INFLUENCE OF NEUTRALIZER ON GROUND FAULT OVERVOLTAGES IN GENERATOR STATOR WINDINGS

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Abstract

This paper analyzes results of simulation studies of ground-fault overvoltages in unit-connected generators with the neutral grounded through a ground-fault neutralizer. The influence of the ground-fault neutralizer's resistance and inductance on voltage during arc ground faults in the stator windings of generators has been determined on the basis of numerical calculations. The analysis was carried out for 60-1110 MVA generators. The real mechanism of ground-fault arc quenching and the real change of its resistance in the transient state were taken into account.

1. INTRODUCTION

Fault overvoltages pose the greatest danger to the insulation of generator stator windings [1,2]. Of these, overvoltages near generator output terminals during arc ground faults are particularly dangerous. The considerable increase in the voltage gradient of the winding's insulation during these faults can cause another ground fault.

Since the ground fault has an interrupted character, it is ignited and quenched repeatedly during the ground fault process and this is accompanied by fast transient states. The pattern of these phenomena has a strong influence on the values of ground-fault overvoltages [3].

The voltage-current transients during ground faults in the stators of unit-connected generators are determined by the parameters in the unit's zero sequence circuit and the intermittent ground fault's mechanism. This applies mainly to elements grounding the generator's neutral point [4-10], elements connected to its output terminals (e.g. the capacitance of generator circuit-breakers) and the conditions of the quenching of ground-fault arc and its resistance [11].

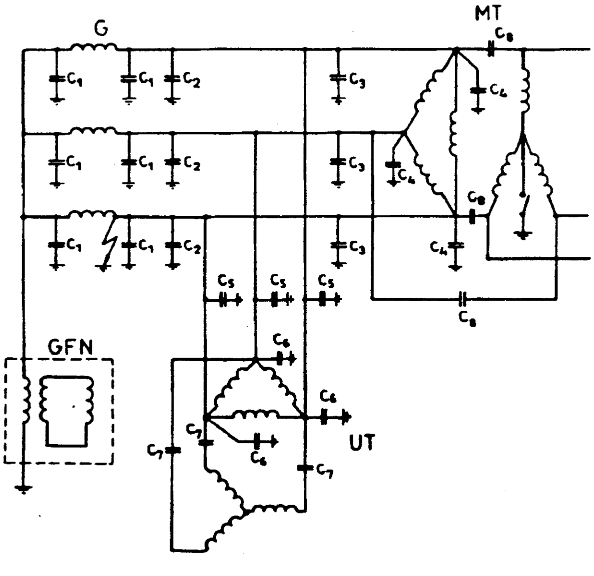
This paper presents results of the simulations studies of ground faults in unit-connected generators with the stator windings' neutral grounded through a ground-fault neutralizer. The influence of the ground-fault neutralizer's parameters on voltage and current during arc ground faults in stator windings of 60-1110 MVA power generators under different values of the ground-fault current compensation coefficient was determined by numerical calculations. The neutralizer's resistance and inductance and the real mechanism of arc quenching were taken into account.

Ground fault voltages were determined for the whole grounding process, including no-current interruptions between consecutive arc quenchings and ignitions. The real change of arc resistance in fast transient states, determined by tests on generator-transformer units, were taken into account in the analysis. Comparative simulation studies of ground-fault overvoltages under constant ground-fault arc resistance within the range of 5-500 Ω also were carried out. It has been found that in real conditions, a ground-fault neutralizer does not increase the overvoltage danger for the generator winding's insulation - in comparison with the one present during ground faults in generators with the ungrounded neutral.

2. GENERATOR SYSTEM'S MODEL AND DATA

The method of grounding the generator's neutral and only a few elements of the generator-transformer unit's ground-fault circuit have a significant influence on the phenomena during ground faults in the stators windings [12]. This refers chiefly to the capacitance of the particular components of the generator-transformer unit and ground-fault arc resistance. When analyzing fast transient state, one should take into account also the inductance of the generator's windings. A diagram of the generator-transformer unit used in the analysis of the influence of the neutralizer grounding the generator's neutral on ground-fault overvoltages is shown in figure 1.

The breakdown of the stators insulation to ground may occur at any place, including the generator's neutral. An analysis of the failure frequency of generator-transformer units shows that ground faults in the second half (from the neutral) of the winding are more frequent. Since because of ground-fault overvoltages faults close to the generator's output terminals are the most dangerous ones, they will be the subject of further analysis.



MT-Main Transformer
UT-Unit Auxiliary Transformer
GFN-Ground-Fault Neutralizer
C_1-half capacitance of generator phase relative to ground
C_2,C_3,C_5-capacitances to ground of particular sections of generator's connections with main transformer and unit auxiliary transformer
C_4,C_8-capacitances of main transformer windings
C_6,C_7-capacitances of unit auxiliary transformer windings

Fig.1. Diagram of ground-faulted generator system with neutralizer neutral grounding

The ground fault always has an arc character, no matter what the cause of the breakdown of the stators insulation to ground is. As time elapses, the properties of the ground-fault channel change. This due to the charring of the organic parts of the insulation at high temperature. The first stage of the ground fault, that immediately follows the breakdown of the insulation, is the most dangerous one. The properties of the ground-fault arc in this time interval were determined in real conditions by effecting the ground fault in the stators of 200 MW unit-connected generators [2].

It has been found that the arcs resistance changes in a very wide range. A fast transient state, in which the arc is quenched, follows each ignition. The quenching occurs at the instant when the voltage on the breakdown channel is close to zero. The voltage on the breakdown channel increases during the no-current interruption until the next arc ignition. The successive ignitions occur at increasingly lower voltages. The duration of a fast transient state usually does not exceed 0.5 ms. Resistance of ground-fault arc in this time interval changes in the manner shown in figure 2. Resistance $r_{a(t_m)}$ values are in the order of several hundred ohms.

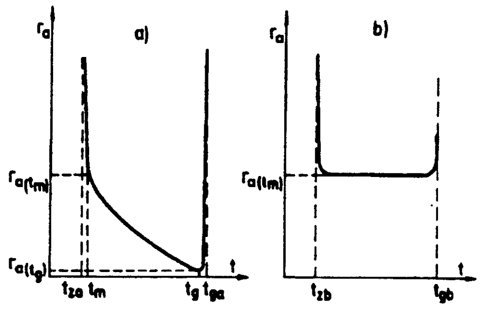


Fig.2. Arc resistance in fast transients: a) in initial ignitions, b) in further breakdowns; t_{za}, t_{ga}, t_{zb}, t_{gb},- times of ignitions and quenching respectively

By substituting a parallel circuit formed by inductance L_N and resistance R_N for the ground-fault neutralizer and dynamic resistance r_a for the arc channel as well as neglecting elements having no significant influence on the pattern of the analyzed phenomenon, e.g. generator windings resistances, the generator-transformer unit diagram can be reduced to the form shown in figure 3.

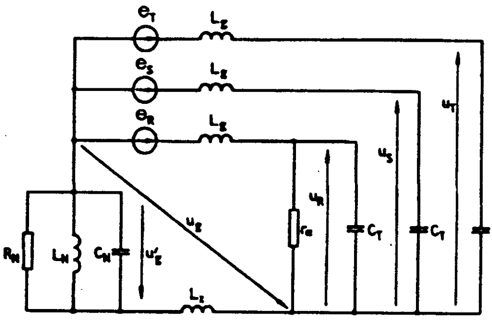


Fig.3. Simplified equivalent diagram of generator-transformer unit

Inductances L_g and L_z that occur in this circuit were determined using the following relationship:

$$L_g = \frac{L''_d + L''_g}{2}, \qquad L_z = \frac{1}{3}\left(L_0 - L_g\right), \tag{1}$$

where: L''_d, L''_g - direct-axis and quadrature-axis subtransient inductances of generator,
L_0 - zero-sequence inductance of generator.

Capacitances C_N and C_T are:

$$C_N = 3C_1,$$
$$C_T = \sum_{k=1}^{8} C_k \cong C_1 + C_2 + C_3 + C_4 + C_5 + C_6. \tag{2}$$

Neutralizer equivalent parameters L_N and R_N depend on the capacitance in the power unit's circuit and on the compensation coefficient assumed for the ground-fault current capacitance component [6,13].

The voltages in the circuit shown in figure 3 are described by the following system of equations:

$$L_g C_T \frac{d^2 u_R}{dt^2} + \frac{L_g}{r_a}\frac{du_R}{dt} - e_R + u_R + u_g = 0,$$

$$L_g C_T \frac{d^2 u_S}{dt^2} - e_S + u_S + u_g = 0,$$

$$
\begin{aligned}
&L_g C_T \frac{d^2 u_T}{dt^2} - e_T + u_T + u_g = 0\,, \\
&u_g - \frac{L_g}{L_g + 3L_z} u_g' + \frac{L_z}{L_g + 3L_z}\left(u_R + u_S + u_T\right) = 0, \qquad (3) \\
&\frac{d^2 u_g'}{dt^2} + \frac{1}{C_N R_N}\frac{du_g'}{dt} + \frac{1}{C_N L_N} u_g' - \frac{1}{C_N r_a}\frac{du_R}{dt} + \\
&-\frac{C_T}{C_N}\left(\frac{d^2 u_R}{dt^2} + \frac{d^2 u_S}{dt^2} + \frac{d^2 u_T}{dt^2}\right) = 0\,.
\end{aligned}
$$

The analysis covered unit generators installed in the Czech Republic power system (table 1). Numerical calculations were done using compensation coefficients k in the range from 0 to 1.0. The parameters of the neutralizer grounding the neutral of the tested generators were determined by means of relationship given in paper [13].

Parameters of generator-transformer units *Table 1*

Generator power [MVA]	62.5	137.5	235	588	1110
Company	ŠKODA				
Voltage [kV]	10.5	13.8	13.8	20	24
C_N[μF]	0.298	0.294	0.315	0.315	0.315
C_T [μF]	0.180	0.111	0.126	0.126	0.163
L_g [mH]	0.809	0.580	0.522	0.487	0.421
L_z [mH]	-0.112	-0.042	-0.072	-0.051	-0.071

The intermittent ground-fault was modeled on the output terminals of phase R. The first breakdown of the insulation occurred at the instant when voltage e_R reached the maximum. The ground-fault dynamic resistance in fast transient state changed as in figure 2a. It was assumed that:

$$
\begin{aligned}
&r_{a(t_m)} = 500\ \Omega\,, \qquad r_{a(t_g)} = 10\ \Omega\,, \\
&t_m - t_{za} \cong 0\,, \quad t_{ga} - t_g \cong 0\,, \qquad (4) \\
&t_{ga} - t_{za} = 0.45\, ms\,.
\end{aligned}
$$

In the time intervals between each quenching and re-ignition of the arc, resistance r_a was approaching infinity. The successive ignitions of the arc would occur when the damaged phase voltage relative to ground was:

$$u_{Rn} = U_m\left[1 - 0.1(n-1)\right], \qquad (5)$$

where: U_m -amplitude of phase voltage,
n-number of successive ignition.

Moreover, a comparative analysis of ground fault patterns under constant values of breakdown channel resistance (500, 60, 15 and 5 Ω) was carried out. The voltages of the particular phases and of the generator's neutral relative to ground were determined in relative units - referred to voltage amplitude U_m.

3. RESULTS OF NUMERICAL STUDIES

Results of simulation studies indicate that the ground-fault voltages are similar for the particular types of generators. The observed differences are insignificant from the point of view of overvoltage values. Therefore, the results of the simulations will be discussed here using a 1110 MVA generator as an example.

Apart from the values of the compensation coefficient, the resistance of the ground-fault arc has a significant influence on the values of ground-fault overvoltages. This is illustrated by figure 4 which shows:

1) voltage runs during two successive breakdowns and the no-current interruption between them, under the arc resistances of 5, 15 and 60 Ω and compensation coefficient k equal to 0;
2) voltage runs during the first breakdown and the no-current interruption that follows, under the arc resistance of 5, 15 and 60 Ω and the compensation coefficient k equal to 1.0.

At compensation coefficient k equal to 1.0, only one arc ignition occurred, since the time of analysis assumed for this phenomenon is shorter than the time after which the damaged phase voltage reaches the value of the second breakdown arc ignition voltage. The amplitude of the oscillatory component in ground-fault overvoltages increases as the arc resistance decreases. Already at the resistance of 5 Ω, it approaches the amplitude of phase voltage. Then maximum overvoltages reach the value of 2.5 U_m.

One should notice that arc resistance also affects the recovery voltage on the ground-fault channel. When its values are low, the voltages of the particular phases during no-current interruptions contain the oscillatory component. This component, when the stator windings' resistance is taken into account, will be damped in real conditions.

Numerical calculations have shown that the ground-fault neutralizer's parameters have little influence on the values of overvoltages during ground faults in generators, independently of the value of ground-fault arc resistance. Voltage of the particular phases and of the generator neutral relative to ground are shown in figure 5. Since the voltage drop on element L_z is negligible, voltage u_g is close to voltage u'_g. The fraction of the oscillatory component in the particular voltages is slight, both when the resistance changes as in figure 2a and when it has the constant value of 500 Ω. Due to this, the maximum ground-fault overvoltages in real conditions, under ground-fault current capacitance component compensation coefficients ranging from 0 to 1.0, will no exceed the double value of the generator's phase voltage amplitude.

It follows from the above that the ground-fault neutralizer does not increase ground-fault overvoltages in comparison with those which occur during faults in generators with the ungrounded neutral (k equal to 0). Since the ground-fault neutralizer determines the generator's neutral voltage relative to ground during the no-current interruption, overvoltages in such systems may be lower by several, and in certain conditions by several dozen, per cent than in generators with ungrounded neutral.

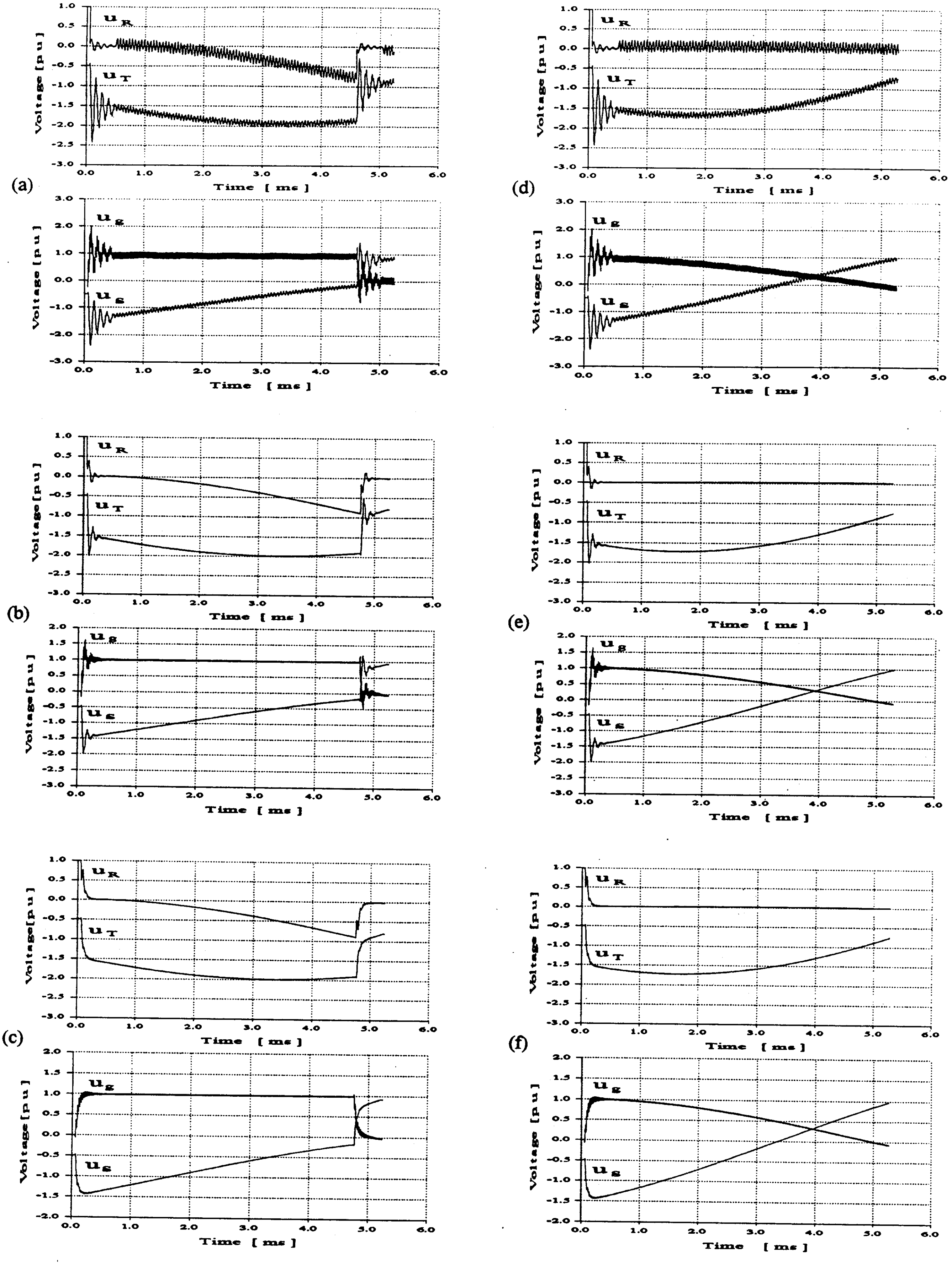


Fig. 4. Voltages during interruption ground fault in generator of 1110 MVA:
- under compensation coefficient k equal to 0 and resistance r_a : 5 Ω (a); 15 Ω (b); 60 Ω (c)
- under compensation coefficient k equal to 1.0 and resistance r_a : 5 Ω (d); 15 Ω (e); 60 Ω (f)

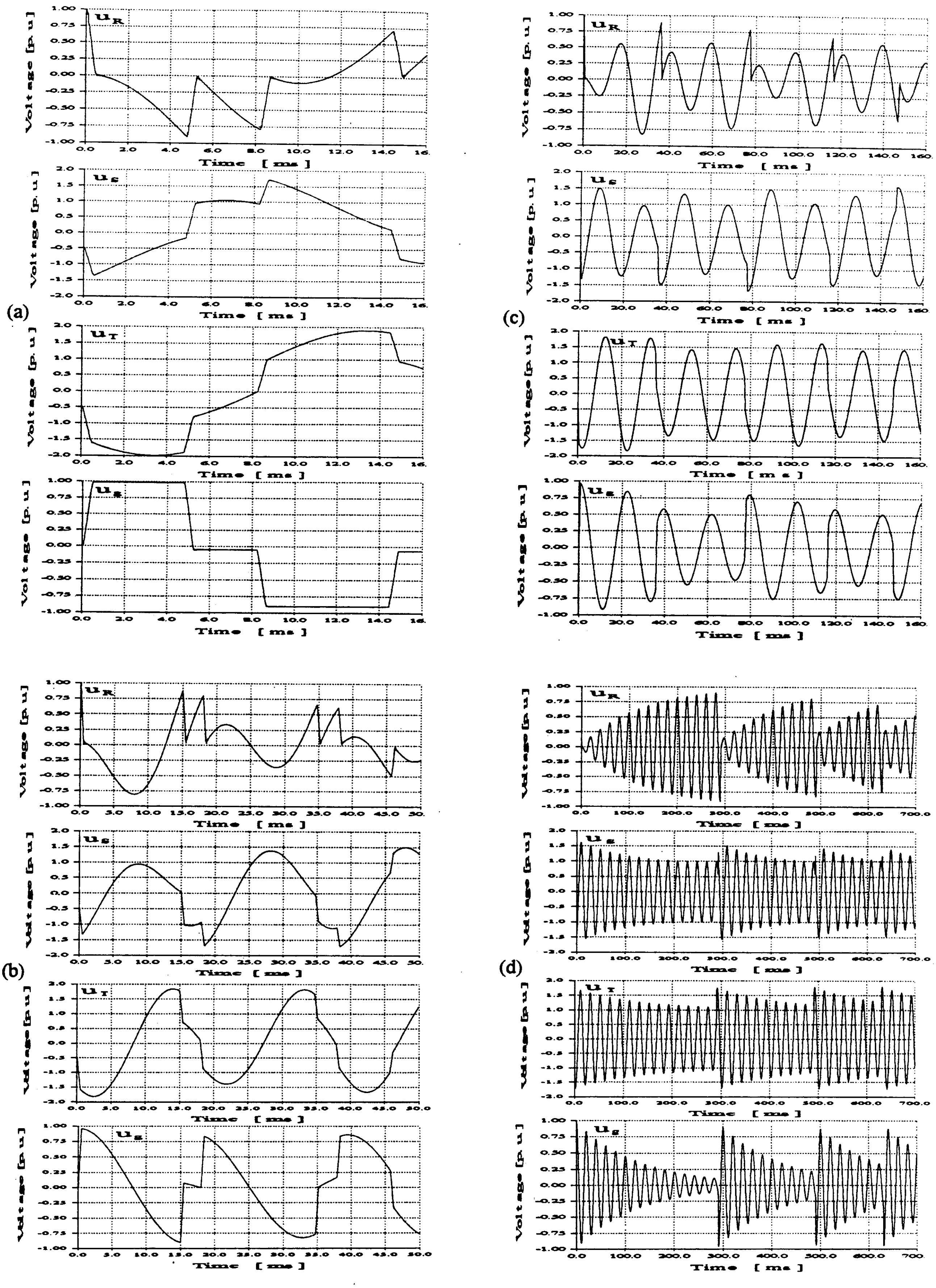


Fig.5. Voltages during arc ground fault in generator 1110 MVA under resistance r_a as in figure 2a and relationship (4): (a) k=0; (b) k=0.4; (c) k=0.8; (d) k=1.0

4. CONCLUSIONS

1. The studies have shown that a ground-fault neutralizer connected between the generator's neutral point and ground has a negligible influence on the values of overvoltage during ground faults in the stator windings of a unit-connected generator.

2. In comparison with generators with the ungrounded neutral or grounded via a resistor, the presence of a ground-fault neutralizer changes the voltages of the particular phases and the gnerator's neutral relative to ground during the no-current interruption. In this case (under real values of ground-fault arc resistance), the neutral voltage does not decrease aperiodically but in an oscillatory manner. Because the highest voltage value of the neutral relative to ground (under compensation coefficients ranging from 0.4 to 1.0) did not exceed the amplitude of the generator's phase voltage, these systems, can be treated as equivalent from the point of view of overvoltage.

3. In real conditions, the maximum ground-fault overvoltages in the tested generators with the neutral points grounded via ground-fault neutralizer will not exceed (under the assumed values of compensation coefficients) the double value of the phase voltage amplitude. Ground-fault neutralizer improve slightly the overvoltage conditions in comparison with those which exist in generators with ungrounded neutral. Depending on the parameters of a ground-fault neutralizer and the character of the interrupted ground fault, the reduction in overvoltage can be from several to several dozen per cent.

4. Further research should determine the influence of the ground-fault neutralizer on the operating conditions of the ground-fault protections of the stators of generators. This refers mainly to protection systems excited by the voltage third harmonic [14,15]. It is anticipated that these systems, with properly selected parameters of the ground-fault neutralizer, will make it possible to optimize the operating conditions of ground-fault protections of large generator-transformer units. This could result in substantial financial gains because of the minimized losses caused by ground faults in the stators of unit connected generators. These benefits will come from the limiting of direct losses caused by ground faults as well as from the improvement in the correct operation of ground-fault protection systems. It is believed that such systems, because of their simple design and the protection of 100% of the stators winding, will be one of the better practicable solutions to be used especially in the case of large generator-transformer units.

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