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Ferroresonance in 35 kV isolated networks: causes and mitigations

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Abstract. The ferroresonant states associated with inductive voltage transformers may be generated by elimination of single-phase short-circuits in isolated distribution networks. The paper presents a qualitative analysis of causes of ferroresonance initiation, and significant parameters impacting ferroresonance, like zero-sequence system capacitance and the number of connected voltage transformers. Using simulations, the causes of short-circuit occurrence for different system scenarios are investigated and damping devices for ferroresonance mitigations in a 35 kV isolated network are presented.

Keywords: ferroresonance, isolated distribution networks, inductive voltage transformer

Feroresonanca v 35 kV izoliranem omrežju: vzroki in zmanjševanje

V izoliranih distribucijskih omrežjih lahko pojavi feroresonanca pri izločitvi enofaznega kratkega stika pri induktivnih napetostnih transformatorjih. V članku analiziramo vzroke za začetek feroresonance in bistvene parametre, ki vplivajo na ta pojav: zmogljivost sistema ničtega reda in število priključenih napetostnih transformatorjev. S simulacijami kratkega stika v omrežju smo analizirali vzroke za nastanek feroresonance pri različnih scenarijih. Predstavili smo tudi gradnike za zmanjšanje feroresonance v 35 kV izoliranem distribucijskem omrežju.

1 INTRODUCTION

Ferroresonance is a nonlinear dynamic phenomenon which belongs to the group of low-frequency electromagnetic transients [1]-[3]. Basic preconditions for the ferroresonance occurrence are a sine-wave source, capacitance, nonlinear inductance and relatively small loss in the system. Ferroresonance appears in the following modes: a periodical, pseudo-periodical, subharmonic and chaotic mode [4]-[5]. Results of ferroresonance are permanent overvoltages and overcurrents in the system, which can affect the normal operation mode of the equipment, equipment malfunction, or its total damage [6]-[7]. The most common examples of ferroresonances are serial feroresonance due to compensation, ferroresonance with irregular operations in three-phase breakers, and ferroresonance with an inductive voltage transformer [1]-[2]. With a high voltage inductive transformer, single-phase ferroresonance can be initiated between a grading and bus capacitance together with a nonlinear inductance voltage transformer. In the middle voltage isolated distributed networks, initiation of ferroresonance occurs between the zero-sequence system capacitance and non-linear inductance of the voltage transformer. In a case of isolated distribution networks, initiation of ferroresonance is usually due to elimination of a single-phase short-circuit from the system. This particular type of ferroresonance is the topic of this research. A special attention is devoted to the analysis of significant parameters on this type of ferroresonance.

The remainder of this paper is organized as follows. Section II presents conditions of initiation of ferroresonance and analysis of important parameters in the electrical circuit for the ferroresonance occurrence. Section III describes ferroresonance in three-phase isolated networks due to single-phase short-circuits. Section IV shows the simulated results for the different scenarios in the electrical distribution network. Section V concludes this paper.

2 PARALLEL FERRORESONANCE

For a simplified description of the ferroresonance phenomena, in most literature, a serial ferroresonance circuit [1]-[2], [5] is analyzed. However, in isolated three-phase networks, ferroresonance can be classified into parallel ferroresonance due to the parallel connection zero-sequence system capacitance (line or cable to the ground capacitance) and nonlinear inductance of the inductive voltage transformer. In order to qualitatively analyze conditions for initiation of ferroresonance in the inductive voltage transformer, a simplified nonlinear circuit shown in Fig. 1 is analyzed.

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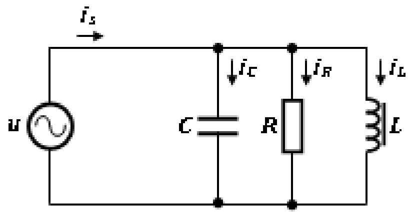

Figure 1. Simplified parallel ferroresonant circuit.

In Fig. 1, u is the input terminal voltage, C is the system capacitance of lines or cables, R is the resistance due to system losses, and L is the nonlinear inductance of the voltage transformer iron core. For the electrical system in Fig. 1, in the time domain, we have the following:

$$i_s(t) = i_R(t) + [i_C(t) + i_L(t)] = i_R(t) + i(t) \tag{1}$$

Let us suppose that the input current is a sine wave with effective value I_s. After transformation into a phasor, and in the domain of effective values, we get the following system of nonlinear algebraic equations:

$$I_s = \sqrt{\frac{U^2}{R^2} + I^2} \tag{2}$$

$$I = |f(U) - \omega C \cdot U| \tag{3}$$

In relations (2) and (3), the capacitance and resistor are shown with linear lines $I_C = \omega C \cdot U$ and $U = R \cdot I$. We can suppose that the inductance curve is defined with non-linear relation $I_L = f(U)$.

2.1 Normal ferroresonant states

At any time, the state of an electrical system can be obtained in the intersection on non-linear curves (2) and (3) in the voltage-current (U-I) the coordinate system as shown in Fig. 2.

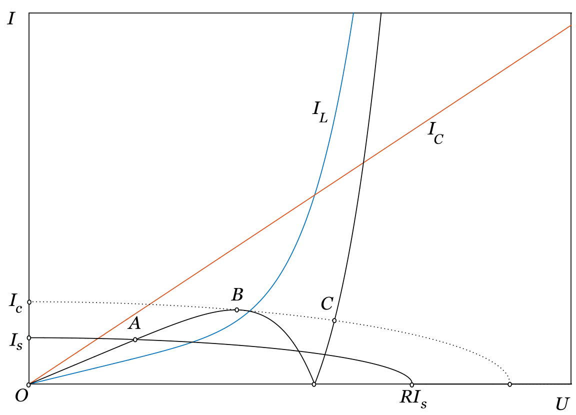

Figure 2. Nonlinear curves of a parallel ferroresonant circuit: basic case.

In a normal state, when the input current of the circuit is I_s, intersection of curves (2) and (3) are point A which corresponds to relatively small currents (voltages) in the electric circuit. When the current rises above critical value I_c, the operating point moves in the position of point C where the values of currents (voltages) in the circuit are large. When the input currents decrease to the starting values, large currents (voltages) remain in the circuit. Therefore, the circuit is in ferroresonance, which, by the theory of settings, remains indefinitely. To make it simple, to initiate ferroresonance, a change is sufficient, such as.an increased input current of the minimal value:

$$\Delta I_{\min} = I_c - I_s \tag{4}$$

Whenever the input current changes above the critical value of $\Delta I \geq \Delta I_{\min}$, ferroresonance is initiated.

2.2 Impact of the system capacitance

Let us now consider the case of increasing the capacitance in a system from C to $C_1 \geq C$, as shown in Fig. 3.

The change in the system capacitance is due to different places of elimination of the ground fault, as well as to a change in the number of connected lines and cables in a system.

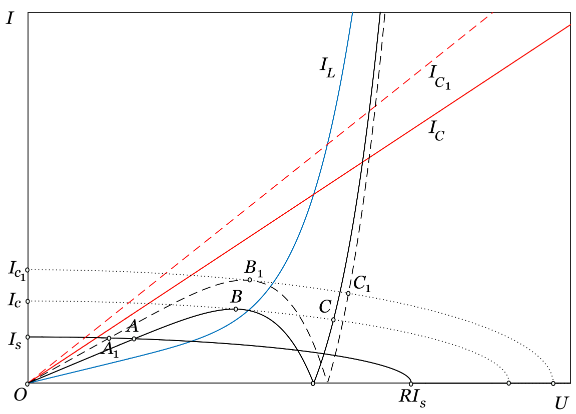

Figure 3. Nonlinear curves of a parallel ferroresonant circuit: a case of an increased system capacitance.

The system capacitance changes the mutual position of nonlinear curves (2) and (3). From Fig. 3 it is clearly seen that increasing the system capacitance leads to a negligible change of the operating point in a normal operating regime (point A_1). Increasing the input current for a minimal value leads to ferroresonance:

$$\Delta I_{\min_1} = I_{c_1} - I_s \tag{5}$$

According to Figs. 2 and 3, the following is applies:

$$\Delta I_{\min_1} \geq \Delta I_{\min} \tag{6}$$

Therefore, it can be concluded that during an increase in the system capacitance, a bigger change in the value of the input current to initiate ferroresonance in the circuit is needed. In other words, while the system capacitance increases, the probability of ferrorresonance initiation in a parallel non-linear ferroresonant circuit decreases. This statement is true for any system capacitance for ferroresonance initiation, i.e. curves I_L and I_C intersect. For a very small parameter C, for example, for which I_C is tangential on I_L, there is only one point of intersection of curves (2) and (3). So, in these scenarios, ferroresonance cannot be initiated at all.

2.3 *Impact of the nonlinear inductance curve*

Now consider the case of changing ("lowering") the curve of a nonlinear inductance (Fig. 4). This scenario happens when two or more inductive voltage transformers are connected on the same bus-bar, which makes the inductance at each point on a new curve smaller than the original inductance, i.e. on the corresponding points of the nonlinear curves, the relations are $L_1 \le L$ (Fig. 4).

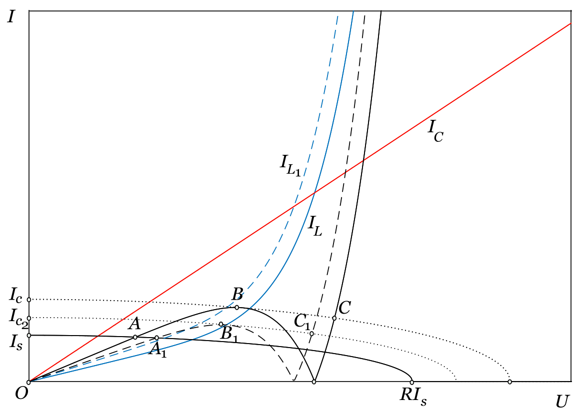

Figure 4. Nonlinear curves of a parallel ferroresonant circuit: the case of changing (decreasing) the inductance nonlinear curve.

Also in this case, with regard to a normal case, the mutual position of nonlinear curves (2) and (3) changes. As clearly seen from Fig. 4, by decreasing the inductance of the nonlinear curve, there is again, a small change in the location of the operating point in the normal operating regime (point A_1). In this case, ferroresonance will be initiated by an increased input current for a minimal value of the current:

$$\Delta I_{\min_2} = I_{c_2} - I_s \quad (7)$$

Based on Figs. 4 and 2, the following is true:

$$\Delta I_{\min_2} \le \Delta I_{\min} \quad (8)$$

One can conclude that for decreasing the non-linear inductance, there is a smaller change in the input current value needed to initiate ferroresonance in the circuit. In other words, decreasing the inductance at any point of the non-linear curve ("lowering" the nonlinear magnetizing curve) increases the probability of initiation of ferroresonance in a parallel nonlinear ferroresonant circuit.

It should be noted that a change in the resistance due to the system loss lead to an eventual damping or elimination of ferroresonance in the system. Namely, as shown in Fig. 2 due to a significant decrease in resistance R, curves (2) and (3) can have only one interception point in the normal operating regime. Therefore, a significant decrease in resistance R can assist in ferroresonance damping in the parallel circuit according to Fig. 1. This is achieved by connecting a resistor in an open delta on the secondary winding of an inductive voltage transformer.

3 Ferroresonance in a Three-phase Isolated Network Due to Short-Circuit Elimination

In this part we analyze a concrete example of a ferroresonance occurrence in a real part of an isolated electrical distribution network (Fig. 5). Ferroresonance is initiated by eliminating a single-phase short-circuit from the system, thus establishing a ferroresonance circuit over the neutral point of the system. In the ferroresonant circuit, the ground to phase capacitance of the cable or lines participates together with the associated nonlinear inductance of the inductive voltage transformers.

Depending on parameters of the electrical system, and as well as on the time of occurrence and elimination of a short-circuit in this three-phase system, ferroresonance can be initiated. Dominant parameters for ferroresonance initiation are the zero-sequence system capacitance and nonlinear curve of the voltage transformer. Other important factors are the residual magnetic flux and loss in the system [1]-[2]. Ferroresonance occurs upon elimination of a single-phase short-circuit from the system. Then, at each system phase, ferroresonant overvoltages appear. On the other side, the ferroresonance initiation is verified by the voltage of the neutral point of the system, which after elimination of the short-circuit turns back to the zero value. However, this voltage is held during the short-circuit (as expected) and after its elimination (which is an abnormal i.e. ferroresonant state). For this reason, it is practical to record the phase voltages, as well as the neutral point voltage, to determine the character of the electromagnetic transients.

The parameters of the real part of the analyzed 35 kV distribution network are:

Parameters of the system, ($j = 1,2,3$):

• source voltage: $e_j(t) = \sqrt{2}\frac{E}{\sqrt{3}}\sin\left[\omega t + (j-1)\cdot\frac{2\pi}{3}\right]$,
• voltage and frequency: $E = 35\ kV, f = 50\ Hz$,
• network resistance: $R_s = 0.055\ \Omega$,
• network inductance: $L_s = 0.5\ mH$,
• zero sequence system capacitance: $C = 150\ nF$.

Parameters of the inductive voltage transformer:
• rated power: $S = 50\ VA$,
• winding resistance: $R_p = 13.7\ k\Omega$,
• leakage inductance: $L_p = 23.5\ H$,
• iron core loss equivalent resistance: $R_m = 65.95\ M\Omega$,

The measured effective nonlinear curve of the current-voltage (I-U) of the inductive voltage transformer is converted to current-flux (i-φ) magnetizing curve following the procedure described in paper [8]. By using the fitting procedure, the nonlinear magnetizing curve of the voltage transformer is described using the following polynomial function:

$$i = a\varphi + b\varphi^5 + c\varphi^{11} \tag{9}$$

Constants in Eq. (9) are:

$a = 1.91\cdot 10^{-5}$, $b = 2.47\cdot 10^{-15}$, $c = 4.07\cdot 10^{-27}$.

The single-phase short circuit in phase 1 is modeled as an ideal breaker with switched on at time $T_0 = 40\ ms$ and switched off at time $T_1 = 295\ ms$.

4 Ferroresonance Simulation in a Three-phase Isolated Network

In this part of the paper, results of a ferroresonance simulation made with a model of a three-phase distributed network given in Fig. 5 are described.

The model is developed in the software package SimPowerSystems [9]. The model of a nonlinear inductance voltage transformer is proposed according to Eq. (10). When simulating a power transformer and inductive voltage transformers a special attention must be paid to solvers and integration steps as well as to the relative tolerance for the simulation configuration parameters. Namely, the form of the state space of a dynamic system with transformers exhibits an extremely stiff differential equation system [10]-[11]. So for this type of dynamic system simulations, the A and L stable numerical methods must be used as they are not prone to numerical oscillations and numerical instabilities. For this reason, for the ferroresonance simulation in a three-phase, a BDF-based solver ode 23tb is used, to implement a combination of the trapezoidal and BDF2 numerical method.

Three different scenarios of the electrical distribution network are analyzed: (a) basic case, (b) impact of the nonlinear magnetizing curve of the inductive voltage transformer and (c) impact of the system capacitance. In each scenario, the phase voltages of the system and voltage of neutral point of the network are simulated. The total simulation time is set at $T_{tot} = 2\ s$. The maximum value of the integration step is $\Delta t_{\max} = 1\ \mu s$, and the relative tolerance is $\varepsilon = 10^{-6}$.

4.1 Basic case of the isolated networks

In the basic case, an inductive voltage transformer is connected per phase and the basic zero-sequence system capacitance is $C = 150\ nF$.

All other parameters are the same as above in this paper. The simulated phase and voltage of the neutral point are shown in Fig. 6.

As seen from Fig. 6, there is no ferroresonance after elimination of a short-circuit from the system.

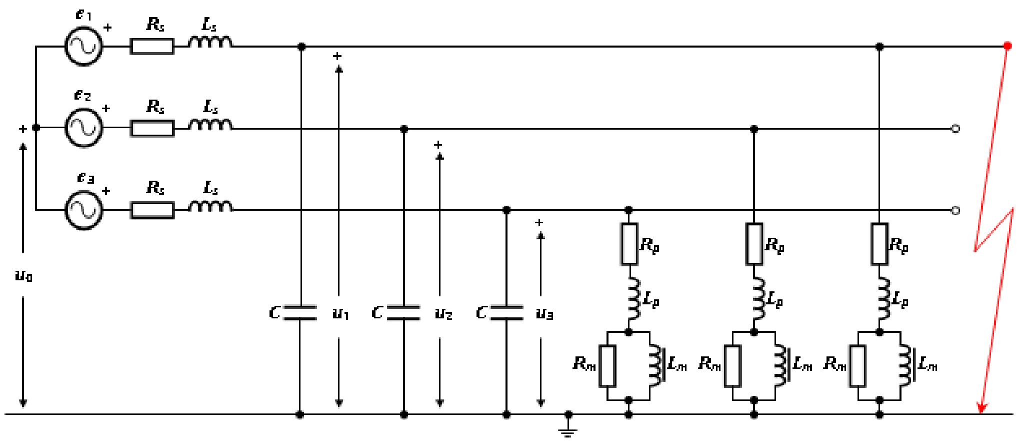

Figure 5. Equivalent model of ferroresonance in a three-phase isolated network: the case of initiation and elimination of single-phase short circuits.

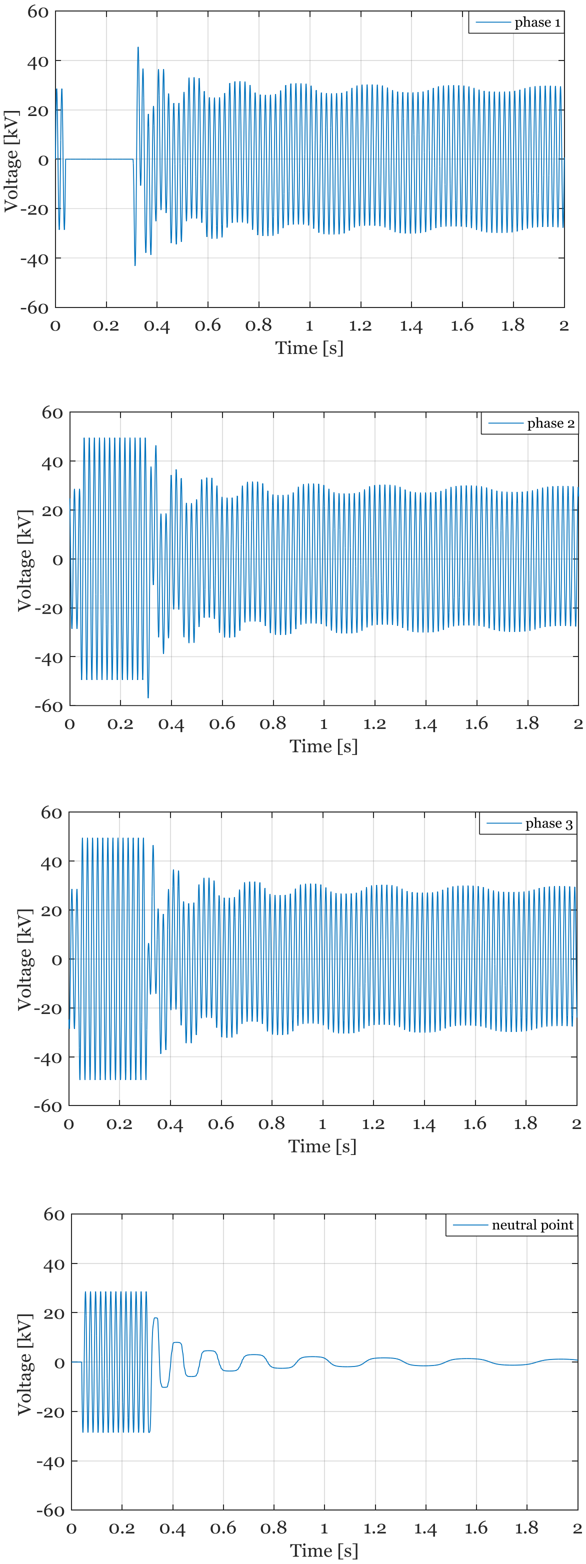

Figure 6. Phase voltages and the voltage of the neutral point, one inductive voltage transformer, $C = 150\ nF$.

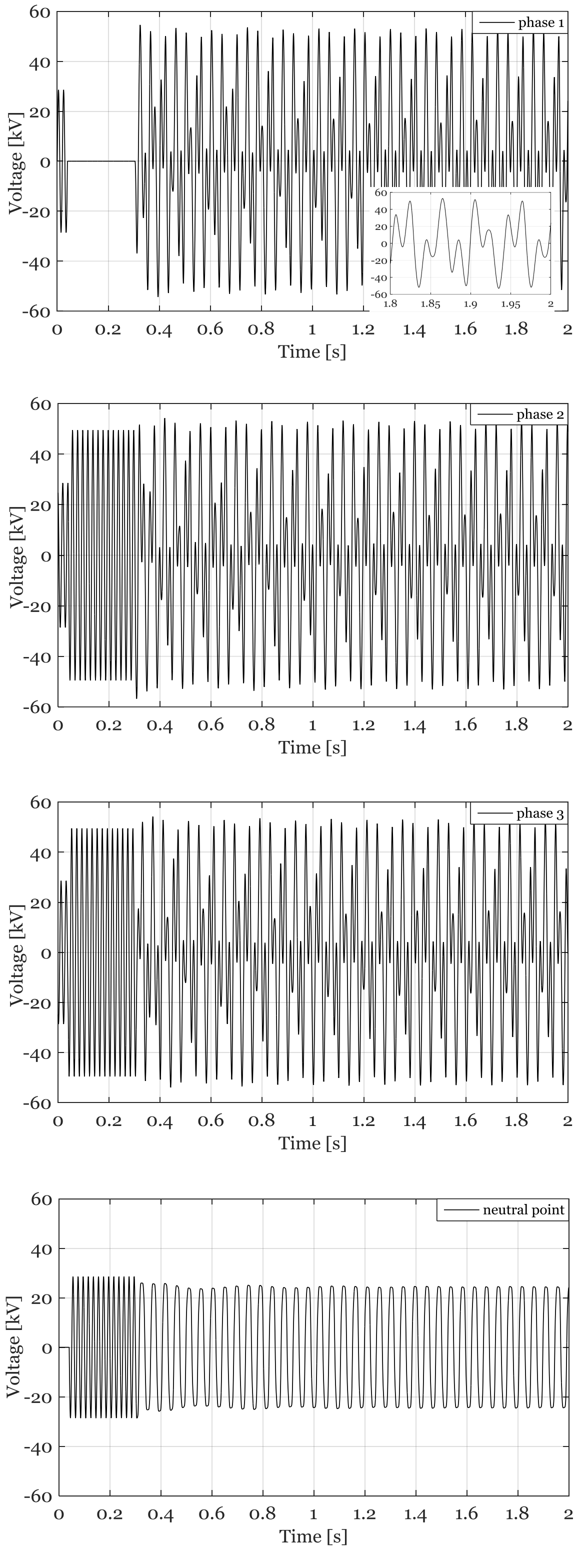

Figure 7. Phase voltages and voltage of the neutral point, two inductive voltage transformers, $C = 150\ nF$.

4.2 Impact of nonlinear curve magnetizing of an inductive voltage transformer

This case involves two inductive voltage transformers per phase; the basic zero-sequence system capacitance is $C = 150\ nF$. Again, all other parameters are the same as above in this paper.

The simulated phase voltage and voltage of the neutral point are shown in Fig 7.

Fig. 7 clearly shows that there is ferroresonance after elimination of a short-circuit from the system. The enlarged part of the voltage phase 1 (time interval from 1.8 to 2 s) shows the dominant seventh subharmonic component.

The main reason for the ferroresonance occurrence is lowering the equivalent nonlinear magnetizing curve of two parallel inductive voltage transformers. Therefore, in each point of the equivalent nonlinear curve of the two transformers, the iron core equivalent inductance of the voltage transformer is decreased.

4.3 Impact of the system capacitance

This case involves two per phase connected inductive voltage transformers and an increased zero-sequence system capacitance at the point of a single-phase short-circuit of value $C = 575\ nF$. The results of the simulated phase voltages and of voltage of the neutral point are shown in Fig. 8.

From Fig. 8 it is shown that in this case there is no ferroresonance after elimination of a short-circuit from the system. The main reason for the ferroresonance disappearance is the increasing zero- sequence system capacitance which significantly decreases the probability of initiation of the ferroresonance state.

4.4 Ferroresonance mitigation

There are three basic types of the ferroresonance damping devices, usually connected in an open delta auxiliary winding of the voltage transformers: (a) damping resistor whose resistance can be calculated based on a permisible thermal load of a voltage transformer secondary winding; (b) electronically controlled resistor with a lower resistance than that of the standard damping resistor. The device protects the equipment against the ferroresonant phenomena, after ferroresonance detection, by a proper and prompt damping action; (c) serial connection of a very low-value resistor and saturable reactor, which must be separately dimensioned for each voltage transformer.
Under normal operating conditions (no fault), the damping device is disconnected from the system.

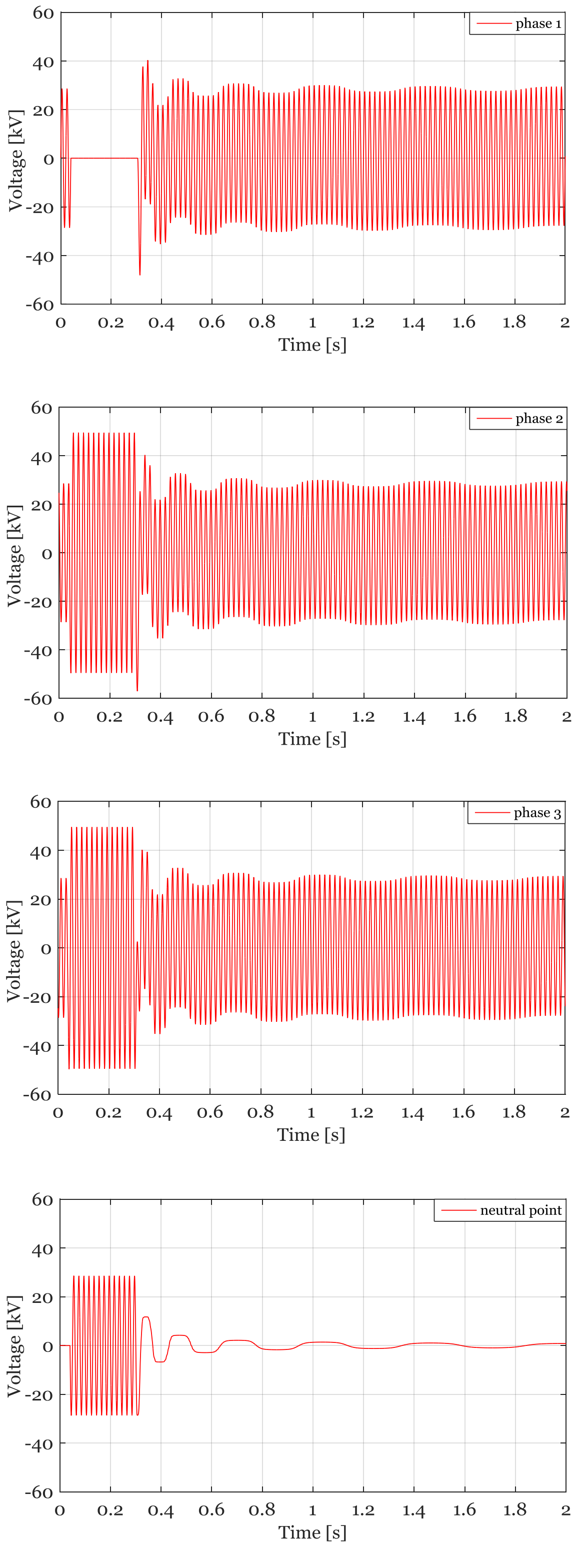

Figure 8. Phase voltages and voltage of the neutral point, two inductive voltage transformers, $C = 575\ nF$.

Fig. 9 shows a simulation result for the ferroresonance case presented in section 4.2 (two voltage transformers and system capacitance of C =150 nF) with a connected damping resistor R_d = 25 Ω in the auxiliary winding of a voltage transformer.

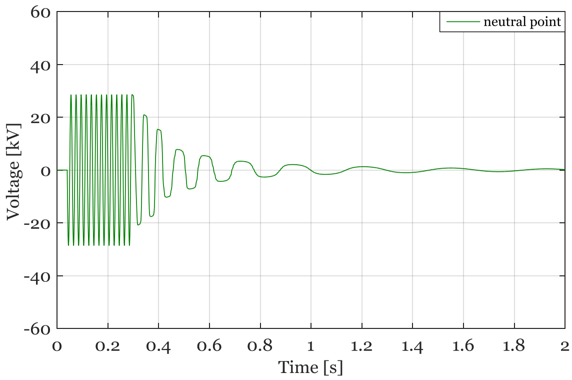

Figure 9. Neutral point voltage, two inductive voltage transformers, $C = 150\ nF$, the damping resistor connected.

As seen ferroresonance is eliminated after switching on the damping resistor.

5 CONCLUSION

The ferroresonance state in the inductive voltage transformers operating in neutral electrical distribution networks can be initiated as a result of clearing operations of single-phase short-circuits. In this paper, some significant parameters for initiation of ferroresonance after elimination of a short-circuit are researched. It is shown that increasing the zero-sequence system capacitance decreases the probability of initiation of ferroresonance. Also, increasing the number of the connected inductive voltage transformers increases the probability of the ferroresonance entering the neutral networks. Damping devices used to mitigate ferroresonance in neutral networks are presented. Our future work will include measurements of ferroresonance in three- phase neutral networks occuring to the elimination of short-circuits.

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