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Experimental Investigations of Temporary Overvoltages

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Abstract: In this paper experimentally determined temporary overvoltages in the electrical power system of Yugoslavia due to: earth faults, load droppings, performances with incomplete phases, Ferranti effects, switching-in unloaded transformers, energizations of overhead lines terminated with unloaded transformers and another switching operations are considered.

On the basis of their analysis, the measures and the means for their reduction and prevention are given.

Keywords: Temporary overvoltage, earth fault, overhead line, transformer.

1 Introduction

Temporary overvoltages are undamped or weakly damped overvoltages having oscillatory nature and relatively long duration [1]. Their frequency of oscillation is most frequently close to the power frequency, but can be even several times lower or higher than the power-frequency.

Overvoltages can provoke significant voltage stresses on insulation and furthermore, thermal overloading and damaging of surge-arresters without spark-gap, thermal overloading of voltage and power transformers, impeded interruption of follow current and damaging of surge-arresters with spark-gap, and the like. Temporary overvoltages occur most frequently as the consequence of: earth- faults, load droppings, performances with incomplete phases, Ferranti effects, switching-in unloaded transformers, switching-in lines terminated with unloaded transformers and other switching operations. These phenomena are considered in the electrical power system of

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Yugoslavia. Presented are phenomena of temporary overvoltages, which occurred as the result of experimental investigations of overvoltages in high-voltage networks [2, 3, 5, 7, 8, 9, 10, 11].

2 Temporary overvoltages due to earth fault appearance

Single phase-to-earth fault is one of the most frequent faults in an electrical power system. Its occurrence causes the permanent disturbance (perturbation) of the system of phase voltages. In other words, occurrence of the single phase-to-earth fault causes the permanent change of the phase voltage amplitudes and their phase angles. Durably increased values of phase voltages, over the values they had before the earth fault occurred, are presenting temporary overvoltages.

They are lasting in the network until an earth fault disappears. Their height depends on the way the network is grounded, that is, on the relation between network positive sequence and zero sequence impedances and their phase displacement. In the networks with isolated neutral point, temporary overvoltages when an earth fault occurs, are equal to phase-to-phase voltages. This is the most common case for networks earthed through a reactor for the compensation of earth-fault current. For resistor earthed networks, temporary overvoltages occurring by earth fault can be over the phase-to-phase voltage level; their values, besides on positive sequence and zero sequence network impedances, are dependent on resistor resistance as well. For solidly earthed networks, such as 110 kV, 220 kV and 400 kV networks in Yugoslavia, the maximum value of temporary overvoltages they can reach due to earth-fault is 40% over the phases voltage values, which existed before the earth fault occurred. Experimental investigations of temporary overvoltages at earth fault appearance are accomplished in the networks from 6 kV up to 400 kV nominal voltage. In the 400 kV, 220 kV and 110 kV networks there were not many investigations because of possible undesirable consequences, which may occur during earth fault due to the appearance of high currents. Most frequently, investigations were performed before putting into work newly built parts of a system (2, 3, 5), but also during exploitation. Earth-fault has been accomplished on the 400 kV, 220 kV and 110 kV lines, usually several kilometres far from transformer substation (S), and the voltages were registered on the TS busbars. Carried out were 9 earth faults (3 on 400 kV, 2 on 220 kV, and 2 on 110 kV lines). Phase-to-earth voltages on S busbars of phases, which are not under earth-fault, were most frequently lower in relation to voltages existing before earth-fault appearance, however after earth-fault disengagement they turned back to their previous values. Only at one earth-fault in the 220 kV network, phase voltages had higher values in relation to those before earth-fault, but did not exceed 1,20 p.u. values.

In 6 kV, 10 kV and 35 kV networks a large number of experimental investigations of temporary overvoltages at earth fault appearance has been carried out [10, 11, 12, 13]. Earth fault in the networks was performed by switching-in the circuit-breaker of the line on which previously was made metal connection between one phase and earth, and in the networks with isolated neutral point, earth-fault was performed by approaching an earthed metal part to one of network phase conductors [10, 11]. In all these networks the voltages on phases which are not under earth-fault, during earth-fault duration, were reaching approximately the values of phase-to-phase voltages, and on the phase under earth-fault the voltage approximately dropped to zero (earth fault has been made on the line beginning) (Fig.1).

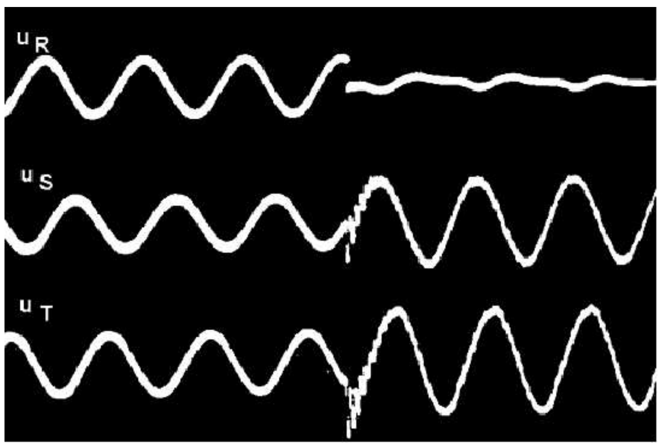


Fig. 1. Phase-to-earth voltage waveforms in 35 kV neutral isolated network on appearance of a metal earth fault in phase R.

3 Temporary overvoltages due to load dropping

Load dropping in electrical power system presents unplanned change in power flows and balances in one part of the electrical power system. It is originated by: switching-out large consumers, falling out of service heavily loaded overhead lines and transformers, or the appearance and switching-out of short-circuits [1, 4, 6, 11]. They are characterised by a transient process, which is being developed predominantly in the period of several milliseconds, after switching-out consumers and with a longer process of increased voltage in electrical power system. This longer process is lasting from several hundred milliseconds to several seconds; therefore, overvoltages due to load dropping are classified as temporary overvoltages. The duration of temporary overvoltages due to load dropping is directly dependent on the velocity of action of automatic voltage-regulator.

Voltage increase in a system is dependent on the relation of reactive power engaged by consumers before dropping out and generator apparent power. The higher this relation the higher the overvoltages.

Experimental investigations were carried out in hydro-power plants HE "Djerdap I" and HE "Djerdap II". At load dropping of one of generators by different characteristical loadings, temporary overvoltages did not exceed 1,14 p.u. value [11]. In the course of experimental investigations on 400 kV transmission line "Nis - Kragujevac" after switching-out an earth-fault the phenomena of temporary overvoltages occurred [3]. Namely, by switching-out the earth-fault on the phase 8 of 400 kV line "Nis - Kragujevac", several kilometres from S "Kragujevac 2", the voltages of two healthy phases turned back to the values existing before earth-fault, and than after one pole APU (automatic reclosing), they increased for approximately 20%. This occurs with the voltage on the phase 8 as well, which also obtains the value like those on the phases 0 and 4. Owing to this phenomenon the overvoltage protection reacted (this protection exists no more) which switched-out three poles of "Nis - Kragujevac" line in S "Kragujevac 2".

4 Appearance of ferroresonance

Ferroresonant oscillations belong to temporary overvoltages. They are characteristic for the networks with isolated neutral point, but can be met in some network configurations having another treatment of neutral point.

In the networks with isolated neutral point can appear phase-to-phase voltages above normal values in the shape of stationary periodic oscillations, which can lead to insulation damage or more frequently to thermal stresses of individual elements of the network [10, 11, 15].

Oscillations are based on the mutual influence of a part of network capacitance and non-linear winding inductance of power transformer, or more frequently, non-linear inductance of one-pole earthed inductive voltage transformers. These oscillations are called ferroresonant oscillations and the phenomenon is called ferroresonance.

Networks with isolated neutral point can have, under some conditions (not simultaneously), two quite different stationary states in relation to earth: normal and ferroresonant state with phase-to-phase voltages considerably higher than normal. Since consumers are connected to phase-to-phase voltages, which are stable, they perform normally, no matter what is the condition between the network and the earth.

Transition from one state of the network to another is caused by transient processes, which occur due to temporary earth-fault, switching operations, and the like.

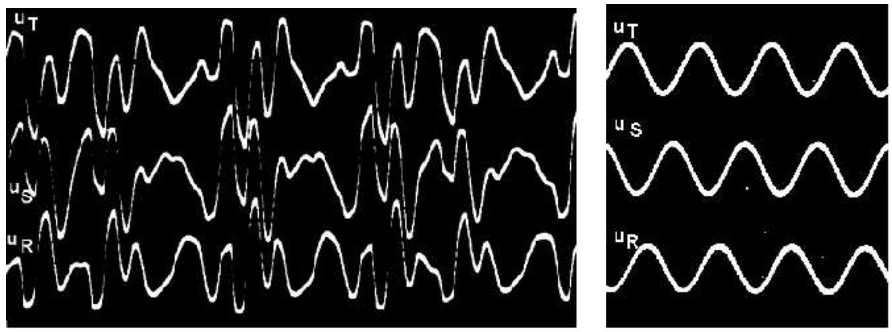
Experimental investigations in 6 kV, 10 kV and 35 kV networks with isolated neutral point have shown the existence of ferroresonant oscillations with different frequencies, namely with:

- triple network-frequency (third-harmonic ferroresonance)
- approximately double network-frequency (second harmonic ferroresonance)
- network-frequency (network-frequency ferroresonance),
- approximately one half of network-frequency (second subharmonic ferroresonance).

The analysis of investigation results has shown the following:

- Second-subharmonic ferroresonance appears most frequently, with voltages to earth 1,7 - 2,1 p.u. It appears predominantly after the disappearance of an earth-fault or as the consequence of circuit-breaker operations.
- When switching-in unloaded power transformers, which are feeding networks with isolated neutral point, ferroresonant oscillations appear on their secondary side. This is most frequently second harmonic ferroresonance with voltages to earth 2.5 - 3.6 p.u. (Fig. 2), and also third harmonic ferroresonance is being remarked with voltages to earth 2.7 - 3.7 p.u.
- By certain circuit-breaker operations network-frequency ferroresonance has appeared with phase to earth voltages up to 1.8 p.u.

In predominant number of cases during experimental investigations, when ferroresonant oscillations appeared, the measure for preventing them is applied - connecting resistors between the ends of the broken delta secondary windings of the voltage-transformer set. By application of this measure, ferroresonant oscillations were effectively eliminated. Resistor values



(a) (b)

Fig. 2. Phase-to-earth voltage waveforms of 6 kV network. (a) During 2nd-harmonic ferroresonance. (b) The same network without ferroresonance.

with which this was achieved amounted in some cases about hundred ohms, but most frequently from 20 Ω to 40 Ω. More efficient damping has been achieved with lower values of resistor. However, low values of resistor can cause overloadings of voltage transformers in the course of an earth fault.

5 Temporary overvoltages at operating conditions with incomplete phases

In the course of an electrical power system operation in its individual parts appear, really rare, operating conditions with incomplete phases. They are predominantly eliminated by protection operation, however it happens sometimes, that they hold on. They appear most frequently from following reasons: failure of closing of one or two circuit-breaker poles in the course of switching-in operation, failure of switching-out of one or two circuit-breaker poles in the course of opening operation and interruption of phase conductor [1, 4, 6, 11, 12]. In such situations in the parts of the system, where it happened, resonant or ferroresonant oscillations can occur, that is, temporary overvoltages as high as 3 p.u.

More probable is the possibility of the appearance of temporary overvoltages by operating conditions with incomplete phases in the networks having isolated neutral point than in the networks with another treatment of neutral point. Their appearance, as well as their amplitude, depends on the line capacitance connection and non-linear inductivity of power transformer. The presence of consumer decreases overvoltages or restrains their appearance. Such configurations can appear in the course of the network formation, because of protection operation during network normal operating conditions or owing to fault appearance (interruption of the phase conductor with or without touching the ground).

Appearance of incomplete phases operating conditions led in some cases to the occurrence of damage in the electrical power system of Yugoslavia. Two of such occurrences were particularly intensive [11]. The first of previously mentioned occurrences was the case of incomplete phases operating conditions (during opening operation, two poles of the 110 kV circuit-breaker of 110 kV / 35 kV / 10 kV power transformer, loaded on 35 kV side did not open) which caused transformer damage. Second occurrence of incomplete phases operation (in the course of opening operation, two poles of 110 kV line circuit-breaker did not open; through this circuit-breaker, over 110 kV / 35 kV / 10 kV transformer, 35 kV network was fed) led to equipment damage in 35 kV network and 0,4 kV network which was fed from 35 kV/10 kV and 10 kV/ 0,4 kV transformers.

Long-term overvoltages, due to operation with incomplete phases, can endanger network insulation; therefore, such operating regimes should be eliminated as soon as possible. Because of possible damages of equipment insulation, experimental investigations at operating conditions with incomplete phases in electrical power system of Yugoslavia were not carried out.

6 Temporary overvoltages due to ferranti effect

The effect of voltage rise on the ends of unloaded transmission lines is called line capacitive effect or Ferranti effect. Thus raised voltages on transmission lines are classified into the set of temporary overvoltages. They are significant only for very long lines. They are not interesting for the lines of electrical power system of Yugoslavia where the lines over 200 km are not met. This also have shown experimental investigations on several 110 kV, 220 kV, and 400 kV overhead lines [12]. For the longest unloaded 400 kV line "Djerdap - Beograd 8 " of 204 km length (now it is divided into two parts "Djerdap - Drmno" and "Drmno - Beograd 8") temporary overvoltages at its ends did not exceed 1.025 p.u.

7 Temporary overvoltages by switching-in unloaded transformers

When switching-in unloaded transformers high currents can appear, several times higher than their rated current. Besides basic current-harmonic, current contains direct component and higher harmonics, which can be significant. In the case were the network has low short-circuit power and with presence of higher capacitances, the appearance of resonance with significant temporary overvoltages is possible.

With experimental investigations of transient regimes when switching-in unloaded transformers and autotransformers in electrical power system of Yugoslavia (investigations were performed for switching-in 5 autotransformers and 5 transformers) established are also the appearances of temporary overvoltages [2, 3, 5, 7, 11] They appeared when switching-in 400 kV/15,75 kV/ 15,75 kV generator transformer at no-load in HPP "Djerdap" and 400 kV / 220 kV / 31 kV autotransformer at no-load in S "Beograd 8" during putting into work 400 kV network, when its short-circuit power was small. They reached the values even up to 1,4 p.u.

During switching-out transformers and autotransformers at no-load in 400 kV, 220 kV and 110 kV networks, when their short-circuit power was significant, there were no temporary overvoltages.

8 Temporary overvoltages when switching-in lines loaded with transformer at no-load

When switching-in the line loaded with the transformer at no-load, the appearance of raised voltages takes place, which contain higher harmonics, particularly second, third and fifth. They are more pronounced as if the network is of low short-circuit power. This appearance of overvoltages because of longer duration and faint damping is classified to temporary overvoltages.

During experimental investigations of transient regimes at switching-in lines loaded by a transformer or autotransformer at no-load in electrical power system of Yugoslavia (investigations were performed in eight different network configurations) established are also temporary overvoltages [2, 3, 5]. The highest values of these appeared in the networks with low short-circuit power and reached values up to 1.5 p.u. This took place by switching-in from HPP "Djerdap" 400 kV line "Djerdap - Beograd 8" loaded in S "Beograd 8" with autotransformers 400 kV / 220 kV / 31,5 kV at no-load and by switching-in of the same line from S "Beograd 8" loaded in HPP "Djerdap " with generator transformer 400 kV / 15,75 kV / 15,75 kV [2].

In the networks with high short-circuit power, when switching-in the lines loaded with transformer or autotransformer there were no temporary overvoltages or they were insignificant.

9 Conclusions

On the basis of the analysis of temporary overvoltages and determining the configurations in which they appear, the following conclusions can be brought:

- The selection of the network kind influences significantly the characteristics of operational configurations. Solidly earthed networks (earth-fault factor ¡ 1,4) have the lowest conditions for origination and continuation of high temporary voltages. Networks with isolated neutral point or networks earthed through reactors are exceptionally inclined to the development and continuation of high temporary voltages.
- Existing 10 kV and 35 kV networks with isolated neutral point should, desirably, be earthed through a resistor having low value. 6 kV networks with short-circuit current over 10 A should be divided unto sections.
- Networks with isolated neutral point should be protected from possible appearances of ferroresonance. From a number of possibilities, proposed is a simple and effective measure: introduction of a resistor about 10 O for 35 kV networks and about 20 O for 10 kV and 6 kV networks, between the ends of open delta secondary windings of one pole earthed inductive voltage transformer sets.
- Earth-fault in the networks with isolated neutral point, should be eliminated immediately after its appearance, if production technology enables it.
- Probability of the appearance of incomplete phases operational regimes (conductor interruption and functioning failure of one or two poles of switching equipment) as well as their duration, should be reduced to minimum. This is in direct connection with the quality of maintenance of substation and switching equipment as well as relay protection.
- In order to reduce the duration and amplitudes of temporary overvoltages due to load dropping, it is necessary to apply fast regulators of generator voltage.
- For large and significant transformer substations and distribution systems detailed analyses of temporary voltages for all presumed irregular states should be performed, in order to choose, on the basis of these analyses , optimal measures for elimination and restriction of temporary overvoltages.

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