Single-Line Ground Fault's Impedance Impact to Electrical Parameters in Ungrounded Electrical System

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Abstract – **In this paper single-line ground fault in ungrounded electrical systems was considered. In accordance with one situation from practice that has been analyzed, appropriate model of ungrounded network and mathematical model that gives values of phase voltages and currents through single-lines to ground capacitances in the ungrounded system with single-line ground fault were given. In order to check all assumptions made for considered case from practice, an experiment in the laboratory environment was implemented and obtained results were presented.**

Keywords – **Ground fault, ungrounded power system, mathematical model, line and phase voltages, capacitive currents**

I. Introduction

As it is widespread known, the system grounding method does not have any impact to power system operation in normal conditions. However, in some non-regular regimes, such as ground faults, ground fault current's amplitude highly depends on the system grounding method. In addition, fault impedance value provides great impact to ground fault current. Generally, all electrical power systems can be classified in two categories: ungrounded and grounded systems. Furthermore, grounded systems can be classified in two groups: effectively (strongly) and none effectively (through reactance (Petersen coil) or through low-impedance) grounded power systems [1-3].

In Serbian electrical energy system all grounded methods are used according to different voltages level. Distribution systems at medium-voltage can be ungrounded, grounded through Petersen coil or low-impedance as opposed to distribution systems at high voltages ($U_n \geq 110\ kV$)that are usually effectively grounded.

In this paper, the emphasis was placed on ungrounded systems and impact that single-line ground fault provides to phase and line voltage's and current's values in those systems. Ungrounded systems are typical for distribution network $10\ kV$, as well as in industrial or mining electrical power systems ($6\ kV$ and $5\ kV$). For these systems it is specified that neutral points of all electric machines windings and elements in galvanic connection with distribution system are isolated from the ground. Single-lines to ground capacitances represent the only connection between distribution system and ground in ungrounded power system [1]. Single-lines to ground capacitances are approximately equal each other, especially when conductors are transposed and they have same lengths. Therefore, the largest number of authors accepts the assumption that there is a capacitive symmetry in ungrounded systems and in accordance with that fact they make their mathematical models. This assumption was also adopted for research described in this paper.

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II. Theoretical Background and Mathematical Model

Considering the problem of single-line ground fault's appearance in electric power system at $10\ kV$ (ungrounded system) in South Serbia, authors noticed some facts that looked atypical at the first sight. Actually, when single-line ground fault occurs in electric power system, electrical parameters, such as phase voltages, didn't have diagrams and values that are usually given in the literature for these situations. Namely, in literature is often said that in the case of single-phase ground fault, phase voltage in the "infected" phase drops to zero and in two other phases voltage increase to the value of line voltage. Line voltages in those cases keep same values as they had before the ground fault happened. However, after detailed literature review, authors determined the fact that described phase voltage's behaviour during single-line ground fault is typical only for non-load totally symmetrical power systems and for single-line ground faults with fault impedance $Z_z = 0$ [1-4].

The problem that followed was how to prove the assumption that it was real single-line ground fault through fault impedance without appropriate mathematical model for this kind of power systems. In addition, situations that were assumed as single-line ground faults in this ungrounded power system were repeated by one usual pattern during the period of power system monitoring: the phase voltage U_C always dropped (but didn't reach 0), phase voltage U_B immediately increased (but didn't reach the line voltage U_{BC}) and finally, U_A increased (but it had less increase than U_B) or just kept the similar value as it had before single-line ground fault. Meanwhile, line voltages kept their values from the steady state. Therefore, according to the fact that there is a usual pattern by which are those situations characterized, it could be assumed that there are parts of transmission lines that had been overgrown by a different vegetation. This vegetation could cause situations assumed as single-line ground faults, during bad weather conditions, such as humidity or wind.

Another observed fact was that phase voltage's drop in one and asymmetrical increase in two other phases in the electric power system $10\ kV$ did not have any impact to phase voltages at the secondary end of transformer $10/0.4\ kV$ with D_{Y_n}connection what leads to suggestion that abnormal situations, as ground faults, in medium voltage networks are not transmitted to the low voltage side for this kind of transformer's connection.

In order to prove all mentioned assumptions, authors made electrical power system's model according to the real considered state that is shown in Fig. 1.

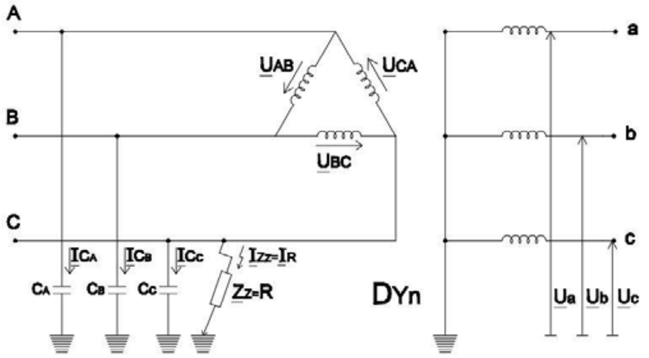

Fig. 1. Single-line ground fault in power distribution network

Primary side of $10/0.4\ kV$ transformer is connected in D and its secondary side is connected in Y_n. Electric power system at $10\ kV$ is ungrounded. Single-line ground fault occurred in phase C through fault impedance $\underline{Z}_z = R > 0\,\Omega$. This is main difference from models usually present in the literature, where $\underline{Z}_z = 0\,\Omega$.

From the model shown in Fig. 2 it can be set following system of equations:

$$\underline{I}_{C_A} + \underline{I}_{C_B} + \underline{I}_{C_C} + \underline{I}_R = 0 \quad (1)$$

where $\underline{I}_{C_A}$, $\underline{I}_{C_B}$ and $\underline{I}_{C_C}$ are capacitive currents that flow through single-lines to ground capacitances C_A, C_B and C_C, respectively, and $\underline{I}_R$ is ground fault current;

$$\underline{U}_A = \underline{Z}_{CC} \cdot \underline{I}_{C_A} \quad (2)$$

$$\underline{U}_B = \underline{Z}_{CC} \cdot \underline{I}_{C_B} \quad (3)$$

where $\underline{U}_A$ and $\underline{U}_B$ are phase voltages and $\underline{Z}_{CC}$ is capacitive impedance that has the same value for all three phases, because it was assumed that $C_A = C_B = C_C$;

$$\underline{U}_A = \underline{U}_{AC} + \underline{U}_C \quad (4)$$

$$\underline{U}_B = \underline{U}_{BC} + \underline{U}_C \quad (5)$$

where $\underline{U}_C$ is voltage of phase C, where single-line ground fault was happened, $\underline{U}_{AC}$ and $\underline{U}_{BC}$ are line voltages that have same values as before the ground fault;

$$\underline{U}_C = \underline{Z}_{CC} \cdot \underline{I}_C \quad (6)$$

$$\underline{U}_C = R \cdot \underline{I}_R \quad (7)$$

Solving the system of equations Eqs. (1) – (7), formulas for phase voltages and currents through single-lines to ground capacitances calculation at the point of single-line ground fault for used power system model, were obtained. Those formulas are given in Eqs. (8) – (14).

$$\underline{U}_C = \frac{-R \cdot [\underline{U}_{AC} + \underline{U}_{BC}]}{\underline{Z}_{CC} + 3 * R} \quad (8)$$

$$\underline{I}_{C_C} = \frac{-R \cdot [\underline{U}_{AC} + \underline{U}_{BC}]}{\underline{Z}_{CC} \cdot (\underline{Z}_{CC} + 3 * R)} \quad (9)$$

$$\underline{U}_A = \underline{U}_{AC} + \frac{-R \cdot [\underline{U}_{AC} + \underline{U}_{BC}]}{\underline{Z}_{CC} + 3 * R} \quad (10)$$

$$\underline{I}_{C_A} = \frac{\underline{U}_{AC}}{\underline{Z}_{CC}} + \frac{-R \cdot [\underline{U}_{AC} + \underline{U}_{BC}]}{\underline{Z}_{CC} \cdot (\underline{Z}_{CC} + 3 * R)} \quad (11)$$

$$\underline{U}_B = \underline{U}_{BC} + \frac{-R \cdot [\underline{U}_{AC} + \underline{U}_{BC}]}{\underline{Z}_{CC} + 3 * R} \quad (12)$$

$$\underline{I}_{C_B} = \frac{\underline{U}_{BC}}{\underline{Z}_{CC}} + \frac{-R \cdot [\underline{U}_{AC} + \underline{U}_{BC}]}{\underline{Z}_{CC} \cdot (\underline{Z}_{CC} + 3 * R)} \quad (13)$$

$$\underline{I}_R = \frac{-[\underline{U}_{AC} + \underline{U}_{BC}]}{\underline{Z}_{CC} + 3 * R} \quad (14)$$

Certainly, it should be mentioned that this model can also be applied for other different voltage levels with the condition that the power system is ungrounded and transformer is in D_{Y_n} connection. However, in this model line impedances and line-to line capacitances were not taken into the account, because line impedances are much smaller than the fault impedance and analogously, line-to line capacitances are much smaller than single-lines to ground capacitances. For this kind of analyses this model satisfies the required precision, but for highest precision calculations, mathematical model that takes them into account can also be made [5].

III. Experimental Investigation

In order to check all assumptions mentioned in section 2, after mathematical model was created, authors decided to make laboratory experiment. Actually, electric power system model presented in Fig. 1 was built by laboratory equipment which connection diagram is shown in Fig. 2.

Two laboratory transformers $400/(100 \cdot \sqrt{3})\ V$, D_{Y_n} connection were used. Transformer T1 represents transformer $10/0.4\ kV$ in ungrounded system at which primary side single-line ground faults occurs, and transformer T2 represents utility source (it is connected to power system through three-phase regulation autotransformer (3fRAT)).

Capacitors C_A, C_B and C_C represent single-lines to ground capacitance in ungrounded electric power system. Those capacitors are $C_A = C_B = C_C = 1.5\ \mu F$, and they were chosen according to the allowed value of metal ground fault current in ungrounded systems. Actually, according to [6], ground fault current for electric power system $10\ kV$ is about

$0.03\ A/km$ which is for ungrounded system of total feeder lines length $50\ km$ (system that authors considered) $1.5\ A$. For transformer $10/0.4\ kV$, rated current $46\ A$ (also parameters from considered system) total fault current of $1.5\ A$ represents $3.26\ \%$. Laboratory transformer has rated current $10\ A$, and, analogously, ground fault current of $3.26\ \%$ is about $0.326\ A$. In this case study, with capacitors of available manufacturer capacitances values, the closest metal ground fault current that was able to achieve was $0.342\ A$ with capacitors of $1.5\ \mu F$.

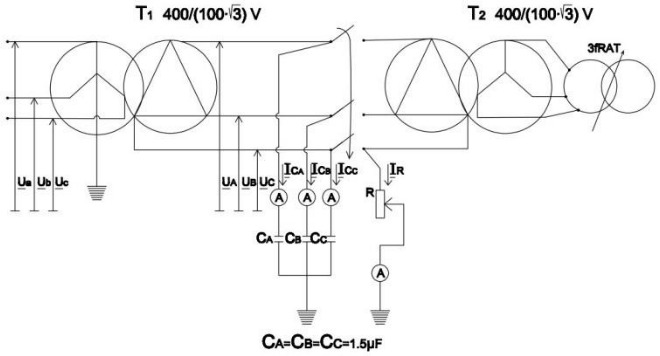

Fig. 2. Connection diagram of electric equipment used for laboratory experiment

From the electric power system using 3fRAT primary ends of transformer T2 were supplied by the line voltage of $400\ V$. Single-line ground faults in phase C through a range of fault impedance R values were tested. Electrical parameters as currents I_{C_A}, I_{C_B}, I_{C_C}, I_R and phase and line voltages U_A, U_B, U_C, U_{AB}, U_{BC} and U_{AC} were measured. It should also be mentioned that phase voltages at the secondary end of transformer T1 (U_a, U_b and U_c) were also monitored in order to verify if the whole state is analogous to the state from $10\ kV$ ungrounded power system that authors analyzed.

The first measuring point was for metal ground fault where fault impedance was $R = 0\ \Omega$. Thereafter, R was increased, in the beginning with small increments, and after a few measurements the R increment was set to the value of $100\ \Omega$ in order to analyze as large as possible range of fault impedance values. Testing was finished for the fault impedance value of $R = 1500\ \Omega$. Results of this experiment presented as measured electrical parameters diagrams as a function of R are given in section 4.

IV. Results and Discussion

First of all it should be said that during the whole experiment phase voltages at the secondary end of transformer T1 (U_a, U_b and U_c) weren't changing their values what proves the assumption that single-line ground fault at the primary side of transformer connected in D_{Y_n} does not have any influence to electrical parameters at its secondary side.

The following situation that was analyzed was about line voltages at the primary end of T1. During the experiment they kept their values of $U_{AB} = 402\ V$, $U_{BC} = 403\ V$ and $U_{AC} = 406\ V$, that is according with the considered situation from the practice.

Measured currents I_{C_A}, I_{C_B}, I_{C_C}, I_R and phase voltages U_A, U_B and U_C change their values with the change of fault impedance what is presented in Figs. 3 and 4.

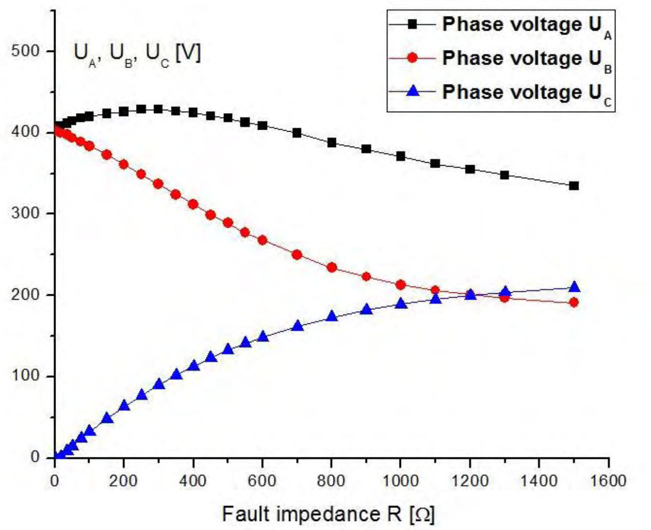

Fig. 3. Diagrams of phase voltages U_A, U_B and U_C as functions of fault impedance R obtained by an experiment

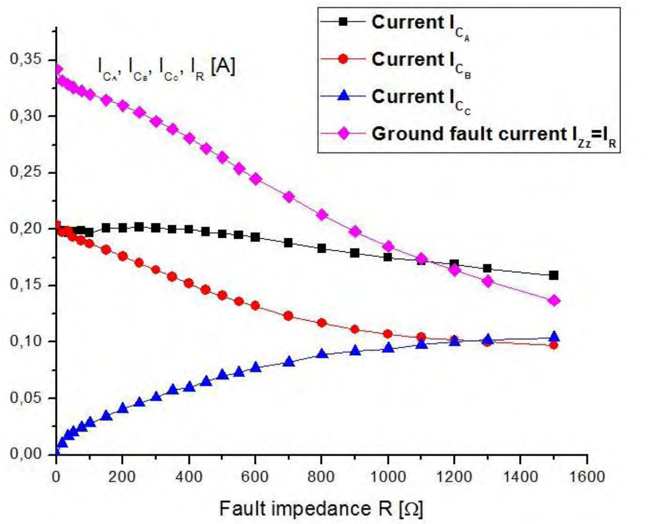

Fig. 4. Diagrams of currents through single-lines to ground capacitances I_{C_A}, I_{C_B}, I_{C_C} and ground fault current I_R as functions of fault impedance R obtained by an experiment

After the laboratory experiment results were obtained, mathematical model from section 2 was used for their checking. Actually, in Eqs. (8) – (14) measured electrical parameters are calculated in complex domain with their arguments, but if it is known that $\underline{U}_{AC}$ and $\underline{U}_{BC}$ can be defined by Eqs. (15) and (16) it is easy to calculate effective values of all electrical parameters obtained by mathematical model and compare them with values gained from the experiment.

$$\underline{U}_{AC} = U_{AC} \cdot e^{-j \cdot \frac{2 \cdot \pi}{3}} \quad (15)$$

$$\underline{U}_{BC} = U_{BC} \cdot e^{j \cdot \pi} \quad (16)$$

Diagrams of electrical parameters changes gained by mathematical model for the same range of R values, as it was in the experimental investigation, are presented in Figs. 5 and 6. It should be noted that in mathematical model R was used without increments in order to obtain continuous diagrams.

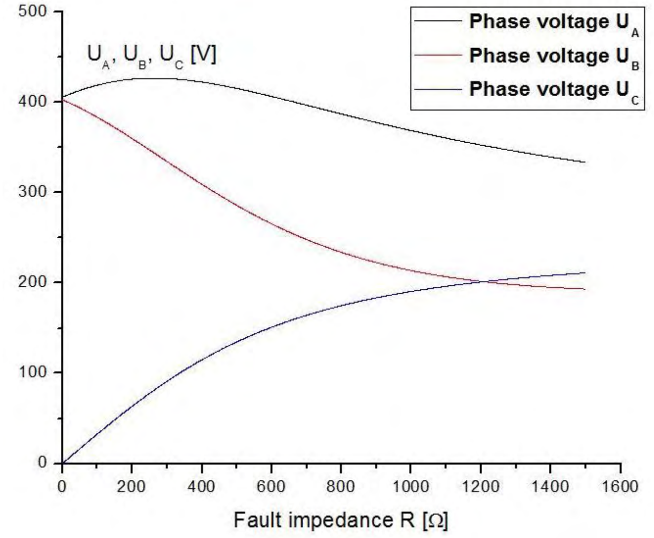

Fig. 5. Diagrams of phase voltages U_A, U_B and U_C as functions of fault impedance R obtained by mathematical model

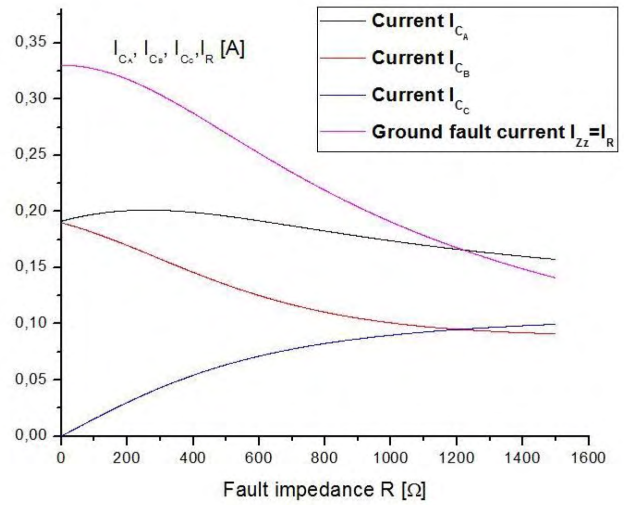

Fig. 6. Diagrams of currents through single-lines to ground capacitances I_{C_A}, I_{C_B}, I_{C_C} and ground fault current I_R as functions of fault impedance R obtained by mathematical model

If Figs. 3 and. 4 are compared with Figs. 5 and 6, it is obvious that phase voltages U_A, U_B and U_C, currents through capacitance C_A, C_B and C_C, I_{C_A}, I_{C_B} and I_{C_C}, respectively, and ground fault current I_R have same diagrams obtained by experiment as diagrams obtained by mathematical model. In this way authors prove their assumptions made about problem with single-line ground fault through impedance in 10 kV ungrounded electric power system that they have been analyzing.

V. Conclusion

Single-line ground fault through different values of impedance in ungrounded electric power system was analyzed in this paper. It was shown that phase voltages and ground fault current in distribution systems highly depends on fault impedance value and that its influence must be taken into the account in ground fault analyses.

In the experiment described in this paper active resistance as fault impedance was used. Future research in this area can cover different impedance characters, such as reactive or combination of active and reactive characters. In future investigation impedance of transmission lines and line-to-line capacitances can be taken into account and mathematical model for highest-precision analyses can be created. Finally, this type of analyses done for ungrounded electric power system can be implemented to grounded systems, including individually all grounding methods.

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