Research Article

Thyristor Voltage Regulators of the Transformer for Distribution Networks

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Abstract—Features of output voltage regulation of power transformers for distribution networks are presented. The approach to implementation of thyristor voltage regulators for on-load mass-produced power transformers is presented. Examples of circuit solutions for creating thyristor voltage regulators are given. Adaptive control algorithms of thyristor voltage regulators are described. Basic requirements for the control system are submitted. MATLAB simulation results are presented. Physical models are developed and experimental results are described.

Keywords—Power transformer; thyristor voltage regulator; on-load tap changing; thyristor switch; voltage regulating, distribution network.

1. Introduction

Nowadays an output voltage regulation of on-load power transformers [1], which are a part of transformer substations, is an urgent task all over the world. The requirement for voltage regulation [2] at the output side of transformer substations is due to the heterogeneity of loads in electrical distribution networks [3, 4] caused by daily voltage fluctuations and capable of changing their nature over time. Such changes entail voltage deviations in electrical networks from the normalized values, which in turn reduces the quality of electric energy supplied to the consumer [5]. One of the factors reducing the quality of electrical energy is the lack of measures for timely modernization of electrical distribution networks [6]. In particular, the solutions lack for regulating the output voltage of on-load power transformers, providing high performance.

The traditional approach to voltage regulation of on-load power transformers, which are the part of transformer substations, involves the implementation of voltage regulation using mechanical on-load tap changers (OLTC) [7, 8], which have low speed performance, large weight and size indicators and arc-extinguishing devices in the form of additional reactors or resistors [9]

The results obtained in the paper were achieved during the implementation of the project using measures of state support for the development of cooperation between Russian higher education institutions, state research institutions and organizations implementing complex projects to create high-tech production, provided by the decree of the Government of the Russian Federation No. 218 of April 9, 2010. The study was carried out by a team consisting of JSC HVE "Electroapparat", NRU "MPEI", JSC "G. M. Khrzhizhanovsky PEI" and JSC "NRDIHVE" as part of the application project "Development and creation of high-tech production of high-speed semiconductor devices for regulating the output voltage of on-load transformers as part of transformer substations of 6-10/0.4kV class of digital distribution networks" (Agreement No. 075-11-2019-060 of December 6, 2019) with financial support from the Ministry of Education and Science of the Russian Federation.

In addition, another classic version of voltage regulation is the use of de-energized tap changers (DETC) [7], which provide adjustment taps switching of the power transformer by mechanical means. In contrast to OLTC devices, implementation of DETC technology provides for disconnecting the power transformer from the supply and the load for the time during which the adjustment taps are switched. This leads to the requirements to switch the entire distribution network to a backup power transformer, or disconnect it from the consumer at all for the time of mechanical switching of the taps and installation works.

The paper is devoted to the development of semiconductor voltage regulators that allows for high-speed switching (about 10ms) of the taps of power transformers [10, 11, 12] without disconnecting the power transformer from the network and load. The analysis of circuit solutions for thyristor voltage regulators is presented, their advantages and disadvantages are indicated. The basic requirements for the control system of thyristor voltage regulators of on-load distribution transformers [13] are formulated. The results of simulation and experimental studies of the physical model of the thyristor voltage regulators are presented.

2. Problem Definition

One of the simplest thyristor voltage regulator for on-load transformers is shown in fig. 1[14, 15].

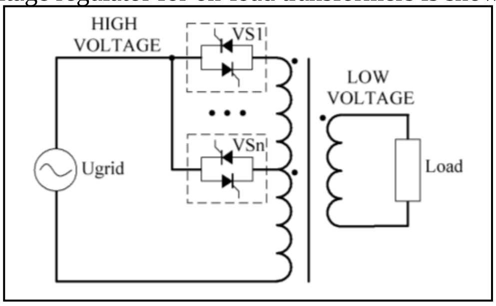

Fig.1. The thyristor voltage regulator for on-load transformer using a single-piece sectioned winding.

The bidirectional switches (VS1–VSn) in circuit fig.1 are realized on counter-parallel connections of two thyristors. Bidirectional switches [16] are connected in series with the power transformer adjustment taps located on the high voltage side (HV). Voltage regulation on the HV side [17] provides switching of lower current values, as well as lower thermal power losses on bidirectional switches. In this case, n - the number of bidirectional switches depends on the number of the power transformer adjustment taps k:

$$m = k + 1 \qquad (1)$$

The number of voltage regulation levels of the circuit$m$ corresponds to the number of bidirectional switches n:

$$n = m \qquad (2)$$

Analysis of the power transformer market shows that the most common mass-produced dry power transformers [18] have a split primary sectioned winding on the HV side. As a rule, each of primary HV windings of such transformers consists of two sectioned half-windings with adjustment taps. The single-phase HV winding of such power transformer is shown in fig. 2.

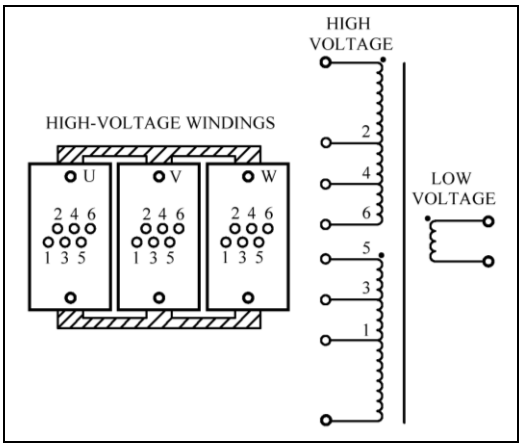

Fig.2. The single phase HV winding with the adjustment taps of mass-produced dry power transformers.

The adjustment taps are numbered 1-6 for each phase of the power transformer. Traditionally, for switching the adjustment taps, DETC devices are used, which provide a connection between one of the adjustment taps of one sectioned half-winding 2, 4 or 6 and one of the adjustment taps of another sectioned half-winding 5, 3 or 1 (fig.2). Very often each adjustment section (is located between the nearest adjustment taps) has an equal number of turns. The technique of voltage regulation is based on changing number of turns of the primary HV winding of power transformer. It allows to form regulating stages at certain voltage levels of the seconday LV windings of the power transformer. As example, the dependence of the LV winding voltage on the regulation stage numbers for power transformer 10/0,4 kV shown in fig. 3. In this case the 10 kV voltage is applied to the HV winding of the power transformer.

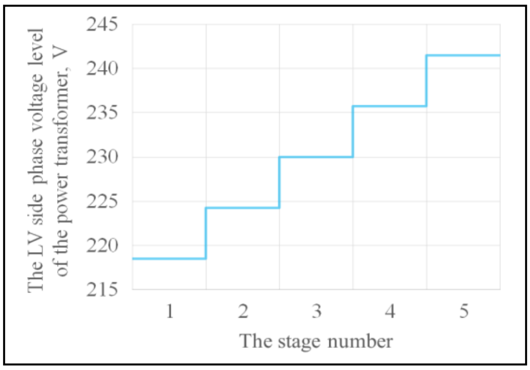

Fig.3. The dependence of LV winding voltage on regulation stage number of power transformer.

The average value from the regulation range in fig 3 is 230 V. It determines the nominal output voltage of LV winding with 10 kV voltage on HV winding of the power transformer. If the maximum regulation range of the output voltage is ±5% of the nominal value, the regulation step will be 2.5%. In this case, the voltage regulation levels of a power transformer with DETC devices in accordance with the connection combinations of various adjustment taps are shown in Table 1.

TABLE I. VOLTAGE REGULATION LEVELS OF A POWER TRANSFORMER WITH A DECT DEVICE, INCLUDING TWO PRIMARY SECTIONED HV HALF-WINDINGS

Voltage regulation stage number	**Voltage level change on the LV winding in relation to the nominal value**	**Connection of the adjustment taps**
1	-5%	5-6
2	-2,5%	5-4
3	0%	3-4
4	+2,5%	3-2
5	+5%	2-1

The maximum number of output voltage regulating levels m for the specified case is defined as:

$$m = k_1 + k_2 - 1 \qquad (3)$$

where k_1 – the number of adjustment taps of one sectioned half-winding, k_2– the number of adjustment taps of another sectioned half-winding. In general, each section can also have an arbitrary number of turns. In this case, the number of voltage regulation levels of the power transformer can be increased. Thus, the following number of voltage regulation levels can be provided by the DETC voltage regulation device:

$$m = k_1 \cdot k_2, \qquad (4)$$

In accordance with the circuit in fig. 2 and expression (4), the number of voltage regulation levels can be up to 9 pcs, since $k_1 = k_2 = 3$.

It should be noted that for the power transformer (fig. 2), can be used the semiconductor regulator, shown in fig. 1. However, it's necessary to connect adjustment taps 5 and 6. Schematically, this can be implemented as shown in fig.4.

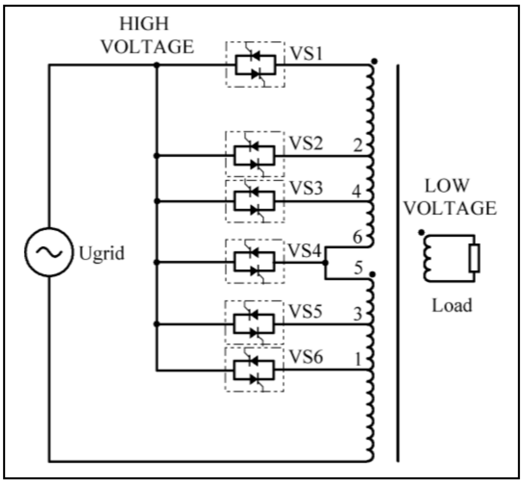

Fig.4. The thyristor voltage regulator of the output voltage of an on-load transformer with the connection of split windings into a whole HV winding.

The maximum number of levels of voltage regulation in this case is:

$$m = k_1 + k_2 \tag{5}$$

In the case of a 0.4 kV class distribution network the semiconductor regulator (fig.4) have the regulating characteristic shown in fig.5.

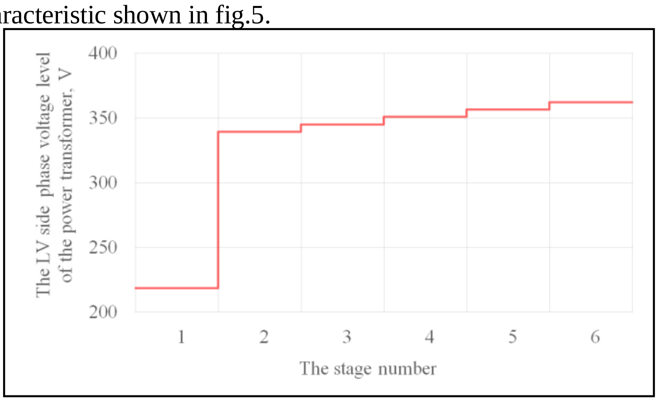

Fig.5. The dependence of LV winding voltage on regulation stage number of power transformer for thyristor voltage regulator fig.4.

If each adjustment section has the same number of turns (2.5% of the total number of turns of the HV winding), the levels of the secondary voltage are significantly biased from the nominal value. The nonuniformity of voltage levels leads to reducing of regulation stage numbers at the regulation range from -5% to +5%. This is presented in table 2.

TABLE II. VOLTAGE REGULATION LEVELS OF THE POWER TRANSFORMER WITH THE TRYRISTOR VOLTAGE REGULATOR FIG.4

Voltage regulation stage number	**Voltage level change on the LV winding in relation to the nominal value**	**Conductive bidirectional thyristor switches**
1	-5%	VS1
2	+47,5%	VS2
3	+50%	VS3
4	+52,5%	VS4
5	+55%	VS5

Voltage regulation stage number	Voltage level change on the LV winding in relation to the nominal value	Conductive bidirectional thyristor switches
6	+57,5%	VS6

At the same time thyristor voltage regulators should have the uniform regulating characteristic in the full range of voltage regulation for the power transformers. So, the task of developing the new thyristor voltage regulators for the power transformers with a split primary HV winding, providing uniform regulating characteristic and maximum numbers of output voltage regulating levels becomes acute.

3. Proposed Solutions

A. Thyristor voltage regulators

One of the voltage regulators for power transformer with a split primary partitioned HV winding is shown in fig. 6 [19]. The scheme (fig.6) provides the uniform regulating characteristic as presented in fig.3. If each adjustment section has the same number of turns (2.5% of the total number of turns of the HV winding). The expression (2) for this case is remain valid and the number of bidirectional thyristor switches can also be reduced to 5 pcs.

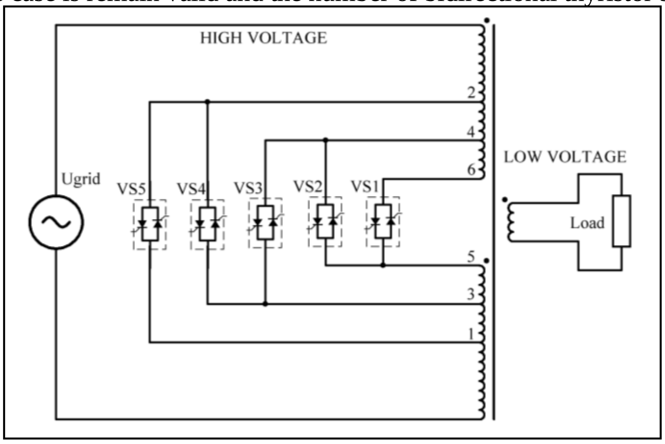

Fig.6. The thyristor voltage regulator the output voltage of an on-load transformer based on 5 bidirectional thyristor switches.

Thyristor voltage regulator (fig.6) has an advantage over the thyristor voltage regulator shown in fig. 4. The number of bidirectional thyristor switches of thyristor voltage regulator fig. 6 is one less, and the voltage regulation levels are consistent with table 1, does not have an offset, as shown in fig 5. The relationship between regulation levels and conducting bidirectional thyristor switches of thyristor volage regulator (fig.6) is presented in table 3.

TABLE III. VOLTAGE REGULATION LEVELS OF THE POWER TRANSFORMER WITH THE THYRISTOR VOLTAGE REGULATOR FIG.6

Voltage regulation stage number	Voltage level change on the LV winding in relation to the nominal value	Conductive bidirectional thyristor switches
1	-5%	VS1
2	-2,5%	VS2
3	0%	VS3
4	+2,5%	VS4
5	+5%	VS5

The thyristor voltage regulator presented in fig.7 provides the maximum number of voltage regulation levels m in the case of each adjustment section of primary HV sectioned winding [20]. The thyristor voltage regulator (fig.7) could be realized any connection combination of each adjustment tap of one sectioned primary HV half-winding of power transformer with each adjustment tap of another sectioned primary HV half-winding of the transformer. For this case, the expression (2) remains valid.

If each control section of the primary HV winding of a power transformer consists of the same number of turns (2.5% of the total number of turns of the HV winding), the maximum number of control levels m will decrease to 5 pcs. The thyristor voltage regulator (fig.7) provides the uniform regulating characteristic as in fig.3. The relationship between regulation levels and conducting bidirectional thyristor switches is presented in table 4.

The thyristor voltage regulator presented in fig.8 has 6 bidirectional thyristor switches [21]. The voltage class of the used bidirectional thyristor switches of voltage regulator fig. 8 is less in comparison with voltage regulator fig. 6. However, power losses in bidirectional thyristor switches are higher in comparison with its previous thyristor voltage regulators.

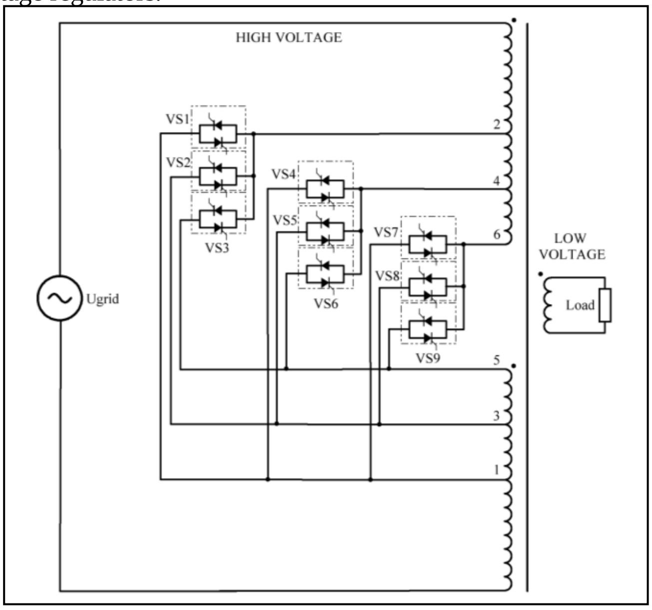

Fig.7. The thyristor voltage regulator of the output voltage of an on-load transformer based on 9 bidirectional thyristor switches.

TABLE IV. VOLTAGE REGULATION LEVELS OF THE POWER TRANSFORMER WITH EOLTC ACCORDING TO THE SCHEME IN FIG.7, INCLUDING TWO PRIMARY SECTIONED HV HALF-WINDINGS

Voltage regulation stage number	**Voltage level change on the LV winding in relation to the nominal value**	**Conductive bidirectional thyristor switches**
1	-5%	VS9
2	-2,5%	VS6 or VS8
3	0%	VS3 or VS5, or VS7
4	+2,5%	VS3 or VS4
5	+5%	VS1

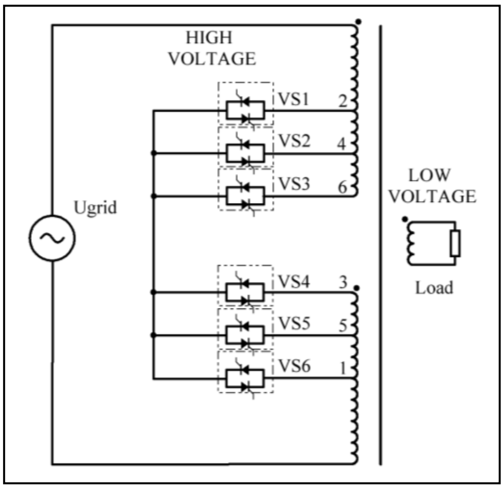

Fig.8. The thyristor voltage regulator with 6 bidirectional thyristor switches

In case, then each section of the primary sectioned HV winding of a power transformer consists of the same number of turns and has 2.5% of the total number of turns of the primary sectioned HV winding, it can be concluded that the total number of control levels will be 5 pcs., in accordance with expression (3). So, the scheme (fig.8) provides the uniform regulating characteristic as in fig.3. The number of bidirectional thyristor switches can also be reduced to 5 pcs. in accordance with expression (2). Thus, one of the bidirectional thyristor switches VS2–VS5, shown at the scheme of fig.8, is excluded and one adjustment tap of the power transformer can be left unconnected to the thyristor commutator's circuit. The relationship between voltage regulation levels and combinations of bidirectional thyristor conducting switches for this scheme (fig. 8) is presented in table 5.

TABLE V. VOLTAGE REGULATION LEVELS OF THE POWER TRANSFORMER WITH THE THYRISTOR VOLTAGE REGULATOR FIG.8

Voltage regulation stage number	**Secondary side voltage value, depending on the nominal voltage**	**Conductive bidirectional thyristor switches**
1	-5%	VS3-VS4
2	-2,5%	VS2-VS4 or VS3-VS5
3	0%	VS2-VS5 or VS1-VS4 or VS3-VS6
4	+2,5%	VS1-VS5 or VS2-VS6
5	+5%	VS1-VS6

It should be noted that for any of thyristor voltage regulators fig. 6,7 and 8 it should be excluded the situation when all bidirectional thyristor switches are in OFF state. Otherwise, high voltage will be applied to each bidirectional thyristor switch. This situation will be avoided in thyristor voltage regulator fig.9. with the contactor with normally closed contacts.

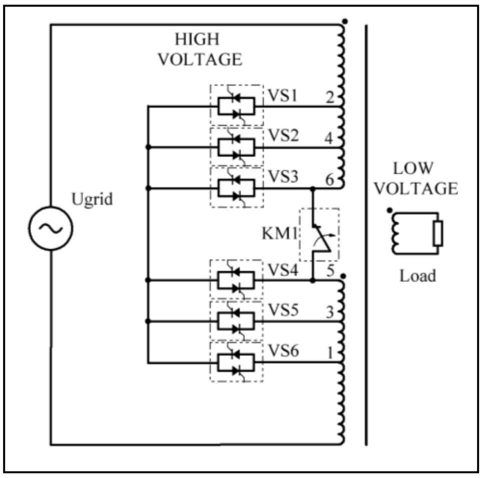

Fig.9. The thyristor voltage regulator with the power contactor with normally closed contacts.

The power contactor with normally closed contacts leads to the fact that in any operating mode of the thyristor switch, the maximum reverse voltage applied to the thyristors isn't exceeded the total voltage of all the adjustment sections of the primary sectioned HV winding of the power transformer.

B. Adaptive control algorithms.

The algorithms for controlling bidirectional thyristor switches of thyristor voltage regulators significantly depend on the nature of the load of the power transformer. They also depend on the derivative of the voltage change at the output of the power transformer. These factors should be taken into account when forming a reliable control of thyristor voltage regulators when regulating the output voltage.

Adaptive control algorithms for thyristor voltage regulators should provide time synchronization of the control processes of bidirectional thyristor switches [14, 15]:

- At the output voltage increasing and any type of the load: turning out of bidirectional conducting thyristor switches is carried out by removal from their control impulses and feeding control impulses to are included bidirectional thyristor switches during the time when instantaneous values of voltage and current of HV winding of power transformer have the same sign.
- At the output voltage decreasing and an active-inductive or an inductive load: control impulses are removed from conducting bidirectional thyristor switches and the instantaneous value of HV winding current is monitored. After the HV winding current drops to zero, it is necessary to apply the control impulses to turn-on correspondent bidirectional thyristor switches should apply. Also, the same control algorithm is carried out at the active load.
- At the output voltage decreasing in the case of an active-capacitive or a capacitive load: control impulses from conducting bidirectional thyristor switches are removed during the time when the instantaneous values of the current and voltage of HV winding of power transformer have different signs. At the same time interval, it is necessary to apply control impulses to turn-on the correspondent bidirectional thyristor switches to provide a new voltage level of thyristor voltage regulator.

C. Basic requirements for the control system.

For designing control systems for thyristor voltage regulators of the output voltage of an on-load power transformers, it is important to take into account the following factors:

- Implementation of thyristor switches control algorithms [22, 23] which allow reliable control of the thyristor voltage regulator with different load types (active, active-inductive, active-capacitive, inductive and capacitive loads) and requirements for the direction of voltage change on the load;
- The time synchronization of switching processes of bidirectional thyristor switches with current and voltage in the HV winding of the power transformer;
- Diagnostics of the state of thyristor bidirectional switches of a thyristor voltage regulator (the ability to track and prevent emergency modes);
- Availability of means of integration into the digital distribution network using modern data exchange protocols [24, 25] (wired and/or wireless data transmission technologies);
- The organization of the power supply system for thyristor drivers and the control system (galvanic isolation for the power supply of the control elements).

The formation of control algorithms taking into account the above features of the control system construction ensures the universality of such a system for any topology of thyristor voltage regulators for power transformers and contributes to the introduction of these devices both in existing and in the latest digital distribution networks.

4. MATLAB Simulation Results

The analysis of electromagnetic processes in thyristor voltage regulators [26] can be carried out on simulation models created in the MATLAB Simulink environment [27]. An example of the simplest two-stage simulation model of the thyristor voltage regulator (fig. 1) is shown in fig. 10 and includes a power supply, two bidirectional thyristor switches (four thyristors), a transformer with an adjustment tap and a load resistance.

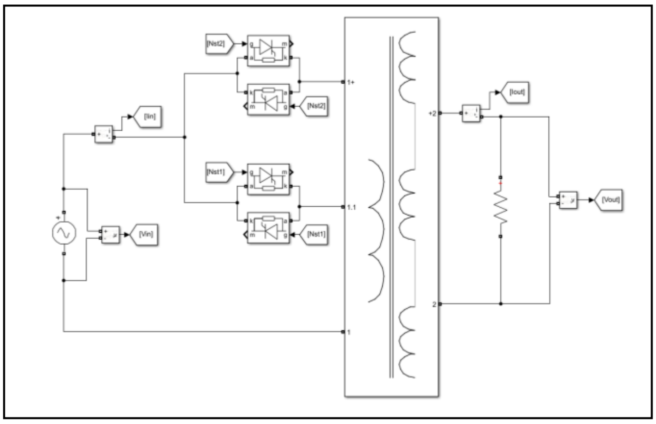

Fig.10. The simplest two-stage model of the thyristor voltage regulator.

Based on the simplest models, more complex multi-stage three-phase models were created for various topologies of voltage regulators for on-load transformers. All models were created on the basis of adaptive algorithms described earlier. The general structure of the three-phase model [28] is shown in fig 11. The three-phase supply network is modeled by a three-phase EMF source. The internal resistance of the source and the linear parameters of the power line are not taken into account in the models, since they don't significantly affect the switching processes of thyristor switches of a semiconductor commutator. As models of thyristor switches, standard built-in models of single-operation thyristors of the Sim Power System module of the Matlab Simulink environment are used.

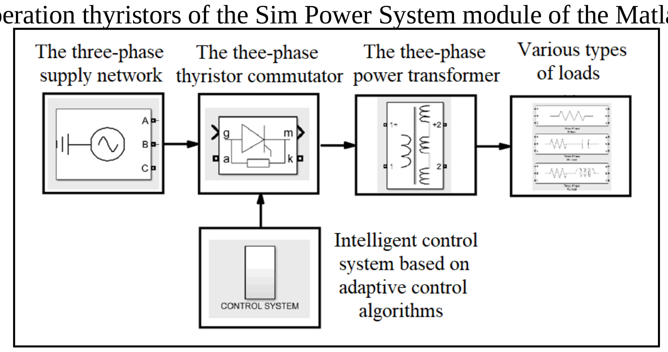

Fig.11. The general structure of the three-phase model of the output voltage regulator for on-load transformer.

The power transformer model takes into account the presence of leakage inductances of the secondary and primary windings. The value of the magnetization inductance is high, which is why the influence of the magnetization current on the flowing electromagnetic processes is not taken into account.

The time diagrams of switching processes of voltage regulation stages are presented in fig. 12. The diagrams (fig.12) demonstrate currents and voltages with different types of the transformer load and the processes of switching from one control stage to another with different direction of the voltage change. The tailling edge of sync pulse [29] indicates the removal of control pulses from the current-conducting bidirectional thyristor switch of the current voltage control stage.

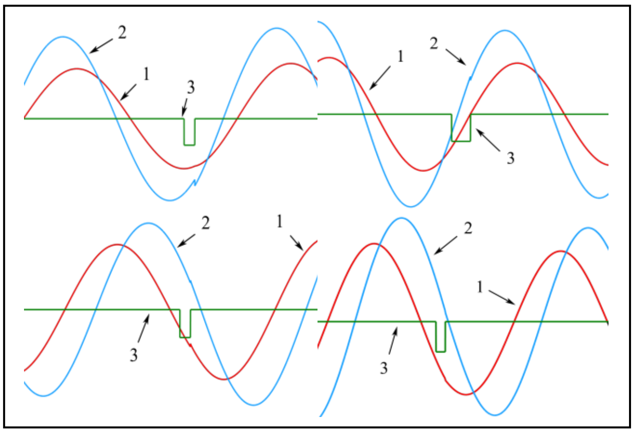

Fig.12. Time diagrams obtained as a result of modeling with different types of load. 1 – load current, 2 – load voltage, 3 – sync pulse.

The front edge of the sync pulse 3 indicates the supply of control pulses to the required controlled thyristor switch for setting a new stage of regulating the output voltage of the transformer. At the same time, as can be seen from the given time diagrams (fig. 12), the voltage does not have zero pauses at commutation moments. It should also be noted that the voltage values of the LV winding of the power transformer, given in tables 1-5, were confirmed on simulation models.

So, simulation modeling results confirmed the operability and the feasibility of adaptive control algorithms for variuos thyristor voltage regulators for on-load power transformers.

5. Physical models and Experimental Results

To confirm the operability of the topologies of the thyristor output voltage regulator presented in the paper and to verify the simulation results, physical models of devices were created in the form of mock-up samples. One of the physical models is shown in fig. 13.

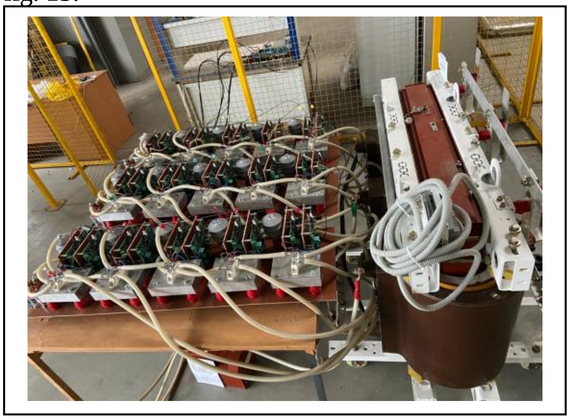

Fig.13. The physical model of the thyristor voltage regulator for an on-load power transformer.

A three-phase network of class 10 kV is used as the supply grid. The power part corresponds to the thyristor voltage regulator shown in fig. 6, taking into account the power contactor, an example of which is shown in fig.9. The model was tested in conjunction with commercially available dry power transformers [30] class 10/0.4 kV 250 kVA. In the course of experimental studies, the load had the following types: active-inductive, active-capacitive, active, inductive and capacitive. The waveforms of switching voltage control stages for various types of loads were obtained, presented in fig. 14. These waveforms confirm the operability of semiconductor regulators of the on-load transformers output voltage, the applicability of the developed control algorithms and simulation models.

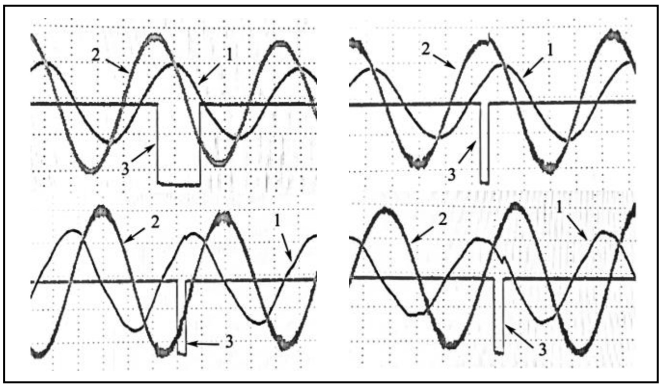

Fig.14. Experimental waveforms with different load types. 1 – load current, 2 – load voltage, 3 – sync pulse.

Experimental waveforms illustrated processes of the three-phase output voltage regulation for the on-load power transformer were obtained. The waveforms (fig. 15) show processes of on-load transformer output voltage increasing. The waveforms (fig. 16) demonstrate processes of on-load transformer output voltage decreasing. Sync pulses edges show the moments of removal and feeding of control impulses for each phase, in accordance with the description for single-phase processes.

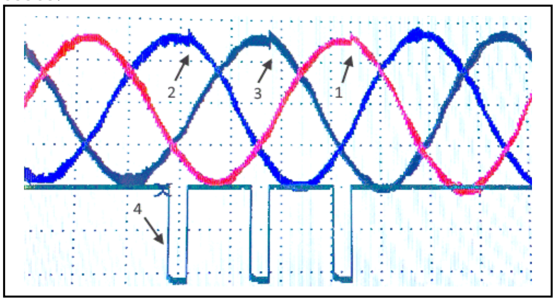

Fig.15. Experimental waveforms of three-phase switching with transformer output voltage increasing. 1 – phase U output voltage, 2 – phase V output voltage, 3 – phase W output voltage, 4 – sync pulse.

On the basis of the developed mock-up samples, a prototype thyristor voltage regulator for a power transformer of distribution networks was constructed. The construction of this prototype is shown in fig17. It has two main sectors: a high voltage sector and a low voltage sector. In the high-voltage sector there are a high-voltage cable input, phase power modules included the semiconductor converter, protection, control and diagnostic systems. The low voltage sector includes voltage and current sensors located on the low voltage side of the power transformer for a distribution network, a top-level control system, and a display with a touch screen.

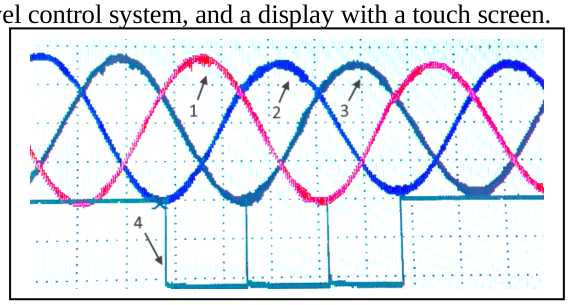

Fig.16. Experimental waveforms of three-phase switching with transformer output voltage decreasing. 1 – phase U output voltage, 2 – phase V output voltage, 3 – phase W output voltage, 4 – sync pulse.

The developed technical solutions for the construction and control of thyristor regulators of the output voltage of distribution transformers are adapted to work with commercially available dry power transformers with a power range of 250-1000 kVA. The control system is provided with functions of diagnostics, monitoring [31], protection and implementation of the digital interface of the IEC 61850 standard [32, 33].

The device's support for data transmission protocol standards (IEC 61850) makes it possible to integrate it into modern digital substations of a new generation. This allows remote monitoring [34] and diagnostics of the internal equipment of both the device and the electrical distribution network.

It also allows remote control of the device in real time, which can be organized both under the control of an external operator taking into account the load operation modes. Thus, thyristor voltage regulator for an on-load power transformers is an intelligent device in the active-adaptive power systems [35].

Fig.17. The prototype of the thyristor voltage regulator for an on-load power transformer. 1 – sensor display, 2 – single phase power module, 3 – local single-phase control system, 4 – HV input.

6. Conclusion

The main advantages of thyristor voltage regulators of the power transformer for distribution networks are:

- The high-speed regulation of the output voltage of an on-load transformer and thereby continuously maintain the voltage level.
- The on-load 0.4 kV voltage regulation of distribution networks without interrupting the current and voltage.
- High reliability of the thyristor voltage regulators due to the absence of mechanical contacts.
- High device efficiency associated with minor power losses at thyristor switches.
- The possibility of phase-by-phase voltage regulation on the LV winding, which allows to balance the voltage in three-phase networks of 0.4 kV.
- Easy integration of the device into a digital substation with a centralized system of monitoring and controlling the operating modes of a power transformer based on the IEC 61850 standard.

Thus, these technical solutions can be applied at modern substations within the framework of reconstruction or creation of new electric distribution networks programs and are a promising direction for the development of the concept of digital distribution networks.

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