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INVESTIGATION OF FERRORESONANCE IN ELECTRICAL NETWORKS AT OPEN-PHASE OPERATING CONDITIONS

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Abstract: This paper presents the analysis and simulation of occurrence and development of ferro-resonance in real electrical networks. The necessary and sufficient conditions for ferroresonance occurrence have been examined. It has been shown that in electrical networks this phenomenon is non-linear, so some special methods should be applied. A computer simulation has been performed to calculate the ferroresonance mode. During the analysis the application of the Jiles-Atherton model has allowed taking into account the hysteresis effect and improving the reliability of simulation. The ways of preventing ferroresonance phenomena in electrical networks at open-phase operating conditions are presented.

Key words: ferroresonance, open-phase mode, electrical networks.

1. Introduction

Ferroresonance is complex nonlinear oscillations that can occur in electrical circuits with serial or parallel connection of nonlinear inductance and capacitance. Methods for ferroresonance study have been already developed for many decades.

According to practical experience and theoretical studies this phenomenon leads to the occurrence of high overvoltages and overcurrents with high levels of harmonic distortion and it cannot be eliminated by traditional means of overvoltages and overcurrents suppression.

In electrical networks, ferroresonance can cause serious damage of the equipment and long-term failure of power supply. Therefore, it must be avoided by all means. Since the number of failures caused by the ferroresonance has not been reduced in the course of networks operation, the given problem is relevant in the present.

In electrical power systems, ferroresonance may occur either at fundamental frequency or at one of the subharmonic or higher order harmonic frequencies. The nonlinear transformer introduces those current and voltage harmonics. Ferroresonance emerges when a capacitance and an inductance tune in with one of these harmonics. Ferroresonance is found to occur at the fundamental frequency mainly while subharmonic ferroresonance may also happen sometimes. In the latter case the ferroresonant overvoltages are less severe and more difficult to mitigate. Such type of ferroresonance occurs sometimes in an extra high voltage transmission network where a voltage transformer is connected to a de-energized transmission line that runs alongside an energized line [1].

Ferroresonance is also considered as a jump phenomenon. The system suddenly jumps from one stable state (the normal mode) to another stable state (the ferroresonant mode) upon a system disturbance, such as a small change in system voltage, circuit capacitance, or transients. This sudden jump is sometimes referred to as bifurcation. Researchers investigated it analytically or by using time domain methods, such as numerical integration techniques. Nowadays they are trying to investigate this phenomenon more deeply by applying the theory of nonlinear dynamics and chaos [2].

2. The ferroresonance conditions

For the occurrence of ferroresonance phenomena in electric networks the necessary and sufficient conditions must be fulfilled. The ferroresonance presence can be expected if the following characteristic features are observed: phase-to-phase and/or phase-to-ground over-voltages; overcurrents; voltage and current distortions; neutral shift; transformer heating (in no-load mode); too loud continuous noise from transformers and reactors; failure of electrical equipment (such as voltage trans-formers). In such cases, the necessary and sufficient con-ditions of ferroresonance processes should be checked.

The necessary conditions include: the presence of relatively large capacitance in electrical networks (long aerial transmission lines; shorter, but relatively more capacitive underground cable lines; capacitive voltage dividers in circuit breakers; capacitive voltage transformers etc.) and the presence of an inductive element with a ferromagnetic core (power transformers, electromagnetic voltage transformers, etc.).

The sufficient condition is the appearance of the relevant disturbance that precedes and induces ferro-resonance (atmospheric overvoltage, connection or disconnection of transformers or loads, short circuit occurrence or clearance and others).

Ferroresonance occurs in power distribution systems with open-phase supply of a power transformer on no-load or low-load, when the transformer coil is fed through the capacitive coupling from other phases or from parallel lines. In such a case, the linear phase-to-phase and phase-to-ground capacitances of the transmission line and the nonlinear inductance of the transformer could compose a series resonant circuit.

Some typical system disturbances that may cause ferroresonance in power distribution system at open-phase operating condition are:

- Sudden de-energization of one phase while the other two phases remain energized. For instance, when a phase conductor is accidentally damaged, or upon loss of a phase due to a blown fuse as a result of a phase-to-ground fault.
- Open-phase switching-on: for instance, two phases are connected simultaneously when the third phase remains open for a few cycles. This could happen in distribution systems where single phase switching is performed. Single phase fuses are still commonly used in rural power grids due to their relatively low cost and also because their utilization enables limited power transmission to be sustained after clearance of frequently-occurring single phase-to-ground faults by powering out the damaged phase.
- Open-phase switching-out may lead to similar ferroresonant overvoltages as open-phase swithing-on.

As it has been mentioned above, such asymmetrical switching operations can lead to essential overvoltage when a transformer at no-load or low load is connected to a transmission line that operates with ungrounded neutral. But the situation gets more difficult when ferroresonance circuit is supplied not only through line capacitance, but also through electromagnetic coupling.

This situation occurs in subtransmission substations with circuits where the step-down transformer is connected to the line by means of a shorting device and disconnector, rather than by a high-voltage circuit breaker. Usually, the step-down transformer has high-voltage wye-connected windings with grounded neutral and low-voltage delta-connected windings. There is a possibility of such dangerous incidents as switching-out or switching-on of a line connected to a transformer on no-load or low-load by operating one of the line breakers and with its other breaker being open (Fig. 1).

The application of three-winding transformers creates favorable conditions for the initiation of ferroresonance, because the tertiary winding has considerably lower power than other windings. Therefore, the leakage inductance of the lowest-voltage winding referred to the primary one is very high.

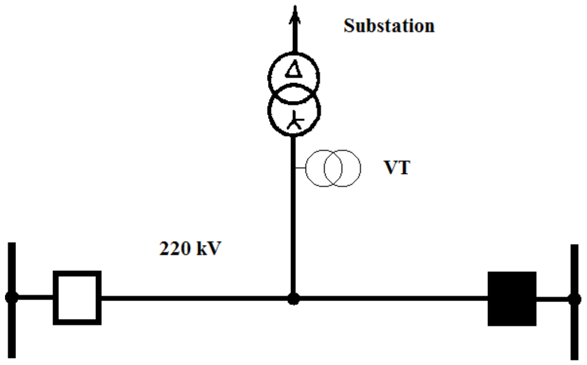

Fig. 1. The ferroresonance occurrence in Ukrainian electrical network.

It should be noted that corona discharge substantially restricts overvoltages due to additional energy losses. However, in a ferroresonance circuit, strong electromagnetic coupling diminishes this effect, so overvoltages can be still significant [3].

Ferroresonance phenomena are featured by long-lasting transients, therefore the use of traditional methods and techniques utilized in studying electromagnetic transients are often ineffective in their case. The most suitable method to be used here is a computer simulation. It has been used for investigation of an accident in Ukrainian electrical network (Fig. 1).

The substation (Fig. 1) is connected to 220 kV line. The line was scheduled for repair. One of the high-voltage circuit breakers worked properly, but another one failed (open-phase swithing-out – only two phases cut out). The personnel of the substation noted a specific loud noise in the voltage transformer VT lasting for about fifteen minutes. Then the noise stopped. After thirty minutes since the start of the commutation, the high-voltage circuit breaker was manually switched out. The voltage transformer VT exploded, when the line was switched on after repairs. A subsequent analysis test indicated decomposition of oil and solid insulation. Close examination of the transformer details also revealed a smell of burnt insulation.

The simulation of the process caused by open-phase operation has been performed for this network and it has been shown that ferroresonance occurred in both transformers connected in parallel (power transformer and voltage transformer). The voltage transformer was damaged first, because it was weaker than the power one.

3. Modeling nonlinear core characteristics of transformers

As mentioned earlier, the appearance of ferroresonance processes in electrical networks requires the existence of an inductive element with a ferromagnetic core. This condition can be fulfilled by the presence of a power transformer on no-load or low-load and a voltage transformer. The accuracy of the mathematical models of the transformers influences considerably the reliability of the results of ferroresonance calculations.

The nonlinear characteristic of the transformers is described as the dependency of magnetic flux density B on magnetic field intensity H (magnetization curve):

$$B = m_0 (H + M), \tag{1}$$

where $m_0 = 4p \cdot 10^{-7}$ *H/m* is the permeability of vacuum; M is magnetization.

For modeling of the power and voltage transformers analytical methods (eg, harmonic balance method) can be used. However, to develop more accurate and adequate mathematical models of the transformers the effect of hysteresis must be taken into account. To simulate the behavior of transformers in electrical networks, the application of Jiles-Atherton model is the most appropriate way [4, 5]. That model was developed with the focus on computer simulation and has a stable algorithm. This model can be described by differential equations; it uses only five parameters and needs only one hysteresis loop, obtained experimentally, for its identification. It should be noted that the original Jiles-Atherton model is valid only for isotropic materials.

According to Jiles-Atherton model, the total magnetization M can be written as the sum of irreversible magnetization M_{irr} and reversible magnetization M_{rev}.

The irreversible magnetization can be determined from the equation:

$$\frac{dM_{irr}}{dH} = \frac{M_{an} - M}{kd - a(M_{an} - M)} \tag{2}$$

where M_{an} is anhysteretic magnetization; k, *A/m* is the value of the hysteresis loop coercive force that determines the width of the hysteresis loop; d is a direction parameter, which takes on the values of either 1 (for $dH/dt > 0$) or −1 (for $dH/dt < 0$); a is a parameter that quantifies the interdomain coupling in the material.

The anhysteretic magnetization can be written as the modified Langevin function:

$$M_{an} = M_s \left(coth\left(\frac{H_e}{a} \right) - \frac{a}{H_e} \right), \tag{3}$$

where M_S is saturation magnetization; $H_e = H + aM$ is effective field acting on magnetic moments within domains [6]; a, *A/m* is a form factor for the anhysteretic curve which is determined as the value of magnetic field intensity at which $M_{an} = M_s / 2$.

The reversible magnetization can be described by the differential equation:

$$\frac{dM_{rev}}{dH} = c\left(\frac{dM_{an}}{dH} - \frac{dM}{dH} \right), \tag{4}$$

where c is the reversibility coefficient which ranges from 0 (completely irreversible magnetization) to 1 (completely reversible magnetization).

Then, the total magnetization can be written as:

$$\frac{dM}{dH} = \frac{1}{(1+c)} \frac{(M_{an} - M)}{kd - a(M_{an} - M)} + \frac{c}{1+c} \frac{dM_{an}}{dH}. \tag{5}$$

Using the mathematical model (5) we can simulate all hysteresis characteristics, such as initial magnetization, saturation, hysteresis losses, etc.

4. The results of ferroresonance simulation

The developed nonlinear inductance model makes it possible to assess directly the impact of losses in the steel on the character of ferroresonance processes in electrical networks. Simulation results of ferroresonance phenomenon at open-phase operating mode have shown that after the ferroresonance initiation the current sharply increased up to several amperes in the high-voltage winding of the voltage transformer. As the result of overheating in the high-voltage winding, short-circuits occurred. Those short-circuits changed the inductance of the voltage transformer, thus the ferroresonance loop was changed and process was terminated, but the winding damage caused subsequently an explosion.

The results of simulation have shown impossibility of suppression with the aid of valve-type arresters. When the voltage of the neutral point reaches a magnitude sufficient for operation of a valve-type arrester, breakdown of its spark gaps occurs and a current surge appears. Voltage decreases promptly to its minimum value, further it rises and then rather slowly decreases once more. At the second and third operation of the valve-type arrester the voltage is less than at first one. Therefore, at consequent operations of the valve-type arrester the amplitude of its high-frequency current component rises and so the necessity for cutting off the current in the valve-type arrester occurs. In turn, it prompts recurrence of the voltage ferroresonance. The calculation has shown that after actuating the valve-type arrester and arc decay of the accompanying current, the overvoltage recurs and is repeatedly reduced in the course of new operation of the valve-type arrester and consequent current decay etc. If the ferroresonant overvoltages were not reduced within specifid time period, sooner or later the arrester would be destroyed due to thermal runaway.

According to simulation results, the above-mentioned ferroresonance can be prevented by ground connection of the neutral of the transformer on no-load through the resistor during open-phase operation of the power line. The value of the resistance in the neutral is determined according to following requirements: to ensure preventing the ferroresonance, not to interfere with the operation of relay protection, to ensure lightning protection of the neutral, and to comply with production conditions. Those requirements are satisfied when the resistance value is of 2 kΩ. Apart from the resistor protection of the transformer from the ferroresonance, it is suggested that the current through the resistor should be continuously monitored, otherwise the resistor may be damaged. By the way, if the delta winding of the power transformer can be open, the conditions of ferroresonance would be eliminated.

For ferroresonance suppression a standard shorting device can be used. In this case there are two variants of its operation: the short-circuiter is used on live phase, so that its actuation causes opening this phase by means of a high-voltage circuit breaker; the short-circuiter is used on open phase and the current which appears in the circuit is approximately equal to the current of the transformer on no-load and the voltage on other open phase equals 0.5 phase voltage. Therefore, utilization of a standard shorting device insures switching-out the line (if eliminator is blocked) or interruption of the dangerous state [7].

5. Conclusion

The analysis of ferroresonance occurrence in the real Ukrainian electrical network at open-phase operating conditions has been conducted. Jiles-Atherton model allows taking into account the hysteresis effect and increasing the reliability of computation results. Thus, the result obtained is the nearest equivalent to the real situation. The proposed methods of the prevention of ferroresonance phenomena help to avoid damage of the main equipment of electrical networks.

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ДОСІДЖЕННЯ ФЕРОРЕЗОНАНСІВ В ЕЛЕКТРИЧНИХ МЕРЕЖАХ ПРИ НЕПОВНОФАЗНИХ РЕЖИМАХ РОБОТИ

Ірина Тугай

У цій статті наведено аналіз виникнення і розвитку ферорезонансу в реальних електричних мережах. Розглянуто необхідні та достатні умови для появи ферорезонансного процесу. Показано, що це явище в електричних мережах є нелінійним, тому повинні застосовуватися спеціальні методи. При проведенні розрахунку було використане комп'ютерне моделювання та модель Джілса–Атертона, що дозволило взяти до уваги ефект гістерезису і підвищити надійність моделювання. Запропоновано шляхи запобігання ферорезонансним явищам в електричних мережах при неповнофазних режимах роботи.

Iryna Tugay graduated from National Technical University of Ukraine “Kyiv Polytechnic Institute” (major in “Electrical Networks and Systems”). She defended her PhD dissertation at the Institute of Electrodynamics of NAS of Ukraine, in Electrical Power Plants, Networks and Systems. She has been working as Senior Research Fellow at the Department of Power-Supply Systems Optimization of Institute of Electrodynamics. Her areas of interest include electrical networks and supply systems, computer simulation of power systems.