Regulation Transformer with Extended Control Range

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Abstract. The paper deals with research of the booster transformer (regulation transformer), which can be attributed to “Sen” family, which has an extended range and higher control accuracy. The main aim of the paper is to study both operational and energy characteristics of the transformer device that implements output voltage longitudinal-transverse regulation principle relative to the input based on power electronics. The most significant research results can be considered new developed circuit design and method for windings sectioning, including their regulating control strategy. The obtained computational experiments results based on developed structural simulation models of the booster transformer demonstrated effectiveness of the proposed device technical solution and its control strategy in terms of significant expansion of the output voltage range both in magnitude and in phase. It is shown that the proposed technical solution provides greater possibilities for phase voltage regulation (relative to the UPFC and “Sen” transformer) with the same restrictions on the longitudinal and transverse components of the boost voltage. Vector diagrams of the studded device were constructed and expressions characterizing its operating parameters were obtained. The characteristics of the device parameters variation in both idle and load mode were obtained and analyzed. The significance of the obtained results consisting in fact, that the proposed technical solution is capable to provide the same control actions in the form of an adjustable additional voltage as FACTS controllers such as UPFC and “Sen” - transformer, but on a simpler basis that is more accessible to practical implementation.

Keywords: booster transformer, active and reactive power, rate power, voltage regulation.

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Transformator de reglare cu capacități extinse de comandă

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Rezumat. În articol se studiază transformatorul de rapel, care poate fi atribuit familiei „Sen”, ce posedă un diapazon larg de reglare şi un nivel mai înalt de precizie. Lucrarea a avut ca scop cercetarea caracteristicilor de regim şi energetice ale instalaţiei de tip transformator, care implementează principiul de reglare longitudinal-transversal al tensiunii de ieşire faţă de tensiunea de intrare şi se comandă cu ajutorul electronicii de putere. Cele mai esențiale rezultate le constituie soluţia tehnică dezvoltată şi modul de secţionare al înfăşurărilor de comandă, inclusiv strategia de comandă cu acestea. Rezultatele obţinute în urma calculelor experimentale realizate pe modelul Simulink dezvoltat au demonstrat eficienţa atât a soluţiei tehnice dezvoltate pentru transformatorul de rapel, cât şi a strategiei de comandă din punct de vedere a extinderii esenţiale a zonei de reglare a tensiunii de ieşire după modul şi fază. S-a demonstrat, că soluţia tehnică propusă asigură o gamă mai extinsă de posibilităţi de reglare a tensiunii după fază (comparativ cu transformatorul UPFC şi „Sen”) pentru aceleaşi limitări a componentelor longitudinale şi transversale ale transformatorului de rapel. Au fost construite diagramele vectoriale şi obţinute expresiile ce caracterizează parametrii de regim ai instalaţiei. Au fost obţinute şi analizate caracteristicile variației parametrilor instalației în regimuri de mers în gol şi sarcină. Importanţa rezultatelor obţinute constă în faptul, că soluţia tehnică propusă este capabilă să asigure aceleaşi acţiuni de reglare, precum controlerele FACTS de tipul UPFC şi „Sen”, dar la un nivel mai simplu şi mai uşor de implementat din aspect practic.

Cuvinte-cheie: transformator cu rapel, putere activă și reactivă, reglare a tensiunii, putere nominală.

Регулировочный трансформатор с расширенным диапазоном управления

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Аннотация. Объектом исследования является вольтодобавочный трансформатор, который можно отнести к семейству “Sen”, обладающий расширенным диапазоном и более высокой точностью регулирования. Целью работы является исследование режимных и энергетических характеристик трансформаторного устройства, реализующего принцип продольно–поперечного регулирования выходного напряжения относительно входного и управляемого средствами силовой электроники. Поставленная цель достигается посредством создания в среде Simulink/Matlab структурно–имитационной модели объекта исследования и проведении на основе SPS- моделей расчетных экспериментов, имитирующих работу вольтодобавочного трансформатора при различных стратегиях управления. Наиболее существенными результатами являются новое схемное решение, вариант секционирования обмоток управления и закон регулирования ими. Результаты расчётных экспериментов, полученные на основе построенных структурно-имитационных моделей объекта исследования, показали эффективность предложенного схемного варианта устройства и стратегии его управления. с точки зрения существенного расширения диапазона выходного напряжения как по модулю, так и по фазе. Показано, что предложенное техническое решение обеспечивает более широкие возможности регулирования напряжения по фазе (относительно UPFC и “Sen” – трансформатора) при тех же ограничениях продольной и поперечной составляющих вольтодобавочного напряжения. Построены векторные диаграммы и получены выражения, характеризующие режимные параметры исследуемого устройства. Получены и проанализированы характеристики изменения параметров устройства на холостом ходу и в режиме нагрузки. Рассчитана типовая мощность элементов вольтодобавочного трансформатора с прямоугольной зоной регулирования. Значимость полученных результатов состоит в том, что предложенное техническое решение способно обеспечить те же управляющие воздействия в виде регулируемого добавочного напряжения, что и FACTS контроллеры типа UPFC и “Sen” – трансформатор, но на более простой и доступной к практической реализации основе.

Ключевые слова: вольтодобавочный трансформатор, активная и реактивная мощность, регулирование напряжения, типовая мощность.

INTRODUCTION

The current development stage of the electric power industry is characterized by a significant increase in energy production through the use of renewable sources, the production of which is significantly subject to daily and seasonal fluctuations. This circumstance is also reflected in the power quality parameters. In these conditions, the problem of controllability of transport and distribution networks is becoming increasingly urgent. Technical devices designed to solve this kind of problems are built on the basis of FACTS technologies. They must guarantee an optimal load factor, i.e. above all, the absence of voltage fluctuations in the network, as well as a high-power factor (reactive power compensation). Modern devices of this kind are largely associated with the use of two-stage energy conversion - rectification and inversion. One of such devices that provides voltage and power regulation in networks is the Unified Power Flow Controller (UPFC) [1]. Much attention is paid both to the issues of modeling such devices [2-5], and to the study of the modes of their use in power systems [6,7] and optimization of their parameters [8]. Similar control effects can also be achieved based on direct (single-stage energy conversion), which allows the use of simpler, more reliable and less expensive technical devices. Devices of this kind include booster transformers of various configurations and purposes, such as the “Sen” transformer [9–11]. “Sen” - transformer, is a combination of a transformer and a tap changer, which are traditionally used to build a control transformer that allows you to control both the voltage module and the phase angle [12–14]. Вопросы моделирования и оптимизации характеристик “Sen” - трансформаторов рассмотрены в [15,16]. A comparative analysis of the use of UPFC and “Sen” transformer when solving similar operating problems shows that, in a number of cases, the advantage is on the side of the latter [17–20]. The relevance of this topic is obvious, which leads to active research in this direction. The scientific novelty of the research performed lies in the new circuit design of the boost transformer with an expanded control range and improved characteristics.The main aim of the paper is to study both operational and energy characteristics of the transformer device that implements output voltage longitudinal-transverse regulation principle relative to the input based on power electronics. The proposed technical solution provides high accuracy and quality of output voltage regulation significantly compared to the classical circuit (Sen) by increasing the number of possible operating states of the device and reducing the regulation step.

MAIN DIAGRAM AND OPERATING PRINCIPLE OF THE DEVICE

This work is devoted to the development and research of a booster transformer device with a rectangular output voltage regulation zone. In the process of research, methods of mathematical and structural simulation modeling were used. The computational experiments were carried out on the basis of the SPS models built in the Simulink/Matlab environment.

The circuit diagram of the study object is shown in Fig.1. The main elements of the device are two power three-winding transformers, one of which performs the functions of parallel (magnetizing), the other functions of series element (voltage booster). The “p” index marks the windings and the corresponding electrical parameters, characterizing the mode of the magnetizing transformer, the index "q" - windings and electrical values of the booster transformer.

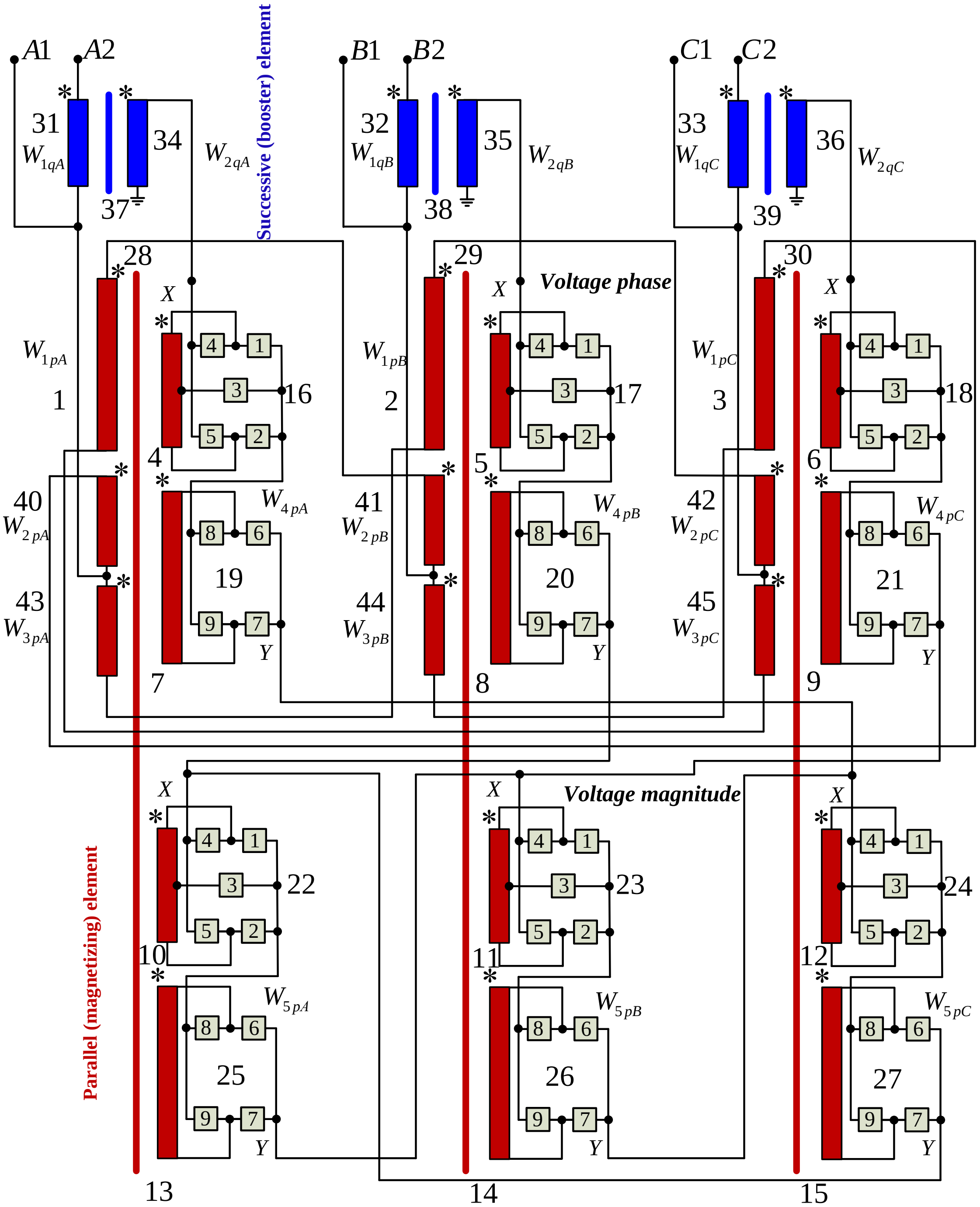
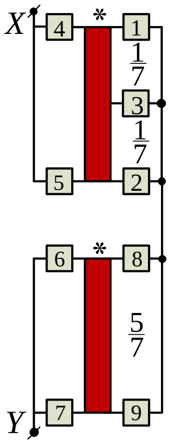


Fig.1. The device schematic diagram with a rectangular control area.

The elements related to the base transformer are numbered 1-30 and from 40 to 45, and the elements related to the additional transformer are numbered 31-39.

The list of designations of the elements presented in Fig.1:

- A, B and C – name of the phases of the three-phase voltage system.
- A1, B1 and C1 – electrical inputs (input terminals) of the device.
- A2, B2 and C2 – electrical outputs (output terminals) of the device.
- 1,2,3 - primary high voltage windings of phases A, B, C of the base transformer (W_{1pA}, W_{1pB}, W_{1pC}), 4,5,6 and 7,8,9 – respectively, the fourth adjusting windings of fine and coarse regulation of the phases A, B, C of the base transformer (W_{4pA}, W_{4pB}, W_{4pC}), which are responsible for regulating the output voltage module. 10,11,12 and 13,14,15 – respectively, the fifth adjusting windings of fine and coarse regulation of phases A, B, C of the base transformer (W_{5pA}, W_{5pB}, W_{5pC}), responsible for regulating the of the output voltage phase, 16,17,18 and 19,20,21 – blocks of power electronic switches of the fourth adjusting windings of phases A, B, C of the base transformer, 22,23,24 and 25,26,27 – blocks of power electronic switches of the fifth adjusting windings of phases A, B, C of the base transformer, 28,29,30 – cores of magnetic circuits of phases A, B, C of the base transformer, 31,32,33 – high voltage windings of phases A, B, C of additional transformer (W_{1qA}, W_{1qB}, W_{1qC}), 34,35,36 – low voltage windings of phases A, B, C of additional transformer (W_{2qA}, W_{2qB} W_{2qC}).
- 37,38,39 – cores of magnetic circuits of phases A, B. C of additional transformer.
- 40,41,42 – second high voltage windings of phases A, B, C of the base transformer (W_{2pA}, W_{2pB}, W_{2pC}).
- 43,44,45 – third high voltage windings of phases A, B, C of the base transformer (W_{3pA}, W_{3pB}, W_{3pC}).
- K1 ÷ K15 – electronic switches. The windings W_{4p},W_{5p} are regulating module, are sectioned and work in accordance with the strategy presented in Fig.2.



a – scheme

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

b – law

Fig.2. The management scheme and law of the control module.

Due to the use of the control windings sectioning, the zone of possible values of the output voltage consists of 225 points and is presented in the form of rectangle (Fig.3).

The control zones of the UPFC and “Sen” transformer are shown for comparison as a circle and a diamond, respectively. It can be seen that the control area provided by the proposed device is much larger.

The accuracy and quality of output voltage regulation are significantly increased compared to the classical circuit (Sen) by increasing the number of possible operating states of the device and reducing the regulation step.

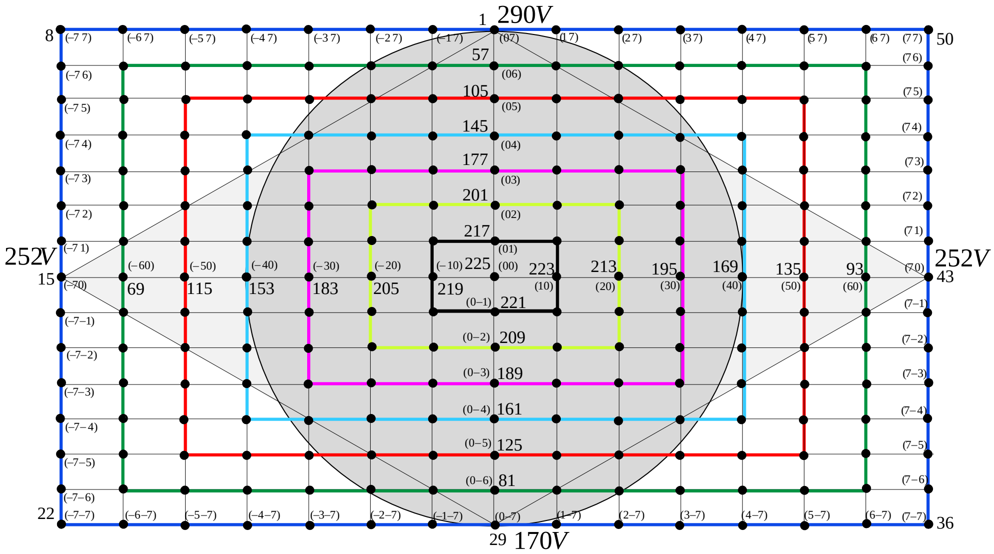


Fig. 3. Location of calculated points of regulated voltage.

The output voltage regulation area of the device can be conditionally divided into eight sectors. In Fig.4, for example, a vector diagram of voltages in the first sector is shown.

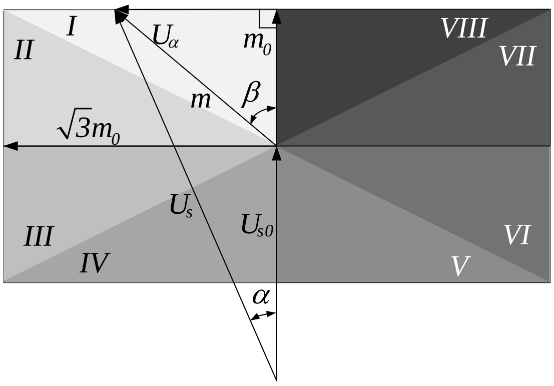


Fig.4. Voltage vector diagram.

Calculation expressions for regime parameters in all sectors of regulation are given in Table 1.

The following designations are accepted on the vector diagram:

U_{s0} – device input voltage;

β – booster voltage vector angle;

$m = U_\alpha$ – boost voltage value;

m_0 – value of the longitudinal component of the boost voltage;

U_s – devise output voltage;

α – the angle of the device output voltage.

Table 1

Formula for regime parameters calculation

Sector	$m = U_\alpha$	α	U_s
I	$m = \dfrac{m_0}{\cos\beta}$	$\alpha = \arcsin\left(\dfrac{m\cdot\sin\beta}{U_S}\right)$	$U_S = \sqrt{m^2 + U_{S0}^2 + 2U_{S0}\cdot m\cdot\cos\beta}$
II	$m = \dfrac{\sqrt{3}\cdot m_0}{\sin\beta}$		
III			
IV	$m = -\dfrac{m_0}{\cos\beta}$		
V		$\alpha = \arcsin\left(-\dfrac{m\cdot\sin\beta}{U_S}\right)$	
VI	$m = -\dfrac{\sqrt{3}\cdot m_0}{\sin\beta}$		
VII			
VIII	$m = \dfrac{m_0}{\cos\beta}$		

The obtained expressions allow to determine the control actions at all control points of the operating parameters of the device.

SIMULATION AND MODE CHARACTERISTICS OF THE DEVICE

Based on the Fig 1 scheme in the Simulink (Matlab) environment, a structural simulation model of the device was created, on the basis of which the object was studied in various operating modes.

Each of the transformers was modeled as a three-phase group of single-phase elements. The parameters of the elements of each transformer were determined taking into account the supply voltage $U = 230V$ and power of the device - $\approx 2kVA$. The parameters of the elements were chosen taking into account the possibility of creating a laboratory sample in perspective. Estimated currents and voltages of the transformer elements of the device (Fig 1) adopted for the simulation model are shown in Table 2.

Table 2

Currents and voltages of the transformer elements windings

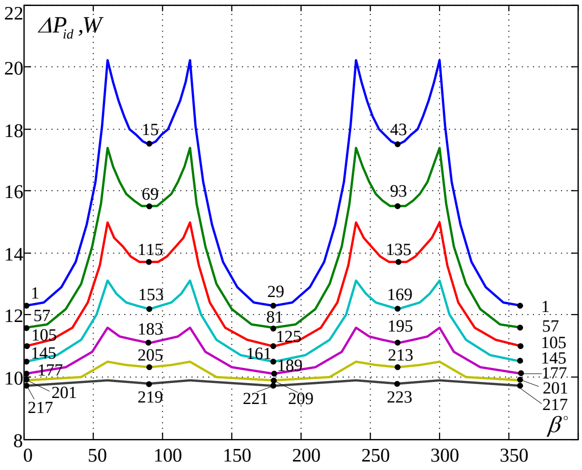
	Q – trans.		P – trans.				
	W_{1q}	W_{2q}	W_{1p}	W_{2p}	W_{3p}	W_{4p}	W_{5p}
U,V	120	120	301,7	96,7	96,7	85,7	86,7
I,A	9,5	10,5	3,2	3,2	3,2	10,5	6

The device model was tested in idle and load modes. When constructing all graphs, the value of the angle of rotation of the booster voltage β was used as an argument. The curves on the graphs correspond to the contours (Fig.3) and are consistent with the numbers of the regulation positions.

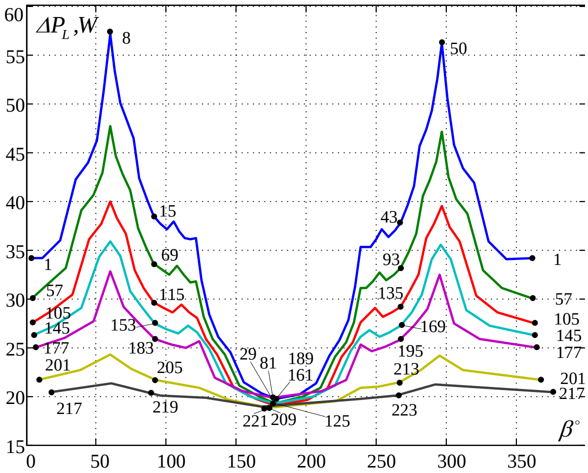
On Fig.5.a,b, respectively, the dependences of active power losses in the idle mode and in the load mode are presented. When conducting a study of the device, the load was modeled in the form of active resistance $R_L = 31,7Ohm$, which provides the nominal load of the regulating transformer.

Losses of active power at idle mode take on maximum values at the angles of booster voltage $\beta = 60^\circ, 120^\circ, 240^\circ, 300^\circ$ and can reach in the process of regulation the value $\approx 1\%$ of the installed power of the device. The minimum values are reached at $\beta = 0^\circ, 180^\circ, 360^\circ$.

It should be noted that the shapes of active loss curves in the load mode differ significantly. At the same time, the maximum values of the parameters are observed at the angles of the boost voltage $\beta = 60^\circ, 300^\circ$ and can reach the value $\approx 2,85\%$ of the installed power of the device, and the minimum values - at $\beta = 0^\circ, 180^\circ, 360^\circ$.



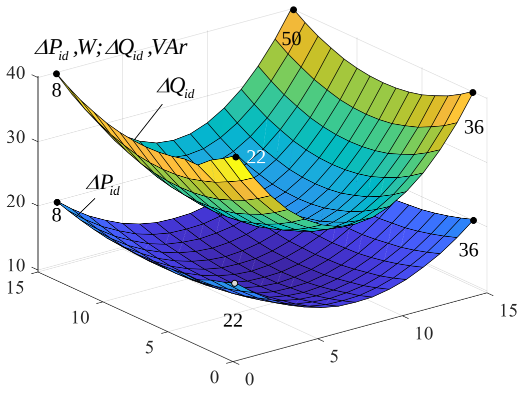
a – in the idle mode



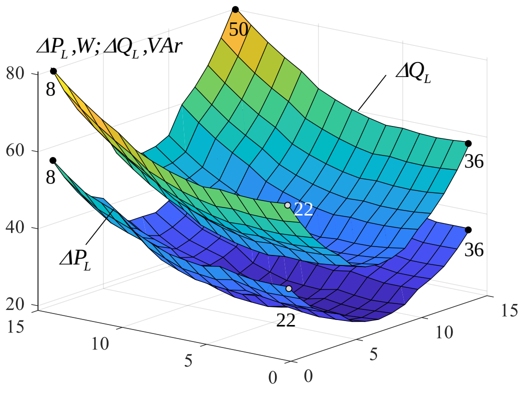
b – in the load mode

Fig. 5. Active power losses.

For better visual perception, the change in active and reactive losses during regulation in idle and load modes are shown as profiles in Fig.6 in a three-dimensional format. On the surfaces, for better orientation, the location of the characteristic points of the external control loop is marked.



a – in the idle mode

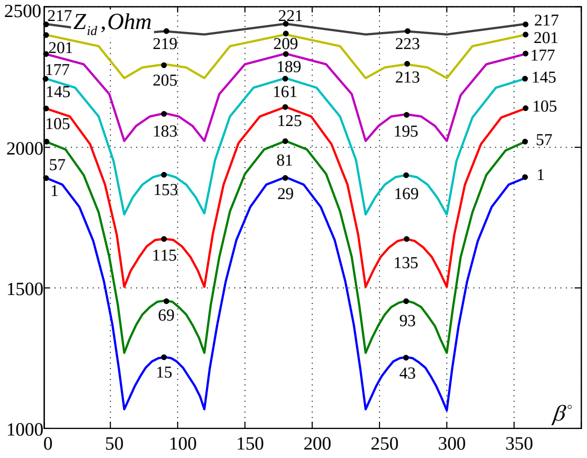


b – in the load mode

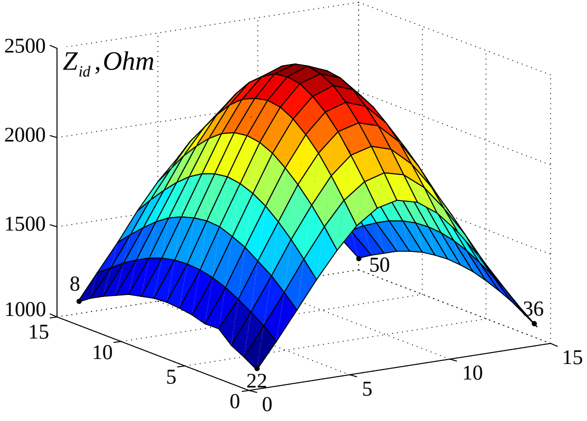
Fig. 6. Active and reactive power losses in three-dimensional format.

Fig.7 shows the characteristics of the change in the impedance of the device during process of regulation in the form of graphs and surface. The resistance takes the minimum values at the boost voltage angles, $\beta = 60^\circ, 120^\circ, 240^\circ, 300^\circ$ respectively. The maximum values are reached at $\beta = 0^\circ, 180^\circ, 360^\circ$. The range of impedance change in the process of regulation is equal to $\approx 130\%$ from the value at point 225 (in the absence of regulation actions).

The characteristics of voltage change at the device output are shown in Fig.8 as an example for three characteristic control loops (see Fig.3). The solid lines refer to the idle mode, and the dotted lines refer to the load mode. Analyzing the above graphs and the surfaces corresponding to them, we can conclude that the characteristics are close in the modes under consideration. This confirms that the device keeps the mode perfectly (the deviation of the voltage from the set values does not exceed 1%).



a – in the form of graphs



b – as a surface

Fig. 7. Changing of device full impedance.

For comparison, during operation, the values of the output voltage were calculated based on mathematical formulas (see Table 1), which fully correspond to those obtained in the SPS simulation in idle mode.

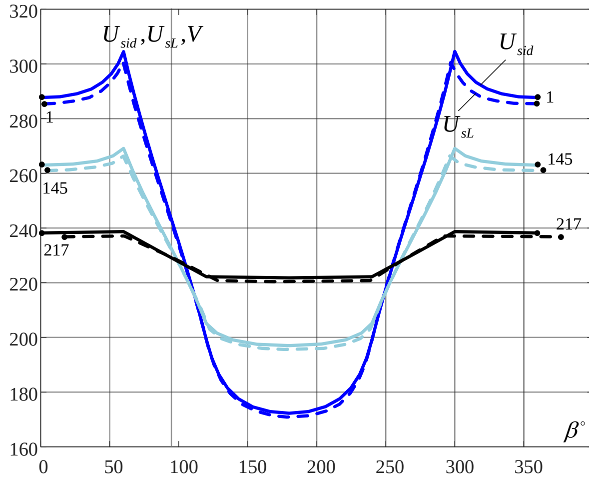
Based on the results of the computational experiments, the elements energy characteristics (typical powers) of the device circuit version with rectangular control region were calculated and shown in Table 3.

Table 3

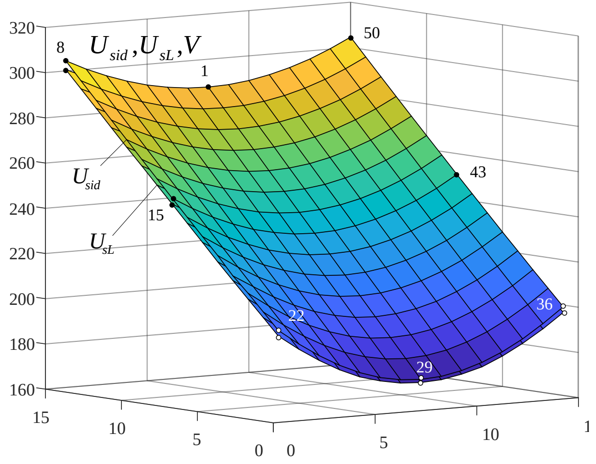
Device energy characteristics

Name of windings	Power, *W/(p.u.)*
W_{1q}	1120.7
W_{2q}	1126.9
W_{1p}	861.6
W_{2p}	278.1
W_{3p}	276.5
W_{4p}	972.9
W_{5p}	563.9
Всего:	2600.3/0.675
Control power	768.4/0.2

The data of Table 3 can be further used for comparative analysis of the energy characteristics of boost devices developed in the future.



a – in the form of graphs



b – as a surface

Fig. 8. The device output voltage.

CONCLUSIONS

Based on the study results, the following conclusions can be drawn:

1. A schematic diagram of device capable to provide the same control actions in the form of an adjustable additional voltage as FACTS controllers such as UPFC and Sen - transformer, but on a simpler and more accessible basis for practical implementation is proposed.

2. A method for sectioning the control windings, as well as the laws for controlling them has been developed. The management strategy has been formulated and formalized.

3. It is shown that the proposed technical solution provides more opportunities for voltage regulation (relative to UPFC and “Sen” - transformer) with the same restrictions on the modulus and phase of the output voltage.

4. Vector diagrams are constructed and expressions are obtained that characterize the operating parameters of the device under study.

5. Verification of the compliance of the steps with the given positions of the switches during the regulation process was carried out.

6. The parameters of the equivalent circuit of the device in idle mode are determined. Studies on proposed device have been provided and the characteristics concerning change in regime parameters in the load regime have been obtained and analyzed. The typical power of the booster transformer elements with rectangular control zone is calculated.

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