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Modelling of the non-contact automatic voltage regulation system on single phase distribution transformers

***Abstract**. This article presents the design and implementation of an on-load automatic voltage regulation system utilizing TRIAC devices for single-phase distribution transformers. A schematic diagram of the system of automatic non-contact adjustment of voltage in a single-phase power transformer is developed, the system's operation is based on a mathematical theory and scheme. Besides the device's operation algorithm and the prototype of an on-load automatic voltage regulation system via TRIAC for a single-phase power transformer was developed and test experiments were conducted.*

***Streszczenie.** W artykule przedstawiono projekt i realizację układu automatycznej regulacji napięcia pod obciążeniem z wykorzystaniem urządzeń TRIAC dla jednofazowych transformatorów rozdzielczych. Opracowano schemat ideowy układu automatycznej bezkontaktowej regulacji napięcia w jednofazowym transformatorze elektroenergetycznym, działanie układu opiera się na teorii i schemacie matematycznym. Oprócz tego opracowano algorytm działania urządzenia oraz wykonano prototyp układu automatycznej regulacji napięcia pod obciążeniem za pomocą TRIAC-a dla jednofazowego transformatora mocy oraz przeprowadzono eksperymenty testowe. (**Modelowanie bezkontaktowego układu automatycznej regulacji napięcia na transformatorach rozdzielczych jednofazowych**)*

***Keywords:** single-phase distribution transformers, thyristors, TRIAC switches, voltage adjustment, voltage deviation, regulation system.*
***Słowa kluczowe:** jednofazowe transformatory rozdzielcze, tyrystory, przełączniki TRIAC, regulacja napięcia, odchyłka napięcia, układ regulacji*

Introduction

Power losses in long-distance power transmission lines and the connection of various types of resistance to the power supply and consumers located far from the distribution transformer leads to situations where the voltage deviates from the limits required by standards [1]. In particular, long-term voltage deviations in the 6-10 kV transmission line negatively affect the reliability of electrical devices and consumers, shorten their service life, and cause additional power loss in these devices [2]. Voltage adjustment in distribution transformers is one of the most common methods of voltage stabilization in the power supply system [3]. Voltage adjustment consists of changing the number of primary or secondary windings of power transformers by mechanical or non-contact devices [4]. In distribution transformers, a) simple-transformer includes devices for adjusting the voltage in the off-state (OCTC) or b) complex-load (OLTC) [5].

Connecting to a chosen tap in the winding, the off-circuit tap-changer's design is quite straightforward. As implied by the name, it is intended to be used exclusively in the de-energized mode of the transformer. There are several disadvantages to adjusting the voltage in this way [6]. With this method, it is possible to adjust the voltage deviation only seasonally. This does not provide an opportunity to eliminate short-term voltage deviations due to load changes in transformers. When adjusting the voltage using OCTC, there is no possibility to control the location of the contacts. This can cause a phase-to-phase short-circuit condition due to limited external monitoring after a change in OCTC setpoint [7]. Failure to operate the device for a long time causes its mechanical contacts to oxidize and cause the device to fail.

According to the requirements of technical installation rules [8], it is required to adjust the voltage in distribution transformers with using an OLTC device on a power capacity higher than 6300 kVA. While one tap is temporarily operating differently from the others, the on-load tap-changer maintains a constant current flow. Our scientific analysis shows that there are several disadvantages of adjusting the voltage under load using an OLTC device in distribution transformers [9]. Typically, an OLTC unit is mounted on the inside of the transformer tank at the bottom of the magnetic core, which causes it to be taller than a conventional transformer, resulting in more material being used for the housing and support. When adjusting the voltage under load using the OLTC device, an electric arc is formed in the mechanical contact part, which leads to the deterioration of the condition of the mechanical contacts and the quality of the transformer oil [10]. The OLTC device requires constant periodic inspection, and its malfunction causes the implementation of extraordinary repair work of the transformer, with each repair work, the insulation of the transformer is seriously damaged [11]. Distribution transformers with OLTC device are more expensive than power transformers without voltage rectifier or with OCTC device. Also, according to statistical studies, 41% of transformer damage occurs as a result of OLTC device damage [12]. Numerous studies on the use of power electronics devices as on-load taps have emerged in tandem with the advancement of power electronics technology [13]. It was suggested in reference to utilize solid-state relays as transformer on-load tap-changers [14]. However, the low voltage of the present solid-state relays makes them unreliable in practice. On another article, thyristor switches are advised for automatic contactless voltage adjustment in power transformers. Power thyristors are capable of carrying a lot of current and have a high power that makes them useful in high-voltage transformers [15]. Nevertheless, in order to alter voltage without contact using thyristor switches, each thyristor's control contact must receive a fixed voltage of a specific pulse at a regular interval. In this instance, the control block should be handled in multiple steps when opening and closing the thyristor switches [16, 17].

In this article, we design an on-load automatic voltage adjustment system in distribution transformers using TRIAC switches instead of mechanical contact devices. There is a device for automatic non-contact adjustment of the voltage under load. The working scheme of the 10 kV distribution transformer and the mathematical expression of the voltage under load and the physical model were developed and experimental studies were carried out.

Principial scheme of the system

A working scheme of an on-load non-contact automatic voltage regulation system designed via TRIAC for distribution transformer is presented in Fig. 1.

According IEEE Standard, the secondary winding is divided into 5 parts for transformers from 25 kVA to 200,000 kVA and divided into additional windings [8]. Here, the secondary winding is divided into three pre-calculated parts, and two additional windings with the same number of windings are connected to it. Each isolated winding allows to increase or decrease the overvoltage by 2.5 % for example, the first and second additional windings reduce the voltage value in the transformer by -5 and -2.5 %, respectively, compared to the instantaneous voltage value. Through the third additional winding, the voltage is ensured to be constant at the nominal value, like ordinary transformers. The fourth and fifth additional windings increase the voltage by +2.5 and +5 % compared to the instantaneous value. Thus, 5 stages of voltage adjustment are formed in the secondary windings of the power transformer.

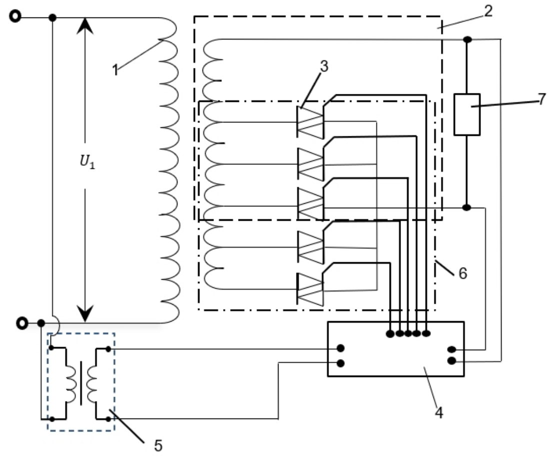

Fig. 1. Working scheme of single-phase distribution transformer via using TRIAC voltage regulation system.

The proposed automatic voltage adjustment device has the following mode of operation: In the working scheme, a voltage transformer (5) is installed at the input of the primary winding (1) of the distribution transformer, and sends the instantaneous value of the primary voltage to the control block (4). In addition, a signal is sent to the control block through an additional winding (6) to determine the voltage at the output of the secondary winding (2) of the distribution transformer.

The power supply of the control block is also supplied from the input of the power transformer using a voltage transformer. The purpose of this is that the comparator device in the control block forms the periodic interval of opening and closing the TRIAC (3) switch from the sinusoidal representation of that phase.

By comparing the instantaneous values of the voltages in the primary and secondary windings, the control block determines which of the TRIAC switches in the secondary winding should be given a signal (command). In TRIAC switches, two thyristor switches located in opposite parallel open and close their contacts alternately in accordance with the signal given to the base part of the switches. As a result, electricity flows from the node located in this TRIAC switch to the load (7). This situation continues until the instantaneous value of the voltage in the network reaches the value specified in the normative documents of the international IEEE standards [8].

Theoretical description of the voltage regulation system.

In the primary winding of the power transformer, the voltage u_1 is generated under the influence of electric current. Voltage on the high voltage side varies with time according to the sinusoidal law [18]:

(1) $$u_1 = U_{\text{м}1} \sin \omega t;$$

The electric motive forces (EMF) are generated in the primary winding changes according to the sinusoidal law when it is expressed by the electric current:

(2) $$\left.\begin{aligned} e_1 &= -w_1 \frac{d\Phi_o}{dt} = -w_1 \omega \Phi_{\text{м}} \cos \omega t - \mathcal{E}_{\text{м}1} \sin \omega t, \\ e_2 &= -w_2 \frac{d\Phi_o}{dt} = -w_2 \omega \Phi_{\text{м}} \cos \omega t - \mathcal{E}_{\text{м}2} \sin \omega t, \end{aligned}\right\};$$

According to Krichhoff's second law, the voltage and current generated in the primary and secondary windings of a power transformer are proportional to each other and we can write the following [5]:

(3) $$\left|\frac{u_2}{u_1}\right| = \left|\frac{e_2}{e_1}\right| \quad \text{or} \quad \frac{U_2}{U_1} = \frac{\delta_2}{\delta_1} = \frac{w_2}{w_1} = k_{tr};$$

The above expressions almost correspond to the idle modes of power transformers, but when the load is connected to the power transformer, a current$-I_2$ is generated, which creates a magnetic flux$-F_2$ in this winding itself (according to Lens's law, this current is opposite to the magnetic flux in the secondary winding) will be in the opposite direction). As a result, the total magnetic field in the magnetic core decreases and e_1 of the primary winding decreases. As a result, the voltage on the high-voltage side decreases and the current increases. This process takes place until it equals the value of the primary magnetic flux.

We assume that the magnetic field flux generated in the primary and secondary windings is the same and constant [19]:

(4) $$F = \frac{I_1 w_1}{R_m} = \frac{I_2 w_2}{R_m};$$

where: μ_a is absolute magnetic permeability of ferromagnetic core and R_m is chain magnetic resistances are found by the following expressions [20]:

(5) $$\mu_a = \mu_0 \mu_r \text{ and } R_m = \frac{l}{\mu_a S} = \frac{l}{\mu_0 \mu_r S};$$

where: cross-sectional area of S is magnetic conductor $[m^2]$; l is average length of the magnetic conductor $[m]$; $\mu_a$is absolute magnetic permeability; μ_0 is magnetic constant (absolute magnetic permeability in vacuum), equal to $\mu_0 = 4\pi \cdot 10^{-7}$ [H/m]; $\mu_r$is magnetic permeability of a ferromagnetic material, which changes depending on the intensity of the magnetic field [7]:

(6) $$H = \frac{I w_i}{l};$$

Combining the above expressions (4), (5) and (6), we calculate the magnetic flux generated in the windings. In this case, the magnetic flux is the same in both windings:

(7) $$E_i = 4{,}44 f w_i \Phi = 4{,}44 f w_i \frac{I w_i \mu_a S}{l} = 4{,}44 f \frac{I w_i^2 \mu_a S}{l}$$

From the last formula, it follows that the amount of electric current generated in the windings of the power transformer can vary depending on the characteristics of the ferromagnetic conductor, its length, cross-sectional surface, and the amount of current it carries.

In the proposed non-contact automatic voltage adjustment scheme, the process of adjusting the voltage deviation in the secondary circuit due to the load change can be expressed as follows:

In practice, changing the amount of electromotive force in the windings is done by changing the transformation coefficient [18]:

(8) $k_{tr} = \frac{w_1}{w_2}$;

That is, by changing the number of windings of the primary or secondary winding, it is possible to adjust the voltage in the winding.

The voltage adjustment range, depending on the number of adjuster windings and the number of main windings, is found from the following expression [2]:

(9) $\Delta U\% = \frac{w_{reg}}{w_{reg}+w_{main}} \cdot 100\%$;

By changing the number of windings of the adjuster winding in step voltage adjustment, the voltage adjustment range is derived [20]:

(10) $U_{int} = U_{nom}\left[\frac{w_{regt,int.1}}{w_{main}+w_{reg,int.1}}+..+\frac{w_{reg,int.n}}{w_{main}+w_{reg,int.n}}\right]$

where: U_{nom} is network nominal phase voltage; $U_{reg,int.i}$; $\omega_{reg,int.i}$ is i (th) adjuster winding voltage and number of windings in step; n is the number of adjuster windings.

In general, the output voltage of the thyristor switches in the thyristor switch, which is used for non-contact automatic voltage adjustment is found by the following formula [20, 21]:

(11) $U_{tr.out} = U_{tr.inp}\sqrt{\alpha}\cos(\alpha-\alpha_0)$;

where: $U_{tr.out}$is output voltage of TRIAC switches; $U_{tr.inp}$ is input voltage to TRIAC switches; α is thyristor opening angle; closing angle of α_0 is thyristor.

Combining the formulas (7) and (10) above, we can find the voltage which is enter to the TRIAC switches:

(12) $U_{tr.inp} = U_{nom} = 4{,}44f\frac{Iw_{main}^2\mu_a S}{l}\left(1+\frac{w_{reg}}{w_{reg}+w_{main}}\right)$

Using the formulas for the input voltage to the TRIAC switches (11) and the opening angle of the thyristor in it (12), we create the formula for the output voltage from the TRIAC switches:

(13) $U_{tr.out} = 4{,}44f\frac{Iw_{main}^2\mu_a S}{l}\left(1+\frac{w_{reg}}{w_{reg}+w_{main}}\right)\sqrt{\alpha}\cos(\alpha-\alpha_0) - I_2 Z_2$

The output voltage from the TRIAC switches of power transformers with non-contact voltage adjustment system is equal to the load voltage, i.e.

(14) $U_{load} = U_{tr.out}$

In short, the output voltage of the power transformer with automatic non-contact voltage adjustment system depends on the number of main and adjuster windings of the transformer, the current entering the transformer, the cross-sectional surface of the windings and the closing angle of the thyristor switches and the waiting time of the opening angle of the TRIAC switches.

Experimental analysis of distribution transformer on-load automatic voltage regulation system designed via TRIAC

On the basis of the working scheme, a single-phase automatic voltage adjustment power transformer with a total capacity of 350 VA was assembled and preliminary experimental studies were carried out.

In our first experimental study, using the LD DIDACTIC [22] laboratory set, the high input voltages of the single-phase automatic voltage adjustment transformer were changed to +10%, +5%, 0, -5%, +10% from the nominal value of the voltage specified in the international IEEE standards. An experimental study was conducted in the case of voltage deviation on the high-voltage side of the transformer in the normal operation mode (Table 1).

Table 1. The voltage parameters of idle power transformer via using TRIAC voltage regulation system

Voltage deviation in the upper wind ΔU_1 [%]	Input voltage U_1 [V]	Output voltage U_2 [V]	Voltage deviation in the lower wind ΔU_2[%]	Voltage phase angle φ_{UA}
-10	198	218.5	-0.68	179.9 °
-5	209	219.6	-0.18	179.9 °
0	220	220.1	0.045	179.9 °
5	231	221.8	0.81	179.9 °
10	242	223.1	1.409	179.9 °

Experimental studies conducted in the mode of operation of the power transformer with automatic contactless voltage adjustment show that in the case of a voltage deviation at the input of the power transformer, the voltage deviation at its output is less than 1%, IEEE standards [8] according to the requirements and on the basis of the norm, which is a clear example of the increase in the reliability of transformers.

In the LD DIDACTIC [22] laboratory assembly, the state of the change in time of the voltage adjustment at the output of the single-phase automatic voltage adjustment power transformer without contact is given below, in which, when the amount of voltage entering this transformer during operation is changed, a certain time (0.3 sec) we can see that the voltage is adjusted during (Fig. 2).

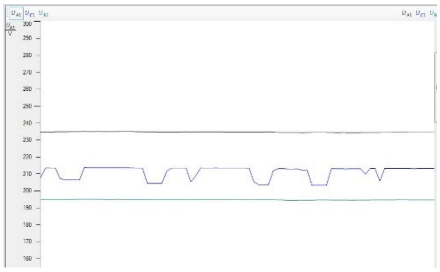

Fig. 2. Time variation of the voltage adjustment at the output of the single-phase non-contact automatic adjustment distribution transformer.

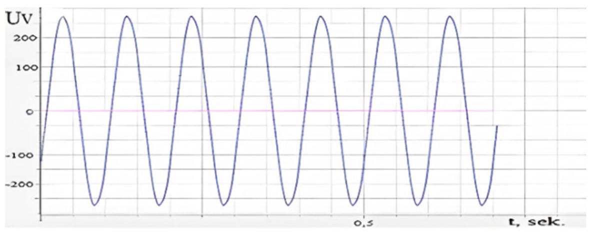

Fig.3. The graph of the voltage changing over time at the output of the non-contact voltage rectifier power transformer operating in the presence of inductive and capacitive loads

According to the results of the analytical research, the sinusoidal state of voltage in power transformers in operating conditions is broken when inductive and capacitive loads are connected to the network. This process has been tested on our proposed non-contact automatic voltage rectifier power transformer. The graph of the voltage changing over time at the output part of the non-contact voltage rectifier power transformer operating in the presence of inductive and capacitive loads was obtained (Fig. 3).

In this case, there is a load with an inductive resistance, we can see that the output voltage of this transformer changes according to the sinusoidal law, and it corresponds to the values in the requirements of IEEE standards [8].

In the next experiment conducted in the research, the output of the single-phase automatic voltage rectifier power transformer is loaded with a mixed resistance through an active load P=40 W and an inductance load with an inductance L=6 Hn and a capacitance C=16 μF (Table 2).

Table 2. Output voltage of on-load automatic voltage regulation system designed via TRIAC for power transformer with the mixed resistances load (Impendence)

Input voltage U_1 (V)	Active load P (W)	Inductance L (Hn)	Capacity, C(μF)	Output voltage U_2 (V)	Deviation of U_2 ΔU_2%	U_2 phase angle φ_{UA}
196.9	40	6	16	214.5	2.5	-178.7°
210	40	6	16	218.9	0.5	-178.7°
220.8	40	6	16	218.6	0.63	-178.7°
232.4	40	6	16	219.2	0.36	-178.8°
242.9	40	6	16	223.9	1.77	-178.9°

Conclusions.

This article designed a type of automatic on-load voltage regulating system of distribution transformer, which applying TRIAC as on-load tap-changer. It provides contactless voltage adjustment in the secondary circuit when there is a voltage deviation on the low voltage side of the power transformer. Contactless voltage adjustment through TRIAC devices is much cheaper and more reliable than traditional types.

The steps of voltage adjustment are carried out in 5 steps of ±2x2.5% in accordance with the requirements of the IEEE standards of voltage adjustment in 6-10/0.4 kV power transformers. This automatic voltage adjustment scheme, which is used in 6-10/0.4 kV distribution transformers in operation, is fully suitable for normal operation and load modes.

The output voltage of the automatic non-contact voltage adjustment device in the power transformer depends on the number of main and adjusting windings of the transformer, the current entering the thyristor, the cross-sectional surface of the windings and the closing angle of the thyristor switches and the waiting time of the opening angle of the transformer changes. In the process of switching tap joint, compared with the traditional mechanical tap-changer, transition process is more reliable and stable and the quality of voltage has been improved. In this paper, the design of automatic voltage regulating system for distribution transformer aims at 10 kV power distribution network. Environment of higher voltage will be studied in following research.

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