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MODES OF THE BOOSTER TRANSFORMER WITH REGULATION IN ZIGZAG

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Abstract. The development of power engineering assumes the increasing flexibility of power networks through the use of various kinds of FACTS, controlled by means of power electronics and being elements of the Smart Grid. These kinds of devices can be attributed to controllers such as UPFS and „Sen” Transformer (ST), which provide regulation of voltage and power flows in networks. Due to the relevance of this topic, technical solutions are proposed that perform similar functions, which implies the need for a comparative analysis of such developments in order to optimize energy characteristics of the equipment. The scope of the paper is to develop and study a regulating transformer which belongs to the „Sen” family, but possessing the extended range and higher control accuracy. Carrying out research, mode parameters of the device were treated, as well as typical power was determined.

Keywords: *booster transformer, load, voltage control, active power, reactive power compensation, operation mode control.*

Rezumat. Dezvoltarea domeniului electroenergeticii presupune creșterea flexibilității rețelelor electrice prin aplicarea de diverse instalații FACTS, mijloace comandate ale electronicii de putere, fiind elemente ale Smart Grid. La dispozitivele de asemenea gen pot fi catalogate controlerele de tip UPFC și transformatorul „Sen”, care asigură reglarea tensiunii și a fluxurilor de putere în rețea. Reieșind din actualitatea acestei tematici au fost propuse soluții tehnice, care realizează funcții prin analogie, urmate de necesitatea analizei comparative a acestor elaborări, având ca scop optimizarea caracteristicilor energetice ale echipamentelor. Scopul lucrării constă în elaborarea și cercetarea transformatorului de reglaj, ce face parte din familia „Sen”, dar care dispune de un diapazon extins și o precizie sporită de reglaj. Pe parcursul cercetărilor au fost analizați parametrii de regim ai dispozitivului și determinată puterea-tip.

Cuvinte cheie: *transformator booster, sarcină, control tensiune, putere activă, compensare putere reactivă, control regim de funcționare.*

Introduction

The present stage of the electric power industry development is characterized by a significant increase of the volumes of generation of energy through the use of renewable energy sources, production of which is significantly subject to daily and seasonal oscillations. Such a circumstance might reflect upon the power quality indicators. Under these conditions the issue of transmission and distribution network's controllability is becoming increasingly relevant. Technical means, destined to the finding of solutions to tasks (provided by FACTS technologies, Smart Grid) of this kind are largely associated with the use of two-stage energy conversion – rectification and inverting.

One of modern devices providing regulation of voltage and power fluxes in networks is UPFC (Unified Power Flow Controller). The device represents itself as a combination of Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSVC) [1–6]. By including the booster longitudinal voltage with regulated phase, the device UPFC is able in the real-time to regulate simultaneously or selectively: the voltage of power lines, impedance, angle or active and reactive power fluxes in the line, to provide independent transversal controllable compensation, active harmonic filtering, as well as other technical procedures to improve the quality of operation of power systems. The topologies of its realization can vary in quite extensive limits. In the case when the role is fulfilled through the use of a regulating transformer, its ends are connected / disconnected by means of electronic keys, which have gained a high performance level due to the fast development of the power electronics domain. Respectively, the area of their utilization extended on majority segments of the power system: power transmission and distribution, local systems of heavy industrial sector, arc furnaces and electric transport infrastructure [7-10].

To the advantages of this technology can be attributed:

- deeper influence on the characteristics of the line mode compared to other means of regulation;
- combination of the properties at once of three devices: static compensator of reactive power, installation of longitudinal compensation and installation for phase rotation.

Disadvantages of UPFC are:

- increasing of the power of regulation devices under the extension of the range;
- significant range of deviations of the output voltage depending on the values of booster voltage and its angle, that can lead to the corona discharge effects of wires and will require the strengthening of insulation;
- decline of the range of regulation of the active power under the increase of the line's length;
- high cost and, as consequence, increased installation and operating costs.

The same control effects can be achieved on the base of direct (one-stage energy conversion), which allows to accomplish much more reliable and less expensive devices. One of such technologies is a booster transformer of various configurations and destinations, well known as ST. [11–19].

By assigning with the help of tap changer needed combination, ST can correct the voltage, controlling its magnitude and phase-angle shifting, i.e. perform the same functions like UPFC. ST disposes the ability to assure the control of crossflow of active and reactive power in most backbone and distribution networks [20–22].

To the advantages of ST can be assigned:

- relative simplicity of design;

- relative not high cost;
- performs the same functions as UPFC.

Disadvantages can be considered:

- limited number of operation states;
- not high control accuracy in a given area due to the limited number of operation states;
- not high operation speed when using the regulation under load mode.

In the process of creating the so-called „intellectual" power grids (Smart Grid) and their transition in the future to the more efficient systems on the highest level, now called Microgrids, certain requirements will be imposed on the power grids to ensure an optimal load factor and a high power factor.

These functions can be realized by means of regulating transformers, controlled by power electronics, belonging to the family Sen.

Common characteristic of the object of research

This paper is dedicated to the development and research of a regulation transformer based on the principle of operation of the ST, but with an extended range and higher control accuracy. In the process of research, methods of mathematical, structural and simulation modeling were applied based on objects built in SPS-models in the Simulink/Matlab environment [23-28]. The principle circuit diagram of research object is shown in Figure 1. Basic elements of the device are two three-winding transformers, one of which performs a function of parallel (magnetizing), the second – functions of series (booster) elements. The index „*p*" marks the windings and the corresponding electrical units characterizing the mode of the magnetizing transformer, the index „*q*" marks the windings and electrical units of the booster transformer.

Elements belonging to the parallel transformer are numbered by Figures 1-30, and elements belonging to the booster transformer are numbered by digits 31-39.

List of designations of elements presented in Figure 1:

A,B,C – nomination of phases of three-phase voltage system;

A1,B1,C1 – electric inputs (input terminal) of the device;

A2,B2,C2 – electric outputs (outputs terminals) of the device;

1,2,3 – primary windings of high voltage phases A,B,C of the magnetizing transformer (W_{1pA}, W_{1pB}, W_{1pC});

4,5,6 – first regulation windings of fine regulations of phases A,B,C of the magnetizing transformer ($W'_{2pA}, W'_{2pB}, W'_{2pC}$);

7,8,9 – first regulation windings of rough regulation of phases A,B,C of the magnetizing transformer ($W''_{2pA}, W''_{2pB}, W''_{2pC}$);

10,11,12 – second regulation windings of fine regulation of phases A,B,C of the magnetizing transformer ($W'_{3pA}, W'_{3pB}, W'_{3pC}$);

13,14,15 – second regulation windings of rough regulation of phases A,B,C of the magnetizing transformer ($W''_{3pA}, W''_{3pB}, W''_{3pC}$);

16,17,18 – blocks of power electronic switches of the first regulation windings of fine regulation of phases A,B,C of the magnetizing transformer;

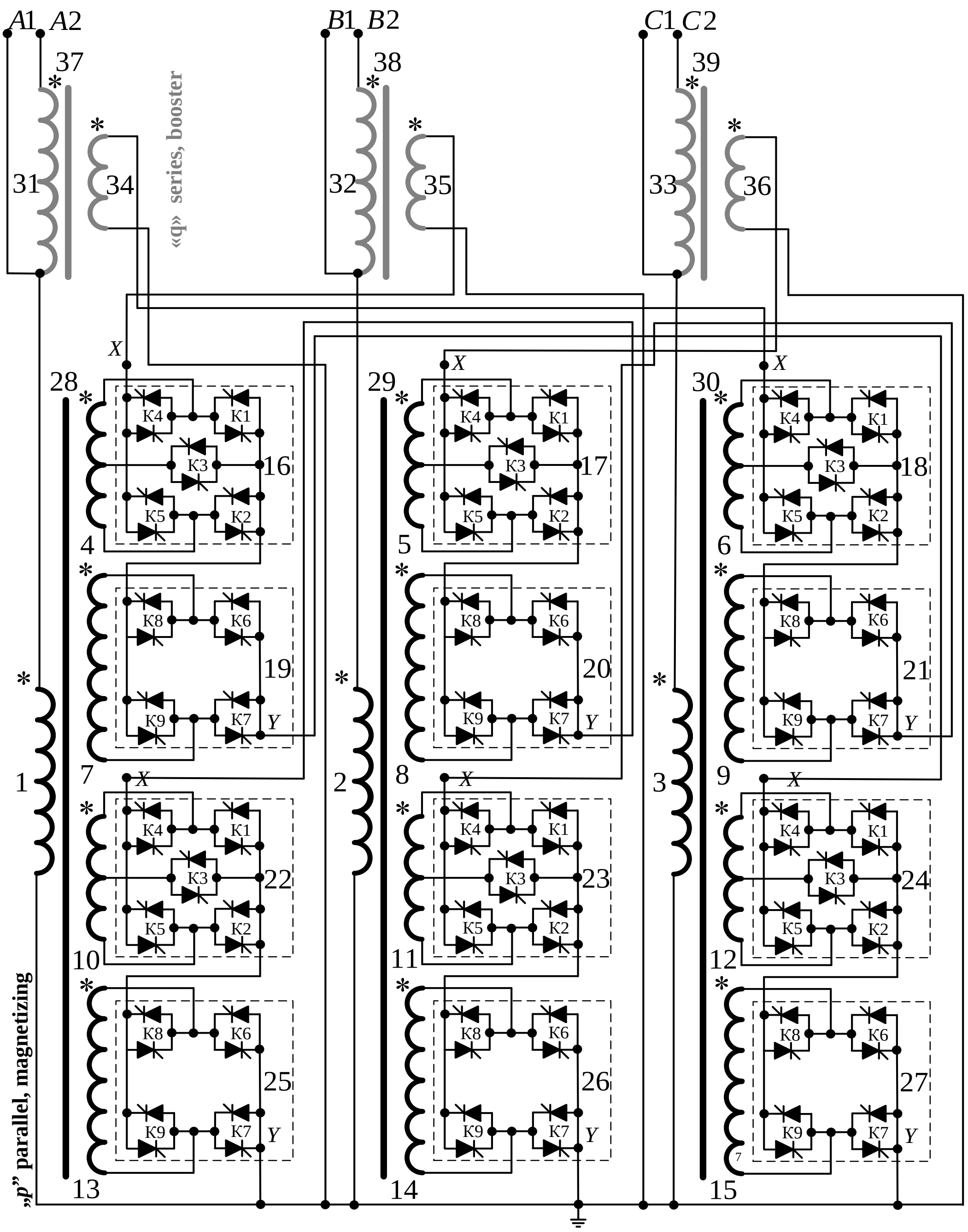


Figure 1. Principle circuit diagram of the device „wye with regulation in zigzag".

19,20,21 – blocks of power electronic switches of the first regulation windings of rough regulation of phases A,B,C of the magnetizing transformer;
22,23,24 – blocks of power electronic switches of the second regulation windings of fine regulation of phases A,B,C of the magnetizing transformer;
25,26,27 – blocks of power electronic switches of the second regulation windings of rough regulation of phases A,B,C of the magnetizing transformer;
28,29,30 – cores of magnetic circuits of phases A,B,C of the magnetizing transformer;
31,32,33 – high voltage windings of phases A,B,C of the booster transformer ($W_{1qA}, W_{1qB}, W_{1qC}$);
34,35,36 – low voltage windings of phases A,B,C of the booster transformer ($W_{2qA}, W_{2qB}, W_{2qC}$);
37,38,39 – cores of magnetic circuits of phases A,B,C of the booster transformer;
K1 $\div$ K9 – switchers of power electronics.

As follows from the circuit diagram (Figure 1), high voltage windings ($W_{1pA}, W_{1pB}, W_{1pC}$) of the magnetizing transformer are supplied from the power network through electric inputs A1, B1 and C1. The ends of these windings are grounded. In turn, supply for booster transformer is provided to its low voltage windings ($W_{2qA}, W_{2qB}, W_{2qC}$) in the form of discretely regulated in magnitude and phase (by means of power electronics) voltages, which are generated by the system of regulation windings ($W_{2pA}, W_{2pB}, W_{2pC}, W_{3pA}, W_{3pB}, W_{3pC}$), located on the legs of the magnetic circuit of the magnetizing transformer. The voltages thus formed, being brought to the high-voltage side by transformation into windings ($W_{1qA}, W_{1qB}, W_{1qC}$), are algebraically summed up with the voltages of the corresponding phases of the supply system, thereby providing the necessary action of regulation. Thanks to the application of the sectioning of control windings, the area for regulating the output voltage of the device (Figure 2) consists of 225 points, which significantly improves the accuracy and quality of output voltage regulation. To each position of regulation modules corresponds a definite combination of power keys. The diagram of the sectioning of control windings W_{2p}, W_{3p} and the control law are shown in Figure 3.

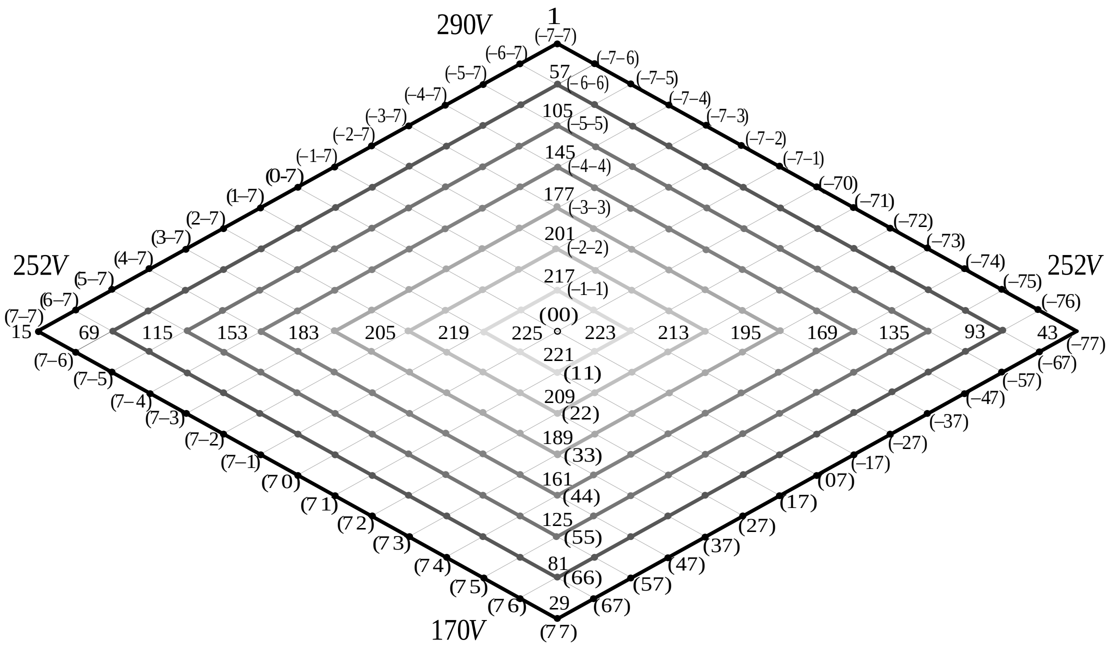
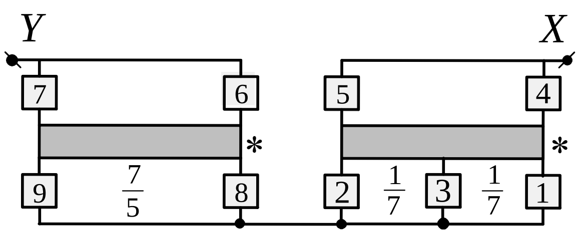


Figure 2. Area of regulation of the output voltage.



7	6	5	4	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	
				●			●		●			●		●	K1
●		●			●					●					K2
	●		●			●		●			●		●		K3
●	●				●	●	●			●	●	●			K4
		●	●	●				●	●				●	●	K5
					●	●	●			●	●	●	●	●	K6
●	●	●	●	●				●	●						K7
●	●	●	●	●	●	●	●								K8
								●	●	●	●	●	●	●	K9

Figure 3. The diagram and control law of the regulation module.

The mode's parameters of the device

The area of regulation of output voltage of the device can be divided conditionally in four sectors, for each of which vector diagrams and calculation expressions for the mode's parameters are shown below in Figure 4 ÷ 7 and Equations (1 ÷ 20).

The following designations are accepted on vector diagrams:

U_{s0} – voltage at the device input;

β – angle of the vector of booster voltage;

$m = U_{\alpha}$ – magnitude of the booster voltage;

m_0 – magnitude of the longitudinal component of the booster voltage;

U_s – voltage at the device output;

α – angle of the device output voltage.

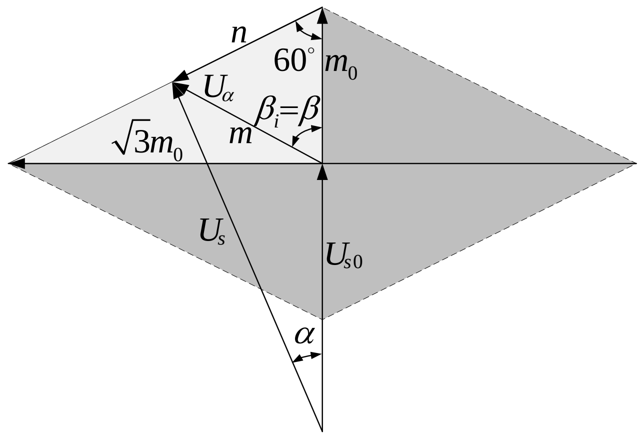


Figure 4. Vector diagram of voltages of the operating device in the first sector.

$$\beta_i = \beta \tag{1}$$

$$m = \frac{\sqrt{3} \cdot m_0}{\sin \beta_i + \sqrt{3} \cdot \cos \beta_i} \tag{2}$$

$$n = \frac{2 \cdot m_0}{1 + \sqrt{3} \cdot ctg \beta} \tag{3}$$

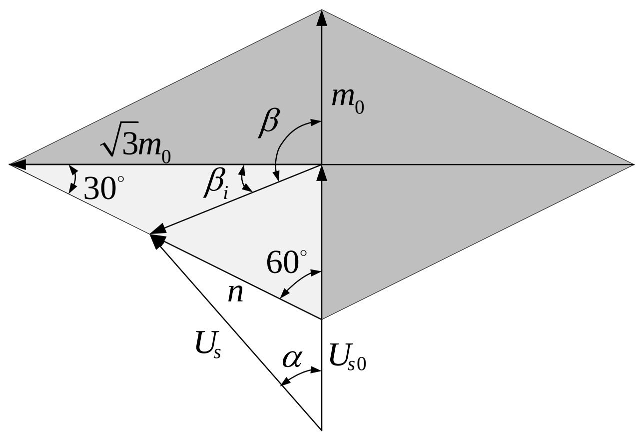


Figure 5. Vector diagram of voltages of the operating device in the second sector.

$$U_S = \sqrt{n^2 + (1+m_0)\cdot(1+m_0-n)}\cdot U_{S0} \tag{4}$$

$$\alpha = \arcsin\frac{\sqrt{3}}{2}\cdot\frac{n}{U_S} \tag{5}$$

$$\beta_i = \beta - 90^\circ \tag{6}$$

$$m = \frac{\sqrt{3}\cdot m_0}{\cos\beta_i - \sqrt{3}\cdot\sin\beta_i} \tag{7}$$

$$n = \frac{2\cdot m_0}{1+\sqrt{3}\cdot tg\beta_i} \tag{8}$$

$$U_S = \sqrt{n^2 + (1-m_0)\cdot(1-m_0+n)}\cdot U_{S0} \tag{9}$$

$$\alpha = \arcsin\frac{\sqrt{3}}{2}\cdot\frac{n}{U_S} \tag{10}$$

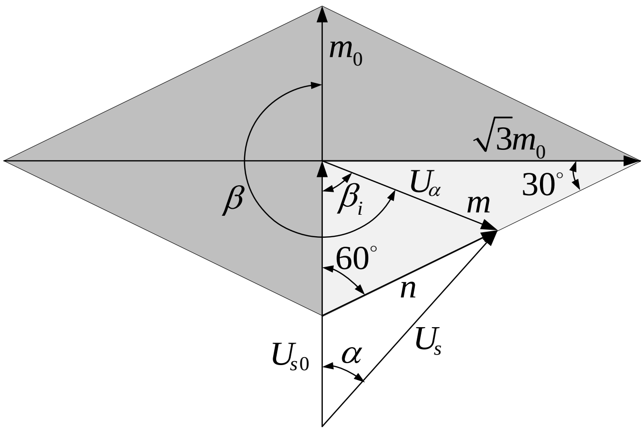


Figure 6. Vector diagram of voltages of the operating device in the third sector.

$$\beta_i = \beta - 180^\circ \tag{11}$$

$$m = \frac{\sqrt{3}\cdot m_0}{\sin\beta_i + \sqrt{3}\cos\beta_i} \tag{12}$$

$$n = \frac{2\cdot m_0}{1+\sqrt{3}\cdot ctg\beta_i} \tag{13}$$

$$U_S = \sqrt{1+m^2-2m\cdot\cos\beta_i}\cdot U_{S0} \tag{14}$$

$$\alpha = \arcsin\frac{\sqrt{3}}{2}\cdot\frac{n}{U_S} \tag{15}$$

$$\beta_i = \beta - 270^\circ \tag{16}$$

$$m = \frac{\sqrt{3}\cdot m_0}{\sqrt{3}\sin\beta_i + \cos\beta_i} \tag{17}$$

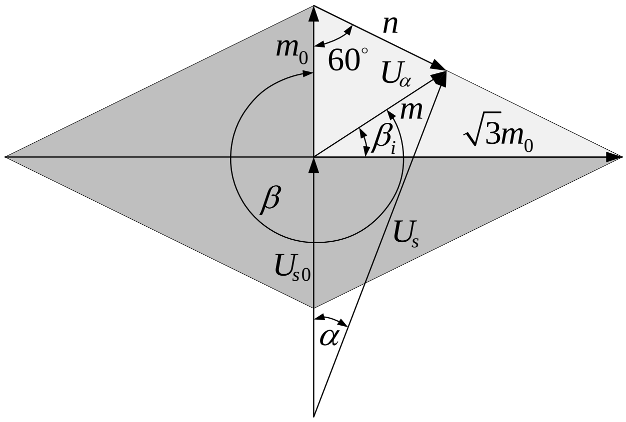


Figure 7. Vector diagram of voltages of the operating device in the fourth sector.

$$n = \frac{2 \cdot m_0}{1 + \sqrt{3} \cdot tg\beta_i} \tag{18}$$

$$U_S = \sqrt{n^2 + \left(1 + m_0\right) \cdot \left(1 + m - n\right)} \cdot U_{S0} \tag{19}$$

$$\alpha = \arcsin \frac{\sqrt{3}}{2} \cdot \frac{n}{U_S} \tag{20}$$

Values m_0 for various regulation loops according to the Figure 2 are shown in Table 1.

Table 1

The value of longitudinal component of the booster voltage

Loop	Value, m_0
1-15-29-43-1	0.2587
57-69-81-93-57	6/7·0.2587
105-115-125-135-105	5/7·0.2587
145-153-161-169-145	4/7·0.2587
177-183-189-195-177	3/7·0.2587
201-205-209-213-201	2/7·0.2587
217-219-221-223-217	1/7·0.2587

The resulting expressions make it possible to determine the control actions at all regulation points of the mode's parameters of the device.

Device modelling

On the base of Figure 1, a structural simulation model of the device which allowed carrying out research on the object for various operation modes was created in the Simulink/Matlab environment. The device has been modelled in the form of a group of single-phase transformers.

The parameters of the elements of which transformer were determined taking into account nominal voltage $U = 230V$ and the power of device $\approx 2kVA$. Rated currents and voltages of the transformer elements of the device (Figure 1), Table 1 contains accepted for simulation model.

Table 1

The currents and voltages of transformer elements

	Windings of the magnetizing transformer *p*					**Windings of the booster transformer *q***	
	W_{1p}	W_{2p}	W_{3p}	W_{4p}	W_{5p}	W_{1q}	W_{2q}
U(V)	3.2	3.2	3.2	10.5	6	9.5	10.5
I(A)	301.7	96.7	96.7	85.7	85.7	120	120

On the base of data contained in Table 1 parameters of SPS-models of the booster and magnetizing elements were calculated and are shown in Table 2.

Table 2

Parameters SPS of transformer's models

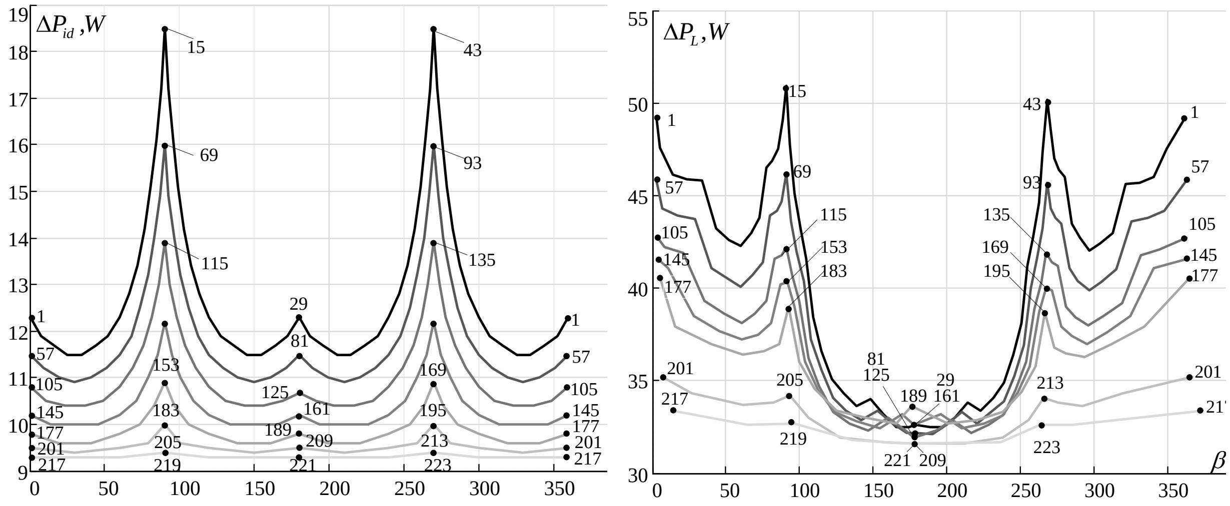
Magnetizing transformer	**Booster transformer**
Normal power and frequency[Pn(VA) fn(Hz)]: [929 50] Winding nominal voltages [U1 U2...Un] (Vrms): [103.18 51.59] Winding resistences [R1 R2...Rn] (Ohm): [0.09 0.0233] Winding leakage inductances [L1 L2...Ln] (H): [0.37e-3 0.009152e-3] Magnetization resistance Rm (Ohm) 1146 Magnetization inductance Lm (H) 1.83 Saturation characteristic [i1(A), phi1(Vs); i2(A), phi2;] [0 0;0.59 0.51;14.75 0.57;29.5 0.59;59.1 0.6; 177.03 0.62]	Normal power and frequency[Pn(VA) fn(Hz)]: [920 50] Winding nominal voltages [U1 U2...Un] (Vrms): [230 4.255 21.275 4.255 4.255 21.275] Winding resistences [R1 R2...Rn] (Ohm): [0.432 0.0019 0.0019 0.0096 0.0019 0.0019 0.0096] Winding leakage inductances [L1 L2...Ln] (H): [1.828e-3 0.00063e-3 0.00063e-3 0.0156e-3 0.00063e-3 0.00063e-3 0.0156e-3] Magnetization resistance Rm (Ohm) 5750 Magnetization inductance Lm (H) 9.16 Saturation characteristic [i1(A), phi1(Vs); i2(A), phi2;] [0 0;0.26 1.14;6.59 1.28;13.17 1.31;26.35 1.35;79.05 1.38]

The modeling's results

The models of the device were tested for both under idle and load modes. When constructing all graphs, the value of the angle of rotation of the booster voltage β as an argument was used. The curves on the graphs correspond to the contours (Figure 2) and are consistent with the numbers of positions of regulation. In Figure 8 dependencies of losses of active power under idling and loaded modes were shown respectively. In the frame of the research related to the above mentioned device the load was modelled as an active resistance $R_L = 19{,}2 Ohm$, which assures the nominal loading of the regulation transformer.

These dependences have a similar complex qualitative structure, differing only in quantitative characteristics.

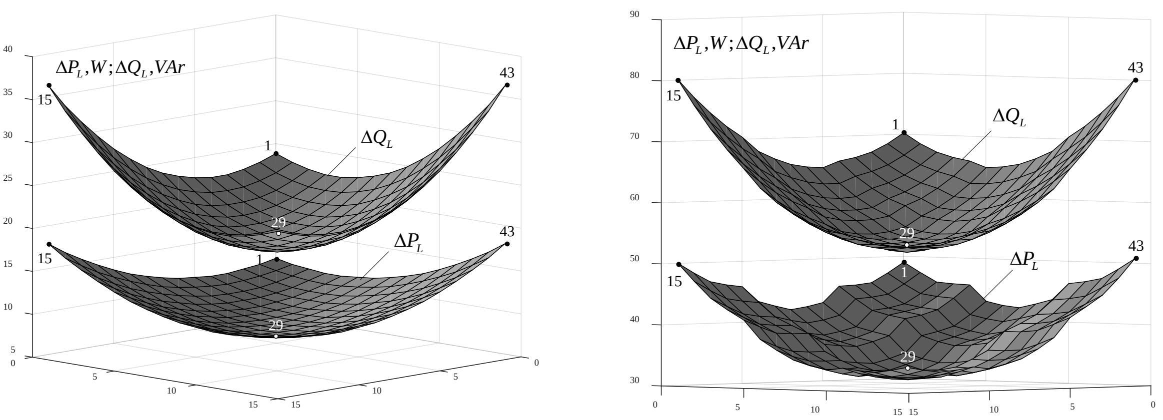
Thus, active power losses at the idle mode reach 1% during the process of regulation, while load mode losses reach 2,5%. The maximum values of the above listed operating parameters are taken at the angles of the boost voltage $\beta = 90^{\circ}$ and $\beta = 270^{\circ}$. The minimum values can be reached at $\beta = 30^{\circ}, 150^{\circ}, 210^{\circ}, 330^{\circ}$. It should be noted that the shapes of the curves in the load mode change slightly, correlating with characteristics built for the same parameters in the idle mode.



a – for idle mode b – for load mode

Figure 8. Active power losses.

For a more visual perception, the change in the values of active and reactive losses during regulation in the idle and load modes are shown as profiles in Figure 9 in a three-dimensional format. On the surfaces, for better orientation, the location of the characteristic points of the external control loop is applied.



a – for idle mode b – for load mode

Figure 9. Active and reactive power losses in a three-dimensional format.

Figure 10 shows the characteristics of the change in the impedance of the device during regulation in the form of graphs and a surface. The resistance takes on minimum values at the boost voltage angles, respectively $\beta = 90^{\circ}$ и $\beta = 270^{\circ}$. The maximum values can be reached at $\beta = 30^{\circ}, 150^{\circ}, 210^{\circ}, 330^{\circ}$. The range of impedance change during regulation is $\approx 46\%$.

The characteristics of the change in voltage at the output of the device are shown in Figure 11 as an example for three typical loops of regulation.

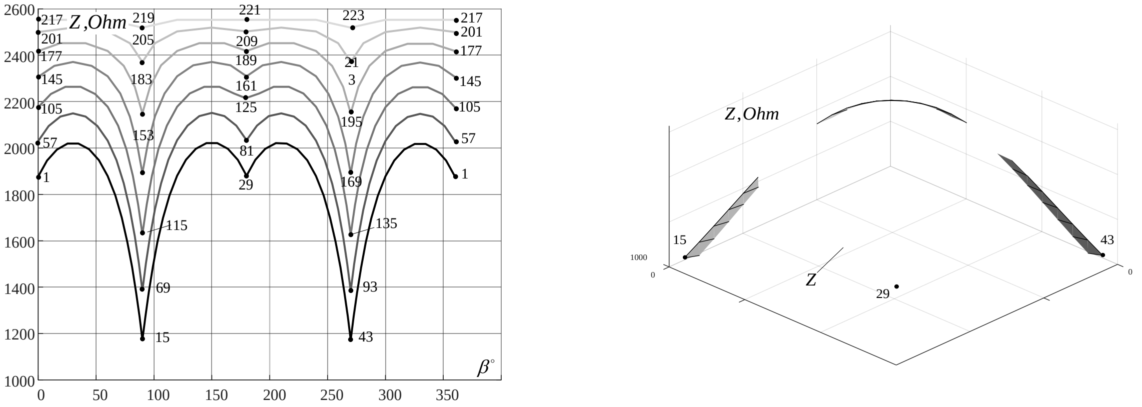


Figure 10. Change of impedance of the device.

The solid lines refer to the idle mode, and the dotted lines refer to the load mode. Analysing the given graphs and the surfaces corresponding to them it can be concluded that the characteristics are close in the considered modes. This confirms the fact that the device holds the mode perfectly. In the course of work, the values of the output voltage were calculated based on mathematical formulas (Figures 4-7), which fully correspond to those obtained in the SPS simulation in the idle mode.

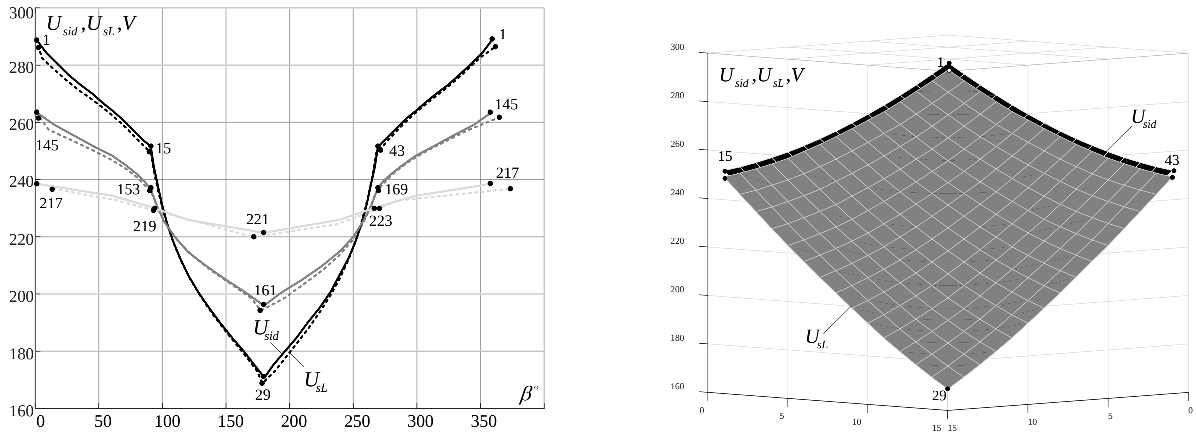


Figure 11. Voltage on the device output.

Based on the results of the experiments, the typical powers of the circuit's elements version of the regulating transformer in zigzag were calculated and are shown in Table 3.

Table 3

The power of the device elements

Winding designation	Power, W/(p.u)
W1q	939.8
W2q	935.4
W1p	874.9
W2p	540.2
W3p	542.4
In all:	**1916.4/0.581**
Power of regulation:	**541.3/1.16**

The data in Table 1 can be used further for the comparative analysis of power characteristics of booster transformers, developed in the prospective future.

Conclusion

Based on the results of the research, the following conclusions can be drawn:

1. The principle diagram of the device, in force to provide the same control actions in the form of booster regulation voltage like FACTS controllers of UPFC and ST types, but on the basis of a simpler and more affordable base of practical accomplishment has been proposed.
2. The techniques of sectioning the regulation windings, as well as laws for its controlling were developed. Control strategy has been formulated and formalized.
3. It is shown that the proposed technical solution provides more opportunities for voltage regulation by phase (relative to UPFC and ST) with the same standards for the allowable limits of its change in module.
4. Vector diagrams are constructed and expressions are obtained that characterize the operating parameters of the device under study.
5. Compliance of the steps with the given positions of the switches during the regulation process was checked.

7. The typical power of the booster transformed with regulation in the zigzag has been calculated.

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