Modeling of Transient Processes at Ground Faults in the Electrical Network with a High Content of Harmonics

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***Abstract*- The paper presents analytical investigations on determination of influence of higher harmonics existing in a ground fault current on the characteristics of transient processes at arcing ground faults. As initial data, results of real oscillography of ground fault currents in the operational 6 kV distribution network are used. It is shown that there are harmonics of high amplitudes in a ground fault current which are 2.6 times greater than a residual 50 Hz reactive current at a single-phase fault location.**

Calculations using the detailed mathematical model of the 6 kV network confirm the fact that negative influence of arcing overvoltages on equipment insulation increases due to the high content of harmonics in a fault current which are not compensated by Petersen coils and worsen conditions for successful arc quenching. It is noted that a ground fault current may cross zero many times without current extinction due to harmonic distortion. Due to high-frequency overvoltages, probability for restrikes increases. It results in expanding of a fault area in cable insulation and reducing of time for transition of single phase-to-ground fault into stable arcing with possible breakdowns of phase-to-phase insulation. To prove these statements, resistances in a fault place taking into account harmonic distortions of an arc current are calculated.

Keywords: mathematical modeling, higher harmonics in a fault current, single phase-to-ground arcing fault, harmonic distortion current, stable arcing, resistance in a fault place.

I. INTRODUCTION

Content of higher harmonics in a ground fault current is defined by non-linear loads (e.g. furnace transformers, power rectifiers, and so on), quantity and power of electrical machines, frequency regulators and motor soft starters [1]. In the case of stable single phase-to-ground faults, the odd harmonics are the most visible. The 3rd, 5th, and 7th harmonics are caused by non-linear magnetizing currents of power transformers, while the 9th and 11th harmonics are defined by rectifier, furnace and motor drive loads. Content of higher harmonics is not regulated by standards due to various factors of their nature.

A harmonic spectrum of arcing ground fault currents contains both 50-Hz harmonics (i.e. 50, 100, 150, 200 Hz, etc), and subharmonics (i.e. harmonics whose frequencies are lower than 50 Hz) and interharmonics (i.e. harmonics between 50-Hz harmonics). Harmonic distortions may force resonance phenomena at non-fundamental frequencies which results in emergency situations.

Petersen coils are used for compensation of the only fundamental frequency of a capacitive ground fault current: at tuning of $|\upsilon| = 1 – 5\%$, residual current I_{RES} at a fault location is determined by higher harmonic currents $I_{(n)}$ for 90-95% and by active conductance currents I_G in network insulation for 5-10%. When a ground fault current is distorted by higher harmonics we may expect the increase of probability for restrikes in cable insulation. Such insulation is supposed to be damaged stronger during arcing ground faults than in the case of lower values of higher harmonic currents due to greater influence of a total ground fault current.

Usually, higher harmonics in a ground fault current are not taken into account during transient process simulation. It may cause some errors in determination of arc current parameters, transient process frequencies, impedance and voltage at a fault location in cable insulation.

The main aims of our investigation are:

1. Determination of the influence of the harmonic content on the character of transient processes at arcing ground faults using the mathematical model of the cable network with harmonic sources based on experimental results.
2. Assessment of higher harmonic influence on the impedance at a fault location in cable insulation during the process of stable arcing.

II. CALCULATIONS OF ARCING GROUND FAULT PARAMETERS USING THE SIMULATION MODEL OF THE NETWORK WITH HARMONIC SOURCES

As initial data, the results of experimental investigations with recording of currents and voltages at artificial ground faults in the cable network of the 6 kV main switchgear at Combined Heat and Power (CHP) Plant are used. The simulated 6 kV network is operated with compensation of capacitive currents. Petersen coil of 2700 kVA total power are connected to neutrals of four power transformers at three busbars. Calculated capacitive current for the 6 kV main switchgear is $I_C = 260.7$ A.

We carried out experiments of artificial solid ground faults with oscillography of ground fault currents. Based on Fourier transform, active and reactive components of a residual current are calculated. The value of the 1st current component is $I_{RES(1)} = 30.6$ A, including inductive component from a Petersen coil of I_L = 27.5 A and active leakage current I_G = 14.3 A. Indirectly calculated current of a Petersen coil is $I_{L\Sigma}$ = 301 A with a total capacitive current of I_C = 273.5 A at over-compensation of υ = 10.8%.

Analysis of real oscillograms of a solid ground fault current shows that there are higher harmonics of great amplitudes in the content of this current. Distortion current for odd and even harmonics from the 2nd to the 13th is I_{HARM} = 2.57 x $I_{RES(1)}$ = 79.59 A. Moreover, the 3rd, 5th, 7th, 9th, 11th harmonics has a great influence on a ground fault current. Influence of odd harmonics greater than 700 Hz (i.e. the 15 harmonic and greater) and even harmonics on a total ground fault current is not significant. This assumption can be applied to the most 6-35 kV networks and a number of operational power facilities that is experimentally proved [2].

Total ground fault current over the fault location consists of capacitive current of power frequency (I_C – without compensation, $|I_L - I_C|$– compensation with Petersen coils), active leakage currents I_G and resistive current I_R (if applicable, in the case of a resistor connected to a neutral), and equivalent higher harmonic current $I_{(n)}$:

$$I_{ground.fault} = \sqrt{I_C^2 + (I_G + I_R)^2} + \sqrt{\sum I_{(n)}^2} \quad (1)$$

When a resistor is not connected, influence of I_G on the total ground fault current is not significant: for normal operation of cable insulation active leakage currents are assumed to be $I_G \le 0.05 I_C$ which corresponds to a damping coefficient of $d \le 0.05$. For continuously operated reduced cable insulation this coefficient is d = 0.05–0.10.

Calculations with higher harmonic currents are performed by inserting non-linear sources and loads into mathematical models of the network. During engineering evaluations we may also simulate harmonic distortions by current sources which parameters are based on values and phases of higher harmonics experimentally obtained.

General simulation model of a three-phase network is presented in Fig. 1. Higher harmonics are simulated as current sources connected to a neutral through the resistance R_Z = 0.5–1.0 Ohm. Using the special Russian software VMAES, we develop a mathematical model for the analysis of transient processes at arcing ground faults in the cable network of the main switchgear at CHP Plant. Higher harmonics which is not compensated by Petersen coils are also taken into account.

Fig. 2 shows simulated oscillograms of overvoltages on the phase A at ground faults at the beginning of a feeding cable of the 6 kV network on the 1st Busbars Group. Calculations are performed for two cases. The first case is grounding through Petersen coils (Fig. 2a); the second case is grounding through Petersen coils and power resistors of R_N = 300 Ohm connected in parallel in the neutrals of the 1st Busbars Group (Fig. 2b). For this network, capacitive current is $I_{C(1\text{-}2\text{-}3)}$ = 46.0 A, inductive current is $I_{L(1\text{-}2\text{-}3)}$ = 170.1 A. In this case, over-compensation current is $\Delta I(+)$ = 124.1 A. Equivalent resistive current of power resistors is $R_{N\Sigma}$ = 100 Ohm – $I_{R\Sigma}$ = 34.65 A.

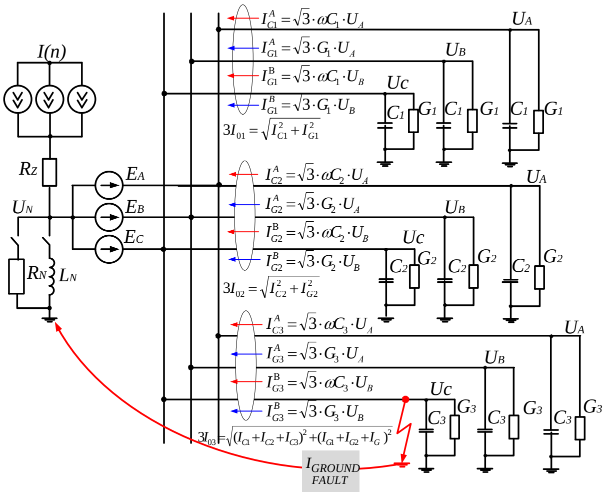
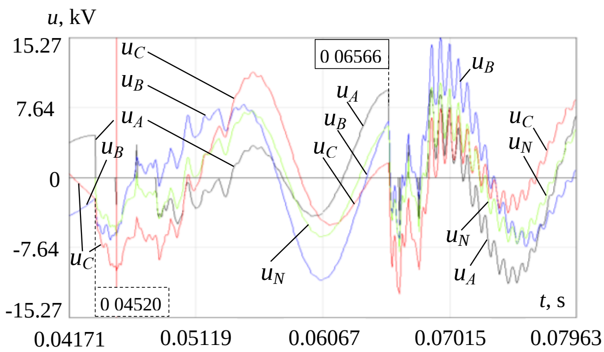
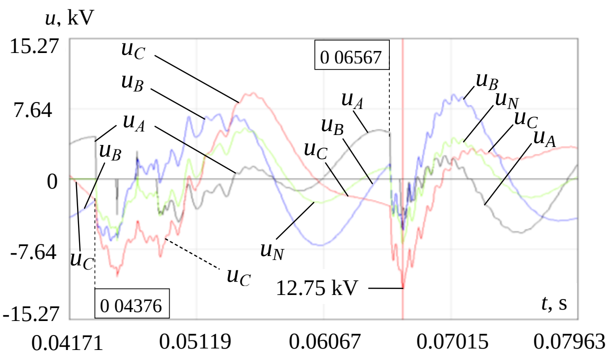


Fig. 1. Simulation model of a combined grounded network for the analysis of transient processes at single phase-to-ground faults with higher harmonic distortion currents (*the model is applicable for the 1st Busbars Group and the 2nd Busbars Group, separately*)



a) υ = + 2.7; $I_{R\Sigma}/\Delta I_{(+)}$ = 0; K_U = 3.03

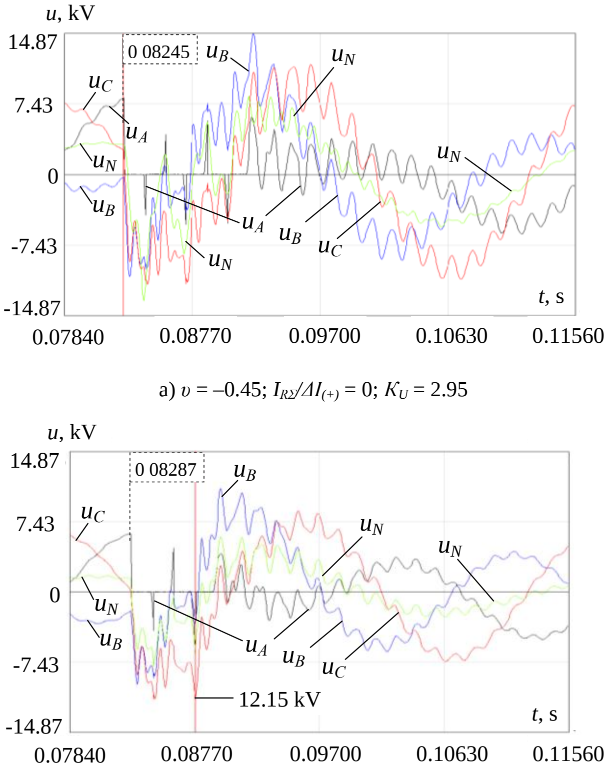


b) υ = + 2.7; $I_{R\Sigma}/\Delta I_{(+)}$ = 0.28; K_U = 2.53

Fig. 2. Transient process at arcing ground fault at the beginning of a feeding cable at the 1st Busbars Group of the 6 kV main switchgear at CHP Plant with a compensation (a) and with a combined neutral grounding, $R_{N\Sigma}$ = 100 Ohm (b)

Fig. 3 illustrates simulated oscillograms of overvoltages on the phase A at ground faults at the beginning of a feeding cable of the 6 kV network on the 2nd Busbars

Group. For this network, capacitive current is $I_{C(4\text{-}5\text{-}6)}$ = 237.7 A, inductive current is $I_{L(4\text{-}5\text{-}6)}$ = 130.9 A. In this case, under-compensation current is $\Delta I(-)$ = 106.8 A. Due to oscillating character of transient process caused by recharging of a phase capacitance arc at arc ignition and arc extinction and by possible influence of higher harmonics and weak damping of oscillations by active leakages, maximum overvoltage level reaches K_{UMAX} = 2.95 (see Fig. 3a).



a) υ = –0.45; $I_{R\Sigma}/\Delta I_{(+)}$ = 0; K_U = 2.95

b) υ = –0.45; $I_{R\Sigma}/\Delta I_{(+)}$ = 0.65; K_U = 2.41

Fig. 3. Transient process at arcing ground fault at the beginning of a feeding cable at the 2nd Busbars Group of the 6 kV main switchgear at CHP Plant with a compensation (a) and with a combined neutral grounding, $R_{N\Sigma}$ = 50 Ohm (b)

Calculations show that for overvoltage limitation at such inadmissible detuning current three power resistors of R_N = 150 Ohm connected in parallel with Petersen coils can be used at the 2nd Busbars Group of the 6 kV network (see Fig. 3b). Equivalent resistive current of power resistors is $R_{N\Sigma}$ = 50 Ohm – $I_{R\Sigma}$ = 69.3 A.

Using simulated oscillograms of arcing ground faults shown in Fig. 2, 3, we assume that arc current i_{ARC} may cross zero many times during transient process due to not only inadmissible detuning factors $|\upsilon| \le 2.7$, but also high values of a harmonic distortion current I_{HARM} = 2.57x$I_{RES(1)}$. Active and reactive components of a residual current in a fault location distort phase-to-ground voltage u_{PH} and neutral-to-ground voltage u_N because of frequency increase more than 5–6 kHz and voltage oscillations of unfaulted phases. Thus, at the same values of overvoltage levels probability for restrikes for faulted and unfaulted phases increases due to the influence of high-frequency overvoltages on network insulation. At higher values of a non-compensated residual current I_{RES} including influence of harmonic currents $I_{(n)}$, conditions for successful arc quenching are worsened.

Voltage recovery rates for a faulted phase can be estimated using the following equation [3]:

$$\frac{du_{RECOV}}{dt} = u_{phMAX}\,\frac{\omega_{50}}{2}\sqrt{\left(2\sqrt{1+\upsilon}-2\right)^2 + d^2}\;,\qquad (2)$$

where ω_{50} = 100π – angular frequency; d – damping coefficient, υ – detuning factor.

According to (2), voltage recovery rates for a faulted phase at damping coefficients d = [0.05; 0.10] reach du_{RECOV}/dt = 1420 V/s (at υ = + 2.7) and du_{RECOV}/dt = 400 V/ms (at υ = –0.45), which significanly greater than voltage recovery rate du_{RECOV}/dt = 54–86 V/ms at admissible level of detuning $|\upsilon|$ = 0.05. It results in reducing of durations of no-current conditions Δt and relatively quick transition of a ground fault into stable arcing with expanding of a fault area in cable insulation. These factors may facilitate emergency conditions in the network with a high content of harmonics in a ground fault current.

III. Assessment of higher harmonic influence on the impedance at a fault location in cable insulation

Assume that at single-phase breakdown of cable insulation, an arcing ground fault is transformed into stable arcing. This suggestion allows us to evaluate an impedance in a fault location correctly.

The n-th harmonic in a ground fault current with rms value of $I_{(n)}$ causes additional voltage drop across the resistance R_{ARC} of an arc channel. Then, rms harmonic distortion of voltage for an arc resistance in cable insulation is estimated as follows:

$$\Delta U_{(n)} = R_{ARC}\cdot\sqrt{\sum I_{(n)}^2} \qquad (3)$$

An average arc resistance can be estimated in the range of R_{ARC} = 0.5–10 Ohm. This range can be limited to R_{ARC} = 2.8–6.5 Ohm for 6-10 kV cable networks [4]. Dynamic arc resistance depends on the stage of arcing. For a grown arcing channel it is lower than 0.1 Ohm (i.e. r_{ARC} < 0.1 Ohm) being inversely proportional to an arc current (i.e. $r_{ARC} \sim 1/i_{ARC}$).

For the 6 kV main switchgear network at CHP Plant with known content of higher harmonics in a ground fault current, we obtained the rms harmonic distortion of voltage as $\Delta U_{(n)}$ = 222.9 – 517.4 V for arc resistances of R_{ARC} = 2.8–6.5 Ohm. Therefore, percentage of $\Delta U_{(n)}$ in the rms breakdown voltage ($U_{BR} \le U_{PH} = 6/\sqrt{3}$ kV) is 6.4 – 14.9%.

Instantaneous values of harmonic distortions for an arc voltage being proportional to harmonic currents are calculated as:

$$\Delta u_{(n)} = R_{ARC} \cdot i_{(n)} = \\ = R_{ARC} \cdot I_{(n)MAX} \cdot \sin(\omega_{(n)} t + +\varphi_{(n)}) \quad (4)$$

Calculations show that maximum instantaneous values of $i_{(n)}$ и $\Delta u_{(n)}$ are observed in the case of ground fault durations lower than 20 ms at the moment of breakdown time t_{BR} = 17.8 ms ($|\Sigma i_{(n)}|$ = 167.7 A; $|\Sigma\Delta u_{(n)}|$= 470–1090 V; $|\Sigma\Delta u_{(n)}|/u_{PHMAX}$ = 0.10–0.22), while minimum values are observed at the moment of breakdown time t_{BR} = 11 ms ($|\Sigma i_{(n)}|$ = 25.03 A; $|\Sigma\Delta u_{(n)}|$= 70.1–162.7 V; $|\Sigma\Delta u_{(n)}|/u_{PHMAX}$ = 0.01–0.03). Therefore, taking into account higher harmonics in a ground fault current and the process of stable arcing, voltage on the faulted phase might be greater than we expect.

Impedance at the fault location at stable arcing with harmonic distortions can be calculated as:

$$Z_F = \frac{\left|\sum i_{(n)}\right|}{I_{RES}} \cdot R_{ARC} = \frac{\left|\sum \Delta u_{(n)}\right|}{\sqrt{I_{RES(1)}^2 + I_{HARM}^2}} \quad (5)$$

For the considered 6 kV network, $I_{RES(1)}$ = 30.6 A, I_{HARM} = 2.57x$I_{RES(1)}$, $|\Sigma\Delta u_{(n)}|_{MAX}$ = (0.10–0.22)u_{PHMAX}. Consequently, equation (5) is transformed into:

$$Z_F = (0.053 \ldots 0.116) \frac{u_{PHMAX}}{I_{RES(1)}} \quad (6)$$

then Z_F = 8.6–19 Ohm.

It can be shown that when we do not take into account higher harmonics, Z_F = 3.9 – 9.0 Ohm, i.e. 2.1–2.2 times lower than (6).

When current is distorted by higher harmonics, there are no evident conditions for increasing of the voltage recovery rate de_{BR}/dt in the breakdown channel. We think that higher harmonics in a ground fault current should not lead to additional heating of gas-oil mixture in a mass-impregnated paper-insulated cable after breakdown. Thus, we may expect an increase of probability for restrikes in cable insulation. With a rise of the number of breakdowns, breakdown voltage u_{BR} and electric strength for a insulation gap decrease with a development of an arc channel. Stabilization of breakdown voltage u_{BR} in the area of its low values (i.e. $u_{BR} \leq$ (0.1–0.2)u_{PHMAX}) characterizes the transition of the fault into stable arcing. Time for reaching of stable arcing may be reduced in theory in the case when higher harmonics exceed the first harmonic (i.e. $I_{(n)} \geq I_{(1)}$). It is caused by harmonic distortion of arc current which increases a residual current at the fault location.

We suppose that an optimal way for any types of networks is reducing of ground fault duration by detection of a faulted feeder by selective relays and its disconnection with a minimum time delay. For these purposes, low-ohmic resistors and customer redundancy are recommended for implementation. Customer redundancy can be performed by quick automatic load transfer with operating times lower than 100 ms.

IV. Conclusions

1. In the cases of distortions of supply voltage by non-linear loads, degradation of power quality, and high levels of damages for power equipment used in 6-35 kV cable networks, higher harmonics in a ground fault current should be assessed. Harmonic distortion current may significantly exceed total or residual 50 Hz ground fault current.
2. High values of residual current at a fault location caused by abnormal detuning factors and harmonic distortion currents lead to degradation of arc extinction conditions and increase of probability for restrikes. Voltage recovery rates for a faulted phase in the considered 6 kV network at detuning factors of $|\upsilon|$ = 0.45–2.7 reach du_{RECOV}/dt = 400–1420 V/ms, which significantly greater than voltage recovery rate du_{RECOV}/dt = 54–86 V/ms at admissible level of detuning $|\upsilon|$ = 0.05. It results in reducing of durations of no-current conditions Δt and relatively quick transition of a ground fault into stable arcing with the development of emergency situations in the network.
3. Resistors connected to neutrals of the network do not influence on the content of higher harmonics in a ground fault current, but result in the increase of voltage recovery rates du_{RECOV}/dt and the decrease of overvoltage ratios K_U by 15-20%.
4. For the 6 kV cable network with known harmonic content at arc resistances of R_{ARC} = 2.8–6.5 Ohm, instantaneous values $\Delta u_{(n)}$ and rms values $\Delta U_{(n)}$ of harmonic distortions for arc voltages are assessed. Percentage of $\Delta U_{(n)}$ in rms breakdown voltage is 6.4 – 14.9%. It is shown that at stable arcing with fault durations lower than 20 ms maximum instantaneous values of $i_{(n)}$ and $\Delta u_{(n)}$ are observed at the moment of breakdown time t_{BR} = 17.8 ms (i.e. $|\Sigma i_{(n)}|$ = 167.7 A; $|\Sigma\Delta u_{(n)}|$= 470–1090 V; $|\Sigma\Delta u_{(n)}|/u_{PHMAX}$ = 0.10–0.22).
5. Impedance at the fault location at stable arcing with harmonic distortions for the considered 6 kV network is Z_F = 8.6–19 Ohm which is approximately two times greater than Z_F calculated for only 50 Hz frequency. Time for reaching of stable arcing may reduces in the case of $I_{(n)} \geq I_{(1)}$ due to increase of a residual current and impedance Z_F at the fault location.
6. An optimal way for protection of power equipment at single phase-to-ground faults in networks with high harmonic content is disconnection of faulted feeders. It can be simply performed by low-ohmic resistance grounding and using of customer redundancy.

V. References

[1] J. Orsagova, P. Toman, "Evaluation of Negative Effects of Distributed Generation". In Proc. 6th International Conference on Power Quality and Supply Reliability (PQ 2008, Parnu, Estonia, August 27-29, 2008), pp. 131 – 135.

[2] A. Shirkovets, A. Vasilyeva, A. Telegin, L. Sarin, M. Ilinykh, “Oscillography of Transient Processes at Physical Phase-to-ground Fault Modeling in Operational 6-35 kV Networks”. In elecronic Proc. 3rd International Youth Conference of Energetics (IYCE 2011, Leiria, Portugal, July 7-9, 2011).

[3] E. Fuchs, L. Fickert, “The Self-Extinguishing Current Limit and the Arc Burning Time of Compensated 20-kV-Power-Grids”.In Proc. 8th International Conference on Power Quality and Supply Reliability (PQ 2012, Tartu, Estonia, June 16-18, 2012), pp. 229 – 235.

[4] V. F. Soldatov, V. P. Kobazev, A.A. Chupaylenko, “Arc resistance estimation at single phase-to-ground faults”, Power Stations Journal, vol. 8, pp. 47-48, 1996.