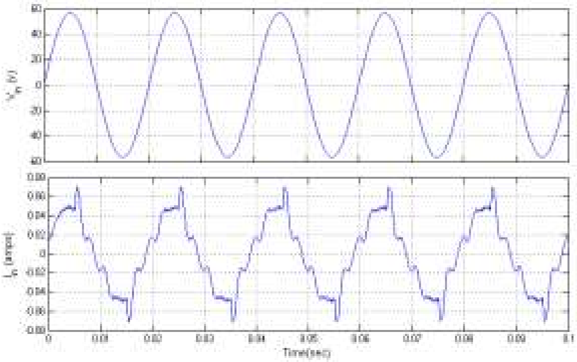

Fig.10 simulation wave form of Input Voltage and Currents Matrix converter R load 100 hz

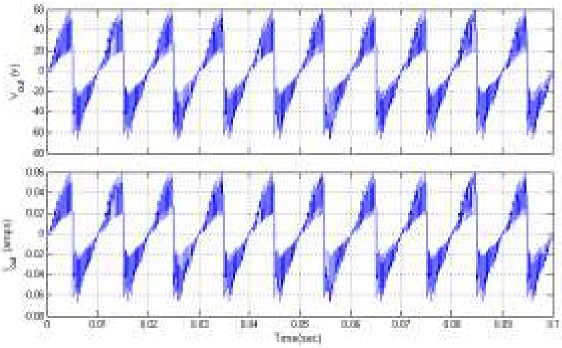

Fig.11 Simulation wave form of Output Voltage and Currents

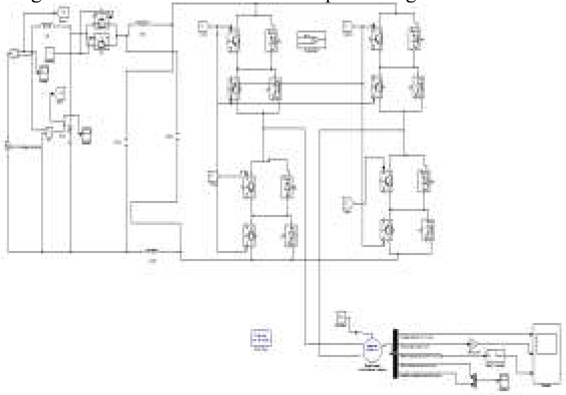

Fig.12. Simulink model of PET based AC voltage Regulator With Motor load

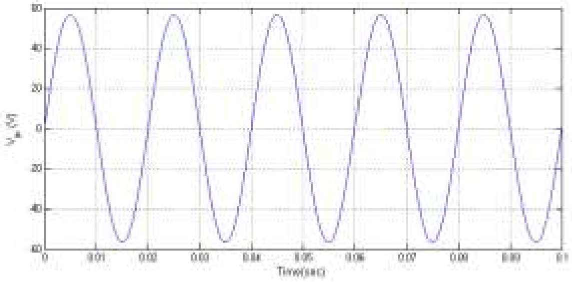

Fig.13. simulation wave form Input Voltage Matrix converter R load with induction motor 50 hz

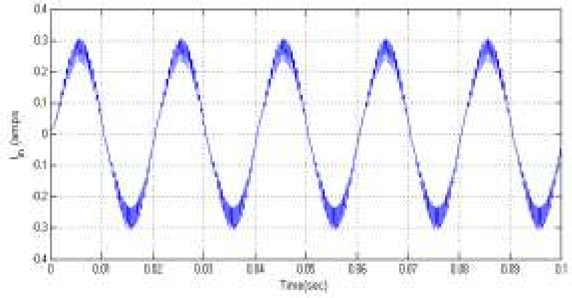

Fig.14. Input current waveform with 50Hz

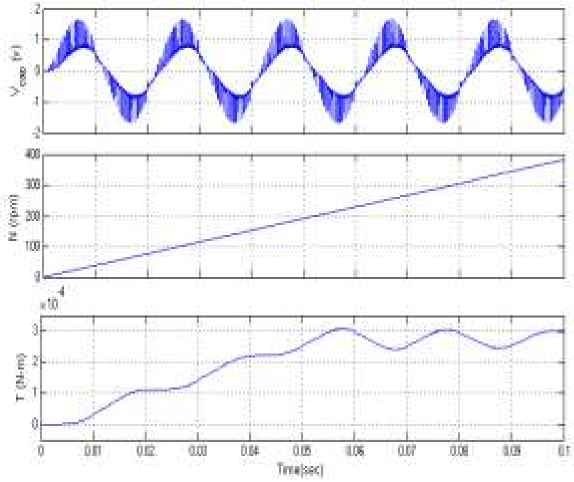

Fig.15.simulation wave form of Voltage Capacitor (Vc), speed and Torque

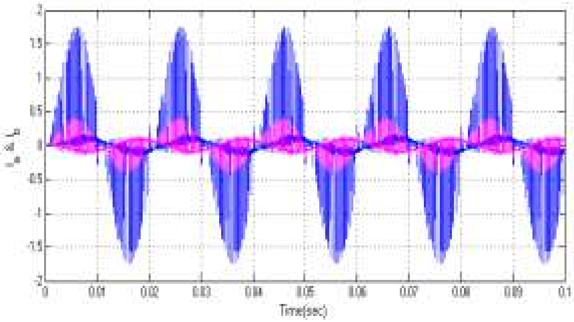

Fig.16. simulation wave form of Currents Ia, Ib

VII CONCLUSION

Problems linked with stabilization of AC voltage can be solved with the AC voltage regulators. It is known that regulators of AC voltage can be also used for stabilization of an ac voltage, regulation of reactive power, active filters. Besides similar converters do not contain electrolytic capacitors, unlike known "back-to-back" of converters that respectively prevents from emergency operation which can occur in their DC-link.

In addition, power electronic transformers based on AC voltage regulators can be classified by power that respectively and allow to define area of their application, namely distributive systems, mobile/autonomous objects (system of power supply of responsible consumers), “smart” networks. The main advantage this PET on the basis of ac voltage regulator, is ability to support single entrance power factor. This research is carried out under the program of the grant №8.1327.2014K. of the Ministry of Education and Science RF

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