INFLUENCE ASSESMENT OF AUTOTRANSFORMER REMANENT FLUX ON RESONANCE OVERVOLTAGE

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*Abnormal resonance overvoltages occur due to the emergence of non-sinusoidal modes of bulk electrical networks. The considered type of overvoltage refers to durable internal overvoltages, which have characteristics that can exceed the maximum permissible magnitude with a certain correlation of the values of the parameters of the extra high voltage power transmission line 750 kV. A typical example of a non-sinusoidal mode of operation of an extra high voltage line is the mode of switching on the line to an unloaded autotransformer. The paper analyzes the effect of remanent magnetization of an unloaded autotransformer on resonance overvoltages. To remove the remanent magnetization of the autotransformer, a set of effective measures for suppressing resonance overvoltages has been proposed.***

Keywords: non-sinusoidal mode, controlled switching, abnormal resonance overvoltages, remanent flux, inrush currents

1. Introduction

The question of the emergence of the second harmonic of the extra high voltage transmissions line (EHV TL) 750 kV is one of the most difficult in modern theoretical electrical engineering. Despite of the fairly large number of publications on this topic, the causes and conditions for the appearance of this harmonic are still not completely clear. Moreover, the published works of different authors contradict each other in some questions [1], [2], [3].

Now there are two main reasons for the occurrence of durable resonance second-harmonic overvoltages in EHV TL. The first is the non-sinusoidal nature of the flux linkage of the nonlinear inductance when it is connected to the source. If there is an aperiodic component in the flux linkage, higher harmonics components will appear in the current [2], [3]. The voltage drops from these components on the circuit elements cause the appearance of corresponding harmonics in the autotransformer (AT) and line. Overvoltages at transient

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resonance are not limited to corona wires and can exist for a long time with a slow decrease in the aperiodic component of the flux linkage [3].

The mechanism of this phenomenon, called self-excitation of the second harmonic, has not been studied enough so far, although many theoretical papers have been published [4], [5]. Unfortunately, not one of these well-known works deals with the study of the physical nature of the phenomena taking place, while clarifying this essence is the only way to develop an engineering approach to the phenomenon and methods for its suppression or, on the contrary, use.

It should be noted that this type of resonance overvoltage was observed on two EHV power lines: the Khmelnitsky nuclear power plant – the substation Rzeszow (Poland) and the South Ukrainian nuclear power station – Isakcha (Romania). The problem of operating an extra-high voltage power line in non-sinusoidal modes with the possible occurrence of resonance overvoltage does not allow to operate the Ukraine-European Union energy bridge during switching of unloaded autotransformers. These lines are characterized by lengths that require the installation of three shunt reactors and, as studies have shown [1], [3], [4] directed at these lines resonance overvoltages at the second harmonic are observed. The studies cited in the article are dictated by the need to ensure reliable and efficient operation of the Ukraine-European Union energy bridge with bulk EHV TL.

2. General characteristics of self-modulation of electric circuits with steel

Self-modulating steel circuits can be divided into two large groups. The first and larger group includes systems that have coils that are magnetized by direct current (controlled non-linear inductors) [6]. In today's bulk electrical networks, such electrical equipment is controlled shunt reactors.

The second group is systems having coils with steel core, which are not magnetized by direct current. This group includes systems with transformers and autotransformers. According to the classification set out in [7], [8] the electrical bulk networks, which have controlled shunt reactors, belong to the first large group of ferromagnetic systems. The systems of the second group include systems in which self-modulation arises in the zone of existence of the second harmonic in the absence of magnetization.

Due to some inconsistency and ambiguity of terminology in literary sources, it is necessary to explain the terms «self-modulation» and «self-oscillation». Self-oscillations in the case of a line being switched on to an unloaded autotransformer are understood to mean an oscillatory process in a dissipative system (that is, in a system with energy losses involved in the process), the characteristics of which are the amplitude of the oscillations, their shape, period and frequency (in a more general sense, in this case spectrum) are determined by the system itself and are not dependent on changes in the initial conditions. Self-oscillations differ from forced oscillations in that the latter are caused by periodic external influences and occur with the frequency of this effect, while the occurrence of self-oscillations and their frequency are determined by the internal properties of the self-oscillating system itself. In this case, the frequency becomes almost equal to the resonance.

Self-modulation is a mode of operation of a nonlinear electric circuit that is under the influence of a periodic driving force, the frequency at which the amplitudes of the currents and voltages in the circuit periodically change without the influence of an external modulating factor. Self-modulation occurs due to the instability of the periodic mode of operation at the frequency of the driving force.

The two terms in the presentation of the material are identical. In a smaller part of the cases, the term "self-oscillation" is used, which to a lesser extent reflects the essence of the processes under consideration harmonical resonance overvoltages.

In both cases, the resonance process occurs in circuits with nonlinear inductance and equivalent capacitance of the ultrahigh voltage transmission line, taking into account the influence of the active power losses. Equivalent inductance is calculated by equalizing the capacitance between phase and ground and the interfacial capacities of the overhead line. Therefore, the equivalent capacitance values determine the resonance process and the frequency of the linear portion of the transmission line.

Normal oscillations, self-oscillations or modes are a set of characteristic types of harmonic oscillations. Each of the normal oscillations of the high-voltage power line is characterized by its frequency. This frequency is called normal frequency or natural frequency [9-13]. The set of frequencies of normal oscillations is the vibrational spectrum. Arbitrary oscillations of the physical system can be represented as a superposition of various normal oscillations. The forced oscillations of the autotransformer resonate at frequencies that coincide with the frequencies of the normal oscillations of this system.

The concept of self-modulation and self-oscillation brings two things together: self-oscillations are usually defined as oscillations occurring in a nonlinear part with a constant forced force, whereas self-oscillation is a process of periodically changing the amplitude of a forced oscillation in a nonlinear system with a periodic forced force; to a falling section of S- or N-like characteristic of nonlinear active resistance, whereas self-modulation in nonlinear systems usually occurs when the point reflecting batch process falls on the incident station S-shaped nonlinear inductance characteristics controlled or managed nonlinear capacity.

Self-oscillations differ from forced oscillations in that the latter are caused by periodic external influences and occur with the frequency of these influences, while the occurrence of self-oscillations and their frequency are determined by the intrinsic properties of the self-oscillating system itself.

The process of occurrence of resonance overvoltages on higher paired harmonic components is related to internal and external feedbacks. Under feedback, we will accept feedback from the original value to the input. In self-modulating a steel circuit, the feedback is rarely explicit, more often it is implicit.

In this case, in a self-modulating system with an unloaded autotransformer, the AC value or the amplitude of the first magnetic induction harmonic dependent on it is taken as the output value. The input value is the current of the oscillating circuit. The complex of interaction of the initial value into the input can be divided into separate subgroups and types according to the classification. It should be noted that the separation of feedback is conditional.

The decisive influence on the operation of self-modulating systems with saturation inductors has the effect of the first and second harmonics of magnetic induction, as well as subharmonics on the average value of magnetic induction. The change in the initial value is accompanied by a change in the amplitudes and phases of the magnetic induction harmonics and interacts with the average value of the magnetic induction.

This interaction group is a hidden interaction group, and since it is magnetically generated, it can be called internal magnetic feedback. The average value of magnetic induction is thus an intermediate agent through which the output circuit interacts with the input. In this case, the internal magnetic coupling is carried out through the amplitude modulated second harmonic with virtually constant amplitude of the first harmonic magnetic induction.

Significant effects on the auto modulation process can be affected by the harmonics of current and flow. The amplitude and phase of the second harmonic induction depend on the relationship between the average value of the field strength, the average value of the magnetic induction, and the amplitude of the first harmonic induction. In addition, if the oscillations are sufficiently high frequency and are accompanied by a sharp change in the amplitude of the second harmonic of current and/or flow, then under certain conditions oscillations supported by modulation of pair harmonics may occur and persist.

The paper deals with two types of appearance effect. The first effect of occurrence refers to the effect of the occurrence of a permanent component of the magnetic magnetization of the ferromagnetic core by two co-sized variable magnetic fluxes, the ratio of frequencies of which is equal, for example, two or four.

The second effect of occurrence is the following. If magnetizing a ferromagnetic core with an alternating current containing the first and second (or, for example, the fourth) harmonics at disproportionate magnetic fluxes, with a certain arrangement of the beginning of the second harmonic of the field strength with respect to the beginning of the first magnetic flux, there is no constant component, that the field strength has a constant component. The emergence of self-oscillatory processes, supported by the modulation of the second harmonic, is most influenced by the second effect.

In the work of the main attention is paid to the process of generation of higher harmonics, in which the nonlinearity of the magnetization characteristics of the autotransformer plays a crucial role. The theory of self-parametric excitation of higher harmonics of even multiplicity is presented.

3. Analysis of processes in the oscillatory circuit with periodic variable inductance in the oscillatory circuit

The section presents the calculation of the areas of self-excitation of even harmonic components of extra-high voltage power lines. The method is based on qualitative analysis of the integral of the differential equation of perturbed motion, which is reduced to the equation with periodic coefficients (Hill equation). It is shown that taking into account all active losses in the system (the most important of which are losses to the crown) sharply reduce the areas of self-excitation of paired harmonic ones. As a result, the probability of self-excitation for real transmission is almost zero.

Today, a significant number of papers have been published [1], [2], [10], [12], [14]. In which methods of calculating the values and areas of existence of higher pair harmonics are proposed. The calculation formulas obtained in these papers found qualitative and, to one degree or another, quantitative confirmation in experiments and simulation models. They have not shown that the phenomenon is critical to losses, that is, there is a critical value of the real part of the input impedance complex, which excludes the self-excitation of paired components.

The latter is the reason that resonance overvoltages on the second harmonic component were observed in the real power grids during the commissioning of the extra-high power lines. The source of losses that are or are not sufficiently taken into account in the calculations and models: corona discharge on the line wires, hysteresis, active component of full resistance, equivalent to the system. Unconditional in this case are the factors brought by the line itself - the corona discharge.

In the oscillatory circuit with periodic amplifying inductance, with certain relations between the parameters of the circuit, a loss of "stability" of the forced mode can occur – the integral of the corresponding differential equation arises to which any small perturbation increases infinitely with time. This phenomenon is called parametric resonance [1], [15], [16]. The integral of the equation describing such circles can in general be represented by a Fourier series whose coefficients in instability regions are increasing with time functions. If one of the frequencies of the natural oscillations of a circle is close to the frequency of any such, for example, the second, component of a series, then in the corresponding region of instability it will be this harmonic.

Any transmission is an oscillating circuit, which also includes the inductance of the magnetization circuit of an autotransformer (transformer), which changes periodically. The inductance fluctuation in this case arises not only from the external mechanical source of energy, but also from periodic changes in the coupling. Therefore, we should talk about the autoparametric nature of the self-excitation of pair harmonics. The auto-parametric nature of the phenomenon will be affected, first of all, by the depth of modulation of the inductance of the magnetization, which has a significant effect on the boundaries of the self-excited regions of pair harmonics and is a direct function of the amplitude of the forced voltage. Calculation of the boundaries of domains of self-excitation pairwise harmonic reduces to the study of conditions of unrestricted growth of small perturbation, which is transmitted to the integral of the original differential equation.

4. The influence of remanent flux on appearance of resonance overvoltages

When an autotransformer is turned on for an alternating voltage, the magnetic core can go into a saturation state, in which a small increment of the magnetic flux through it causes a sharp increase in current through the transformer winding [5], [15-17]. At the same time, the resulting magnetic flux through the magnetic core at the moment of switching on, Wb, plays the determining value for the current value:

$$\Phi_{rez} = \Phi_{st} + \Phi_{tran} \pm \Phi_{rem}, \tag{1}$$

where Φ_{st} – steady state magnetic flux, Wb;

Φ_{tran} – magnetic flux of transient process, Wb;

Φ_{rem} – remanent flux, Wb.

When excitation is removed from the AT, some of the magnetic domains retain a degree of orientation relative to the magnetic field that was applied to the core. This phenomenon is known as residual or remanent magnetism. Remanent flux Φ_{rem} that value of flux which would remain in the core 3 min after the interruption of an exciting current of sufficient magnitude to induce the saturation flux.

The most effective and most justified among the methods for reducing the inrush current of AT when turned on is to reduce the resulting magnetic flux by the beginning of the transient process in the "AT primary winding – line" circuit.

The use of a device for removing the residual magnetization of the Φ_{rem} AT magnetic circuit is preliminary before switching the AT into a random phase, it allows to obtain the value $\Phi_{rem} = 0$, then the resulting magnetic flux of the through the magnetic conductor at the moment of switching on:

$$\Phi_{rez} = \Phi_{st} + \Phi_{tran}, \tag{2}$$

Switching on the transformer according to the method of reducing the starting current of the AT at the time when the alternating voltage of the network is in the phase of 90°, after preliminary implementation of the method of removing the residual magnetization of the AT magnetic circuit, allows to get the values $\Phi_{rem} = 0$, then the resulting magnetic flux through the magnetic core at the moment inclusions:

$$\Phi_{rez} = \Phi_{tran}, \tag{3}$$

5. Processes at commutations of an autotransformer

The physical nature of the appearance of resonance overvoltages on second harmonic is due to the periodic change in the inductance of the magnetic shunt AT when passing through it alternating current [2], [4], [5]. As a result of the capacitive effect, the voltage on the AT increases caused by the saturation of its magnetic circuit. This in turn causes deep modulation of the inductor of the AT that will vary with a double frequency in relation to the applied voltage, since the degree of magnetization does not depend on the direction of the current. The appearance in the spectrum of the second harmonic component and is a sufficient condition for the emergence of resonance overvoltages on the ultraharmonics of pairwise multiplicity.

During switching in the magnetic circuit of the AT there is a free decaying aperiodic component of the flux, which leads to the appearance in the magnetization current of harmonic components. The latter, in turn, cause, on the elements of the electric circuit, a voltage drop equivalent to the introduction of a corresponding frequency in the range of longitudinal electromotive force.

The problem of studying resonance overvoltages that occur when an unloaded autotransformer is turned on is that: today there is no exact answer to the question about the cause of this type of overvoltage. Since the beginning of the

1950th [2], [4], as soon as they began to construct and operate EHV TL, studies were carried out to identify the determining factors for the occurrence of resonance overvoltages on higher harmonic components.

In the case of connecting an unloaded autotransformer, autoparametric resonance and oscillations occurring in the system due to periodic changes in those system parameters that determine the amount of stored energy will occur. In this case, parametric oscillations in the oscillating circuit are excited due to the periodic change in the nonlinear inductance of the magnetic circuit.

The main drawback of the first studies is the presence of a too fundamental theoretical substantiation of the nature of the occurrence of resonance oscillations in circuits with nonlinear inductance. A significant bias has been made towards the physical nature and classification of resonance phenomena in electrical networks and systems. All of the above refers to the steady-state regimes of circuits with nonlinear inductances. As for the transient processes, they are practically not studied at all. It is not known what initial conditions lead to the occurrence of a harmonic, and which are not. The magnetization of AT due to its energization is considered the most unfavorable case, causing inrush currents of magnetization of the greatest amplitude. When an AT is disconnected, the magnetization voltage is zero, the magnetization current decreases to zero, while the magnetic induction varies according to the magnetization characteristic of the core. This causes the presence of remanent induction in the core. When, after some time the autotransformer is re-energized, the magnetic induction begins to change according to the sinusoidal law, but with a shift to the value of remanent induction. The residual induction can be 80-90% of the nominal induction, and thus the point can move beyond the magnetization curve knee point of the magnetization characteristic, which, in turn, causes a large amplitude and distortion of the current waveform Fig. 1.

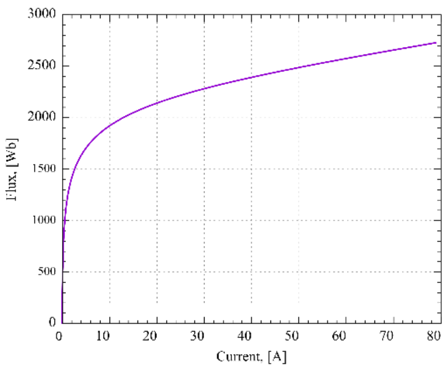


Fig. 1. Magnetization curve of the autotransformer 333000/750/330

This eventually led to a DC component in the AC circuit, but not from a DC source, but from the fact that the core is saturated at the peaks of the AC sinusoid and the inductance stops hindering the flow of current – the current peaks grow to infinity.

For investigation such a complex process, the simulation model has been developed, because we investigate electromagnetic transients. All results and figures have been obtained by simulation model. The model has been developed for studying the processes in the environment MATLAB/Simulink which are illustrated on Fig. 2. This model includes additional models of group shunt reactors and arc of alternating current to investigate resonance overvoltages as against [2], [18]. There were made calculations to find the effective measure to prevent this kind of overvoltages. The three phase power system is simulated by voltage sources with fixed voltage and inductance. The overhead line is simulated by two parts, which are given complex matrices with distributed elements or values on the forward and reverse sequence.

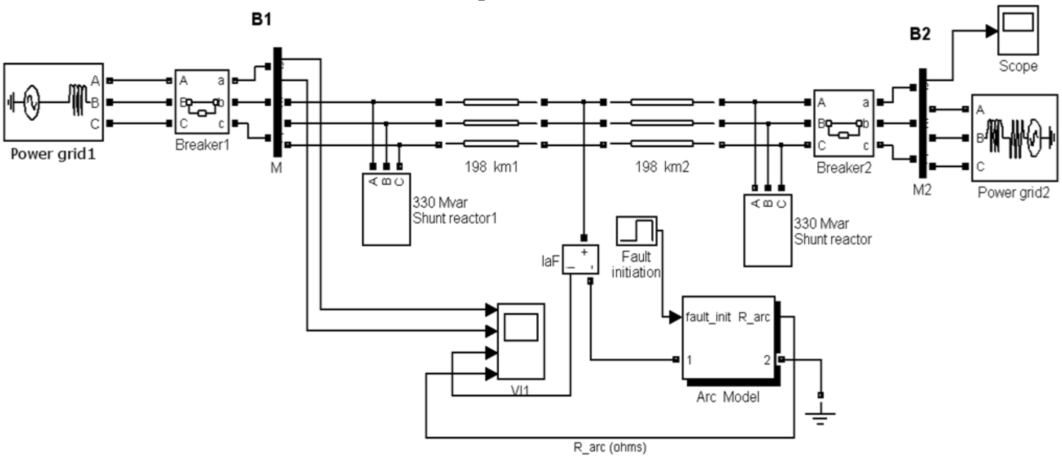


Fig. 2. Model of extra high voltage transmission line

The resonance overvoltages were obtained for real transmission line Khmelnytsky Nuclear Power Plant (Ukraine) – Rzeszow (Poland) with value of parameters which are shown in Tables 1 and 2. In Table 2 are shown parameters of equivalent stems.

The second possible reason for the appearance of a long second harmonic is a periodic change in the inductance of the AT magnetizing shunt. In this case, the oscillogram seems to be completely unclear: the second harmonic, initially small, begins to develop after quite a long time (0.1-0.5 seconds) (Fig. 3) a certain switching, for example, when the line is switched on to an unloaded AT. Moreover, it increases, reaching significant values after 0.8-1.2 seconds.

Table 1

Parameters of transmission line							Parameters of equivalent systems				
L_0, 10^{-4} H	C_0, 10^{-9} F	L_1, 10^{-3} H	C_1, 10^{-8} F	Numbers of groups shunt reactors, *n*	Numbers of groups shunt reactors, *n*	Lenght, 10^3 m	Voltage U, 10^3 V		Impedance of system Z, Ω		Inductance of shunt reactor L_P, H
							1	2	1	2	
2.44	9.89	8.9	1.305	3	3	396	768	745	5.68+65.85i	8.78+70.85i	5.981

In the case when the autotransformer is idling, its secondary and tertiary windings are open, the switching process is described by the voltage equation of the primary winding. In this equation, the total inductance of the primary winding L is equal to the ratio of the flux linkage of the winding to the current causing it, i.e.

So, we have to consider equation (3) more detailed. Φ_{st} the instantaneous value of steady flow that takes place after the end of the transition process

$$\Phi_{st} = \Phi_m \sin(\omega t + \psi - \varphi_0) \tag{4}$$

where $\varphi_0 = arctg(\frac{\omega L}{r})$, L, r – transformer winding equivalent circuit parameters.

Since $\omega L >> r$, then $\varphi_0 = \frac{\pi}{2}$ we will have

$$\Phi_{st} = -\Phi_m \cos(\omega t + \psi) \tag{5}$$

The magnitude of magnetic flux of transient process we will have after solving equation $\Phi_{tran} = Ce^{-t\frac{r}{L}}$.

The integration constant C is determined from the initial conditions. At the moment of switching on, the magnetic flux is equal to the residual value of the Φ_{rem} flux, which can be directed both in accordance with and counter to the flux caused by the winding current. At $t = 0$:

$$\Phi_{tran} + \Phi_{st} = -\Phi_m \cos\psi + C = \pm\Phi_{rem} \tag{6}$$

Whence $C = \Phi_m \cos\psi \pm \Phi_{rem}$

And consequently

$$\Phi_{tran} = (\Phi_m \cos\psi \pm \Phi_{rem}) e^{-t\frac{r}{L}} \quad (7)$$

Substituting in (4) the expression Φ_{st} according to (5) and Φ_{tran} according to (7), we obtain the equation of the instantaneous value of the flow

$$\Phi = \Phi_m \left[\cos\psi e^{-t\frac{r}{L}} - \cos(\omega t + \psi) \right] \pm \Phi_{rem} e^{-t\frac{r}{L}} \quad (8)$$

Analyzing (8), we see that the autotransformer flux consists of a steady-state component and two aperiodic components, and the value of the first, determined by the cosine of the angle ψ, depends on the moment of switching on, and the value of the second depends on the value of the residual magnetism Φ_{rem}. The smallest flow occurs when the autotransformer is switch on at $\psi = \frac{\pi}{2}$ (Fig. 3), and $\Phi_{rem} = 0$. Then, immediately after switching on, the flow has one steady-state component i.e. $\Phi = \Phi_m \cos(\omega t + \frac{\pi}{2}) = \Phi_m \sin \omega t$.

The Fig. 4 shows the characteristic form of magnetization current surges. This waveform displays the presence of a long-decaying aperiodic component that can be characterized by the content of different harmonics and a large current amplitude at the initial moment of time (up to 30 times the value of the AT rated current). The curve decays significantly in tenths of a second, but the total attenuation is characteristic after a few seconds. Under certain circumstances, the inrush current magnetized decays only minutes after the transformer is energized.

The highest value of the flow is obtained when it is switched on at the moment $\psi = 0$ when if $\omega L >> r$ (Fig. 3)., then the flow reaches the maximum value of approximately only half a period, i.e. at $t = \frac{T}{2} = \frac{\pi}{\omega}$

In this case

$$e^{-t\frac{r}{L}} \approx 1 \quad (9)$$

The residual flow can be significant, sometimes reaching half normal. Assuming that $\Phi_{rem} = 0,5 \cdot \Phi_m$, then the maximum value of the flow (8) taking into account (9) is equal

$$\Phi_{\max} = 2.5 \cdot \Phi_{rem} \tag{10}$$

As a result of turning on the transformer at a moment of time corresponding to the maximum flow $\Phi_{\max}$ (10), the current when turned on can be exceeded by 6-10 times the rated current (Fig. 5). This phenomenon is explained by the inequality of the steady flow at the time of switching and residual flow in the transformer. With the largest difference between these fluxes, the resulting magnetic flux can be twice or more than the nominal magnetic flux, which leads to saturation of the transformer steel, a decrease in its inductive resistance and, as a result, the appearance of maximum inrush currents of the magnetization.

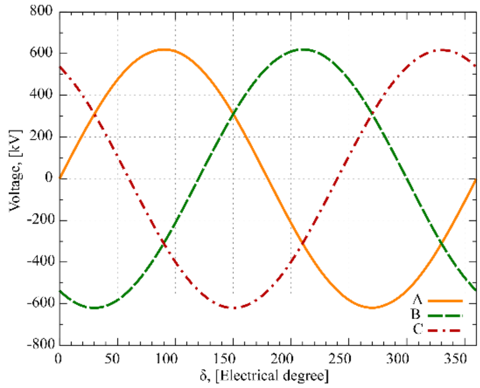


Fig. 3. Sine wave voltage

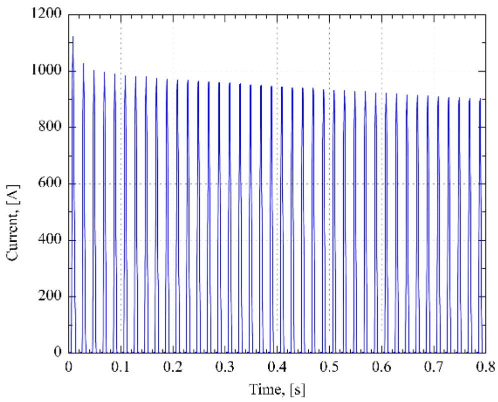


Fig. 4. Inrush currents of autotransformer

As you can see Fig. 5 a), due to the saturation of the magnetic system, the inrush current of magnetization when turned on reaches very large values that can exceed even the rated current of the AT. The results obtained by modelling by simulation model of EHV TL which are depicted on Fig. 2. When power AT are turned on, there is a sharp inrush of magnetization current, which has a decaying character Fig. 3.

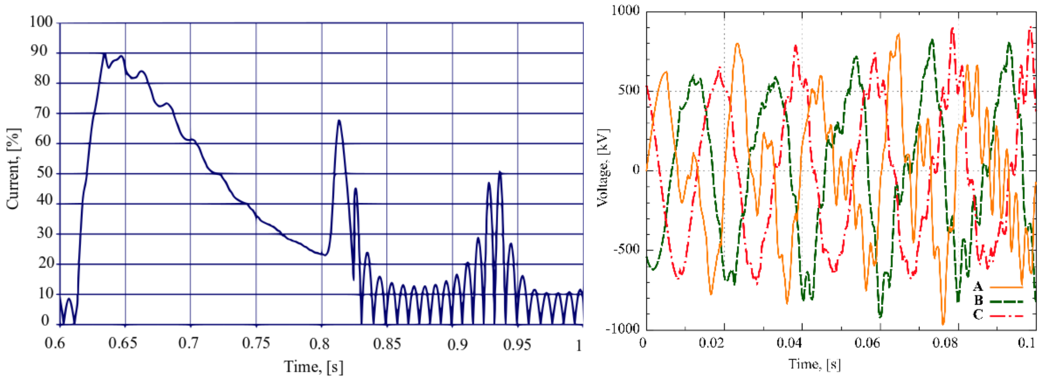
- the current curve is asymmetrical, until the current reaches a steady-state value;
- the curve can be decomposed into aperiodic component and sinusoidal currents of different harmonics. The aperiodic component has a very large specific value in the rated current;
- the time of attenuation of currents is determined by the time constants of the AT and the network, and can reach 2-3 seconds. The more powerful the AT, the longer the attenuation lasts;

- the initial inrush current can reach 6-10 times the transformer rated current. Power AT has a multiplicity less than low-power ones.

It is well-known facts that for compensating the charging power of the line, shunt reactors are used that are installed at substations [19]. Respectively shunt reactors significantly affect the percentage of the aperiodic component of the switching current of the transient process [19]. When the power supply autotransformer is turned off, an aperiodic current is formed with a high percentage in relation to the total current, as can be seen from the Fig. 5.

So, when the autotransformer of the power line with installed shunt reactors is switched off, an aperiodic component with a high percentage is formed in the current, which causes asymmetric saturation of the magnetic circuit. At the same time, the operation of the autotransformer at idle shifts the working point of the magnetization curve to the nonlinear part and with an asymmetric change in the field strength, residual magnetization is formed, which significantly affects the starting magnetization currents and the development of resonance overvoltages.

The Φ_{rem} in the magnetic circuit reaches its maximum when the transformer is switched off with an active load, when the current and voltage coincide in phase and the switch off occurs when they pass through zero. Moreover, in accordance with the law of electromagnetic induction, Φ_{rem} in the core reaches a maximum and lags 90 ° from the current and voltage. Subsequent switching to idle of the transformer will be accompanied by the maximum possible surge of magnetization current with an unfavorable sign of the aperiodic component of the switching current. With an inductive (capacitive) load of the transformer, the Φ_{rem} will correspond to the possible minimum, and in load conditions and in the short circuit mode it does not reach a maximum. Abnormal resonance overvoltages on second harmonic component are shown on Fig. 5 b).



a) b)

Fig. 5. Inrush currents of autotransformer a); abnormal resonance overvoltages on second harmonic component b).

To assess the effect of residual magnetization on the values of resonance overvoltages, a series of simulations with 15 possible options was carried out. The simulation results are shown in table 3 with the indicated cases of switching autotransformer. As can be seen from table 3 for any of the options there are resonance overvoltages exceeding the limit permissible values.

Table 3

The effect of remanent flux on resonance overvoltage

№	Φ_{rem}^{A}	Φ_{rem}^{B}	Φ_{rem}^{C}	U^{A}, kV	U^{B}, kV	U^{C}, kV
1	$-\Phi_{max}$	$\Phi_{max}/2$	$\Phi_{max}/2$	1125	1100	1105
2	$-\Phi_{max}$	0	Φ_{max}	1117	1101	1304
3	$-\Phi_{max}$	Φ_{max}	0	1470	1257	1358
4	$-\Phi_{max}/2$	0	$\Phi_{max}/2$	1298	1459	1345
5	$-\Phi_{max}/2$	$\Phi_{max}/2$	0	1287	1114	1587
6	0	Φ_{max}	$-\Phi_{max}$	1147	1456	1258
7	0	$-\Phi_{max}/2$	$\Phi_{max}/2$	1235	1358	1208
8	0	$-\Phi_{max}$	Φ_{max}	1117	1258	1205
9	0	$\Phi_{max}/2$	$-\Phi_{max}/2$	1005	1298	987
10	$\Phi_{max}/2$	0	$-\Phi_{max}/2$	1070	1289	989
11	$\Phi_{max}/2$	$-\Phi_{max}/2$	0	1465	1356	1458
12	Φ_{max}	$-\Phi_{max}$	$-\Phi_{max}$	985	998	990
13	Φ_{max}	$-\Phi_{max}/2$	0	1268	1150	1258
14	Φ_{max}	$-\Phi_{max}/2$	$\Phi_{max}/2$	1289	1247	1236
15	Φ_{max}	$\Phi_{max}/2$	$-\Phi_{max}/2$	1139	1198	1058

6. Measures of supression resonance overvoltages on second harmonic

The article does not consider well-studied measures to suppress resonance overvoltages: controlled switching, arresters and pre-insertion resistances [19-21]. These activities are included in the optional means of SF_6 switches. At the moment, it is of practical interest to use alternative measures based on studies of the effect of residual magnetization.

A method of reducing the inrush current of a AT and resonance overvoltages, including interruption at the time of reaching the maximum instantaneous voltage value in the phase of 90°. Such commutation is completely demagnetized prior to the closing of the switch contacts when the AT is connected to the network the residual magnetization of the magnetic circuit by applying a direct current to the primary winding [22-26].

The second method of suppression consists in demagnetizing the magnetic circuit from residual magnetization, which occurs as a result of a sudden discharge of the supply voltage and a break in the current when it passes through non-zero. Removal of residual magnetization is performed by passing a direct current of opposite polarities through one of the windings of each core of a AT magnetic circuit. The process of demagnetization is carried out in several cycles. In the first cycle, the demagnetization current must be at least twice the no-load current of the autotransformer at rated voltage. In each subsequent cycle, the demagnetization current should be approximately 30% less than the current of the previous cycle. In the last cycle, the demagnetization current should not be greater than the no-load current of the autotransformer at voltage.

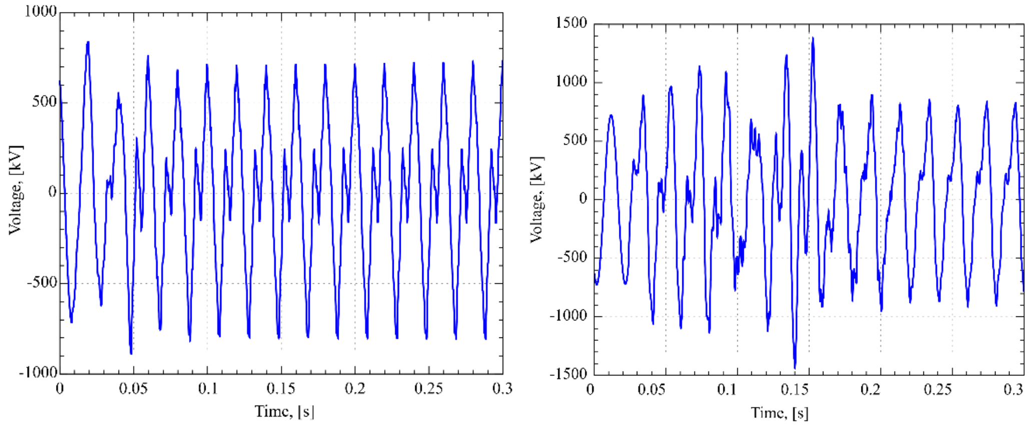
Portable batteries, rectifying devices can be used as a source of direct current. For example, recommendations are given for suppressing resonance overvoltages, which resolve into to the following algorithm for connecting an unloaded AT:

- load connection from the AT windings;
- connection of the line to the AT.

Such a sequence of connecting an unloaded autotransformer, according to the author, allows suppression of resonance overvoltages. Thanks to the simulation, a series of calculations were made on the effect of the nature and values of the load on the autotransformer on the conditions for the occurrence of resonance overvoltages. Results of such algorithm you can see on Fig. 7 a).

As you can see on Fig. 7 a) the moment of connection autotransformer coincides with moment of connection of the load value 200 megawatt. So in this case algorithm of connection supress resonance overvoltages but does not eliminate the second harmonic component.

If the load is connected after connecting an unloaded autotransformer with an interval of 0.15 seconds, overvoltage will be observed at the second harmonic component, as can be seen from Fig. 7 b). Connecting an active load has a dissapative effect on resonance overvoltages.



a) b)

Fig. 7 Supression of resonance overvoltages in case of coincide moment of connection autotransformer and load a); Supression of resonance overvoltages in case of noncoincidence moment of connection autotransformer and load b).

7. Conclusions

1. It is determined that the residual magnetization of the autotransformer is one of the key factors in the appearance of resonance overvoltages on higher harmonic components. The residual magnetization that occurs when an unloaded autotransformer turns off at an unfavorable moment leads to an auto-parametric resonance process and modulation of higher harmonic components.

2. Methods are proposed for suppressing resonance overvoltages in the non-sinusoidal mode of operation of the extra-high voltage power transmission line. The use of a device of controlled switching for switching off an unloaded autotransformer at the moments of sinusoids corresponding to the maximum allows reducing the value of the residual magnetization to a minimum and performing switching at any moment of the sinusoid. Such an event can reduce the value of characteristics and suppress higher harmonic components. In the case of the absence of a controlled switching device, it is potentially possible to use a demagnetization device, which requires the presence of specially trained personnel and the necessary time to perform demagnetization. The device of demagnetization is also in the same way and the device of controlled switching allows suppressing resonance overvoltages and higher harmonic components. Performing switching of a load of greater magnitude before switching on the autotransformer allows reducing the values of the characteristics of resonance overvoltages, but not excluding the presence of higher harmonic components in the sinusoid of voltages and currents. In this case, the load connection is detuning the resonance.

REFERENCES

[1]. *V. V. Kuchanskyi*, "The application of controlled switching device for prevention resonance overvoltages in nonsinusoidal modes", Proc. 37th IEEE International Conference on Electronics and Nanotechnology (ELNANO 2017), Kiyv, Ukraine, 17-19 April 2017, pp. 394--399.

[2]. *V. G. Kuznetsov, Yu. I. Tugay, O. G. Shpolianskyi*, "Analysis of internal overvoltage in extra high voltage electrical networks and development of measures for their prevention and restriction", In Works of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine, 2013, **vol. 2**, pp. 117-123.

[3]. *Y. Tugay*, "The resonance overvoltages in EHV network", Proceedings of IEEE Sponsored Conference EPQU'09 – International Conference on Electrical Power Quality and Utilisation, Poland, Lodz, September 15-17, 2009 pp. 14-18.

[4]. *A. I. Dolginiv*, Resonance in electrical networks and systems, Moskva, Gosenergoizdat, USRR, 1957.

[5]. *M. S. Libkind*, Higher harmonics generated by transformers, Moskva, Publishing house of the academy of sciences of the USSR, Moskva, USSR,1962.

[6]. *V. Kuchanskyy*, "Application of Controlled Shunt Reactors for Suppression Abnormal Resonance Overvoltages in Assymetric Modes", 6th International Conference on Energy Smart Systems (ESS), 2019, pp. 122-125.

[7]. *I. Hunko, V. Kuchanskyy, A. Nesterko, O. Rubanenko*, Modes of electrical systems and grids with renewable energy sources, Academic Publishing, 2019.

[8]. *I. O. Hunko, V. V. Kuchanskyy, A. B. Nesterko*, Engineering sciences: development prospects in countries of Europe at the beginning of the third millennium: Collective monograph. **vol. 2**, Riga, Izdevniecība "Baltija Publishing", 2018.

[9]. *F. De Leon, A. Farazmand, S. Jazebi*, "Elimination of residual flux in transformers by the application of an alternating polarity dc voltage source", IEEE Transactions on Power Deliver., **vol. 30**, no. 4, Aug. 2015, pp. 1727-1734.

[10]. *W. Chandrasena, D. Jacobson, P. Wang*, "Controlled Switching of a 1200 MVA Transformer in Manitoba", IEEE Transactions on Power Delivery, **vol. 31**, no. 5, 2016, pp. 2390-2400.

[11]. *Yundong Song et al.*, "Simulation analysis of inrush current of three phase transformer based on Matlab", Control and Decision Conference IEEE, 2017, pp. 3983-3985.

[12]. *Saeed Jazebi et al.*, "Reduction of Inrush Currents in Toroidal Transformers by Sector Winding Design", IEEE Transactions on Power Electronics, **vol. 31**, no. 10, 2016. pp. 6776-6780.

[13]. *R. Doğan, S. Jazebi, F. de León*, "Investigation of transformer-based solutions for the reduction of inrush and phase-hop currents", IEEE Trans. Power Electron., **vol. 31**, no. 5, 2016, pp. 3506-3516.

[14]. *Bilawal Rehman; Chongru Liu*, "Analysis of Harmonic Overvoltages During Transformer Energization for Mass Rapid Transit Systems", Bydgoszcz, Poland: IEEE, 2016.

[15]. *S. G. Abdulsalam, W. Xu*, "A sequential phase energization method for transformer inrush current reduction-transient performance and practical considerations", in IEEE Transactions on Power Delivery, 2007, **vol. 22(1)**, pp. 208-216.

[16]. *J. H. Brunke, K. J. Fröhlich*, "Elimination of transformer inrush currents by controlled switching – part II: application and performance considerations", in IEEE Transactions on Power Delivery, 2001, **vol. 16(2)**, pp. 281–285.

[17]. *N. Chiesa, H. K. Holidalen*, “Novel approach for reducing transformer inrush currents: Laboratory measurements, analytical interpretation and simulation studies“, in IEEE Transactions on Power Delivery, 2010, **vol. 25(4)**, pp. 2609-2612.
[18]. *R. S. Girgis, E. G. Nyenhius*, “Characteristic of inrush current of present designs of power transformers“, Proc. IEEE Power and Energy Society General Meeting, Tampa, USA, June, 2007.
[19]. *V. Kuchanskyy*, “The prevention measure of resonance overvoltges in extra high voltage transmission lines“, 2017 IEEE First Ukraine Conference on Electrical and Computer Engineering (UKRCON), Kiev, 2017, pp. 436-441.
[20]. *Jiang Wei, Qiu Lu, Zheng Le, Li Canbing, Xia Yongwei*, “Study on Application of Metal Oxide Arresters for Transient Overvoltage Suppression in the Half-Wavelength Transmission System“, Smart Grid and Electrical Automation (ICSGEA) 2017 International Conference on, pp. 139-142, 2017.
[21]. *Rubanenko O., Kazmiruk O., Bandura V., Matvichuk V., Rubanenko O.* “Determination of optimal transformation ratios of power system transformers in conditions of incomplete information regarding the values of diagnostic parameters“, Eastern European Journal of Enterprise Technologies. 2017, **vol. 4**, Issue 3-88, pp. 66-79
[22]. *Rubanenko O., Grishchuk M., Rubanenko Olena* “Planning of the experiment for the defining of the technical state of the transformer by using amplitude-frequency characteristic”, Przeglad Elektrotechniczny, (3), 2020, pp. 190-194
[23]. *Orosz, T., Sleisz, Á., Tamus, Z. Á.* “Metaheuristic Optimization Preliminary Design Process of Core-Form Autotransformers”, IEEE Transactions on Magnetics, 52(4), Article number: 8400310, 2016. *Enterprise Technologies*. 2017. № 4. Issue 3-88. P. 66-79
[24]. *Rubanenko E. O., Komar V. O., Petrushenko O. Y., Smolarz A., Smailova S., Imanbekova U.* “Determination of similarity criteria in optimization tasks by means of neuro-fuzzy modelling“. Przegląd Elektrotechniczny, R. 93, nr 3, 2017, pp. 93-96.
[25]. *A. Kylymchuk, P. Lezhnyuk and O. Rubanenko*, “Impact of linear regulator, installed in the electric grid of energy supply company, on power losses“,IEEE First Ukraine Conference on Electrical and Computer Engineering (UKRCON), Kiev, 2017, pp. 411-416.
[25]. *Orosz, T., Borbély, B., Tamus, Z. Á.* “Performance Comparison of Multi Design Method and Meta-Heuristic Methods for Optimal Preliminary Design of Core-Form Power Transformers”, Periodica Polytechnica Electrical Engineering and Computer Science, 61(1), 2017, pp. 69-76.
[26]. *Diego Teruo Mendes de Souza, Jose Antenor Pomilio*, “Comparison between lumped models for high-voltage high-frequency transformers”, *Industry Applications (INDUSCON) 2018 13th IEEE International Conference*, 2018, pp. 112-117.