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Contribution to earth fault current compensation in middle voltage distribution networks

Abstract*. The earth fault state balancing of the electricity distribution networks is covered by capacitive earth fault current compensating devices. The correct compensation contribute to fast arc quenching, surface voltage gradient decrease. Moreover there is certain possibility to keep the network in operation. The aim of the paper is to propound the theoretical background of the resonance earthing, the characteristics of Petersen coil circuit and case study of diagnostic measurements for the coil status assessment.*

Streszczenie*. W bilansie prądów zwarciowych doziemnych trzeba uwzględniać pojemnościowy prąd doziemny urządzeń kompensujących. Przy prawidłowej kompensacji i szybkim gaszeniu łuków powierzchniowy gradient napięcia maleje. Celem pracy jest przedstawienie podstaw teoretycznych rezonansowego doziemienia, charakterystyki obwodu cewki Petersena i diagnostyki stanu cewki. (****Udział prądu zwarcia doziemnego kompensacyjnego w sieci dystrybucyjnej średniego napięcia****)*

Keywords: Petersen coil, compensation, diagnostics, testing
Słowa kluczowe: cewki Petersena, kompensacja, diagnostyka, badania

Introduction

In distribution networks, there are several earthing concepts, such as unearthed, compensated, earthed through impedance, and solidly earthed at their neutral. Compensated earthing has grown in interest and its practical applications have increased [1]. Middle voltage distribution networks have no intentional direct earthing and operate with neutral connected to earth through impedance.

The way of the neutral to earth connection determines the behavior of a power system during a single phase to earth fault. From the safety point of view, the earth fault current causes a hazard voltage between the structure of the faulted equipment and earth. The earth fault compensation is widely used to solve this dangerous situation. Compensated distribution networks are earthed by the so-called Petersen coil connected to the neutral. Properly operated (tuned) compensating device cause a corresponding decrease of earth fault currents.

The unearthed and compensated distribution systems are crucial to obtain the optimal power supply quality in electrical network design. The main advantage of the treatment of the neutral point is the possibility of continuing the network operation during a sustained earth fault. Therefore, this reduces the number of interruptions of the power supply for the customer [2].

Authors in [3] discuss the possibility and advantages of distributed compensation. The purpose is that neutral point reactors are not ideal in networks with long cable radials due to losses that contribute to the active earth fault current. Another problem related to the compensated distribution systems is coupled with detecting earth faults that seems to be nontrivial problem [4, 5]. Finally, several works concerning simulations of fault arcs and identification of the compensated distribution systems parameters were published during last decade [6–8]. Petersen coil should be precisely tuned within given certain limits. Generally, the problem is to separate resonance points generated by disturbances and real resonance. There are several methods of improvement the accuracy of the Petersen coil tuning [9].

Line-to-earth fault – theoretical background

Although readers may already know theory concerning network compensation, brief theoretical introduction may be useful for unbroken text reading. In medium voltage networks with compensated system (which obviously means resonant grounding) a single line-to-earth fault is reduced by the use of the Petersen coil. The Petersen coil is tuned during operation of the network to achieve the compensation of the fault-capacitive current by application of inductive current component. Generally, simplified equivalent circuit is widely used for description of electrical parameters in a faulty distribution system, see Fig. 1. Ideal symmetrical three-phase voltage sources and negligible line resistances and inductances are considered. The fault model can be redesigned using Thevenin's theorem. Healthy network consider the phase voltage *E* at fault location. That's why the model can be simplified according the Fig. 2.

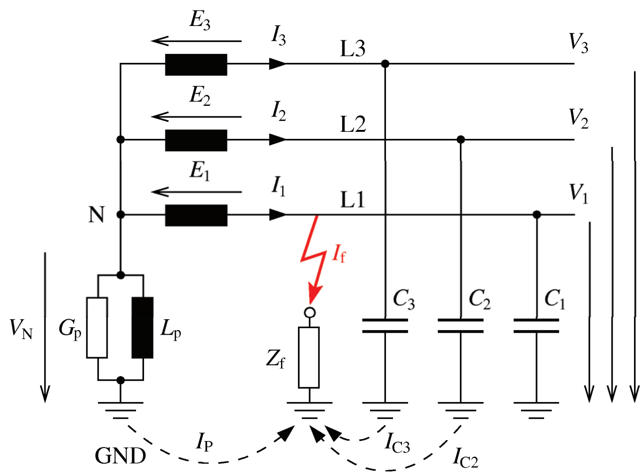

Fig.1. Equivalent circuit for compensated distribution network

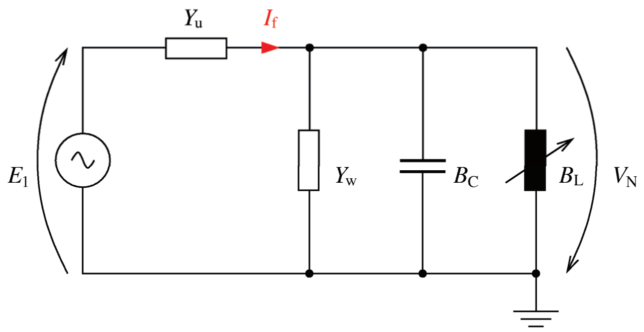

Fig.2. Single phase equivalent circuit for compensated distribution network

In the Fig. 1 E_1, E_2, E_3 correspond to source voltages, V_1, V_2, V_3 phase voltages, V_N neutral-to-earth voltage, N is the neutral point, Z_f is impedance in the earth fault, L_p and G_p are inductance and conductance of the Petersen coil. Fault current I_f flows through the earth fault place. This causes balancing I_P current of the Petersen coil. C_1, C_2 and C_3 represent line-to-earth capacitances. Healthy lines L2 and L3 are loaded only by capacitive current I_{C2} and I_{C3}. In the equivalent circuit according Fig. 2, the voltage distribution may be simply analyzed using the method of node analysis as follows:

(1) $$V_N(Y_u + Y_w + jB_C - jB_L) = -Y_u E_1$$

where: V_N – neutral-to-earth voltage, Y_u – unbalance of the fault location, Y_w – active part of Y_0, B_C – capacitive part of Y_0, B_L – inductive part of Y_0, E_1 – phase voltage, $\omega = 2\pi f$ and f is angular frequency of the system.

In the formula (1) following simplification can be made:

(2) $$Y_u = \Delta G + j\omega C,$$

(3) $$Y_w = 3G + G_P,$$

(4) $$B_C = 3\omega C,$$

(5) $$B_L = \frac{1}{\omega L_P}.$$

Consequently, by modification of the formula (1), the form of frequency dependent voltage divider can be written as:

(6) $$V_N = \frac{Y_u E_1}{Y_u + Y_w + j(B_C - B_L)} = \frac{-Y_u E_1}{Y_u + Y_0}$$

and

(7) $$Y_0 = Y_w + j(B_C - B_L).$$

Characteristics of the Petersen coil

To describe properties of technical Petersen coil there are several ways to do it. The text that follows proposes information about Petersen coil function in the network to readers. Let us recall propound basic characteristic of Petersen coil by means of graphical interpretation of electro-physical parameters in the faulty state.

For the fault current elimination the inductive reactance of Petersen coil plays the main role. The coil is connected between power network neutral point and earth. The inductive reactance value is tuned in the manner of total capacitive current returning to the fault minimization. The overall analysis requires that the resistance losses in the coil, lines, transformers, corona losses and insulator leakage which cause so called residual fault current have to be taken into account. The vector diagram is shown in the Fig. 3. In the figure the source voltages E_1, E_2, E_3 are drawn as three vectors mutually rotated by 120°. Fault current I_f is compensated by addition of current I_P which flows through Petersen coil windings and capacitive current I_C which means total vector of capacitive current components. The figure is showing ideal case where fault current and source voltage vector E_1 are mutually co-phasal.

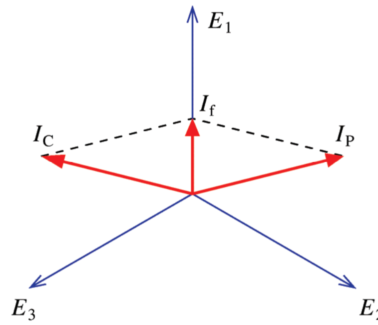

Fig.3. Vector diagram of a 3-phase system with resonant earthing and earth fault in one line

It is assumed, that the resistance of the Petersen coil is much lower than its inductive reactance. Therefore the losses of the Petersen coil are summed up with the phase-to-earth losses. The maximal impedance is obtained if the imaginary part of the (7) is equal to zero. That is, when the Petersen coil is exactly in tune (resonance). It is clear from the Fig. 1, that line-to-earth capacitances C_2 and C_3, the inductance of the Petersen coil and the ohmic losses are forming parallel resonance circuit with the resonance frequency

(8) $$\omega = \sqrt{\frac{1}{3 L_P C_e}},$$

where: C_e – line-to-earth capacitance.

The fault current can be expressed by means of the detuning factor v and the damping d as

(9) $$I_f \approx \sqrt{3 E_1 \omega C_e (d + jv)}$$

where

(10) $$v = 1 - \frac{1}{3\omega^2 C_e L_P},$$

(11) $$d = \frac{G}{\omega C_e}.$$

In case of well tuned operation ($v = 0$) the fault current is a pure ohmic current

(12) $$I_{f_{res}} = \sqrt{3 E_1 \omega C_e d}.$$

The Petersen coil is usually a tunable plunger-coil with continuous adjustment of the reactance. Successive tuning operation brings the coil into the resonance. Voltages and residual current in the case of an earth fault and displacement voltage without earth fault are graphically shown in the Fig. 4. There are two main graphs in the figure. Upper one shows line-to-earth voltages V_1, V_2, V_3 due to detuning factor relation. There are two critical values defined as U_{max}/U_{LE} and U_{min}/U_{LE}. Maximal and minimal permissible values (U_{max}, U_{min}) are defined in specification. Tuning of the Petersen coil enables three modes: total tuning with $v = 0$ resulting in total ohmic residual current on the earth fault location, undertuning with $v < 0$ resulting in ohmic-capacitive residual current and overtuning with $v > 0$ resulting in ohmic-inductive residual current. Practically, small overtuning up to v = 10 % is recommended due to capacitance changes in the case of switching of lines.

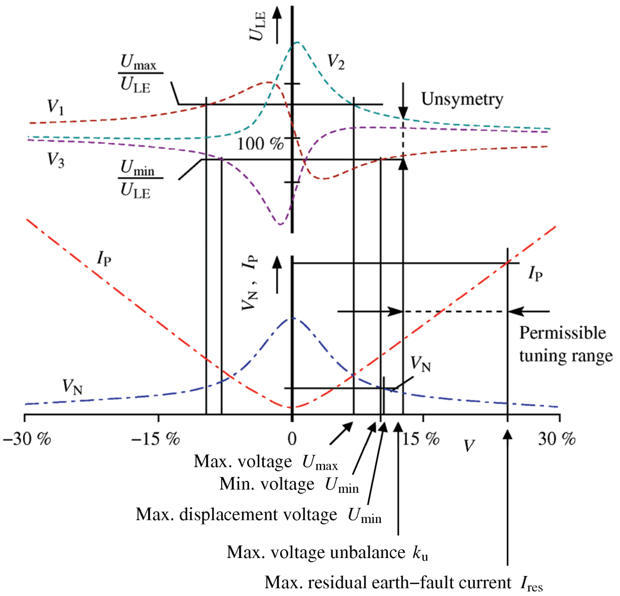

Fig.4. Voltages and residual current in the case of an earth fault; displacement voltage without earth fault [10]

Another factor that limits the range of detuning of the Petersen coil is phase-to-earth voltages defined for different tuning factors. Minimal and maximal permissible voltages and a permissible asymmetry of the three voltages are taken into the consideration. Thence it follows the permissible tuning range of the Petersen coil ranging from 12 % to 22 %. As it can be seen in the Fig. 4 the displacement voltage measured at the Petersen coil is maximal in the case of resonance tuning and the value depends on the capacitive asymmetry and on the losses of the reactor. On the other hand the earth fault current will be minimal in this case. Detailed description of the Petersen coil tuning is referred in the reference [10]. The tuning algorithm has been widely studied e.g. in [11].

Properties of modern Petersen coil controllers

The modern technology has brought excellent possibility for the process automation. Present state regulators are designed as freely-programmable devices which can be used to tune continuously – adjustable Petersen coils. They are able to control all other measurement and recording tasks related to Petersen coils. Moreover, E-LAN system bus can be used for multiply devices connection.

Recent research has adverted to two possibilities of solution of control solution. First one is so called “*without current injection*“ and second one is called “*with current injection*”.

The properties of the first solution of controlling by means “*without current injection*“ are given by requirements of the tuning of the Petersen coil only with zero-sequence voltage by changing the coil position. Enough zero-sequence voltage has to be available. Zero-sequence voltage should be used from the Petersen coil.

When “*with current injection*“ method is taken into account, the procedure allows find the correct tuning position, even if the natural zero-sequence voltage is zero respectively if the disturbances in the zero-sequence voltage are not negligible. Existing algorithms that are used to determine the network parameters respectively to tune the Petersen coil can be sort to items that follow:

- artificial earth fault,
- determination of maximal residual voltage,
- least square method based on inverse of resonance curve,
- locus diagram of residual voltage,
- artificial current injection into neutral point of the system in the case of no unsymmetrical current from the natural asymmetry.

Detailed description of methods above can be found in [12–14].

Experimental

Although there are possibility of modern control devices utilization in the power networks, there are numerous devices that can be classified as older without possibility of automatic testing. That’s why let us introduce simple procedure for testing such devices.

Coil testing is specified in appropriate specification, in Slovak territory in STN 333070. Testing is based on measuring in resonance circuit. Voltage is recorded due to different circuit parameters. The Petersen coil, set to the minimum current shall be connected to the network without a earth fault. Gradually readings for each setting value of the current through the Petersen coil and the value of induced voltage on the measuring winding need to be recorded. During measurement in the power network, performing no changes in the transmissions, measured in the usual lines and transformers involved. The measurement is carried out gradually in full tuning range, while settings at the value of highest voltage on coil are determined. Results are plotted in a graph. Measurement circuit is shown in the Fig. 5.

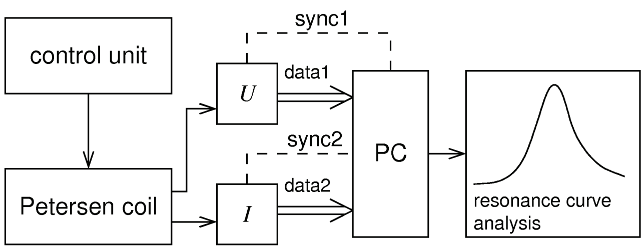

Fig.5. Schematic diagram of measuring circuit

The resonance curve is necessary to determine the characteristic values of the network. The magnitude of the capacitive current is the same as the Petersen coil current magnitude, when there is resonance in the circuit.

$$I_C = I_{res}, \tag{13}$$

where: I_C – overall capacitive current in the network, I_{res} – Petersen coil current magnitude when tuned in resonance.

Leakage current due to earth fault can be derived from the resonance curve as follows: current limits I_{P1}, I_{P2} are computed from data measured in $0.707U_{res}$.

$$I_w = \frac{I_{P1} - I_{P2}}{2}, \tag{14}$$

where: I_w – wattmetric current over the fault location.

Now the damping factor is given by formula:

$$d = \frac{I_v}{I_C} = \frac{I_v}{I_{res}} \tag{15}$$

and unbalance of network k

(16) $$k = \frac{U_{res}}{100} \cdot d \,.$$

To make such testing easier, the experimental setup and analyzing algorithm has been developed for this purpose. Setup design is based on current common measurement devices where only data transfer to control computer is required. Automated analysis is proposed by means of small computer procedure that can be ported or translated into various numbers of numerical analysis programs and platforms. The principle is based on the procedure which flowchart is in the Fig. 6.

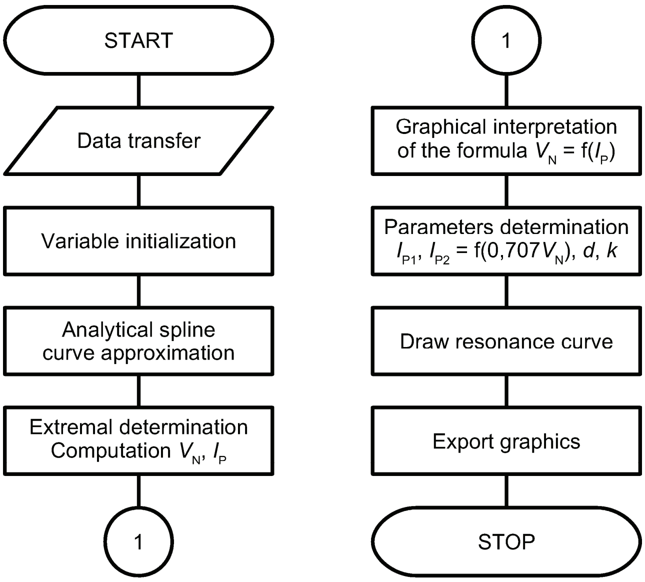

Fig.6. Analyzing procedure flow chart

Discussion

The program has been realized in virtual instrumentation environment. After resolving the problems coupled with measuring devices communication and data transfer, global variables need to be initialized. They are needed for global functionality of the procedure. Spline approximation of data measured provides extended presentation capability of resulting analysis. The core of the procedure lies in next three boxes. After extreme voltage determination, the criteria comparison of measured data against to specification is done. Result of the procedure provides overall status affirmation. It can be either the "*coil is good*" or the "*coil is bad*". Although it seems to be simple, lot of staff from network utility companies has sought such a simplification. Mathematical computation may be realized by calling external mathematical tool, or by code programming in the frame of the main procedure.

The procedure was tested in the power station in 6 kV and 22 kV power networks. The case of 6 kV is written in the text following. Two Petersen coils were tested in order to uncover hidden failures in Petersen coil functionality. Test circuit was arranged according the one in the Fig. 5. The data stream was recorded to remote computer data storage and passed to the analyzing procedure. The procedure results in graphical interpretation are presented in the Fig. 7. From Fig. 7a, it is clear that procedure confirms the measured coil PC1 as able to compensate earth faults in right manner. In opposite side the Fig. 7b unleash the problem in the measured coil PC2. The PC2 is not compliant with the specification. The main problem is that the coil can not be tuned properly so earth fault can cause problem and faulty current will not be compensated. The earth fault in the network and possibly brings network operation into breakdown.

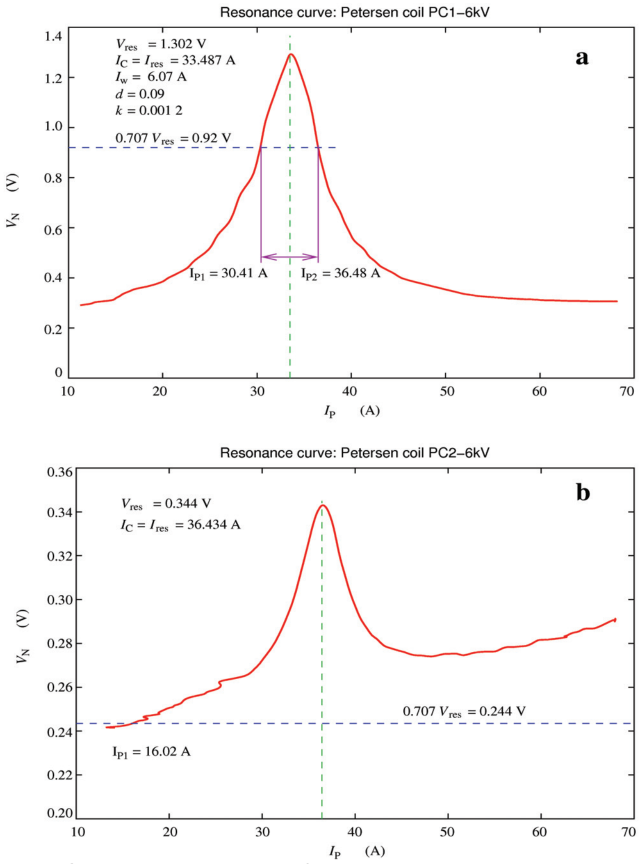

Fig.7. Graphical interpretation of analyzing procedure results

Conclusions

Ungrounded systems are connected to ground through the line-to-ground capacitances in order to fault eliminating. Single line-to-ground faults shift the system neutral but leave the phase-to-phase voltage triangle intact. Compensated systems are grounded through a variable impedance reactor, the Peterson coil, which compensates the system phase-to-ground capacitance. If the value of the Petersen coil is correctly tuned the current of a possible earth fault can be reduced and the immediate protection tripping can be delayed. From plant-engineering point of view, the possibility of testing of older devices can prevent network from large scale failure incidents. The measurement system design and program interface are intended to reach high accuracy of critical parameters.

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