The effect of the thyristor energy router on harmonics

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ABSTRACT

Energy routers (ER) are the key equipment of the energy internet that provides control over bidirectional power flows and the voltage level of an electric network. The paper presents the thyristor-powered ER (TER) for an Internet-style medium voltage distribution electric network (6, 10, 20 kV). The developed scheme of the device implements longitudinal and transverse voltage regulation at the ER connection point and it allows changing the power flow and the voltage level in the network. The article is devoted to the study of the harmonic components of voltage introduced into the electrical network by the semiconductor elements of the TER. A mathematical and a computer model and a prototype of an electric network section with a TER have been developed. The studies carried out with the help of the developed models have shown that the device does not significantly distort sinusoidally. The harmonic components factor of the output voltage has acceptable values over the entire range of an effective regulation.

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1. INTRODUCTION

The energy internet (EI) is considered to be the second version of the smart grid [1] and was proposed as an evolution of the energy system in order to increase its efficiency in terms of energy production, transmission and consumption [2]. Unlike the smart grid which focus on the informatization and intellectualization of the existing energy system, the energy internet is the solution to energy problems in the Internet-style through bidirectional integration of information and energy flows. The construction of internet-style power systems will allow to expand the interaction of energy producers and consumers by ensuring free power flows in a medium voltage (MV) distribution electric network (DEN). New network participants can integrate seamlessly into the common infrastructure and exchange electricity as easily as when transmitting information over the internet.

The construction of an Internet-style power system is possible using a smart power flow control device, which is an energy analog of an Internet router. This device or energy router (ER) is the basic device of the energy internet which allows users to interact within the united groups of participants in the energy market [3].

An analysis of the publications devoted to EI showed that most articles are reviews. The works are dedicated to the features of EI [4], [5], the EI architecture [1], [5], information and communication technologies (ICT) application in EI [1], [6], [7], the key equipment of EI [4], [8], technologies and applications of EI Blockchain [9] and some other issues. The main problems associated with the creation of an internet-style electrical network concerning the architecture, control system, power equipment, are considered conceptually.

Specific solutions are not given but the main approaches to the solution are developed. As well as the ER which is the most important element of the internet-style electrical network because it creates a network structure between various EI components by connecting and controlling bidirectional power and data flow. Many ER concepts are presented. Teams all over the world are developing energy routers for MV electric networks. For example, the paper [10] describes a study of the functional design architecture and characteristics of energy routers [10] by a team from the United States. A paper [11] from China describes the study of an ERs with a new design. The ERs have switching matrix with a plug-and-play function and load switching with the maximum use of renewable energy source. The realizations of ERs, functional structures and their classification are considered in [12]. The genetic algorithm and fuzzy logic algorithm application is considered to improve the quality of electricity and the reliability of the electrical system. Control system of FACTS devices on fuzzy logic is given in [13]–[15]. Emergency congestion management of power systems by static synchronous series compensator is considered in [16]. A hybrid genetic algorithm with fuzzy logic controls that used to control and expand the grid performance of the power system presented in [17]. Studies enhancement of transient stability by setting purpose genetic algorithm described in [18]. Ali *et al.* [19] presents the automatic correction of the power factor for a three-phase system using reactive power compensation. Harmonic enhancement in microgrid with applications on sensitive loads discusses in [20]. Widjonarko *et al*. [21] researchers proposed a capacitor bank control system that can adapt to plants with different capacitor values without using any calculations by using an artificial neural network with a closed-loop controller. The results of theoretical and experimental studies on the problems of effective application of shunt active filters for power quality improvement and electromagnetic compatibility ensuring were presented in [22]. The [23] and [24] aims to improve the voltage stability and minimize losses of transmission grid by allocating FACTS devices in the optimal locations and optimal sizes. The objective function of the problem is fitted using particle swarm optimization and whale optimization algorithm. Optimal placement of FACTS devices to reduce power system losses using evolutionary algorithm and multi-objective particle swarm optimization algorithm described in [25] and [26], respectively. The paper [27] aims at improving the reliability in an electric power distribution system by optimizing the number and location of sectionalizes using the ant colony optimization and simulated annealing methods.

To control power flows both in direction and in magnitude, it is proposed to use a thyristor energy router (TER). The TER is a smart power flow regulator developed in the NNSTU n.a. R.E. Alekseev [28]. The TER is designed on thyristor switches, shunt and series transformers and has an active-adaptive control system [29]. It combines the functions of an on-load tap-changer and a phase-shifting device. TERs control the flow distribution and the quality of electricity in MV DEN by introducing a boost voltage into the power line with transverse and longitudinal voltage regulation at the connection point. Figure 1 shows an Internet-style power system with TERs.

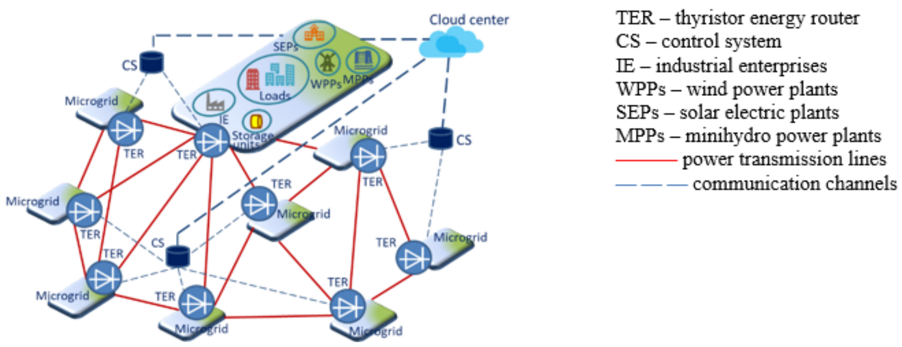


Figure 1. Power system diagram on the energy internet principle

The TER makes both transverse and longitudinal voltage boost. In general, the regulation is longitudinal-transverse. It is possible due to the transformation ratios of parallel and series TER transformers [29]. The TER thyristors are controlled by a pulse-phase method according to the algorithm of two-zone alternating regulation [30]. Figure 2 shows the connection diagram of the TER to the distribution electric network (DEN).

The primary windings of the transformer *T*1 are connected to the input TER terminals (6 (10) kV network). The *T*1 secondary windings are connected to the *T*2 primary windings through the transverse and longitudinal control modules. The *T*2 secondary windings connected between the input (*A*, *B*, *C*) and output

(*A*2, *B*2, *C*2) TER terminals (in the line section) introduce a longitudinal-transverse voltage component regulated by thyristor switches in phase and magnitude.

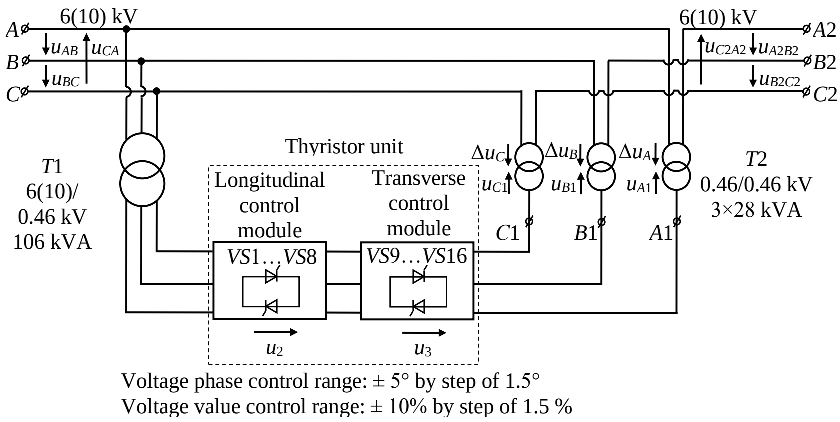


Figure 2. Simplified TER connection scheme to the MV DEN: *T*1 – shunt transformer; *T*2 – series transformers

The TER has a two-level control system. The technological control system (TCS) is a first-level control system. The task of the TCS is to form commands for controlling the thyristors of the modules of longitudinal and transverse regulation. The active-adaptive control system is a second-level control system that performs the functions of monitoring and TER remote control.

The TER is characterized by high speed and accuracy of voltage regulation. On the one hand, the TER should meet the requirements for voltage deviation, but on the other hand, it should not have a negative impact on other indicators of the quality of electric energy. As is known, devices with semiconductor elements can generate higher voltage harmonics during their operation.

The main forms of the influence of higher harmonics on the elements of power supply systems are; resonant phenomena, heating and additional losses in transformers, electric machines and cables of the distribution network, overheating and failure of capacitors, increased acoustic noise in electric machine equipment, vibrations in electric machine systems, interference in telecommunications systems and control networks, accelerated aging of the insulation of electrical equipment and cables, reduction of their service life, disruption of relay protection.

The operation of the TER semiconductor elements can lead to non-sinusoidal network voltage. For the widespread implementation of the developed TER, it is necessary to exclude its negative impact on power quality. Therefore, it is necessary to investigate the effect of the operation of thyristor switches TER on the non-sinusoidal voltage of the electrical network [31], [32]. The work objective is to study the TER effect on the non-sinusoidally of DEN. The problem was solved using mathematical and computer modeling. The simulation results were tested on a TER prototype.

2. RESEARCH METHOD

The mathematical model of a distribution electric network section with a thyristor energy router is based on the equations which describe the parameters of a three-phase electrical network and the principle of thyristor switches operation. Figure 3 shows a three-phase diagram of the network section. The regulation of the voltage magnitude under the action of the TER is carried out by introducing a *U*2 voltage additive into the line of each phase that coincides or is in antiphase with the *U*1 phase voltage of the source. It enables to obtain line voltage at the output of the TER that coincides in phase with the input ones and are increased or decreased relative to the input voltages by the *U*2 value.

The voltage phase regulation is implemented by introducing a *U*3 voltage additive into the line of each phase, shifted by ±90° relative to the *U*1 phase voltages of the network. It allows to get line voltages at the TER output that are lagging or ahead of the input voltages by an θ angle. Lagging voltages are formed by the introduction of inverse voltages of transverse regulation, advancing ones-by the introduction of direct voltages.

In the mathematical model of a network section with a TER, the supply source is replaced by an equivalent EMF system connected according to the "star" scheme. The replacement scheme of the DEN section with TER is shown in Figure 4. The E_{1A}, E_{1B}, E_{1C} in EMF system with U_{1A}, U_{1B}, U_{1C} phase voltages simulate a power source with unchanged parameters. E_{2A}, E_{2B}, E_{2C} EMF with U_{2A}, U_{2B}, U_{2C} voltages and E_{3A}, E_{3B}, E_{3C} EMF with U_{3A}, U_{3B}, U_{3C} voltages are regulated, and simulate, respectively, the TER module of longitudinal and transverse regulation.

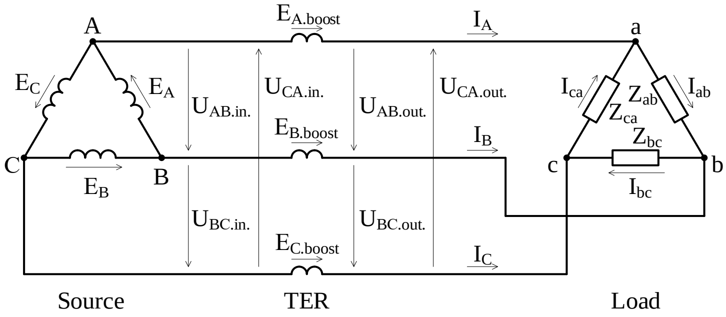


Figure 3. Diagram of fragment DEN with TER

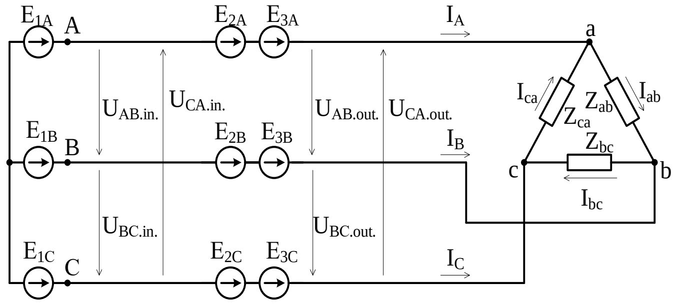


Figure 4. Equivalent circuit of DEN with TER section

2.1. Calculation of TER output voltages

The instantaneous values of the energy source phase voltages u_{1A}, u_{1B}, u_{1C}, kV, are described by (1).

$$u_{1A} = U_{1m} \, sin(\omega t);$$
$$u_{1B} = U_{1m} \, sin(\omega t - \tfrac{2}{3}\pi);$$
$$u_{1C} = U_{1m} \, sin(\omega t + \tfrac{2}{3}\pi); \quad (1)$$

Where U_{1m} is the equivalent source phase voltage amplitude, kV; ω is the angular frequency of the sinusoidal current; t is the time, s.

$$U_{1m} = \frac{U_{nom}}{\sqrt{3}} \cdot \sqrt{2},$$

Where U_{nom} is the rated voltage of the MV network, kV.

The angular frequency of the sinusoidal current is determined by the equation: $\omega = 2\pi f$, where $f = 50$ Hz is the nominal frequency of the sinusoidal current. The instantaneous voltage values of the A phase of the longitudinal control module are (2),

$$u_{2A} = \begin{cases} \pm U_{2m} \, sin(\omega t) & \text{at} \alpha \le \omega t \le \pi + \varphi \\ 0 & \text{at} \varphi < \omega t < \alpha \end{cases} \quad (2)$$

where U_{2m} is the amplitude value of the voltage of the longitudinal control module, kV; α is the thyristor control angle, rad; φ is the angle between the current and voltage of the load, rad. The instantaneous voltage values of the B and C phases of the longitudinal control module are determined similarly as (2) taking into account the phase shift angle. U_{2m} depends on the required output voltage regulation range D of the model (when $D = \pm$ 10 %, $U_{2m} = D \cdot U_{1m} = 0{,}1 \cdot U_{1m}$). The instantaneous voltages values of the A phase of the transverse control module, kV, are (3),

$$u_{3A} = \begin{cases} \pm U_{3\mathrm{m}} \sin(\omega t - \frac{\pi}{2}) & \text{at } \alpha + \frac{\pi}{2} \leq \omega t \leq \pi + \varphi + \frac{\pi}{2} \\ 0 & \text{at } \varphi + \frac{\pi}{2} < \omega t < \alpha + \frac{\pi}{2} \end{cases} \quad (3)$$

where $U_{3\mathrm{m}}$ is the amplitude value of the voltage of the transverse control module, kV.

The instantaneous voltage values of the *B* and *C* phases of the transverse control module are determined similarly as (3) taking into account the phase shift angle. $U_{3\mathrm{m}}$ depends on the range θ of the voltage shift angle regulation at the output of the model (when θ= ± 5 % $U_{3\mathrm{m}} = 0{,}1U_{1\mathrm{m}}$). The instantaneous values of phase voltages at the TER output, kV, are (4),

$$\begin{aligned} u_{A.out} &= u_{1A} + u_{2A} + u_{3A}; \\ u_{B.out} &= u_{1B} + u_{2B} + u_{3B}; \\ u_{C.out} &= u_{1C} + u_{2C} + u_{3C}. \end{aligned} \quad (4)$$

the instantaneous values of linear voltages at the TER input, kV, are (5),

$$\begin{aligned} u_{AB.in} &= u_{1A} - u_{1B}; \\ u_{BC.in} &= u_{1B} - u_{1C}; \\ u_{CA.in} &= u_{1C} - u_{1A}. \end{aligned} \quad (5)$$

the instantaneous values of linear voltages at the TER output, kV, are (6),

$$\begin{aligned} u_{AB.out} &= u_{A.out} - u_{B.out}; \\ u_{BC.out} &= u_{B.out} - u_{C.out}; \\ u_{CA.out} &= u_{C.out} - u_{A.out}. \end{aligned} \quad (6)$$

2.2. Calculation of TER output currents

The calculation of the TER output currents according to the substitution scheme in Figure 4 is carried out in the following sequence.

– The instantaneous values of the phase load currents are determined when the load resistances are connected to the "star", A:

$$\begin{aligned} i_a &= i_{1a} + i_{2a} + i_{3a}; \\ i_b &= i_{1b} + i_{2b} + i_{3b}; \\ i_c &= i_{1c} + i_{2c} + i_{3c}, \end{aligned} \quad (7)$$

where i_1, i_2, i_3, are instantaneous values of currents in the load phases *a*, *b*, *c* flowing under the action of u_1, u_2, u_3 voltages of the corresponding phases.

$$\begin{aligned} i_{1a} &= \frac{U_{1m}}{Z} \sin(\omega t - \varphi) \cdot 10^3; \\ i_{1b} &= \frac{U_{1m}}{Z} \sin(\omega t - \frac{2}{3}\pi - \varphi) \cdot 10^3; \\ i_{1c} &= \frac{U_{1m}}{Z} \sin(\omega t + \frac{2}{3}\pi - \varphi) \cdot 10^3, \end{aligned} \quad (8)$$

Where $Z = \sqrt{R^2 + X^2}$ is total load resistance of one phase, ohms. The active *R* and inductive *X* resistances of the load phase are determined by (9), ohms:

$$\begin{aligned} R &= 3 \frac{U_{nom}^2}{S_{nom}} \cos\varphi \cdot 10^3; \\ X &= 3 \frac{U_{nom}^2}{S_{nom}} \sin\varphi \cdot 10^3, \end{aligned} \quad (9)$$

where U_{nom} is the rated (linear) load voltage, kV; S_{nom} is the rated load power, kV·A.

$$i_{2a} = \begin{cases} \pm \frac{U_{2\mathrm{m}}}{Z} \begin{bmatrix} \sin(\omega t - \varphi) - \\ - \sin(\alpha - \varphi) \cdot e^{\frac{-(\omega t - \alpha)}{\mathrm{tg}\varphi}} \end{bmatrix} \cdot 10^3 & \text{at } \alpha \leq \omega t \leq \pi + \varphi \\ 0 & \text{at } \varphi < \omega t < \alpha \end{cases} \quad (10)$$

The currents i_{2b} and i_{2c} are determined similarly (10) taking into account the phase shift angle.

$$i_{3a} = \begin{cases} \pm \frac{U_{3m}}{Z}\begin{bmatrix} sin(\omega t - \frac{\pi}{2} - \varphi) - \\ - sin(\alpha - \varphi) \cdot e^{\frac{-(\omega t - \pi/2 - \alpha)}{\text{tg}\varphi}} \end{bmatrix} \cdot 10^3 \text{ at } \alpha + \frac{\pi}{2} \le \omega t \le \pi + \varphi + \frac{\pi}{2} \\ 0 \qquad \text{at } \varphi + \frac{\pi}{2} < \omega t < \alpha + \frac{\pi}{2} \end{cases} \tag{11}$$

The currents i_{3b} and i_{3c} are determined similarly (11) taking into account the phase shift angle.
– The instantaneous values of the phase load currents are determined, A:

$$\begin{aligned} i_{ab} &= i_a - i_b; \\ i_{bc} &= i_b - i_c; \\ i_{ca} &= i_c - i_a. \end{aligned} \tag{12}$$

– The instantaneous values of linear currents at the TER output are determined according to the first Kirchhoff law for nodes *a*, *b* and *c* in Figure 4, A:

$$\begin{aligned} i_A &= i_{ab} - i_{ca}; \\ i_B &= i_{bc} - i_{ab}; \\ i_C &= i_{ca} - i_{bc}. \end{aligned} \tag{13}$$

2.3. Determination of the harmonic composition of output voltages and currents

The voltage and current curves at the TER output are constructed using (6) and (13). The harmonic composition of voltages and currents is determined by the decomposition of the obtained curves into a Fourier series (14).

$$f(t) = A_o + \sum_{v=1}^{\infty} A_v \, sin(\text{v}\omega t + \psi_v) \tag{14}$$

Where A_0 is the constant component or zero harmonic; *v* is the number of the harmonic; A_v is the amplitude of the v-th harmonic; ψ_v is the initial phase of the v-th harmonic.

In accordance with the standard for the power quality [33], the harmonic components of voltage up to 40 orders of magnitude are subject to normalization. To analyze the harmonics of current and voltage using the coefficients obtained from (14), the expressions are used (15).

$$\begin{aligned} K_{A(v)} &= \frac{A_v}{A_1} \cdot 100 \ \%; \\ THD &= \frac{\sqrt{\sum_{v=2}^{40} A_v^2}}{A_1} \cdot 100 \ \%, \end{aligned} \tag{15}$$

Where $K_{A(v)}$ are coefficients of harmonic components, %; *THD* is the total coefficient of harmonic components, %.

The mathematical model allows studying the harmonic composition of TER voltages and currents in various modes of its operation at different values of the thyristor control angle in the range 0–180°, (one half-period), at an active load and at an active-inductive load with different values of the φ angle. Table 1 shows the values of the higher harmonics of the TER output voltage for transverse, longitudinal and longitudinal-transverse modes, obtained using a mathematical model.

Table 1. Values of the TER output voltage higher harmonics

Load power factor (cosφ)		THD, %	$K_{U(v)}$, %, at harmonic number *v*		
			5	7	11
Transverse control	1.0	2.064	1.151	0.830	0.670
	0.87	2.291	1.398	1.012	0.850
	0.5	2.871	1.621	1.021	0.984
Longitudinal control	1.0	2.287	1.251	1.021	0.790
	0.87	2.421	1.598	1.180	1.057
	0.5	3.369	2.334	1.235	1.142
Longitudinal-transverse control	1.0	4.029	3.151	2.417	0.755
	0.87	4.082	3.412	2.419	1.032
	0.5	4.213	3.477	2.422	1.200

3. COMPUTER MODEL OF A DISTRIBUTION ELECTRIC NETWORK SECTION WITH THYRISTOR ENERGY ROUTER

A computer model was created in the MATLAB software package. The model consists of 5 main blocks shown in Figure 5. The model contains auxiliary blocks that allow to output information about the voltage shift angle taking into account the regulation, about the effective values of the phase and line voltage, about the magnitude and shape of the longitudinal and transverse regulation curve, and other TER parameters.

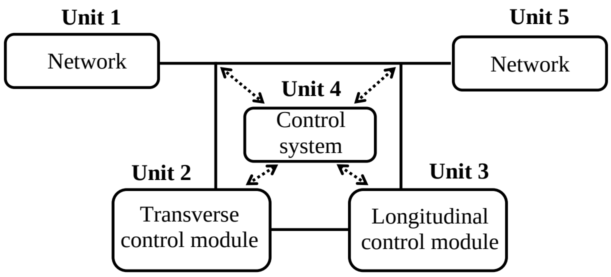


Figure 5. Computer model structure diagram of DEN with TER

The blocks of longitudinal and transverse voltage regulation are an alternating voltage source connected using thyristors to an *RLC*-circuit which simulates the nature and magnitude of the load. The pulse generator unit is used to set the opening time of the thyristors. The pulse delivery time depends on the specified control angle of the thyristors. Separate control of the blocks responsible for longitudinal and transverse voltage regulation is provided. You can set different control angles for the longitudinal and transverse control units, as well as the control sign, thereby modeling the addition and decrease of voltage, advance and phase lag. It allows to analyze more accurately the various operating modes of the device.

4. RESULTS AND DISCUSSION

For the model operation, the following parameters are set: device power, load power, rated network voltage, the angle between current and voltage, the control angle of the thyristors of the longitudinal control unit, the control angle of the thyristors of the transverse control unit, the maximum value of the additive for longitudinal control, the maximum value of the additive for transverse control. Setting the control area, namely, increasing the voltage or decreasing it, advancing or lagging in phase is carried out manually in the model itself, it is done for greater clarity of the model. Figures 6 to 9 show waveforms of phase and line voltage in the mode of longitudinal-transverse regulation.

Table 2 shows the results of harmonic analysis of the output voltage TER for transverse, longitudinal and longitudinal-transverse voltage regulation for loads with different cosφ values. The maximum THD value is 4.23% and corresponds to the joint operation of the longitudinal and transverse control modules at cosφ=0.5.

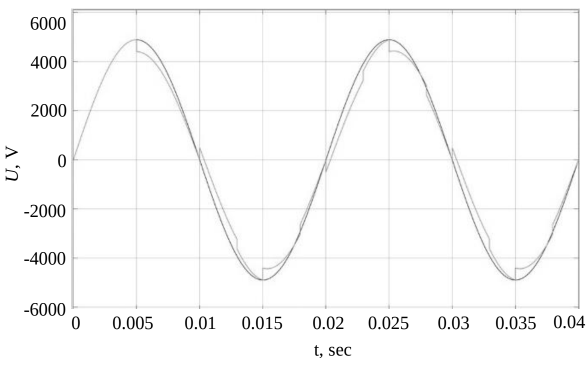


Figure 6. *A* phase voltage before and after regulation (cosφ=0.5, voltage step-down/lagging mode α=90°/90°)

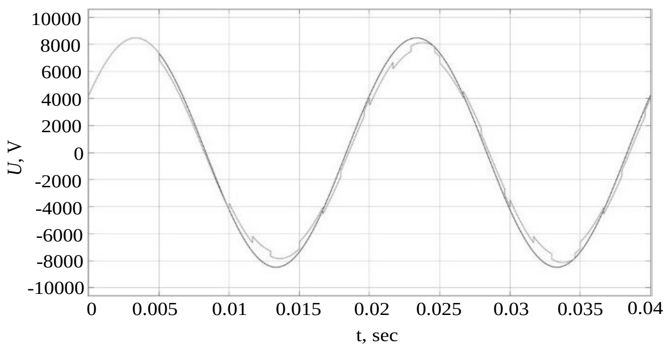


Figure 7. *AB* line voltage before and after regulation (cosφ=0.5, voltage step-down/lagging mode α=90°/90°)

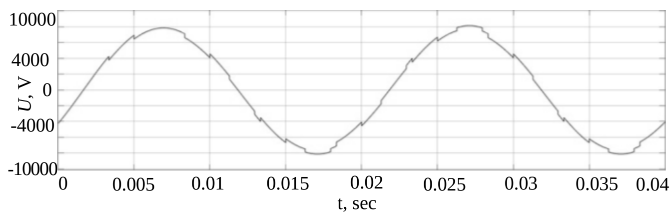


Figure 8. Oscillogram of *AC* line voltage on load (cosφ=0.5, voltage step-down/lagging mode α=90°/90°)

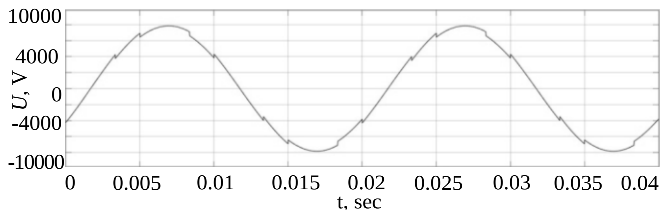


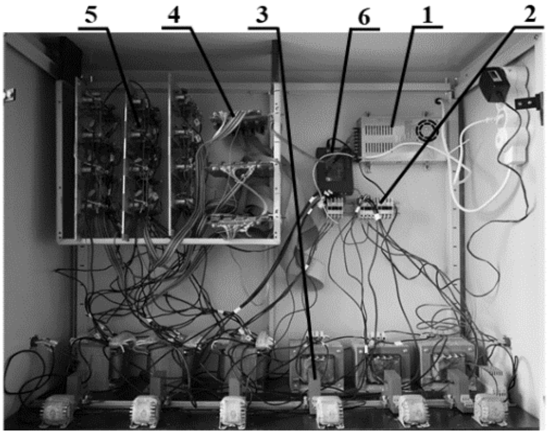
Figure 9. Oscillogram of *AC* line voltage on load (cosφ=1, voltage step-down/lagging mode α=90°/90°)

Table 2. Research results of the TER output voltage harmonic composition

Load power factor (cosφ)		THD, %	$K_{U(v)}$, %, at harmonic number v		
			5	7	11
Transverse control	1.0	2.092	1.177	0.911	0.897
	0.87	2.391	1.475	1.082	1.025
	0.5	2.973	1.711	1.353	1.091
Longitudinal control	1.0	2.347	1.192	1.159	0.801
	0.87	2.485	1.663	1.238	1.082
	0.5	3.404	2.441	1.537	1.184
Longitudinal-transverse control	1.0	4.091	3.198	2.434	0.891
	0.87	4.122	3.427	2.459	1.191
	0.5	4.235	3.521	2.498	1.262

5. THYRISTOR ENERGY ROUTER PROTOTYPE

The TER prototype is designed to verify the results of mathematical and computer modeling. The prototype photo is shown in Figure 10. The TER prototype provides the ability to verify the performance of the required functions and verify the results of computer modeling. The TER prototype consists of the following elements: series and shunt transformers; thyristor switch modules; pulse amplifier boards; current and voltage transformers and a control system. The harmonic distortion coefficients were obtained using the AKE-824 electrical energy quality analyzer. The analysis of the non-sinusoidally level was made for different load with cosφ=0.5; 0.87; 1 shown in Table 3.



1 – source
2 – contactor
3 – power and measurement transformers
4 – pulse amplifier boards
5 – thyristor switcher modules
6 – control system controller

Figure 10. Photo of the TER prototype

Table 3. Measurement results of the TER output voltage harmonic composition

Load power factor (cosφ)		THD, %	$K_{U(v)}$, %, at harmonic number v		
			5	7	11
Transverse control	1.0	2.158	1.253	1.008	0.995
	0.87	2.454	1.592	1.184	1.112
	0.5	2.985	1.732	1.382	1.225
Longitudinal control	1.0	2.591	1.295	1.137	0.954
	0.87	2.640	1.721	1.235	1.127
	0.5	3.538	2.558	1.679	1.231
Longitudinal-transverse control	1.0	4.250	3.209	2.487	0.924
	0.87	4.284	3.549	2.571	1.218
	0.5	4.344	3.632	2.582	1.285

6. CONCLUSION

The mathematical and the computer models and the prototype of the DEN section with TER have been developed to study and verify the results of the harmonic analysis. The order and values of the higher harmonics for the entire zone of effective TER regulation have been determined. The results of mathematical, computer and physical modeling have a high correlation. The studies have shown that there are no third and multiple harmonics in the output voltages of the TER. The deviation of non-sinusoidally coefficients (not more than 3%) is explained by taking into account voltage drops in the supply line and the power elements of the TER during simulation modeling, as well as by taking into account switching intervals during which the added voltage is practically equal to zero. It should be noted that the obtained coefficients of the higher harmonic components over the entire range of effective TER control do not exceed the permissible limits.

The values of the higher harmonics at fixed control angles of the thyristors allow to provide the possibility of compensating the coefficients of the higher harmonic components of the voltage, and therefore completely eliminate the TER influence on the non-sinusoidal voltage of the electrical network. Thus, the TER use enables to adapt MV DEN to changes in electrical loads and ensure the required power quality.

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