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ANALYSIS OF CHAOTIC FERRORESONACE IN HIGH VOLTAGE ELECTRIC GRIDS

Analysis is carried out, complex mathematical model, that most accurately takes into account all the initial conditions and adequately describes chaotic ferroresonance processes in electric circuits of real grid, is suggested.

Key words: *chaotic ferroresonance, electric grid, overvoltage, overcurrent.*

Introduction

Ferroresonance – complex nonlinear oscillations, that may emerge in any circuits of electric grid with nonlinear inductance and capacitance and are accompanied by long- lasting overvoltages and overcurrents, that are not limited by conventional methods of suppression.

Electromagnetic voltage transformers may serve as nonlinear inductive elements in electric grids. Capacitive voltage dividers in the switches, capacities of the buses and connected equipment may be capacitance elements.

Under such conditions, any transient processes, atmospheric overvoltages, connections or disconnections of transformers, emergence or elimination of short-circuits and other disturbances may cause the emergence of ferroresonance process. These processes are accompanied by overvoltages and overcurrents that stipulate the danger of such modes in practice. Especially it concerns ferroresonance on basic frequency. However, after introduction of modern digital means of registration of abnormal processes in electric grids there appeared the probability of emergence of non-conventional ferroresonance processes, such as chaotic ferroresonance. Chaotic ferroresonance processes are mainly initiated in case of switching operations and may lead to incorrect operation of relay protection and automation devices and to emergence of dangerous overcurrents in transformer windings, that is why, the analysis of such phenomena is rather urgent problem.

Main part

Electric grids with rated voltage higher than 110 kV operate with efficient neutral grounding and voltage transformers, installed in these grids, are manufactured single-phase. That is why, for the investigation of ferroresonance it is expedient to use single-line equivalent circuit with the model of single – phase voltage transformer that by means of elementary equivalent transformations may be reduced to classic scheme of serial ferroresonance circuit. Such ferroresonance circuit consists of the supply source E; integral capacity of voltage dividers of the switch, capacities of the buses and equipment, connected to the buses C; resistance R, that takes into consideration losses in voltage transformer and non-linear inductance of voltage transformer L [1].

Depending on the peculiarities of the course of the process, ferroresonance is divided into four groups:

1. Periodic ferroresonance on the basic frequency. In such ferroresonance process voltages and currents are periodic, with a period, equal to the period of the system and may have various number of harmonics. Spectrum of the signal is discrete and consists of the basic frequency of the system and its higher harmonics;
2. Subharmonic ferroresonance. Voltages and currents are also periodic, with the period, multiple to the period of supply source. Spectrum has both basic frequency and its higher harmonics.
3. Quasi-periodic ferroresonance. It is not periodic. Spectrum of harmonic components under such mode is discrete.
4. Chaotic ferroresonance. Such resonance is not periodic. Corresponding spectrum of harmonic components is continuous, i.e., any frequency is not passed [2].

For the solution of the problem of chaotic ferroresonance processes analysis to prevent their emergence and development, it is necessary to have facilities for revealing necessary and sufficient conditions of ferroresonance processes emergence.

For obvious reasons, experimental research of chaotic ferroresonance on the buses of high voltage substations are limited, that is why to define the reasons of these phenomena and preventing their possible negative consequences, it is necessary to study the models, applying the methods of mathematical modelling.

As it is known, characteristic feature of ferroresonance phenomena is long transient process and usage of conventional models and methods, intended for investigation of fleeting electromagnetic transient processes, often becomes inefficient. Such methods do not allow to determine dangerous deviations of circuit parameters and modes and there exists the danger of emerging ferroresonance processes, especially this concerns chaotic ferroresonance. That is why, to determine the needed conditions, it is necessary to develop mathematical models that describe more adequately the chaotic ferroresonance processes as compared with conventional models.

As it was mentioned above, for emerging of ferroresonance processes in electric grids the availability of inductive element with ferromagnetic core is necessary. Accuracy of mathematical models of the transformers above all influences the truth of ferroresonance results calculation. The usage of the polynomial of the 11 th order provides the most satisfactory accuracy. However, for the development of more adequate mathematical models of the transformers in order to analyze chaotic ferroresonance it is necessary to take into consideration the hysteresis effect. Gillas – Atterton model enables to realize this, thy model is written in the form of differential equation and for its identification one hysteresis loop, obtained experimentally, is sufficient:

$$\frac{dM}{dH}=\frac{1}{(1+c)}\frac{(M_{an}-M)}{k\delta-\alpha(M_{an}-M)}+\frac{c}{1+c}\frac{dM_{an}}{dH}, \tag{1}$$

where M – total magnetization of the steel core of the transformer; $M_{an}=M_s\left(cth\left(\frac{H_e}{a}\right)-\frac{a}{H_e}\right)$ – anhysteretic magnetization; M_s – saturation magnetization; $H_e=H+\alpha M$ – effective field of domains; a – coefficient of anhysteretic curve form, defined as the value of intensity, at which: $M_{an}=\frac{M_s}{2}$; k – coefficient that defines the width of hysteresis loop; α – coefficient, constant of domain boundaries binding; δ – back magnetization coefficient, assumed as: $\delta=1$ if $\frac{dH}{dt}>0$ and $\delta=-1$ if $\frac{dH}{dt}<0$.

By means of mathematical model (1) we can simulate all the features of hysteresis, for the description of non-linear induction behavior it is necessary to set five main parameters. Algorithm of the given hysteresis loop identification has two cycles – internal and external. On the internal cycle the system of algebraic equations is solved. On the external cycle the system of differential equations is solved, applying Runge – Kutta method. The degree of model adequacy to real data may be considered to be sufficient and in any case much greater than traditional usage of basic magnetization curve. Besides, this model is developed for application in the sphere of computer engineering, that is why it has rapid and stable realization algorithm [3].

For the analysis of chaotic ferroresonance process output circuit of the substation “Pivnichna” (Fig. 1) was used, that was provided by the services of Central energy system. By means of equivalent transformations it was reduced to the scheme of serial ferroresonance circuit. Necessary inductive element for contour formation was III section buses voltage transformer and capacities were capacities of switches dividers BB-330 and BB-330-I of Chernobyl Nuclear Power Plant and capacities of transmission line, equipment and buses of the substation relatively the ground.

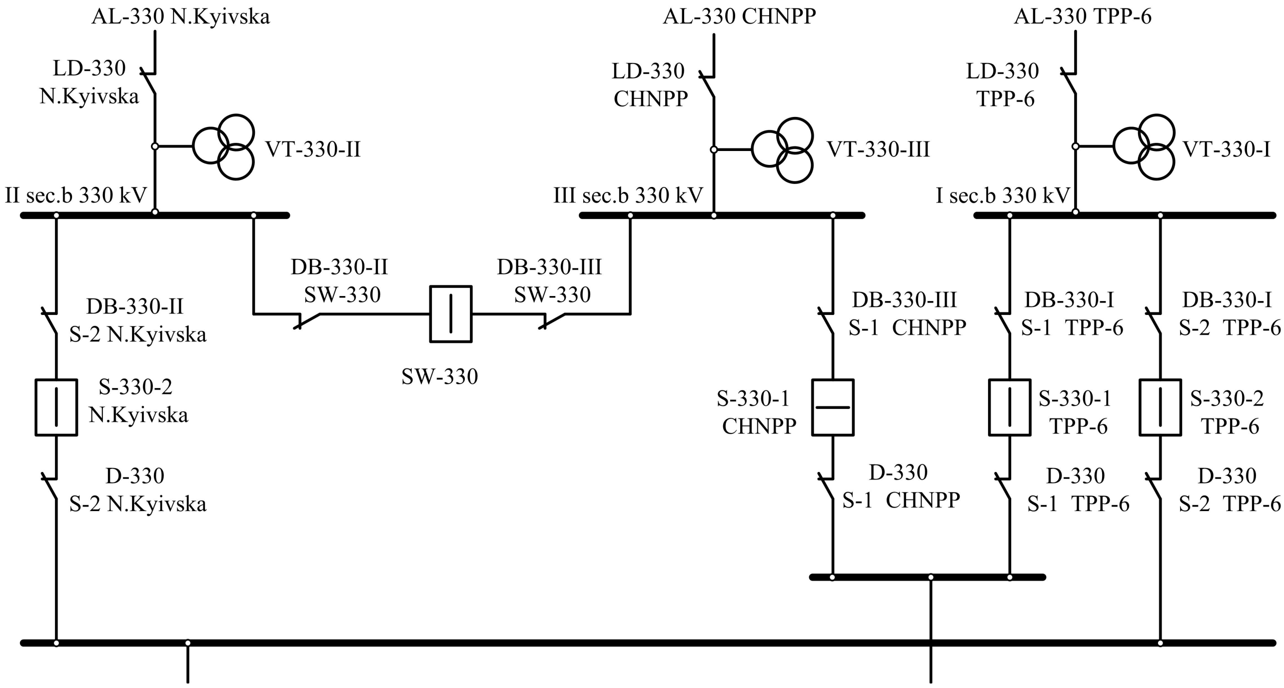

Fig. 1. Scheme of the switch-gear of substation “Pivnichna” 330 kV of Central energy system

As it may be seen from Fig. 1, voltage of the amplitude of about 70 % from operating one emerged on the phase A, but on phases B and C such voltage increase is not observed. Such mode is inadmissible, as the information, regarding the voltages obtained from primary sensors, is doubtful. Besides, taking into account the fact, that the current, passing in the winding, exceeds limiting admissible, heating and thermal destruction of insulation takes place, that leads to turn short-circuiting and, as a result, to the damage of voltage transformer. Chaotic ferroresonances have negative impact on relay protection and automation devices, connected to the secondary circuits of voltage transformer. This impact becomes apparent in incorrect information in the process of buses testing on the subject of voltage presence and, as a result, failure of ASS buses after elimination of arc short-circuit. As a result, buses remain disconnected.

This concerns the calculation for determination of sufficient conditions of chaotic ferroresonance emergence. The reasons of difficulties, dealing with determination of necessary conditions of chaotic ferroresonance development become understandable after application of the approaches of non-linear dynamics. As it is known, the equation for oscillation system, instantaneous state of which is set by two values, generalized coordinate x and its derivative, on which external periodic force acts , is determined by non-linear dissipation oscillator:

$$\frac{d^2x}{dt^2}+\gamma\frac{dx}{dt}+f(x)=A\cos\omega t, \qquad (2)$$

where t – time, ω – angular frequency of the system.

Differential equation, that describes the process in ferroresonance circuit:

$$\frac{d^2\psi}{dt^2}+\frac{G}{C}\frac{d\psi}{dt}+\frac{1}{C}i_L=\omega E\,cos(\,\omega t+\delta\,), \qquad (3)$$

where ψ – magnetic-flux linkage of voltage transformer winding; G – conductivity, that takes into account losses in magnetic circuit of the substation voltage transformer; C – equivalent total capacitance of voltage dividers of the switch C_s, buses capacitance and equipment, connected to the buses C_b; E – electromagnetic force.

If we compare differential equation of ferroresonance circuit state (3) with the equations of the theory of non-linear dynamics (2) it becomes obvious, that under the action of external periodic force, this oscillator may have three types of motions: periodic (with the basic frequency or multiple to it); pseudoperiodic (spectrum consists of the frequencies, non-multiple to basic one) and chaotic (continuous spectrum of frequencies). Also, it is important to note, that any of these types has its attractor – the set, where all the tracks, that started in a certain area of the space – basin of the attractors, converge.

For us it is important, that in spite of its improvidence, in phase space of dissipative systems attractors exist even for chaotic tracks. These are so called strange attractors – complex sets, that have much thinner structure at different levels of their divisions and non-integer dimensionality.

Thus, although it is practically impossible to forecast the location of the system at certain moment of time, in certain point of phase space, area of object location and its motion to the attractor is foreseen.

This gives grounds to state, that there exists the possibility to evaluate the availability of necessary conditions to chaotic ferroresonance process in real electric networks at any combination of parameters, since it is sufficient to study the attractions of dissipative system. That is why, in spite of the existence of chaotic improvidence of ferroresonance process, the availability of attractors and their basins shows the possibility of dangerous zones determination in the space of parameters change.

Methods of bifurcation diagrams of the point, where the system passes from one type of mode into another, may be used to reveal the zone of dangerous values of parameters, that may cause chaotic ferroresonance. The search of these points can be carried out by means of direct calculations but each parameter will require tens of thousands of these calculations. That is why, it is expedient to perform the directed exhaustive search of possible variants: more from one point of stability to another point of stability to another point, performing linear search in the vicinity of the last point – setting on points of control. For this purpose we used WiNPP software package, that is freely accessible. The package has two functional parts. The first part enables to find initial point for construction bifurcation diagram, i.e., normal steady-state mode without overvoltages. The second part enables to realize the method by the chosen parameter of equivalent circuit of the ferroresonance circuit. The results can be observed in the form of serial construction of bifurcation diagram [4].

To carry out the research dealing with availability of necessary conditions of chaotic ferroresonance emerging in the circuit of switch gear of substation of rated voltage 330 kV (Fig. 1), the system of equations was calculated, the system was used in the program WiNPP. For this purpose differential equation was considered:

$$\frac{d\psi}{dt} + \frac{1}{C}\int idt + Ri = E' \sin \omega t, \tag{4}$$

where R – losses in windings, caused by loading of the secondary winding of the voltage transformer; E' – equivalent electromotive force, determined by the expression: $E' = E\frac{C_s}{C_s + C_b}$.

Approximation of magnetization curve of voltage transformer was carried out by the polynomial of 11 th degree.

$$i_L(\psi) = a\psi + b\psi^{11}, \tag{5}$$

where i_L – magnetization current ; a, b – approximation coefficients of voltage transformer magnetization curve.

Then the system of equations for WiNPP program may be written as:

$$\begin{cases} \dfrac{d\psi}{dt} = \psi_1; \\ \dfrac{d\psi_1}{dt} + \dfrac{G + aRC + 10bRC\psi^{10}}{C(1+RG)}\psi_1 + \dfrac{a}{C(1+RG)}\psi + \dfrac{b}{C(1+RG)}\psi^{11} = E'' \cos \omega t, \end{cases} \quad (6)$$

where E'' – equivalent electromotive force, calculated by the formula: $E'' = \dfrac{\omega}{1+RG}E'$.

Calculations, made by means of WINPP program showed that chaotic ferroresonance is initiated in limited range of capacitances values of switch gear buses of substation “Pivnichna”, 330 kV of the Central energy system, and in the process of transition from normal mode to chaotic ferroresonance bifurcation is observed. After construction of bifurcation diagram for loading parameter it was determined that bifurcation with the emerging of chaotic ferroresonance is possible only to the value of resistance of 500 MOhm. Further on the diagram, branches of only ferroresonance on the basic frequency emerge.

Conclusions

Emergence and development of chaotic ferroresonance in high voltage electric networks is studied by means of mathematical model, that describes chaotic ferroresonance processes more adequately as compared with conventional models. Analysis was performed for substation “Pivnichna” 330 kV of the Central energy system. Similar studies may be carried out for typical circuits of switch gears of 110 – 500 kV substations with electromagnetic voltage transformers.

The results of the given studies can be applied in the process of development of new normative document of the Ministry of Energy and Coal Mining of Ukraine, regarding the revealing of ferroresonance processes in high voltage electric networks and avoiding them, as well as for the development of new software to be used in energy systems of National Energy Company “Ukrenergo”.

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