Lappeenranta University of Technology
School of Technology
Degree Program in Energy Technology

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THE TITLE OF THE WORK - THE INFLUENCE OF HIGH CABLE PENETRATION IN DISTRIBUTION NETWORKS ON EARTH FAULT CURRENTS AND THE OPERATION OF RELAY PROTECTION**.**

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ABSTRACT

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Recent Storms in Nordic countries were a reason of long power outages in huge territories. After these disasters distribution networks' operators faced with a problem how to provide adequate quality of supply in such situation. The decision of utilization cable lines rather than overhead lines were made, which brings new features to distribution networks.

The main idea of this work is a complex analysis of medium voltage distribution networks with long cable lines. High value of cable's specific capacitance and length of lines determine such problems as: high values of earth fault currents, excessive amount of reactive power flow from distribution to transmission network, possibility of a high voltage level at the receiving end of cable feeders. However the core tasks was to estimate functional ability of the earth fault protection and the possibility to utilize simplified formulas for operating setting calculations in this network.

In order to provide justify solution or evaluation of mentioned above problems corresponding calculations were made and in order to analyze behavior of relay protection principles PSCAD model of the examined network have been created. Evaluation of the voltage rise in the end of a cable line have educed absence of a dangerous increase in a voltage level, while excessive value of reactive power can be a reason of final penalty according to the Finish regulations. It was proved and calculated that for this networks compensation of earth fault currents should be implemented. In PSCAD models of the electrical grid with isolated neutral, central compensation and hybrid compensation were created. For the network with hybrid compensation methodology which allows to select number and rated power of distributed arc suppression coils have been offered. Based on the obtained results from experiments it was determined that in order to guarantee selective and reliable operation of the relay protection should be utilized hybrid compensation with connection of high-ohmic resistor. Directional and admittance based relay protection were tested under these conditions and advantageous of the novel protection were revealed. However, for electrical grids with extensive cabling necessity of a complex approach to the relay protection were explained and illustrated. Thus, in order to organize reliable earth fault protection is recommended to utilize both intermittent and conventional relay protection with operational settings calculated by the use of simplified formulas.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

a	Network coordinate base of three phasors
$\dot{B}_L$	Susceptance of the Petersen coil
$\dot{B}_{L1}$	Susceptance of the Petersen coil connected to protected line
$\dot{B}_{L2}$	Susceptance of the Petersen coil connected to background line
C_a	Capacitance of phase A
C_b	Capacitance of phase B
C_c	Capacitance of phase C
C_{ph}	Capacitance of phase
C_{tph}	Total phase capacity of the network
C_{tph-ph}	Total phase-to-phase capacity of the network
C_f	Phase capacity of the damaged power line;
C_{eqiv}	Equivalent phase capacity of intact power lines;
C_{nom}^{n}	Capacitance per unit of length with cross-section of n mm^2
$C_{\lim}$	Limit for the total value of shunt capacitance in the network
C_i	Specific capacitance of the feeder i
$C_{\sum}$	Sum of phase capacitances
d	Relative total conductance of the phases with respect to the ground
df	Damping factor
$\dot{\mathrm{E}}_{\mathrm{a}}$	Sinusoidal electromotive force in phase A
$\dot{E}_b$	Sinusoidal electromotive force in phase B
$\dot{\mathrm{E}}_{\mathrm{c}}$	Sinusoidal electromotive force in phase C
$\dot{\mathrm{E}}_{\mathrm{ph}}$	Sinusoidal electromotive force in phase
$E_{ph\nu}$	Amplitude of phase electromotive force of ν-th harmonic

$\dot{E}_{a\nu}$	Sinusoidal electromotive force in phase A of ν-th harmonic
$\dot{E}_{b\nu}$	Sinusoidal electromotive force in phase B of ν-th harmonic
$\dot{E}_{c\nu}$	Sinusoidal electromotive force in phase C of ν-th harmonic
e_a	Nonsinusoidal electromotive force in phase A
e_b	Nonsinusoidal electromotive force in phase B
e_c	Nonsinusoidal electromotive force in phase C
FP	Financial penalties
f_1	The lowest natural vibration frequency of the voltage of the damaged phase
f_2	Higher natural frequency of the voltage
G_a	Active conductivity of phase A
G_b	Active conductivity of phase B
G_c	Active conductivity of phase C
G_f	Conductivity at the fault point
G_{f1}	Conductivity at the fault point in protected line
G_{f2}	Conductivity at the fault point in background line
G_{ph}	Active conductivity of phase
G_L	Conductance, which reflects the loss at arc suppression coils
G_{Σ}	Sum of phase active conductivities
I	Total current of the power line
$\mathrm{I_a}$	Current in phase A
$\mathrm{I_b}$	Current in phase B
$\mathrm{I_c}$	Current in phase C
$\dot{I}_f$	Earth fault current
I_{f*}	Relative earth fault current
$\dot{I}_{f\nu}$	Earth fault current of ν-th harmonic

I_{1r}	Reactive component of the fundamental frequency current
I_{A1}	Active component of the fundamental frequency current
I_{Ind1}	Inductive component of the Petersen Coil current
I_{a1}	Current in phase A of protected line
I_{b1}	Current in phase B of protected line
I_{c1}	Current in phase C of protected line
I_{a2}	Current in phase A of background line
I_{b2}	Current in phase B of background line
I_{c2}	Current in phase C of background line
$\dot{I}_{L1}$	Current in arc suppression coil connected to protected line
$\dot{I}_{L2}$	Current in arc suppression coil connected to background line
$\dot{I}_{L}$	Current in central arc suppression coil
I_{Li}	Inductive current of i-th arc suppression coil
$\dot{I}_{0}$	Sum of currents in the protected line
I_{fibr}	Current threshold for ventricular fibrillation
$I_{C\nu}$	Capacitive component of high harmonics current
I_{Cap1}	Capacitive component of earth fault current
$I_{C\Sigma}$	Total earth fault current
$I_{\mathrm{C(i)max}}$	Largest earth fault current among connected feeders
I_{C1}	Earth fault current in line 1
I_{C2}	Earth fault current in line 2
I_{trip}	Value of tripping current
$I_{\nu C\Sigma}$	Current in the protected feeder of ν-th harmonic
$\mathrm{I}_{\nu \mathrm{C(i)}}$	Current in the intact feeder of ν-th harmonic

$\dot{I}_{0\,fault}$	Zero-sequence current during earth fault
$\dot{I}_{0\,pre-fault}$	Zero-sequence current before earth fault
I_{ri}	Earth fault current in summation transformer
I_{fi}	Earth fault current generated by i-th feeder
$k_{\mathrm{r}.f.}$	Reliability factor
k_{in}	Inrush factor
$\mathrm{k_S}$	Sensibility factor
L	Inductance of arc suppression coil
L_{ps}	Inductivity of the power supply
L_{l}	Inductivity of the load
L_{d}	Inductivity of phases of the damaged line
L_{int}	Inductivity of phases of intact lines
L'_{eqiv}	Equivalent phase inductance of intact power lines
L_{t}	Total inductance of arc suppression coils in the network.
$L_{1}^{0.95}$	Inductances of local arc suppression coil which compensates 95% of total shunt capacitance of the network
l_{f}	Distance to the earth fault
l	Length of the cable line
l_{i}	Length of the feeder i
n	Coefficient of relay protection
P_{h}	One hour average active power
P	Active power
P_{loss}	Active losses in power line
$P_{loadlosses}$	Value of load losses in transformer
$P_{loadlosses}^{nom}$	Values of load losses at nominal load and voltage in transformer

Q_{S1}	Reactive power input limit
Q_S	Reactive power output limit
Q_M	One hour average reactive power
Q_h	Transformers' reactive power losses
Q	Reactive power
Q_c	Charge capacity of the cable line
Q_P	Nominal reactive power of Petersen coil
R_f	Transient resistance
R_{f*}	Resistance at the fault point as the proportion of the equivalent capacitance of the network with respect to the ground
R_m	Earthing resistance
r_{nom}^{n}	Resistance per unit of length with cross-section of n mm^2
R	Resistance of the power line
R_l	Neutral resistor
S	Apparent power
S_N	Apparent power of the largest generator
S_{nom}^{n}	Nominal cross-section of n mm^2
T	Duration of time of current flow through human body
t_{start}	Start time reference
t_{stop}	Stop time reference
t_{tr}	Round-trip time
t_k	Peak usage time
Δt	Time interval between start and stop time references
$\dot{U}_n$	Neutral point voltage
$\dot{U}_a$	Phase to ground voltage in phase A
$\dot{U}_b$	Phase to ground voltage in phase B

$\dot{U}_c$	Phase to ground voltage in phase C
$\dot{U}_{n\nu}$	Neutral point voltage of ν-th harmonic
$\dot{U}_{a\nu}$	Phase to ground voltage in phase A of ν-th harmonic
$\dot{U}_{b\nu}$	Phase to ground voltage in phase B of ν-th harmonic
$\dot{U}_{c\nu}$	Phase to ground voltage in phase C of ν-th harmonic
U_m	Earthing voltage
U_0	Zero-sequence voltage
$\dot{U}_{0\_fault}$	Zero-sequence voltage during earth fault
$\dot{U}_{0\_pre-fault}$	Zero-sequence voltage before earth fault
V	Pulse velocity in the line
V_r	Voltage at the receiving end
V_s	Voltage in the sending end
W_{Output}	Output active power
W_{Gen}	Net active power production
X_{Wye}	Reactance of wye-connected reactors
X_{Delta}	Reactance of delta-connected reactors
$\dot{Y}_a$	Admittance of phase A
$\dot{Y}_b$	Admittance of phase B
$\dot{Y}_c$	Admittance of phase C
$\dot{Y}_{a1}$	Admittance of phase A of the protected line
$\dot{Y}_{b1}$	Admittance of phase B of the protected line
$\dot{Y}_{c1}$	Admittance of phase C of the protected line
$\dot{Y}_{a2}$	Admittance of phase A of the protected line
$\dot{Y}_{b2}$	Admittance of phase B of the protected line
$\dot{Y}_{c2}$	Admittance of phase C of the background line

$\dot{Y}_{a\nu}$	Admittance of phase A of ν-th harmonic
$\dot{Y}_{b\nu}$	Admittance of phase B of ν-th harmonic
$\dot{Y}_{c\nu}$	Admittance of phase C of ν-th harmonic
$\dot{Y}_{ph}$	Admittance of phase
$\dot{Y}_1$	Total admittance of the protected line
$\dot{Y}_2$	Total admittance of the background line
$\dot{Y}_0$	Zero-sequence admittance
$\dot{Y}^{\nu}$	Admittance of the line of ν-th harmonic
$\dot{Y}_0^{\nu}$	Zero-sequence admittance of the line of ν-th harmonic
$\dot{Y}_0^{1}$	Fundamental frequency admittance,
$\sum\dot{Y}_0^{\nu}$	Harmonic admittances sum of ν-th order.
υ	Detuning of compensation
ω	Rate of phase change
ω_0	Resonant frequency of the oscillating circuit which is formed by the grid capacity and inductance of the Petersen coil
ν	Number of harmonic
δ_G	Unbalance factor of active conductance
δ_C	Factor of capacitance unbalance of the network
β	Fitness ratio of the earth fault
Ω	Ohm

Abbreviations

ABB-Asea Brown Boveri

CPS-Cumulative Phasor Summing

DFT- Discrete Fourier transformation

FF-Fundamental frequency

1 INTRODUCTION

1.1 Background

Nowadays quality of power supply in networks is an extremely important topic. Due to the progress in many fields modern and complex devices have been created which are significantly sensitive to the quality of supply. Also, even small outages of power supply can cause serious damage to plants and factories with continues flow process. Thus, the importance of power supply in the network is determined by customers’ requirements. The negative influence of malfunctions in networks can be minimized by the use of modern means of relay protection and automation. The biggest amount of outages is occurred because of faults in medium voltage distribution networks; this fact defines the topic of this work.

Medium voltage networks can experience much variety of different types of faults. However the most widespread type of fault is the earth fault. Ordinary distribution networks in rural areas consist of overhead lines with bare conductors which cross forests and rural woodlots. It is evident, that trees and its branches can be a cause of earth faults. In Finland in purpose to decrease number of faults in medium voltage networks variety of methods are utilized. For instance, implementation of wires with insulation allows to achieve up to 50 percentage of earth fault reductions while differences in investment costs are not remarkable. The most radical way to reduce amount of outages in medium voltage networks, induced by earth faults, is to replace overhead lines by cable lines. However this decision is not a cost effective from the investment point of view for networks with low power consumption and low density of consumption.

At the same time, planning of networks should consider all possible affecting factors in specific location. For Nordic countries climate conditions define types of lines utilized in distribution networks in rural areas. Storms in Finland as Tapani were a reason of long power outages in a huge territory; it is obvious, that overhead lines cannot withstand such harsh weather conditions. After these disasters distribution networks' operators faced with a problem how to provide adequate quality of supply in such situation. The decision of utilization cable lines rather than overhead lines were made, which brings new features to distribution networks.

1.2 Goals and delimitations

In rural areas power lines covers long distances and consequently the length of a cabled feeder can be remarkable. Also parameters of cable lines significantly differ from parameters of overhead lines, high specific capacitance of cable lines defines high value of earth fault currents and high value of charge capacity. Thus, long length of cable feeders and high value of shunt capacitance bring new challenges such as:

- high values of earth fault currents,
- the influence of cable specific active and inductive impedances on earth fault currents ,
- excessive amount of reactive power flow from distribution to transmission network,
- possible dangerous increase of voltage at the receiving end of cable feeders.

High specific capacitance of cable lines defines high value of earth fault currents in distribution networks with high level of cable lines penetration. Large earth fault current is a threat for humans' life and according to the Finish regulation touch voltage should be limited for determined level. In order to satisfy safety regulations and also to prevent possible damage to network equipment relay protection has a great significance.

Conventionally for calculations of earth fault current in distribution networks specific capacitances of power lines are used to estimate value of the current. However implementation of this method to networks with long cable lines provides wrong results which reveal that series impedance cannot be neglected for long cabled feeders. According to this earth fault current cannot be fully compensated by the arc suppression coils, because examined current has inductive and resistive parts.

According to the Finish regulations amount of reactive power transferred from transmission to distribution networks or in another direction is limited. For conventional medium voltage networks situation, when reactive power flow from distribution network exceeds limits, has a low probability. However for electrical grids with long cable lines, because of the large amount of charge capacitance, during the period of low loads it can be observed. It is evident that in case distribution system operator will be penalized, thus, a problem of reactive power compensation exists.

In medium voltage distribution networks with overhead lines Ferranti phenomena practically does not affect to voltage level. However in case when long cable lines are presented in the electrical grid, because of high capacitive currents during low load conditions, the voltage rise can be observed. The main danger of these phenomena is determined by the constant voltage level at the sending end of the power line. Thus, substation does not observe any changes and in this case voltage at the receiving end of the feeder will not be adjusted by on-load tap changer. Main substation is blind for Ferranti effect and in high voltage networks such phenomena can cause serious breakdown of equipment in the receiving end.

In the master thesis work will be represented main challenges of medium voltage distribution network with high level of cable penetration and provide assessment of their significance. The main idea of the work is not to calculate electrical quantity for the specific network but to estimate influence of long cable lines on a network from different point of views in general. The desired result of this work is a list of conclusions and assessments which can be used in a future as a base for making decisions regarding to the planning of distribution networks with excessive cabling.

2 EARTH FAULTS IN DISTRIBUTION NETWORKS

2.1 Networks with isolated neutral.

In networks with isolated neutral wires of the three-phase system are connected to the ground via a capacitances and insulation resistances, distributed along the length of the lines. Fig.1 shows the equivalent circuit of the grid with isolated neutral without load.

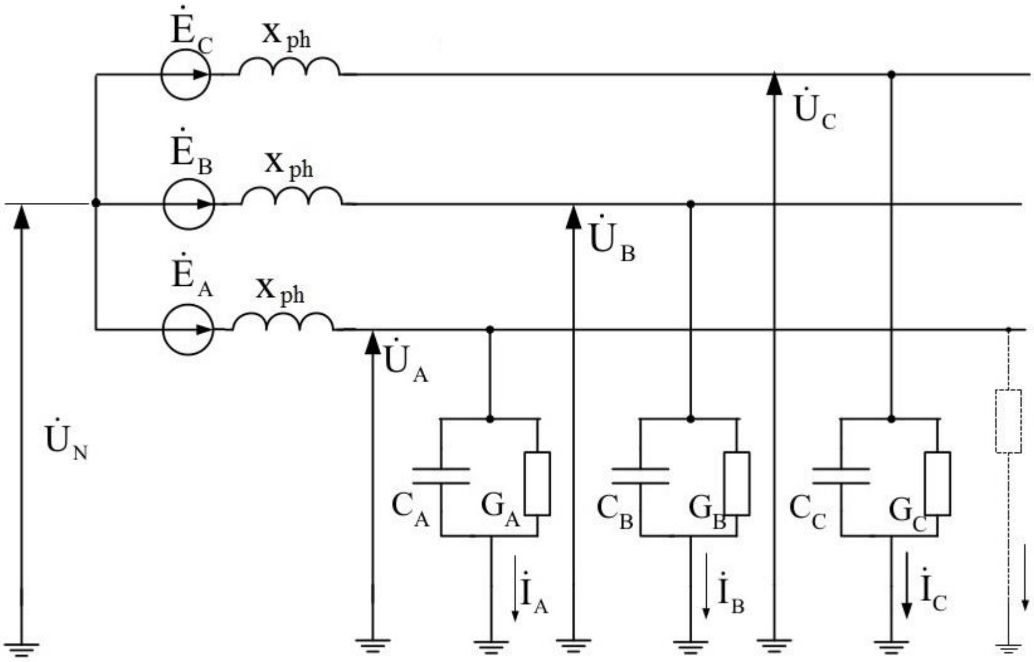


Fig.1. The equivalent circuit of the network with isolated neutral [1]

Equivalent circuit includes a power source, the equivalent line, capacitances (C_a, C_b, C_c) and active conductivity (G_a, G_b, G_c) of phases, which assumed as lumped values. This is quite acceptable in the frequency domain, which occupy processes under consideration. The internal resistance of the power supply lines and longitudinal resistance of the network are much lesser than the resistance of the phase with respect to ground, so during earth faults it can be ignored.[1]

With above mentioned assumption it can be written:

$$\dot{I}_a = (\dot{E}_a + \dot{U}_n) \cdot \dot{Y}_a; \quad (1)$$

$$\dot{I}_b = (\dot{E}_b + \dot{U}_n) \cdot \dot{Y}_b; \quad (2)$$

$$\dot{I}_c = (\dot{E}_c + \dot{U}_n) \cdot \dot{Y}_c. \quad (3)$$

Where $\dot{U}_n$ is neutral point voltage,

$\dot{E}_a = \dot{E}_{th}$, $\dot{E}_b = a^2\dot{E}_{th}$, $\dot{E}_c = a\,\dot{E}_{th}$ are electromotive forces of phases A, B, and C cosequently.

$$\dot{Y}_a = G_a + j\omega C_a, \tag{4}$$

$$\dot{Y}_b = G_b + j\omega C_b, \tag{5}$$

$$\dot{Y}_c = G_c + j\omega C_c. \tag{6}$$

Where ω - rate of phase change, $\dot{Y}_a, \dot{Y}_b, \dot{Y}_c$ are phase admittances.

Without a ground fault the current sum I_a, I_b, I_c is zero, i.e.

$$(\dot{E}_a + \dot{U}_n)\cdot\dot{Y}_a + (\dot{E}_b + \dot{U}_n)\cdot\dot{Y}_b + (\dot{E}_c + \dot{U}_n)\cdot\dot{Y}_c = 0, \tag{7}$$

Solving this Equation (7) with respect to $\dot{U}_n$, we will obtain:

$$\dot{U}_n = -\dot{E}_{ph}\left(\frac{G_a + a^2G_b + aG_c}{\dot{Y}_a + \dot{Y}_b + \dot{Y}_c} + j\omega\frac{C_a + a^2C_b + aC_c}{\dot{Y}_a + \dot{Y}_b + \dot{Y}_c}\right). \tag{8}$$

Since $1 + a + a^2 = 0$, the voltage $\dot{U}_n$, as it follows from Equation (8), does not equal to zero only when admittances $\dot{Y}_a, \dot{Y}_b, \dot{Y}_c$ are not equal to each over, i.e. the symmetry of phases at the network are broken. The Absolute value of the voltage $\dot{U}_n$, which takes place in the normal working mode of a network is called neutral-point displacement voltage. [1]Let's represent Equation (8) in another manner:

$$\dot{U}_n = -\dot{E}_{ph}\left(\frac{G_a + a^2G_b + aG_c + j\omega(C_a + a^2C_b + aC_c)}{G_\Sigma + j\omega C_\Sigma}\right), \tag{9}$$

$$G_\Sigma = G_a + G_b + G_c, \tag{10}$$

$$C_\Sigma = C_a + C_b + C_c, \tag{11}$$

Where G_Σ is the sum of phase active conductivities and C_Σ is the sum of phase capacitances. Dividing the numerator and denominator of the obtained expression by ωC, we obtain:

$$\dot{U}_n = -\dot{E}_{ph}\left(\frac{\delta_G + j\delta_C}{d + j}\right). \tag{12}$$

Where δ_G is the unbalance factor of active conductance:

$$\delta_G = \frac{G_a + a^2 G_b + aG_c}{\omega C_\Sigma}. \quad (13)$$

δ_C is a factor of capacitance unbalance of the network:

$$\delta_C = \frac{C_a + a^2 C_b + aC_c}{C_\Sigma}. \quad (14)$$

d -us a relative total conductance of the phases with respect to the ground:

$$d = \frac{G_\Sigma}{\omega C_\Sigma}. \quad (15)$$

During normal operational mode active conductance of phases with respect to the ground is much lesser than capacitive conductivities ($\delta_G \ll \delta_C$) and therefore the virtually absolute value of the neutral-point displacement voltage is:

$$U_n = E_{ph} \frac{\delta_C}{\sqrt{d^2 + 1}}. \quad (16)$$

At cable networks the unbalance ratio and, consequently, $\dot{U}_n$ are negligible, since the phase of the cable located symmetry with respect to its armature. At networks with overhead lines capacities C_a, C_b, C_c are not strictly the same, even with transposing wires. Therefore for them the unbalance ratio is 0,005 ÷ 0,02. As it can be seen in Fig. 2a. phase to earth voltages become unequal in magnitude and an angle shift differs from 120 electrical degrees. Currents I_a, I_b, I_c, determined by the conductivity phase network, also form a nonsymmetrical star. [2]

2.1.1 Regime of the permanent earth fault.

At systems with isolated neutral earth fault can be permanent or through an arc. Permanent earth faults in its turn are separated to the solid and through the transient resistance, which is denoted by R_f. Consider the regime of the permanent earth fault at the phase A. For this regime the following equation is correct:

$$(\underline{E}_a + \underline{U}_n) \cdot \underline{G}_f + (\underline{E}_a + \underline{U}_n) \cdot \underline{Y}_a + (\underline{E}_b + \underline{U}_n) \cdot \underline{Y}_b + (\underline{E}_c + \underline{U}_n) \cdot \underline{Y}_c = 0, \quad (17)$$

where G_f is a conductivity at the fault point

$$G_f = \frac{1}{R_f}. \tag{18}$$

Solving Equation (17) with respect to the $\dot{U}_n$, we will obtain:

$$\dot{U}_n = -\dot{E}_{ph}\left(\frac{\dot{G}_f}{\dot{Y}_a + \dot{Y}_b + \dot{Y}_c + G_f} + \frac{\dot{Y}_a + a^2\dot{Y}_b + a\dot{Y}_c}{\dot{Y}_a + \dot{Y}_b + \dot{Y}_c + G_f}\right). \tag{19}$$

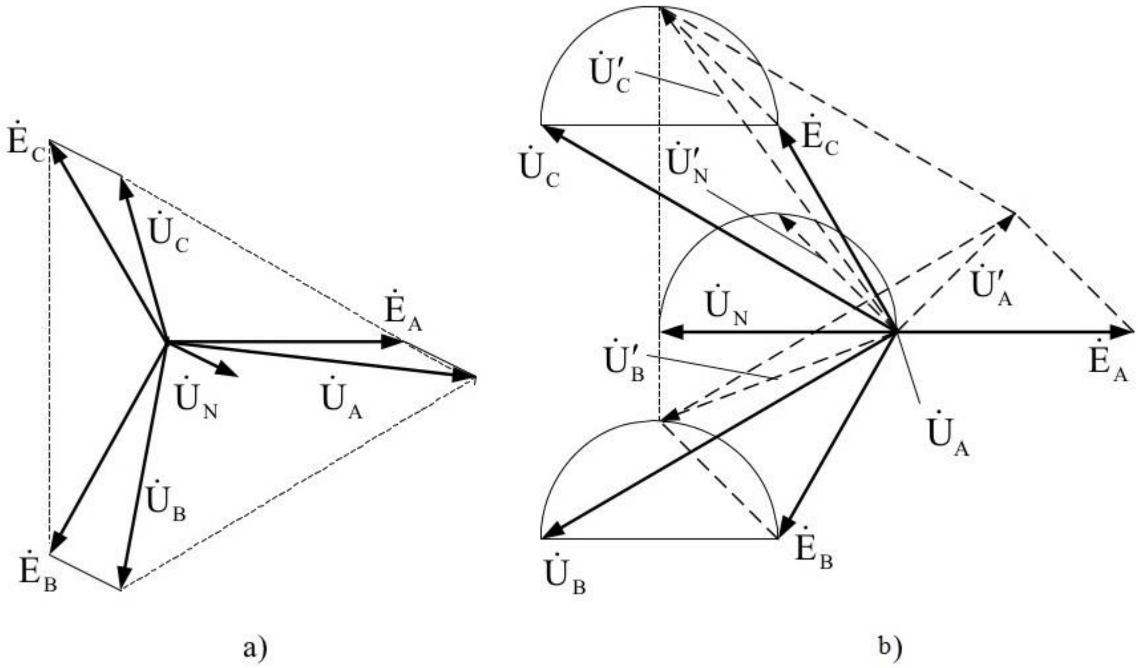


Fig. 2. Vector diagrams of voltages.[1]

a) for the normal mode when the $U_n \neq 0$;

b) for the earth fault of the phase A

When determining the neutral point voltage during the earth fault a possible unbalance of the network can be neglected, that is, considered $\dot{Y}_a = \dot{Y}_b = \dot{Y}_c = \dot{Y}_{ph}$. Thus

$$\dot{Y}_a + a^2\dot{Y}_b + a\dot{Y}_c = 0. \tag{20}$$

Consequently,

$$\dot{U}_n = -\dot{E}_{ph}\left(\frac{\dot{G}_f}{3\dot{Y}_{ph} + G_f}\right). \tag{21}$$

Transforming Equation (21) to the form:

$$\dot{U}_n = -\dot{E}_{ph}\left(\frac{1}{1+R_f(3G_{ph}+3j\omega C_{ph})}\right), \tag{22}$$

where $G_{ph} = G_a = G_b = G_c$

The ratio of the absolute value of the voltage at the neutral point according to its value when $R_f = 0$ is called the fitness ratio of the earth fault β:

$$\beta = \frac{1}{\sqrt{(1+3G_{ph}R_f)^2 + (3\omega C_{ph}R_f)^2}}. \tag{23}$$

From Equation (22) it follows that the voltage at the neutral point increases while resistance at the fault location decreases. When $R_f = 0$ the voltage at the neutral point has a maximum value and equal to the phase electromotive force.

Phase voltages with respect to ground during the earth fault can be defined as follows:

$$\dot{U}_a = \dot{U}_n + \dot{E}_a = \dot{E}_{ph}\frac{3G_{ph}R_f + 3j\omega C_{ph}R_f}{1+3G_{ph}R_f + 3j\omega C_{ph}R_f}, \tag{24}$$

$$\dot{U}_b = \dot{U}_n + \dot{E}_b = \dot{E}_{ph}\left(\frac{a^2(3G_{ph}R_f + 3j\omega C_{ph}R_f)-1}{1+3G_{ph}R_f + 3j\omega C_{ph}R_f}\right), \tag{25}$$

$$\dot{U}_c = \dot{U}_n + \dot{E}_c = \dot{E}_{ph}\left(\frac{a(3G_{ph}R_f + 3j\omega C_{ph}R_f)-1}{1+3G_{ph}R_f + 3j\omega C_{ph}R_f}\right). \tag{26}$$

Vector diagram of voltages during earth fault at phase A is represented in Fig. 2b. As it can be seen from the diagram and Equations (24,25,26) for $R_f = 0$ (vectors drawn by the solid lines) absolute value of the neutral-point voltage is equal to the absolute value of phase EMF and line to ground voltages of the intact phases are equal to the line to line voltage ($\sqrt{3}E_{ph}$).[1]

While increasing the resistance at the fault point the neutral-point voltage decreases. At that, the end of the vector $\dot{U}_n$ travels on the semicircle. Vectors of the intact phases, which are equal to the vector sum of the EMF of the corresponding phase and the neutral-point voltage, also glide along the semicircle. The position of vectors is shown with dotted line in Fig. 2b. , when the resistance at the place of the earth fault is equal to the total capacitive reactance of the network with respect to the ground $R_f = \frac{1}{3\omega C_{ph}}$ .Triangle of the line-to-line voltages remains unchanged, that is, the earth fault does not affect to the connected electrical load.[3]

At the Figure 3 changes of the neutral point voltage and phase voltages are represented while changing the resistance at the fault point.

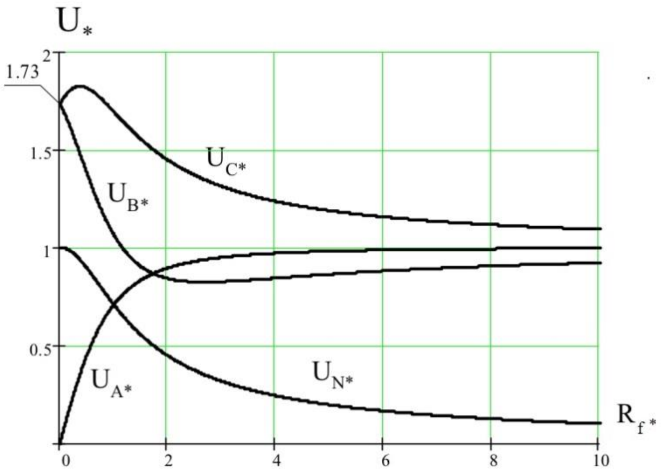


Fig. 3. Neutral point and phase voltages.[1]

This resistance is expressed as the proportion of the equivalent capacitance of the network with respect to the ground $R_{f*} = R_f 3\omega C$. All voltages are also presented in relative units, where the base voltage is equal to E_{ph}. The curves at the Figure 3 are based on formulas 23, 27-29. In this connection, it is assumed that active impedance of the phase insulation is infinite, that is, $G_{ph} = 0$. From Fig. 3. it is obvious that for a certain value R_{f*} the voltage of the intact phase can exceed the line voltage.[1]

According to the scheme at the Fig. 1. the earth fault current $\dot{I}_f$ can be defined as follows:

$$\dot{I}_f = -\dot{I}_a - \dot{I}_b - \dot{I}_c = -(\dot{E}_a + \dot{E}_b + \dot{E}_c + 3\dot{U}_n)\dot{Y}_{ph}. \qquad (27)$$

After the substitution of the U_n from Equation (23) and taking into account that $\dot{E}_a + \dot{E}_b + \dot{E}_c = 0$, the result will be:

$$\dot{I}_f = \frac{\dot{E}_{ph}}{R_f + \frac{1}{3G_{ph} + 3j\omega C_{ph}}}. \quad (28)$$

Based on the Equation (28), the equivalent circuit (Fig. 4.) of the zero sequence can be represented. The Fig. 5. reflects changes at the absolute value of the relative earth fault current $I_{f*} = \frac{I_f}{I_{f(R_f=0)}}$ in terms of R_f .

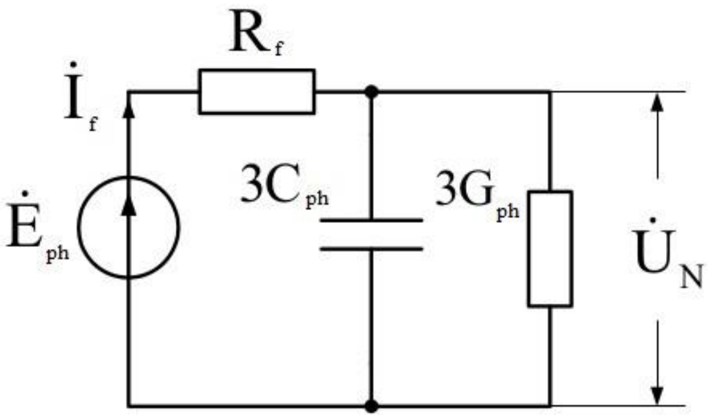


Fig. 4. Equivalent circuit of the zero sequence.[1]

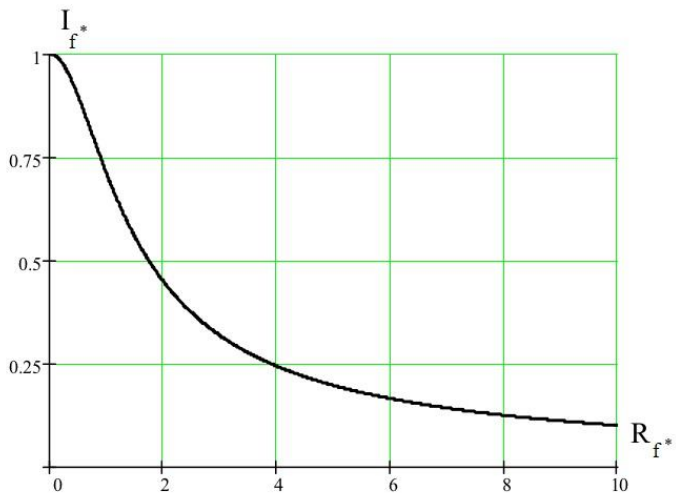


Fig. 5. Earth fault current in terms of R_f .[1]

2.2 Resonant earthed system.

In large overhead line or cable systems with isolated neutral, the problem is in a strong capacitive connection to ground and hence extensive earth fault currents. In order to fulfill required safety regulations the large capacitive earth fault current must somehow be decreased. In resonant earthed systems, the earth fault current is decreased by use of inductive neutral point reactors called Peterson coils. The Peterson coils, which are connected between an arbitrary number of the transformer neutral points and earth, decrease the resulting capacity strength of the system.

The most common way to connect Petersen coils is the use of special earthing transformers with star-delta connection which is illustrated in Fig. 6. Power transformers can also be used for this purpose, if the winding connection is star-delta.[4]

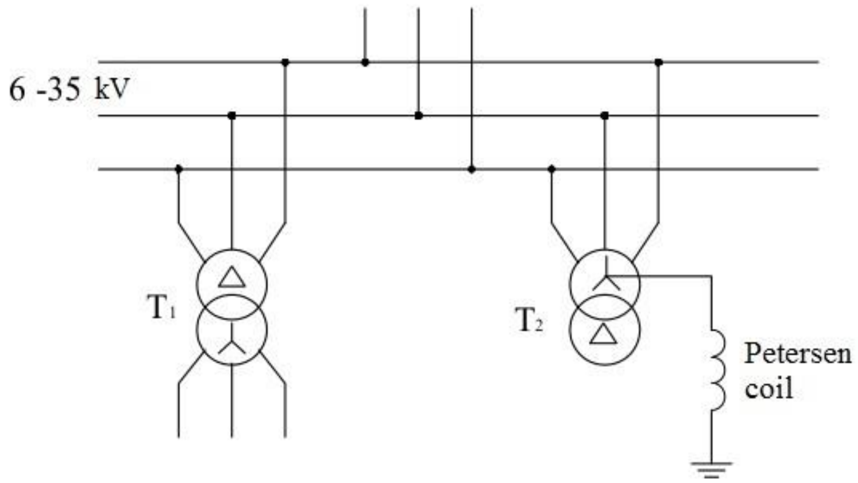


Fig. 6. System diagram of the compensated network.[1]

The design, nominal rating power and vector group of transformer have an influence on its resistance. For the best utilization of Petersen coils transformers to which they are connected should have as small as possible resistance. Transformer with a star-delta connection is the most suitable transformer for the connection of the arc suppression coil.[4]

Compensation currents in the star windings create magnetic flux which induces EMF and currents in the delta windings. In return currents in the delta windings determine magnetic flux in the transformer core which is opposite to fluxes induced by the star windings. Thus, magnetic fluxes are practically fully compensated and a small, in comparison with Petersen coil, inductance leakage corresponds to the inductance leakage flux of the windings. When an arc suppression coil is connected to the neutral point of a transformer with star-star winding connection currents and magnetic fluxes split up in different manner. During earth fault currents flow only in the primary winding, this is the reason why the magnetic flux in the transformer coil are not compensated. The presence of uncompensated magnetic fluxes determines EMF of self-induction which blocks current flow in the windings. It can be presented like the significant increase of the winding resistance during single-phase load, also the choke effect appears. [4]

The power transformer to which Petersen coil is connected should be selected based on its load and additional current of the arc suppression coil. If the transformer is used only for connecting the arc suppression coil, its capacity should be equal to the reactor power. In this case, the equivalent reactance of the transformer to zero-sequence currents is equal to a few percent of the arc suppression coil resistance. The presence of the series resistance is practically does not affect processes during the earth fault, if the resistance of the arc suppression coil is selected according to this resistance. As a result the three-phase equivalent circuit compensated network for further analysis is shown in Fig. 7.[1]

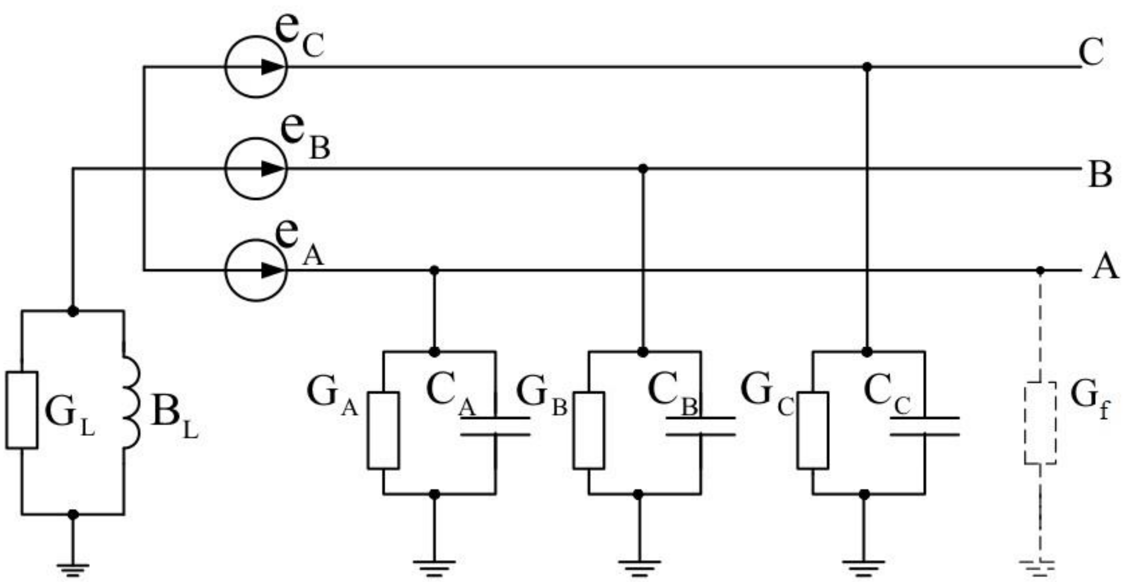


Fig. 7. Equivalent three-phase circuit of a resonated network.[1]

2.2.1 Regime of the permanent earth fault.

At compensated networks, as it will be seen later, in case of ground faults, it is necessary to consider that practically no electromotive force sources are strictly sinusoidal, so

$$e_a = \sum_{1}^{\nu} E_{ph\nu} \sin(\nu\omega t), \tag{29}$$

$$e_b = \sum_{1}^{\nu} E_{ph\nu} \sin(\nu\omega t + \frac{4}{3}\nu\pi), \tag{30}$$

$$e_c = \sum_{1}^{\nu} E_{ph\nu} \sin(\nu\omega t + \frac{2}{3}\nu\pi), \tag{31}$$

We assume that the EMF of the source is symmetric.

$\nu = 1,7,13...$ -Three phase systems of the positive sequence.

$\nu = 5,11,17...$ - Three phase systems of the negative sequence.

$\nu = 3,9,12...$ - Three phase systems of the zero sequence.

For any value of ν electrical quantities characterizing the regime of a compensated network at earth fault through the transition conductance G_f , for example, in phase A, are defined by following relations[1,2]:

voltage at the neutral

$$\dot{U}_{n\nu} = -\frac{\dot{E}_{a\nu}\dot{Y}_{a\nu} + \dot{E}_{b\nu}\dot{Y}_{b\nu} + \dot{E}_{c\nu}\dot{Y}_{c\nu} + \dot{E}_{a\nu}G_f}{\dot{Y}_{a\nu} + \dot{Y}_{b\nu} + \dot{Y}_{c\nu} + G_f + G_L + \dot{B}_L}. \tag{32}$$

Voltage of the broken phase:

$$\dot{U}_{a\nu} = \dot{E}_{a\nu} + \dot{U}_{n\nu} =$$
$$= \frac{\dot{E}_{a\nu}(\dot{Y}_{a\nu} + \dot{Y}_{b\nu} + \dot{Y}_{c\nu}) + \dot{E}_{a\nu}(G_L + \dot{B}_L)}{\dot{Y}_{a\nu} + \dot{Y}_{b\nu} + \dot{Y}_{c\nu} + G_f + G_L + \dot{B}_L} - \frac{\dot{E}_{a\nu}\dot{Y}_{a\nu} + \dot{E}_{b\nu}\dot{Y}_{b\nu} + \dot{E}_{c\nu}\dot{Y}_{c\nu}}{\dot{Y}_{a\nu} + \dot{Y}_{b\nu} + \dot{Y}_{c\nu} + G_f + G_L + \dot{B}_L}. \tag{33}$$

Earth fault current:

$$\dot{I}_{f\nu} = \frac{\dot{E}_{a\nu}(\dot{Y}_a + \dot{Y}_b + \dot{Y}_c + G_L + \dot{B}_L)G_f}{\dot{Y}_a + \dot{Y}_b + \dot{Y}_c + G_L + \dot{B}_L + G_f} - \frac{G_f(\dot{E}_{a\nu}\dot{Y}_a + \dot{E}_{b\nu}\dot{Y}_b + \dot{E}_{c\nu}\dot{Y}_c)}{\dot{Y}_a + \dot{Y}_b + \dot{Y}_c + G_L + \dot{B}_L + G_f} \tag{34}$$

Voltage of intact phases

$$\dot{U}_{b\nu} = \dot{E}_{b\nu} + \dot{U}_{n\nu} =$$
$$= \frac{\dot{E}_{b\nu}(\dot{Y}_{a\nu} + \dot{Y}_{b\nu} + \dot{Y}_{c\nu} + G_f + G_L + \dot{B}_L)}{\dot{Y}_{a\nu} + \dot{Y}_{b\nu} + \dot{Y}_{c\nu} + G_f + G_L + \dot{B}_L} - \frac{\dot{E}_{a\nu}G_f + \dot{E}_{a\nu}\dot{Y}_{a\nu} + \dot{E}_{b\nu}\dot{Y}_{b\nu} + \dot{E}_{c\nu}\dot{Y}_{c\nu}}{\dot{Y}_{a\nu} + \dot{Y}_{b\nu} + \dot{Y}_{c\nu} + G_f + G_L + \dot{B}_L}, \tag{35}$$

$$\dot{U}_{cv} = \dot{E}_{cv} + \dot{U}_{nv} =$$
$$= \frac{\dot{E}_{cv}(\dot{Y}_{av} + \dot{Y}_{bv} + \dot{Y}_{cv} + G_f + G_L + \dot{B}_L)}{\dot{Y}_{av} + \dot{Y}_{bv} + \dot{Y}_{cv} + G_f + G_L + \dot{B}_L} - \frac{\dot{E}_{av}G_f + \dot{E}_{av}\dot{Y}_{av} + \dot{E}_{bv}\dot{Y}_{bv} + \dot{E}_{cv}\dot{Y}_{cv}}{\dot{Y}_{av} + \dot{Y}_{bv} + \dot{Y}_{cv} + G_f + G_L + \dot{B}_L}. \quad (36)$$

$\dot{E}_{av} = \dot{E}_{bv} = \dot{E}_{cv} = \dot{E}_{ph}$ - are rms values of the phase EMF with frequency νω.

$\underline{Y}_{av} = G_a + j\nu\omega C_a;\ \underline{Y}_{bv} = G_b + j\nu\omega C_b;\ \underline{Y}_{cv} = G_c + j\omega\nu C_c;$ - are admittances of phases with respect to ground at the frequency νω.[1]

Where $\dot{B}_L$ susceptance of the Petersen coil

$$\dot{B}_L = \frac{1}{j\nu\omega L}, \quad (37)$$

G_L - conductance, which reflects the loss at arc suppression coils.

Real unbalance at phase conductivities has little effect at the earth fault current, so it can be considered: $G_a = G_b = G_c = G_{ph}$, $C_a = C_b = C_c = C_{ph}$,

consequently : $G_a + G_b + G_c = 3G_{ph}$, $C_a + C_b + C_c = 3C_{ph}$

For harmonic components forming the system of positive and negative sequences EMF with the frequency of these components $\dot{E}_{av} + \dot{E}_{bv} + \dot{E}_{cv} = 0$ and therefore the fault current is [1]

$$\dot{I}_{fv} = \frac{\dot{E}_{av}(3G_{ph} + G_L + j3\nu\omega C_{ph} - j\frac{1}{\nu\omega L})}{R_f(3G_{ph} + G_L + j3\nu\omega C_{ph} - j\frac{1}{\nu\omega L} + \frac{1}{R_f})} \quad (38)$$

For the zero sequence:

$\dot{E}_{av} = \dot{E}_{bv} = \dot{E}_{cv}$,

$$\dot{I}_{fv} = \frac{\dot{E}_{av}(G_L - j\frac{1}{\nu\omega L})}{R_f(3G_{ph} + G_L + j3\nu\omega C_{ph} - j\frac{1}{\nu\omega L} + \frac{1}{R_f})}. \quad (39)$$

Let's assume that $R_f = 0$, than:

$$\dot{I}_{fv} = \dot{E}_{av}(\frac{1}{j\nu\omega L} + G_L). \quad (40)$$

From Equation (40) it is obvious that the harmonic currents with frequencies multiple of three determine resistance of the arc suppression coil, which at the frequencies of these harmonics is large. Therefore, at the place of earth fault the current harmonic multiples of three are small and will not take into account in the future.

Let us return to the expression (38) for current harmonics not multiples of three. This expression corresponds to the equivalent circuit of the zero-sequence shown in Fig. 8.

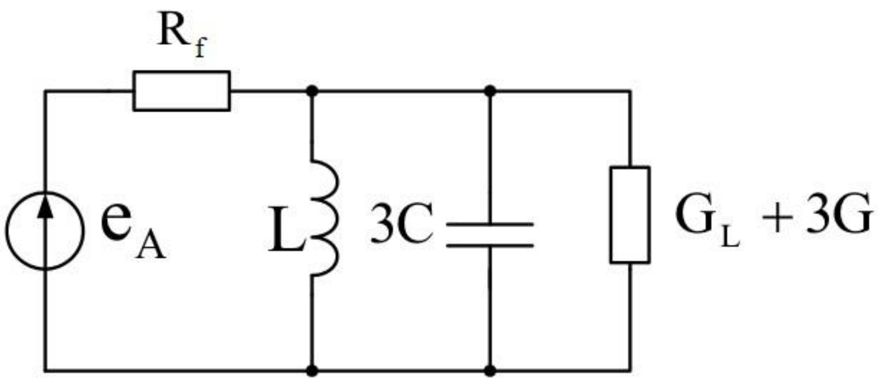


Fig. 8. Equivalent circuit of the zero sequence for the positive and negative sequences.
From the Equation (38), as well as from the equivalent circuit of the zero sequence it can be seen that if inductance of the Peterson coil at v=1 $\frac{1}{\omega L} = 3\omega C$, than the reactive component of the earth fault current with main (industrial) frequency is equal to zero for any value of the transient resistance at the fault point. Hence the mechanism of the compensation action of the Petersen coil has become clear, also it is obvious that under above mentioned conditions that only the current of the industrial frequency is compensated. Currents with higher harmonics are not decompensated substantially, as for all $\nu > 1$ $\frac{1}{\nu\omega L} << 3\nu\omega C$.[3]

It is important to determine the value of the fault current at the metal earth fault, i.e. when $R_f = 0$. For this case, the expression of the effective value of the current can be represented in the following form [1]

$$I_f = \sqrt{E_{ph\nu}^2 (3\omega C_{ph} - \frac{1}{\omega L})^2 + \sum_1^{\nu} E_{ph\nu}^2 (G_L + 3G_{ph})^2 + \sum_3^{\nu} E_{ph\nu}^2 (3\nu\omega C_{ph} - \frac{1}{\nu\omega L})^2} \quad (41)$$

In this Equation, the first term - reactive current component of the fundamental frequency, the second - the effective value of the active component of the current, and the third - the effective value of the reactive component of the current due to higher harmonics.

In real networks, the amplitude of higher harmonics of the EMF is much smaller than the amplitude of the fundamental harmonic, so the active component can be taken into account only the fundamental frequency. The reactive component of the highest harmonics should not be neglected, as it significant even at low amplitudes of harmonics EMF due to the increase in capacitive conductivity of a network at frequencies of the highest harmonics. In contrast, the conductivity of the arc suppression coil at the higher harmonics is reduced and therefore the highest harmonic currents, branching into it, are small and can be neglected.[1,2]

At the earth fault current following components are taken into consideration:

1. Reactive component of the fundamental frequency:

$$I_{1r} = E_{ph1}(3\omega \mathrm{C}_{ph} - \frac{1}{\omega L})\ . \tag{42}$$

2. Active component of the fundamental frequency:

$$I_{A1} = E_{ph1}(3\mathrm{G}_{ph} + \mathrm{G}_{L}). \tag{43}$$

3. Capacitive component of high harmonics:

$$I_{C\nu} = \sqrt{\sum_{3}^{\nu} E_{ph\nu}\nu 3\omega C_{ph}}. \tag{44}$$

Let's consider these components of the earth fault current in more detail. I_{1r} component due to the fact that practically always there is a deviation from the exact condition of the compensation, i.e. $\frac{1}{\omega L} \neq 3\omega C_{ph}$. The degree of deviation from the exact compensation is characterized by a detuning of compensation υ, which is defined as follows:

$$\upsilon = 1 - \frac{I_{Ind1}}{I_{C1}} \tag{45}$$

Where I_{Ind1} is an inductive component of the Petersen Coil current:

$$I_{Ind1} = E_{ph1}\frac{1}{\omega L}, \tag{46}$$

I_{C1} is a capacitive component of earth fault current:

$$I_{C1} = E_{ph1} 3\omega C_{ph}. \quad (47)$$

With an accurate compensation the inductive component of the arc suppression coil current is equal to the capacitive network current and $\upsilon = 0$.When $I_{Ind1} < I_{C1}$ network operates with undercompensation $\upsilon > 0$, when $I_{Ind1} > I_{C1}$ the network operates with overcompensation $\upsilon < 0$. Obviously, υ may be represented as follows:

$$\upsilon = 1 - \frac{1}{\omega L \bullet 3\omega C_{ph}} = 1 - \frac{\omega_0^2}{\omega^2}. \quad (48)$$

Where ω_0 is the resonant frequency of the oscillating circuit which is formed by the grid capacity and inductance of the Petersen coil.

$$\omega_0 = \sqrt{\frac{1}{3LC_{ph}}}. \quad (49)$$

The active component of the current I_{A1} consists of two terms. One of them is $-E_{ph} 3G_{ph}$ determined by bushing leakage current of the network, when the condition of isolation is good it comprises 2 ÷ 3% of the capacitive current of the network. The second component appears due to losses in the arc suppression coils and it is about 2% of the current I_{Ind1}.

The active component of the current is usually characterized by a dimensionless quantity:

$$df = \frac{I_{A1}}{I_C} = \frac{3G_{ph} + G_L}{3\omega C_{ph}}, \quad (50)$$

which is named the damping factor. According to the above mentioned possible values of the insulation conductance of the network and losses of arc suppression coils the damping factor usually is $df = 0,05$.

Capacitive component of higher harmonics in Equation (44) is determined by the degree of distortion of phase voltages. Currently, the industrial enterprises are increasingly being used to install and processes that require DC power. For transformation alternative current into direct current controlled and noncontrolled semiconductor converters are applied. The load which is supplied via semiconductor converters consumes nonsinusoidal current, containing odd harmonics. Due to the voltage drop across the longitudinal resistance because of the nonsinusoidal current, there is a distortion of phase voltages. What is more, the content of higher harmonics, the greater the grid point is electrically closer to the load which is consuming nonsinusoidal current. Phase voltage harmonics with relatively small amplitude produce significant conducive earth fault current. For example, if the amplitude of the 11th harmonic of the EMF is equal to 5% of the amplitude of the fundamental harmonic ($E_{ph11} = 0,05E_{ph1}$), the RMS value of the 11th harmonic of the capacitive earth fault current is equal:

$$I_{11} = 0,05E_{ph1} \bullet 3 \bullet 11\omega C_{ph} = 0,55E_{ph1} 3\omega C_{ph} \qquad (51)$$

that is, more than a half of the capacitive current of the fundamental frequency. Higher harmonic components, as it follows from the above, are not compensated by Petersen coils. When its' value is great it significantly worsen conditions of an arc extinction.
Further, the designation of the first harmonic ("1") at the index of electrical quantity is omitted. [1]

The voltage of intact phases and the neutral voltage can be determined during steady earth fault. Phase conductivities with respect to the ground are assumed equal. As it can be seen from the above, the higher harmonics of EMF have a significant effect only on the fault current, but voltage levels practically are not affected, so only EMF with fundamental frequency is consider.[1]

An expression for the neutral point voltage by Equation (32) under such conditions and the earth fault at phase A:

$$\dot{U}_N = -\dot{E}_A \frac{\frac{1}{R_f}}{j(3\omega C_{ph} - \frac{1}{\omega L}) + 3G_{ph} + G_L + \frac{1}{R_f}}. \qquad (52)$$

$R_{f*} = R_f \bullet 3\omega C_{ph}$ - transient resistance at the point of the earth fault which is determined in the ratio of capacitance determined by the total capacity of the network with respect to the ground. Thus, the neutral point voltage can be represented as follow:

$$\dot{U}_n = -\dot{E}_A \frac{(\mathrm{dR}_{f*}+1) - \mathrm{j}\upsilon\,\mathrm{R}_{f*}}{(\mathrm{dR}_{f*}+1)^2 + (\upsilon\,\mathrm{R}_{f*})^2}. \qquad (53)$$

The absolute value of the neutral point voltage:

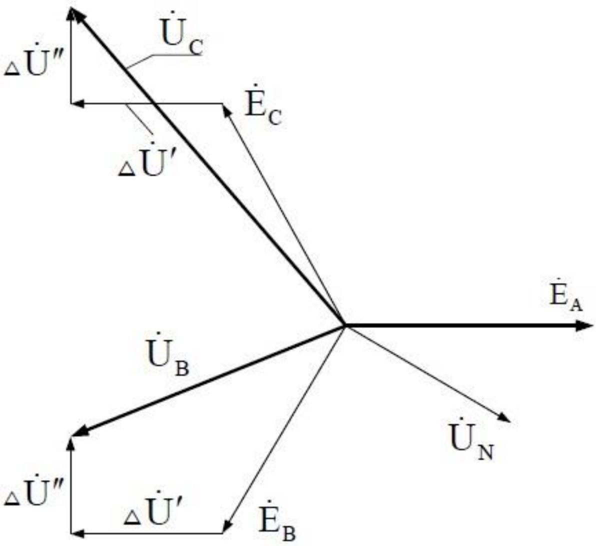
$$U_n = \frac{E_{ph}}{\sqrt{(\mathrm{dR}_{f*}+1)^2 + (\upsilon\,\mathrm{R}_{f*})^2}}. \tag{54}$$

The voltage at the intact phases under the same conditions:

$$\dot{U}_B = \dot{E}_B - \dot{E}_A \frac{(\mathrm{dR}_{f*}+1) - \mathrm{j}\upsilon\,\mathrm{R}_{f*}}{(\mathrm{dR}_{f*}+1)^2 + (\upsilon\,\mathrm{R}_{f*})^2}, \tag{55}$$

$$\dot{U}_C = \dot{E}_C - \dot{E}_A \frac{(\mathrm{dR}_{f*}+1) - \mathrm{j}\upsilon\,\mathrm{R}_{f*}}{(\mathrm{dR}_{f*}+1)^2 + (\upsilon\,\mathrm{R}_{f*})^2}. \tag{56}$$

Equations (55-56) correspond to the vector diagram in Fig. 8. constructed when $\upsilon > 0$, i.e. at undercompensation.



$$\Delta\dot{U}' = \frac{\mathrm{dR}_{\Pi*}+1}{(\mathrm{dR}_{\Pi*}+1)^2 + \left(\upsilon \mathrm{R}_{\Pi*}\right)^2}, \quad \Delta\dot{U}'' = \frac{\upsilon \mathrm{R}_{\Pi*}}{(\mathrm{dR}_{\Pi*}+1)^2 + \left(\upsilon \mathrm{R}_{\Pi*}\right)^2}.$$

Fig. 9. Clock diagram of the earth fault through the transient resistance in compensated networks.[1]

Through the use of this diagram the absolute value of the voltage at intact phases can be found

$$U_{C,B} = E_{ph} *$$

$$* \sqrt{\left[0,5 + \frac{R_{f*}+1}{(\mathrm{dR}_{f*}+1)^2 + (\upsilon\,\mathrm{R}_{f*})^2}\right]^2 + \left[\frac{\sqrt{3}}{2} \pm \frac{\upsilon R_{f*}}{(\mathrm{dR}_{f*}+1)^2 + (\upsilon\,\mathrm{R}_{f*})^2}\right]^2}. \tag{57}$$

"Plus" sign in the formula (57) refers to the advanced phase with respect to the damaged phase, and "minus" sign - to the delayed phase. When υ <0, the signs are reversed.

In Fig. 10a. reflects how neutral point voltage and the voltage on intact phase depends of transient resistance at the earth fault point when $\upsilon = 0,2$, $\upsilon = 0$ and for the comparison with $\upsilon = 1$, which corresponds to the network with isolated neutral.[1]

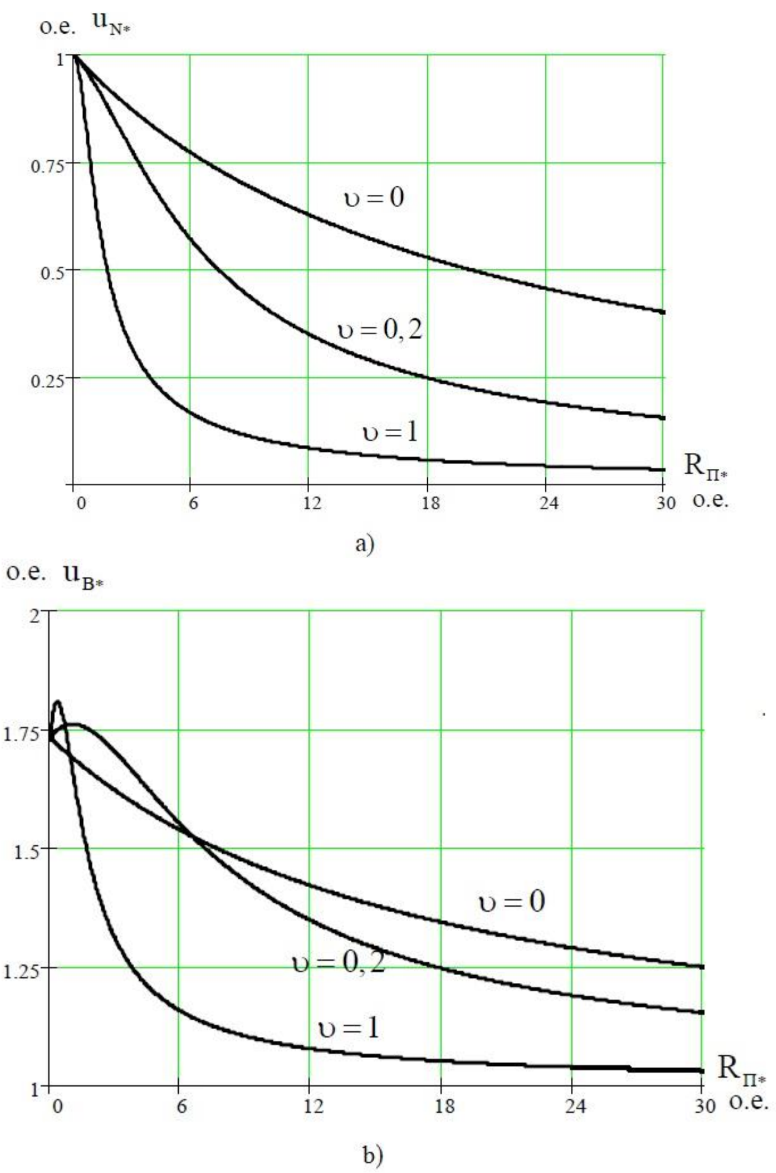


Fig. 10. The influence of the neutral point voltage (a) and the voltage of intact phases (b) during permanent earth fault in compensated networks with respect to transient resistance and compensation detuning.[1]

From the Fig. 10b. it can be seen that the maximum voltage during the metal earth fault are almost equal to the line to line voltage regardless of the value υ. [1]

According to this aspect practically there is no difference from the network with isolated neutral. At the same time it is obvious that the network with compensated neutral is more sensitive to the earth fault from the viewpoint that a significant neutral point voltage and thus an increase of the voltage at intact phases occur with large transient resistance than in a network with isolated neutral. This "sensitivity" the greater the closer the setting arc suppression coil to a resonance setting and then lesser d.

2.3 Compensated and hybrid networks

When one or more not adjustable arc suppression coils are connected to the feeders it is called distributed compensation. The conductivity of the Petersen coils compensate some part of the capacity of the particular distribution line. The big advantage of this principle is that the level of compensation is always stable, because lines and their arc suppression coils can be only together connected or disconnected . Also this feature significantly simplify the process of choosing power of Petersen coils, due to that fact, that coils are selected for the particular grid lines, rather than the hole network. It should be mentioned that the flow of the earth current through the network impedances is limited. This is beneficial especially with long rural cable feeders, where otherwise a large resistive earth-fault current component would be introduced.[5]

The most rational compensation of the earth fault current can be reached with hybrid compensation, hybrid network is represented in Fig.11. In such case central coil (adjustable) is connected to the neutral point of the transformer at the main substation and some small not adjustable arc suppression coils are located on the feeders.
Earth faults in hybrid compensated networks.[5]

The distribution network is represented with two lines: protected and background. The background line is an equivalent of n parallel medium voltage lines. For the simplification of the further equation admittances of the background and protected line without taking into account admittances of distributed compensation can be represented as follows[5]:

$\dot{Y}_1$ - total admittance of the protected line (without Petersen coil);

$$\dot{Y}_1 = \dot{Y}_{a1} + \dot{Y}_{b1} + \dot{Y}_{c1}, \tag{58}$$

$\dot{Y}_2$ - total admittance of the background line (without Petersen coil)

$$\dot{Y}_2 = \dot{Y}_{a2} + \dot{Y}_{b2} + \dot{Y}_{c2}. \tag{59}$$

Where $\dot{Y}_{a1}, \dot{Y}_{b1}, \dot{Y}_{c1}$ and $\dot{Y}_{a2}, \dot{Y}_{b2}, \dot{Y}_{c2}$ is admittances of phases of the background and protected lines.

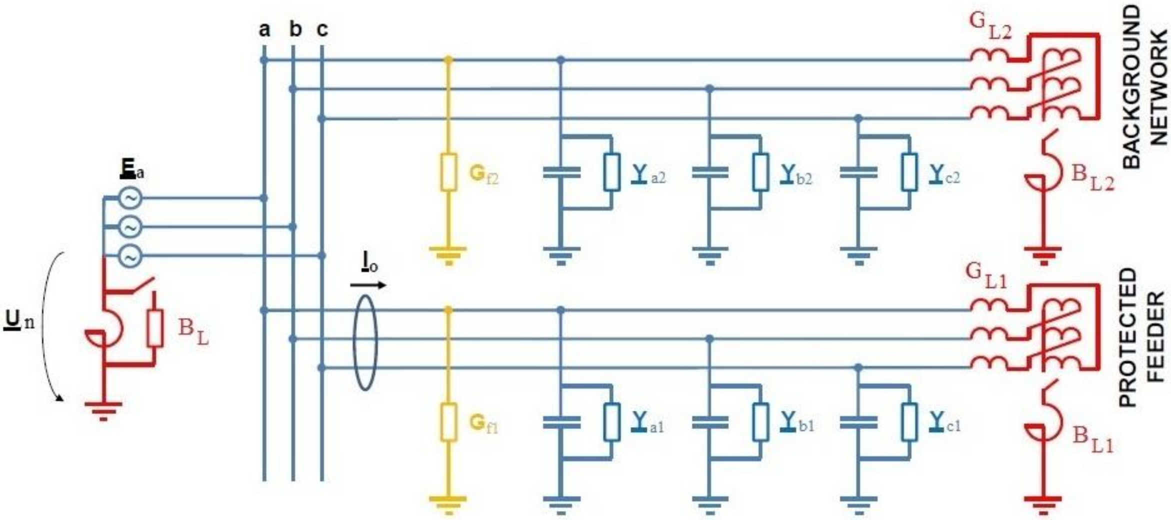


Fig. 11. Equivalent circuit of the hybrid compensated network with earth fault in the phase A located on protected or background line. [5]

It is possible to get equation for $\dot{U}_n$ and $\dot{I}_0$ from the equivalent circuit of the hybrid compensated network. The formula is derived for the earth fault in the phase A, however for earth faults in other phases the final equation is similar. The internal resistance of the power supply lines and longitudinal resistance of the network is much less than the resistance of the phase with respect to ground, so during earth faults it can be ignored.[55] Also it is assumed that phase EMF form symmetrical system $\dot{E}_a = \dot{E}_{ph}$, $\dot{E}_b = \dot{E}_{ph} \cdot a^2$, $\dot{E}_c = \dot{E}_{ph} \cdot a$ and line admittances with respect to the ground are fully symmetrical $\dot{Y}_{a1} = \dot{Y}_{b1} = \dot{Y}_{c1} = \dot{Y}_{ph1}$, $\dot{Y}_{a2} = \dot{Y}_{b2} = \dot{Y}_{c2} = \dot{Y}_{ph2}$.

With above mentioned assumption it can be written:

$\dot{I}_{a1} = \dot{Y}_{a1}(\dot{E}_a + \dot{U}_n)$; $\dot{I}_{b1} = \dot{Y}_{b1}(\dot{E}_b + \dot{U}_n)$; $\dot{I}_{c1} = \dot{Y}_{c1}(\dot{E}_c + \dot{U}_n)$; $\dot{I}_{f1} = G_{f1}(\dot{E}_a + \dot{U}_n)$; - protected line currents;

$\dot{I}_{a2} = \dot{Y}_{a2}(\dot{E}_a + \dot{U}_n)$; $\dot{I}_{b2} = \dot{Y}_{b2}(\dot{E}_b + \dot{U}_n)$; $\dot{I}_{c2} = \dot{Y}_{c2}(\dot{E}_c + \dot{U}_n)$; $\dot{I}_{f2} = G_{f2}(\dot{E}_a + \dot{U}_n)$

- background line currents;

$\dot{I}_{L1} = \dot{B}_{L1}\dot{U}_n$; $\dot{I}_{L2} = \dot{B}_{L2}\dot{U}_n$; $\dot{I}_L = \dot{B}_L\dot{U}_n$; - Petersen coil currents.

$$\dot{U}_n = \frac{-\dot{E}_a(\dot{Y}_{a1}+\dot{Y}_{a2}) - \dot{E}_b(\dot{Y}_{b1}+\dot{Y}_{b2}) - \dot{E}_c(\dot{Y}_{c1}+\dot{Y}_{c2}) - \dot{E}_a(G_{f1}+G_{f2})}{\dot{Y}_{a1}+\dot{Y}_{a2}+\dot{Y}_{b1}+\dot{Y}_{b2}+\dot{Y}_{c1}+\dot{Y}_{c2}+G_{f1}+G_{f2}+\dot{B}_L+\dot{B}_{L1}+\dot{B}_{L2}} \tag{60}$$

After some transformation the Equation (60) can be presented as follows:

$$\dot{U}_n = \frac{-\dot{E}_a(G_{f1}+G_{f2})}{\dot{Y}_1+\dot{Y}_2+G_{f1}+G_{f2}+\dot{B}_L+\dot{B}_{L1}+\dot{B}_{L2}}. \tag{61}$$

$\dot{I}_0$ – sum of currents in the protected line

$$\begin{aligned} \dot{I}_0 &= \dot{I}_{a1}+\dot{I}_{b1}+\dot{I}_{c1}+\dot{I}_{f1}+\dot{I}_{L1} = \\ &= \dot{Y}_{a1}(\dot{E}_a+\dot{U}_n)+\dot{Y}_{b1}(\dot{E}_b+\dot{U}_n)+\dot{Y}_{c1}(\dot{E}_c+\dot{U}_n)+G_{f1}(\dot{E}_a+\dot{U}_n)+\dot{B}_{L1}\dot{U}_{L1}. \end{aligned} \tag{62}$$

After some transformation Equation (62) can be presented as follows:

$$\dot{I}_0 = \dot{U}_n(\dot{Y}_1+G_{f1}+\dot{B}_{L1})+\dot{E}_a(G_{f1}). \tag{63}$$

These Equations (63, 61) are the very important result and are the main dates for the relay protection. Furthermore these formulas reflect the influence of resistance at the fault point, degree of compensation and parameters of the lines on the neutral point voltage.

2.4 Earth fault location.

Even nowadays it is very challenging task to find earth fault point by the use of automation. This can be explained by the feature of earth fault currents. Value of the earth fault current does not depend on the distance between bus-bar of the substation and earth fault point. Thus, location of the earth fault point in the network can be done by direct measurements of currents and voltages. However, one of the progressive methods for fault location is based on measurements of signals reflected from earth fault point at the beginning of earth fault. This method is explained further.

The described device can be used to determine the distance to the places of the single-phase ground fault in distribution networks with radial structure. The main principle of determining the distance to a single-phase ground fault in distribution networks, based on the voltage registration of the damaged phase at the beginning of the line. In the measured voltage at transition state during earth fault the frequency corresponding to the natural frequency during the phase capacitance discharge of the faulty phase, is separated. After this the result is compared to the design bandwidth for the faulty phase of the feeder. By the use of distance - natural frequency relationship for the specific feeder the distance to the fault place can be estimated. The significant advantage of this method is that the distance to the earth fault in the distribution network with the radial structure can be determined easily without disconnecting of the damaged line. It is known the method for determining the distance to an earth fault in distribution networks, which is based on measuring the time between sending the monitoring electric impulse in the line and when the reflected from the earth fault point impulse came back to the beginning of the line. The impulse is sent in the line and the round-trip time t_{tr} of the impulse to the earth fault point is measured.[6] The distance to the earth fault l_f point can be found by the use of following formula:

$$l_f = \frac{t_{tr}V}{2}, \tag{64}$$

where V - pulse velocity in the line.

The implementation of this method at substation with large amount of feeders in automatic mode is challenging because of multiple reflection from intact lines which interferes in the desired signal. Another disadvantage of this method is that all measurements should be done during the arcing process, considering that only in this period of the earth fault measured information is significant. However the time of the arcing process is very small and lasts quarter of milliseconds, what make the process of measuring significantly complex. Furthermore it is known a method to determine the distance to the earth point fault in distribution networks, which is used without need to disconnect lines from the grid. The main working principle of this method is based on the measurement of the time interval between start time reference t_{start} , when the high voltage wave edge, which is originated due to the electrical breakdown in the place of the earth fault, comes to the beginning of the line, and the stop time reference t_{stop} , when the high voltage wave edge after two reflections (in the earth fault place and in the sending end of the line) comes to the sending end of the feeder. [6]The time interval can be determined as follows:

$$\Delta t = t_{stop} - t_{start} = \frac{2l_f}{V}. \qquad (65)$$

From the Equation (59) the distance to the earth fault point l_f can be defined:

$$l_f = \frac{\Delta t}{2}, \qquad (66)$$

In this method as in the method described earlier there are waves reflected from the end of intact lines which in the networks with large amount of lines do not allow achieving accurate results. In case of network with big amount of cable lines the desired signal due to obstacles and transition joints is distorted, thus it is complex to calculate Δt or even some time impossible. In conclusion it should be highlighted that with the use of two these methods it is challenging to find distance to the earth fault point in distribution network with big amount feeders. The new method allows determining distance to the earth fault point in automatic regime in distribution networks with big amount of power lines. This method is based on the idea which is used at the second method. Such result can be achieved by the next way:

the voltage of damaged phase is registered in the beginning of the power line, based on this time interval Δt between the moment when edge of the voltage wave which is originated in the earth fault point come to the beginning of the power line and the moment when this voltage wave after two reflections comes to the beginning of the power line. The result is calculated by Equation (66) $l_f = \frac{\Delta t}{2}$.

In the registered voltage of the damaged phase at transient state of the earth fault the frequency which is equal to the natural frequency of the capacitive discharge of the damaged feeder is found. When the frequency was found it is compared with the design bandwidth for the specific power line and by the use of distance - natural frequency relationship this distance can be measured.[6]

2.4.1 Principle of work.

One of the possible network topology is represented in Fig. 12 a. For this power grid the described method is implemented when the earth fault is in the power line number 3. The

Fig. 12 b. reflects the equivalent circuit of the network utilizing which the natural frequency.[6]

The lowest natural vibration frequency of the voltage of the damaged phase after the insulation rupture during the earth fault is determined by the next parameters of the network: inductance of the power supply (1), load (6-9), inductive and capacitive parameters of power lines (2-5).[6]
This frequency f1 can be approximately determined by the use of next formulas:

$$f_1 = \frac{1}{2\pi\sqrt{2(\mathrm{C}_{tph} + \mathrm{C}_{tph-ph})\,\mathrm{L}}}, \tag{67}$$

$$L = \frac{(\frac{3L_{ps}}{2} + \frac{L_{\text{int}}}{4} + \mathrm{L}_d \mathrm{l}_f)(\frac{3L_l}{2} + \frac{L_{\text{int}}}{4} + \mathrm{L}_d(1 - \mathrm{l}_f))}{\frac{3(\mathrm{L}_{ps} + \mathrm{L}_l)}{2} + \frac{L_{\text{int}}}{2} + L_d}, \tag{68}$$

C_{tph} - total phase capacity of the network,

C_{tph-ph} - total phase-to-phase capacity of the network,

L_{ps} -inductivity of the power supply,

L_l -inductivity of the load,

L_d - Inductivity of phases of the damaged line,

L_{int} - Inductivity of phases of intact lines.

As it can be seen from the Equation (66) variations in l_f do not lead to significant changes in numerator: the influence on the product is negligible because of the first multiplier is increased - the second one is decreased and vice versa. What is more, terms of sum $L_f l_f$ and $L_f(1 - l_f)$, ordinary, few times smaller than the sum of others. Thus, it can be concluded, that L and consequently f_1 is not strongly affected by the distance to the earth fault point.[6]

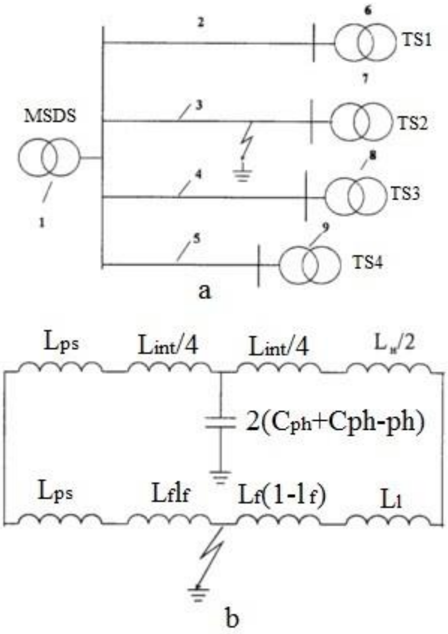


Fig. 12. Structure of the network and its equivalent circuit.[6]

Higher natural frequency f_2 of the voltage, which is measured at power supply buses, is determined by capacitive discharge of the damaged phase. After the transformation equivalent circuit represented in Fig. 13 a. to the single frequency circuit in Fig. 13 b, where

$$C_{equiv1} = \frac{C_{equiv} L'_{equiv} + 2C_{equiv} L_f l_f + L_f C_f l_f^2}{2(L'_{equiv} + L_f 1_f)}. \quad (69)$$

The frequency f_2 can be determined as follows:

$$f_2 = \frac{\sqrt{2}}{2\pi\sqrt{C_{equiv} L'_{equiv} + 2C_{equiv} L_f l_f + L_f C_f l_f^2}}. \quad (70)$$

Where

C_f - phase capacity of the damaged power line;

C_{eqiv} - equivalent phase capacity of intact power lines;

L'_{eqiv} - equivalent phase inductance of intact power lines.

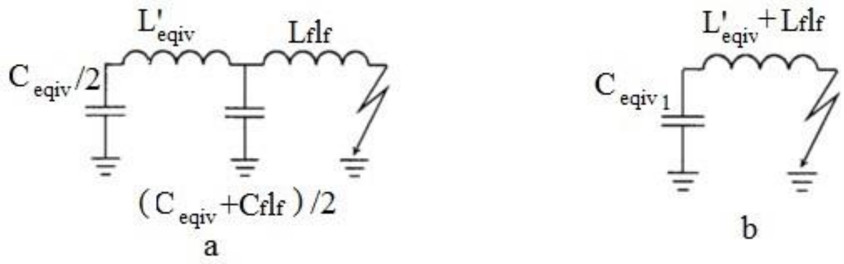


Fig. 13. Equivalent circuit of the part of the network.

The f_2 frequency significantly depends on the distance to the earth fault place. Parameters of the power supply and load practically have no influence at the frequency f_2, the most influencing parameters are the phase inductivity of the damaged power line till the fault place $L_f l_f$ and the phase conductivity of the damaged power line till the fault place $C_f l_f$. The maximum value of the frequency f_2 is determined by the total capacity C_{equiv} and total inductivity L'_{equiv} (earth fault close to the power supply buses) of intact power lines, and the lowest value is determined by the longest power line when the earth fault point is at the end of it. For each feeder there is its own range of natural frequencies.[6]

2.5 Personal safety

Electric injury can be explained as trauma caused by an electric current or electric arc.
Elektro traumatism characterized by such features: a defensive reaction appears only after voltage is applied across the human body, i.e. when an electric current is already flowing through the body; electric current acts not only in places of contact with the human body and on the path through the body, but also causes a reflex action, which manifests itself in violation of the normal functioning of the cardiovascular and nervous system, breathing and so on. Electric injury can be caused by direct contact with conducting parts, and with an injury by contact or step voltage, or through an electric arc.[7]

The human body is a conductor of electric current. However, different tissues of the body have an unequal current resistance. Effects which arise as a result of electric current to the human depends on many factors, namely:

- the amplitude and frequency of current flow;

- the duration of its effects, the longer the duration of the current action on the body, the heavier the consequences;
- the path, the current flowing through the brain and spinal cord, the zone of heart and respiratory constitute the greatest danger;
- physical and psychological state of the person. A human body has a certain resistance; the resistance varies depending on the condition of the person.[7]

The effects of current exposure:

- The current threshold for perception is less than 1 mA . A 1 mA current is not dangerous as such but the sensation might give people unintentional reactions with possibly dangerous consequences, such as falls.
- If, what is called, the let go current level is exceeded the exposed person cannot control; the muscles to let go of energized equipment. This current level is in the range of 5 to 10 mA. It is painful and if the situation continues long enough the body resistance might decease, current level increase and the consequences become severe and even lethal.
- Respiratory problems normally occur in the range of 20 to 40 ma, depending on current duration. If the exposure remains for several seconds, risk of injures is large.
- Ventricular fibrillation is alive threatening condition that can only by the use of defibrillation. The threshold for ventricular fibrillation depends on current duration T and estimated according to :

$$I_{fib} = \frac{100}{T} mA \tag{71}$$

$$0.2s \leq T \leq 2s. \tag{72}$$

The probability of ventricular fibrillation depends on the phase of the current and where in cardiac circle the body is exposed to the current. [7]

Nowadays network companies are obligated by law to ensure the customers' safety. In Finland SFS-6001 is the regulation for high voltage installations. Because of the high level of dangers to the customers and possible damages in low voltage equipment during earth faults there were developed detailed safety requirements. The SFS-6001 provides contact voltage with respect to the earth fault current, which is presented in Fig. 13.

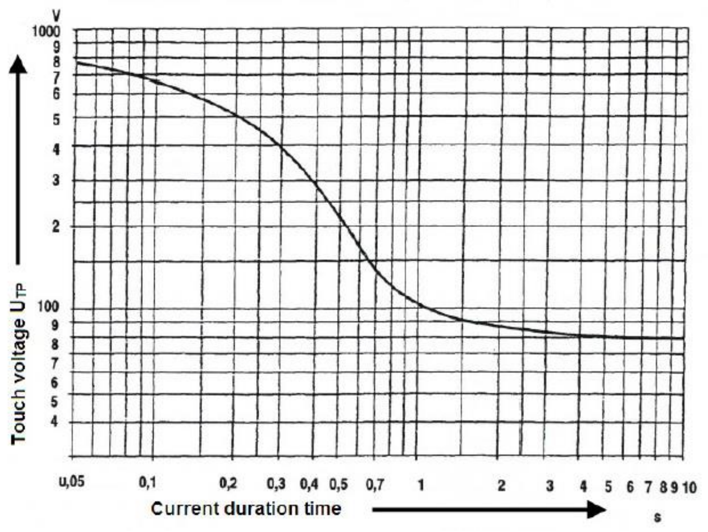


Fig. 14. The touch voltage respective to the current duration time.[8]

In the earth fault point can be observed an earthing voltage which is caused by the earth fault current. In order to estimate allowed voltage levels during the earth fault, the most dangerous for humans health situation should be chosen , in other words with the maximum earthing voltage. In such case, the earth fault current passes through the earthing of equipment in distribution network. The earthing voltage U_m can be calculated by the next formula:

$$U_m = I_f R_m, \tag{73}$$

where R_m is earthing resistance.[9]

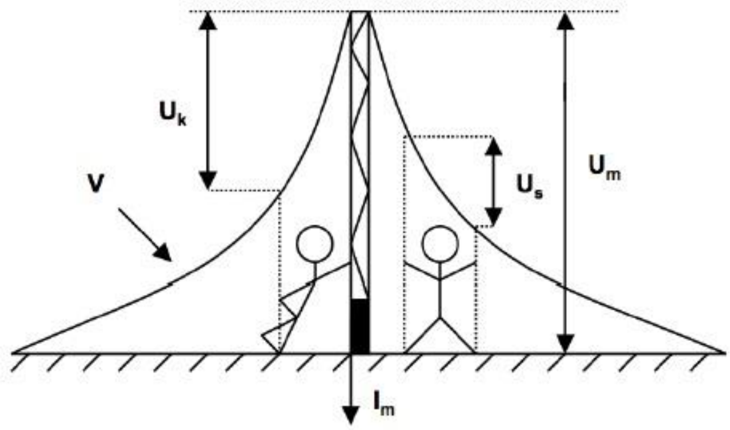


Fig.15. Earthing voltage.[9,10]

3 RELAY PROTECTION.

For the medium voltage distribution networks with isolated, compensated neutral or resistive grounding several principles to determine earth fault can be implemented:

- Zero-sequence voltage measurements;
- zero-sequence fundamental frequency current measurements;
- Measurement and comparison of the zero-sequence power direction;
- Measurement and comparison of harmonic components of the earth fault current in all feeders;
- Measurements of transient currents and voltages at the reference time of the earth fault;
- superposition of the alternative current with non-fundamental frequency[11]

General requirements for the earth fault protection.
1 Earth fault relay protection devices have to guarantee the fixation as permanent earth faults as intermittent earth faults through an arc.
2 In networks which are operating with isolated, compensated neutral or with high-resistive grounding, relay protection devices should also provide the fixation of short-period self-extinguished isolation rupture.
3 Relay protection devices should initiate tripping or a signal.
4 Relay protection device which is initiating a signal should selectively determine the damaged direction.
5 Relay protection devices which are initiating tripping should selectively determine the damaged network element.
6 Relay protection devices should initiating tripping with as low as practicable time delay:

1)all feeders, in networks which are operating with low-resistive grounding

2)In networks which are operating with isolated, compensated neutral or with high-resistive grounding:

- electrical plants, where the tripping of the earth fault is necessary according to security requirements;
- in generators, high-power electric motors or in other cases, when the expected damage because of the unexpected tripping of the damaged element is lower than the damage caused by the long time period under earth fault conditions;

- in all cases when the unexpected tripping of the damaged eleven does not inflict a loss.

7 Relay protection devices should initiate tripping with a time delay:

- in case, when it should be done in purpose of selectivity;
- in case, when the unexpected tripping is intolerable or cause a loss(for example due to the technological reasons or safety regulations)

8 Relay protection devices initiating tripping should continuously act in the earth fault steady-state.

9 Relay protection devices should initiate a signal in all cases apart from listed in items 6 and 7.[12,3]

3.3 Earth faults relay protections based on the usage of fundamental-frequency values

3.3.1 General non-selective zero-sequence voltage protection.

This type of protection initiates a signal (with or without time delay) and implemented at all networks which are operating with isolated, compensated neutral or with high-resistive grounding. Non-selective voltage protection can be implemented as a back-up protection and initiate tripping in networks with exclusive safety requirements or with low-resistive grounding.

Insulation monitoring device determines earth fault in the network by measuring zero-sequence voltage $3U_0$. To gain this voltage generally five-legged voltage transformer with two secondary sides, one of which has an open delta winding circuit, is used. The secondary side with open delta winding circuit represents zero-sequence voltage filter. To gain this voltage generally five-legged voltage transformer with two secondary sides, one of which has an open delta winding circuit, is used. The secondary side with open delta winding circuit represents zero-sequence voltage filter. Insulation monitoring device also comprises three voltmeters PV1-PV3, as it shown in Fig. 16, which are measure phase voltages and voltage-sensitive relay KV1 which is connected to the second side of the voltage transformer. It is possible to use the insulation monitoring with time delay (time-delay relay KT1), but in this case short-period self-extinguished isolation rupture is not detected. In normal operating mode readings of voltmeters PV1-PV3 are the same and equal $\frac{100}{\sqrt{3}}$ V.[3,11,12]

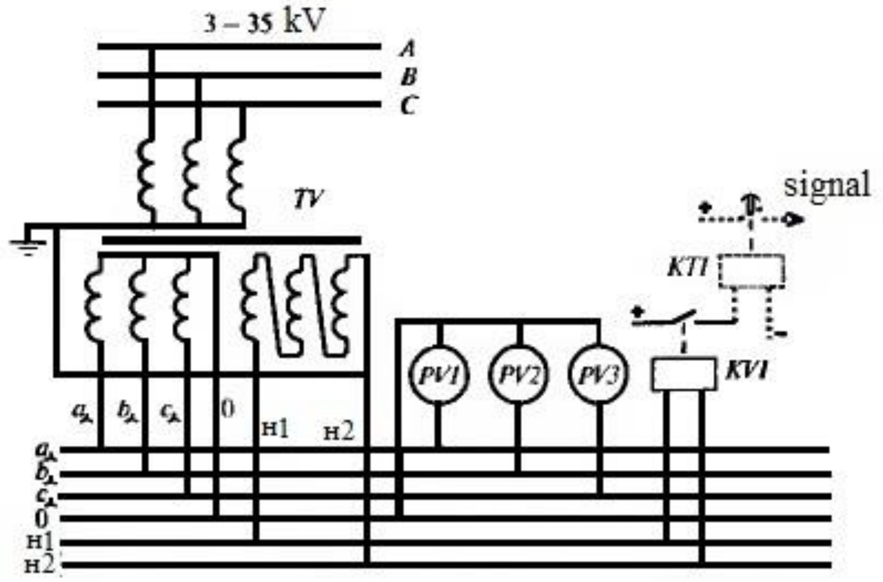


Fig. 16. Schematic circuit diagram of the insulation monitoring.[3]

In case of the earth fault the reading of the voltmeter at the damaged phase $0 < U \leq \frac{100}{\sqrt{3}}$ V and readings of voltmeters at the intact phases are $\frac{100}{\sqrt{3}} < U \leq 100$ V. If zero-sequence voltage appears, voltage relay KV1 initiates signaling. If there is no selective earth fault protection on the feeders of the network element or in case of the relay protection failure, than the damaged feeder can be found by the sequential disconnections of power lines.[11,12]

3.3.2 Zero-sequence current protection.

This type of protection is implemented as the earth fault protection, which initiates selective tripping or signaling in grids operating with low resistive grounding or with isolated neutral. Discriminating element of the relay protection device is connected to the zero-sequence current filter. The disadvantage of the filter which is consists of three single transformers, which is represented in Fig. 17 a, is a high imbalance current in the regimes without earth fault(operating mode, the starting or self-starting of electro motors, external short circuits). Such imbalance in current is determined by different magnetization characteristic of transformers. This results in problems of sensitivity and restricts the usage of the method. [12]

The second way to get zero-sequence current, as it shown in Fig. 17 b, is based on the implementation of the special three phase current transformer, which is closed magnetic core with the secondary winding on it.[12]

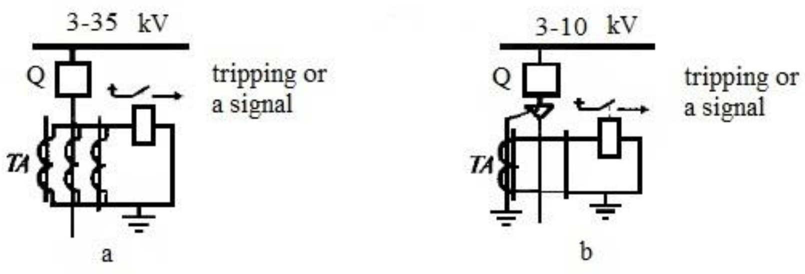


Fig.17. Diagram of two types of the zero-sequence filter: a) three single transformers, b) special three phase current transformer[13]

The primary winding is three phases of one or some cables. For the implementing three phase zero-sequence current transformer at overhead lines, the inserted cable should be represented which is a disadvantage. The key feature of this transformer is the low level of imbalance currents in the operating mode without earth fault. The position of the cable conductors is symmetrical relative to the second winding of the three-phase transformer.[12]

The selective operation of this protection can be provided if the earth fault current $I_{\mathrm{C(i)max}}$ of the i-th feeder is n times smaller than the total earth fault current $I_{C\sum}$ of the network :

$$\frac{I_{C\sum}}{I_{C\mathrm{(i)max}}} \geq n. \tag{74}$$

The coefficient n is determined for each relay protection device. This condition is gained from two selecting conditions of the trip current:

nonoperation during the external earth fault:

$$I_{trip} \geq k_{\mathrm{r.}f.} k_{in} I_{C\mathrm{(i)max}}, \tag{75}$$

where

$k_{r.f.}$ is a reliability factor;

k_{in} -inrush factor is implemented in purpose of reflecting inrush of the capacitive current at the first moment of the earth fault and also the ability of an relay protection device to response it.[12]

And the tripping condition:

$$k_S = \frac{I_{C\Sigma}}{I_{trip}} = 1{,}5 \div 2, \quad (76)$$

where k_S is a sensibility factor.

For modern relay protection devices as SPAC 800 produced by "ABB Cheboksary" k_{in} can be chosen $1 \div 1{,}5$. However even with the modern relay protection terminals and the three phase zero-sequence transformer it is not possible to provide the selective operation of the zero-sequence earth fault protection in the grids with isolated neutral. Small amount of feeders, short cable or overhead lines are the main reasons. Also this can be implemented for the networks with the compensated neutral which works under over or under compensation conditions. If the earth fault current is completely compensated, than this type of relay protection cannot be used in this network.[3]

3.3.3 Directional Zero-sequence current protection.

This type of protection is implemented when the constancy of performance of the zero-sequence current protection cannot be provided. Under the certain conditions (over or under-compensation of the earth fault current, sufficiently high values of the resistive part or higher frequency harmonics of the residual earth fault current) the constancy of performance can be provided in compensated networks. Connection diagram of the relay protection device is represented in Fig. 18.

The working principle of this protection can be briefly explained with next example. When the earth fault occurs at the line 3, currents I_{C1} and I_{C2} are determined by the capacity of the intact power lines 1 and 2. These currents have conventional direction to the earth fault point and as it can be seen from the Fig. 19. Their directions in intact and damaged feeders are not the same. The principle of the directional zero-sequence current protection is based on this feature.

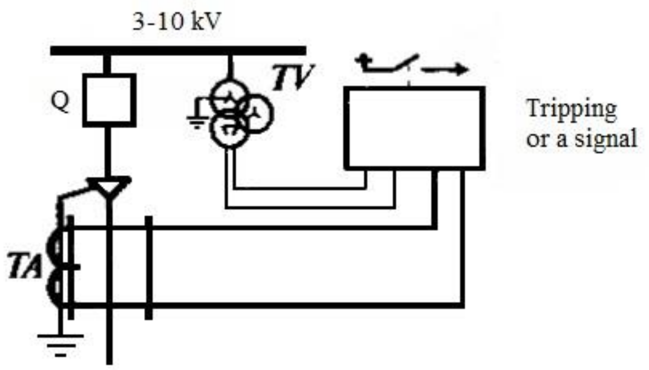


Fig. 18. Diagram of the directional zero-sequence current protection[11]

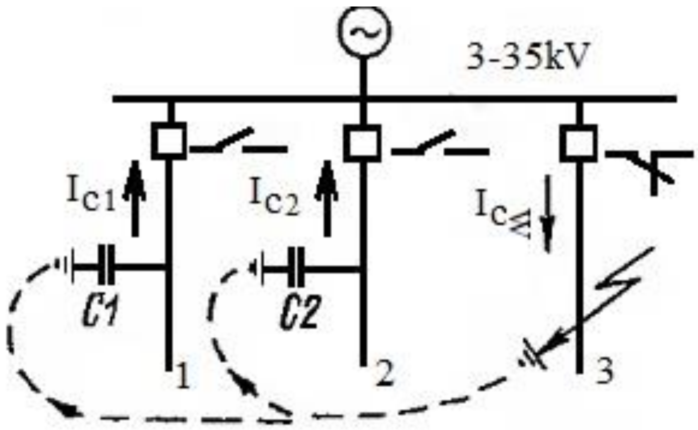


Fig. 19. Earth fault in the network with isolated neutral.[11,12]

In case when the direction of the current I_C in the line is to the bus bar then the relay protection must not operate, because this feeder is not damaged. However if the direction of the current $I_{C\sum}$ is from the bus bar and its value exceed the setting value I_{trip} , then the relay protection must operate. The decision of the relay protection device to operate is based on the measurements of the zero-sequence current I_0 , zero-sequence voltage U_o and the angle between them φ . [3,12]

In networks with isolated neutral the setting value of this angle is $90-\Delta\varphi \le \varphi \le 90+\Delta\varphi$. The setting value of the earth fault current should guarantee nonfunctioning of the relay protection in normal operating mode, because even in this regime the value of the zero-sequence current is small but does not equal to zero. The operating region of the directional zero-sequence current protection in the network with isolated neutral is represented in Fig. 20.[3,11,12]

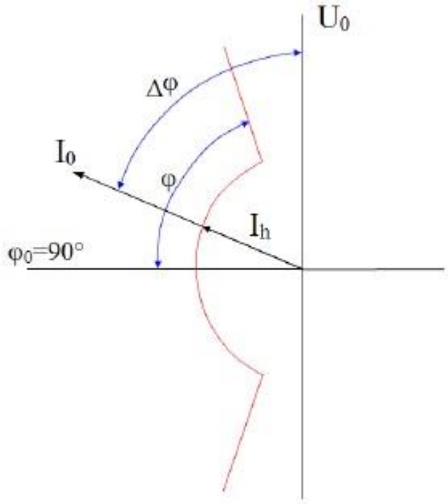


Fig. 20. Earth fault current in the damaged feeder of the network with isolated neutral.[13]

In case of compensated networks the value of the reactive part of the earth fault current is insignificant and the relay protection devise uses the active current component with the phase shift $0 \pm \Delta\varphi$ which is reflected in Fig.21. This active part of the earth fault current is determined by the resistance of phases and leakage resistance of power lines and also the resistance of arc suppression coils. In purpose to increase the earth fault current the parallel connection of the resistance to the Petersen coil can be made. This resistance can be connected continuously or it is connected only after the location of the earth fault.[13]

To insure reliable operation of the relay protection the total earth fault current $I_{C\sum}$ of the network should exceed setting value. Generally in modern distribution grids this requirement is satisfied, however in case of repairing works or over situation when this current is decreased, protection cannot operate. In this case the backup non selective zero-sequence voltage protection should be implemented on a substation. This relay protection should with a time delay 05-07 s, initiate tripping of the supply transformer and the operation of the automatic transfer switch, automatic reclosing switch should be blocked.

Such non selective tripping of the transformer is necessary in order to provide safety requirements.[11,13]

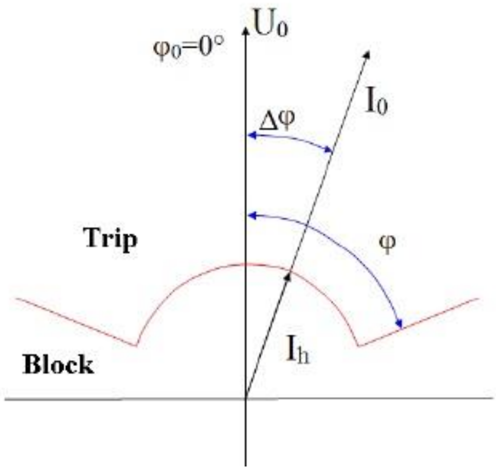


Fig. 21. Earth fault current in the damaged feeder of the network with the compensated neutral.[13]

The main disadvantage of the current and directional current protections based on the usage of the fundamental frequency values is the possible operating failure (because of the unnecessary operating during external earth faults or operating failure during the internal earth fault) during intermittent earth faults through an arc.[3,12]

3.4 Earth fault protections which are based on the usage of higher frequency harmonics.

This type of relay protection is used only in the Russian Federation and former members of the USSR. Relay protection devices which are based on the usage of higher frequency harmonics of the earth fault current or voltage are implemented in compensated network, but also can be used in networks with isolated or resistive grounded feeder. However in non-compensated networks types of relay protection based on the fundamental frequency values which is mentioned above provide more simple and reliable protection against earth faults. Relay protection which is respond to phase proportions of higher harmonics of zero-sequence currents and voltages are the most flexible. It is simple to realize directional protections which are react to the reactive power direction of the high frequency harmonic.

However, this principle cannot provide stable protection of networks, because of non-stability of the higher frequency constitution.[3]

Nowadays there are two the most common types of relay protection devices:

- devices which are operate based on the absolute determination principle;
- devices which are operate based on the relative determination principle.

Course of action of the absolute determination earth current protection is similar to the course of action of the zero-sequence earth current protection and is based on that in case of the internal earth fault the value of the current in the protected feeder $I_{\nu C\sum}$ is bigger than in over intact feeders $\mathrm{I}_{\nu\mathrm{C(i)}}$. However, this principle is not widely used because of the difficulties in setting value choosing and possible nonselective protection operation when arc earth faults occur.[3]

Nowadays the device "УСЗ-3М" is widely implemented in middle voltage distribution networks in Russia. The connection layout of the device is represented in Fig.22. The working principle of these devise is based on the measuring higher frequency harmonics of the earth fault current (from 150 Hz to 650 Hz). More than 30 years' experience of the usage of this device proves that "УСЗ-3М" is convenient in service and reliable relay protection device. [11]

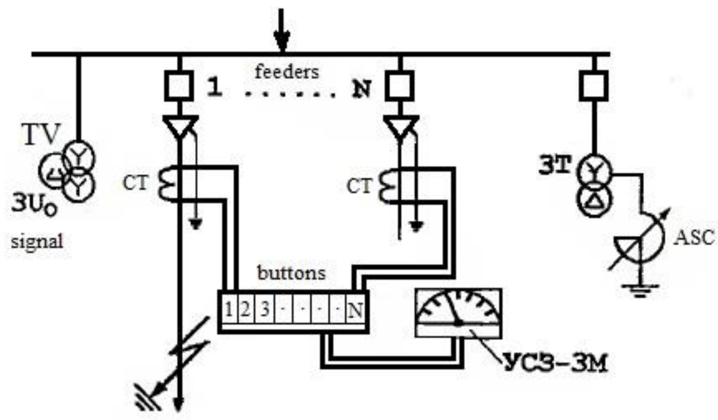


Fig. 22. Connection layout of the device " УСЗ-3М".[11]

However there are some disadvantages like: ΩΩ

"УСЗ-3М" cannot be used in networks with parallel lines and complex structure,

there is no possibility to fixate short-duration earth faults ;

also operating employees have need move to a substation to perform a big amount of measurements in order to find damaged feeder.[11]

Nowadays modern relay protection terminals can determine the damaged power line with the use of relative principle in automatic regime. SPAC 801.013 is an example of the relay protection device with this function.[3]

3.5 Earth fault protection based on the usage of superimposed currents.

The main field of the implementation of this type of relay protection is networks with compensated neutral. The advantage of relay protection devices which use artificial created current of the non-fundamental frequency (superimposed currents), in comparison of protection which is respond to higher frequency components, is relative stability of the energizing quantity in different regimes, which provide stable operating during internal and external earth faults. The disadvantage of the earth fault protection based on the usage of superimposed currents is that the special current source should be connected to the network, an increase in the earth fault current at the fault point, possible failure to operate in case of intermittent arc earth faults.[3]

During permanent earth faults the biggest part of the superimposed current flows through the damaged feeder and responded by the specific protection.[3]

3.6 Earth fault protections which is based on the usage of electrical values of the transient phenomena.

Such type of relay protection devices are developed in purpose of earth fault protection in compensated networks. However this principle of work allows implementing specific protection in networks with isolated neutral or with high resistive grounding. Advantages of the usage electrical values of the transient phenomena are:

- the possibility to fixate all kinds of earth faults;
- relay protection operation does not depend on the grounding type;

- high sensitivity to high impedance earth faults (this feature can be explained, because at the incipient state an arc impedance determines the transient resistance);
- big values of the transient currents provide interference resistance and high sensitivity.[12]

Based on the research and experiments it was shown, that the earth fault protection which is respond to the transient phenomena is more flexible, when on of this principles are used:
principle is based on the comparison of transient currents amplitudes of the protected feeders;
principle is based on the determination of the zero-sequence instantaneous power sign at the incipient state of the transient phenomena.[13]

3.7 Admittance based earth-fault protection.

These type of relay protection was invented and researched by group of scientists lead by Jozef Lorenc from the Poznan University of Technology in Poland.[5]

Thanks to the progress, nowadays the admittance is calculated by the means of microprocessors in relay protection terminals. For this purpose the fundamental frequency phasor of $\dot{I}_o$ is divided by $-\dot{U}n$:

$$\dot{Y}_O = \frac{\dot{I}_0}{-\dot{U}_0} \tag{77}$$

Also it is possible to utilize the change in the admittance because of the earth fault:

$$\dot{Y}_O = \frac{\dot{I}_{0\,fault} - \dot{I}_{0\,pre-fault}}{-(\dot{U}_{0\_fault} - \dot{U}_{0\_pre-fault})} \tag{78}$$

Theoretically such method allows fully get rid of network asymmetry and resistance at the fault point under certain conditions. In the admittance protection, the fault detector controls the value of $\dot{U}n$ and operates only then this value exceeds operating value. In order to exclude false start of the relay protection the setting value for $\dot{U}n$ must be higher than $\dot{U}n$ of the intact distribution network. Ordinary practically there is no asymmetry in cable line networks. At this work network with deep penetration of cable lines is under research, so Equations (61) and (63) can be used for calculations. However if there is a big amount of overhead lines which is caused high asymmetry it should be taken into account. Formula

(78) reflects the influence of asymmetry in residual admittances on neutral point voltage $\dot{U}n$ and current $\dot{I}_O$ .In purpose of representing selectivity of the particular type of relay protection calculation of the admittance is made for background line (without earth fault) and protected line (with earth fault).As it was mentioned above the results is achieved only for symmetrical networks.[5]

Result of admittance calculation when the fault is located outside the protected feeder: Because the earth fault is located outside the protected line $G_{f1} = 0$

$$\dot{Y}_0 = \frac{\dot{U}_n(\dot{Y}_1 + G_{f1} + \dot{B}_{L1}) + \dot{E}_a(G_{f1})}{-\dot{U}_n} = -(\dot{Y}_1 + \dot{B}_{L1}). \tag{79}$$

As it can be seen from Equation (79) in case when the earth fault is located outside the protected feeder the admittance relay protection measures the total admittance of the protected line which consists of feeder capacity and inductivity of the Petersen coil (if it is connected). It should be noted that the sign of the result is negative. In case of central compensation the calculated susceptance is determined only by the admittance of the protected line. From the practice of utilization admittance relay protection for the short distribution lines with such a small conductivity that calculations provide admittance with positive sign. This can be explained by inaccuracies in $\dot{U}n$ and $\dot{I}_o$ measurements. In case of hybrid compensation or distributed compensation the calculated admittance also can be positive. Such strange behavior can be determined by overcompensation and should be taken into account; otherwise some possible options will be missed.[5]

Result of admittance calculation when the fault is located inside the protected feeder: Because the earth fault is located inside the protected line $G_{f1} \neq 0$

$$\begin{aligned} Y_0 &= \frac{\dot{U}_n(\dot{Y}_1 + G_{f1} + \dot{B}_{L1}) + \dot{E}_a(G_{f1})}{-\dot{U}_n} = \\ &= -(\dot{Y}_1 + \dot{B}_{L1} + G_{f1}) + \frac{G_{f1}(\dot{Y}_1 + \dot{Y}_2 + G_{f1} + \dot{B}_L + \dot{B}_{L1} + \dot{B}_{L2})}{G_{f1}}. \end{aligned} \tag{80}$$

Finally $\dot{Y}_0$ can be represented as follows:

$$Y_0 = \dot{Y}_2 + \dot{B}_L + \dot{B}_{L2}. \tag{81}$$

The result from Equation (80) shows that in case of the earth fault in protected line the measured admittance is determined by the susceptance of the background feeder and inductivities of central and distributed Petersen coils, except the inductance of arc suppression coils connected to the protected lines. It should be noted that result is opposite to the result in the first case and positive by sign. However the sign of the result depends on compensation degree and when distributed coils are connected to the grid, also on their inductivity. Furthermore this formula (80) reveals the biggest advantage of the admittance principle, as it can be seen there is no G_{f1} or G_{f2} in specific equation. The result of measurements is not influenced by the resistance at the fault point which significantly simplifies process of choosing operating values. The summary of the admittance calculation results, Equation (78) and Equation (80), are illustrated in the admittance domain in Fig. 23.[5]

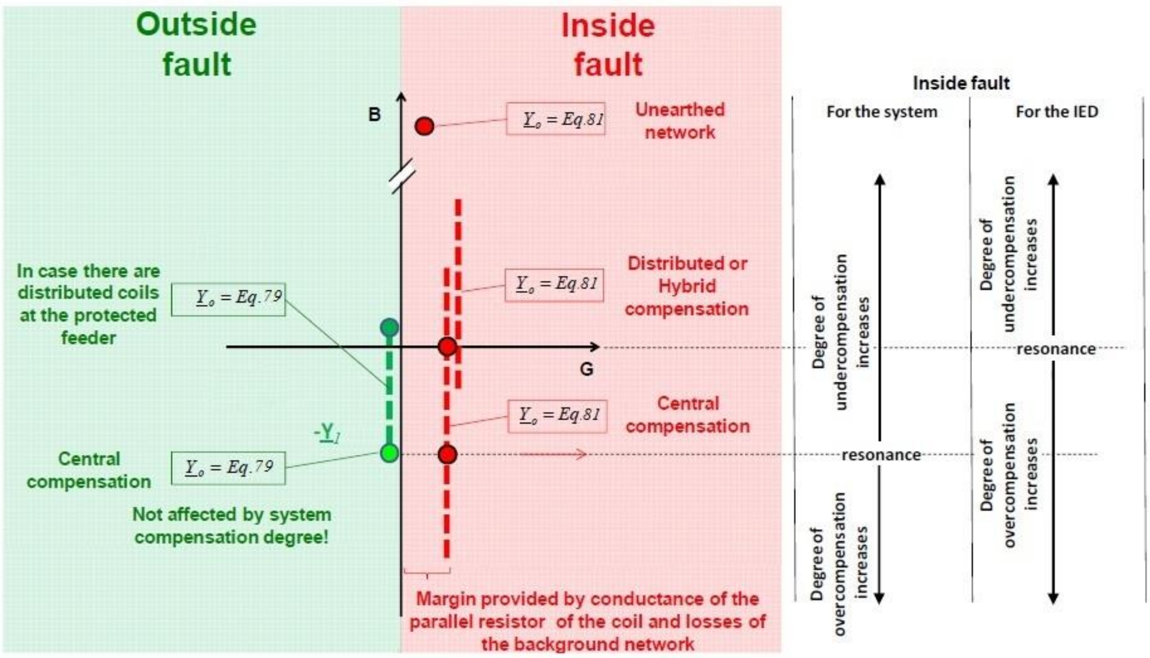


Fig. 23. Illustration of the measured admittances of the admittance protection principle in inside and outside faults.[5]

These tripping conditions can be satisfied by using admittance characteristic. Due to the electronic terminals of relay protection it is possible to set any kind of needed geometry of the characteristic. When the value of the measured admittance are outside of the boundary line of the characteristic the protection operates. The geometry of the characteristic should fully represent the admittance achieved from Equation (78), also because of different inaccuracies the characteristic should be larger to mitigate them. Modern type of admittance characteristics are represented in the Fig. 24.[14]

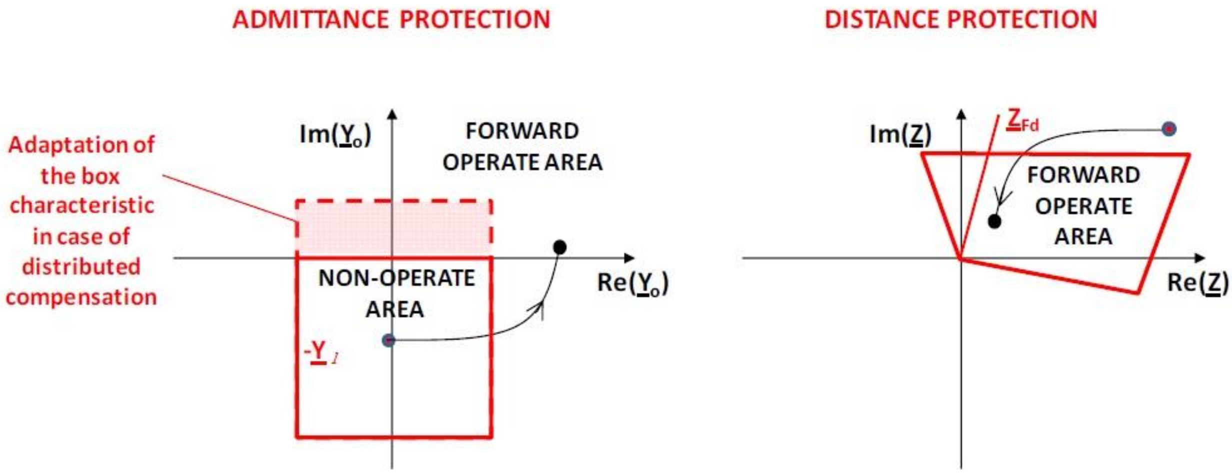


Fig. 24. Admittance and distance protection characteristics.[14]

Such box-shaped characteristic is based on results from formulas (79) and (81) and allow covering of measured admittance $\dot{Y}_0 = -(\dot{Y}_1 + \dot{B}_{L1})$ with sufficient margin. The shaped-box characteristic is a zone in the admittance plane which is similar to the characteristic of the distance protection. The relay protection with this characteristic allows operating when the system works with isolated neutral. In this case it is easier to distinguish which feeder is broken. As it can be seen from Equations (79) and (81) the admittances clearly differ in amplitudes and signs.[5]

Exceptional sensitivity can be achieved with the “Box”-characteristic in the undercompensated and overcompensated cases, where the operation is possible even without a parallel resistor. This is valid when the earth-fault current produced by the protected feeder is lower than the amount of system undercompensation in amperes, or when the amount of system overcompensation exceeds the boundary line limiting the nonoperate area in the direction of the negative Im(Yo) -axis. Typically this is the case for short feeders.[5]

As it was described earlier, in the networks with hybrid or distributed compensation the susceptance of the result from Equation 79 can be positive, due to overcompensation. This specific feature of the grid can be taken into account by enlarging characteristic to a positive zone $\mathrm{Im}(Y_0)$.[5]

3.7.1 Admittance based earth-fault protection utilizing harmonics

Petersen coils are adjusted to compensate earth fault current with fundamental frequency. From the inductive impedance of the arc suppression coil $\frac{1}{\omega L}$ and the capacitive impedance of the feeders $\frac{1}{3\omega C}$ it is clear that compensation of other frequency components is impossible with such adjusted coils. This uncompensated current components can be used to distinguish earth fault, which allows improving of sensitivity of the earth fault protection. The principle are determined by the following facts.[5]

The capacitive impedance of feeders differs at different harmonics. The fundamental frequency is $f = 50Hz$ and for $\nu \cdot f$ frequency the admittance of the line can be represented as follows:

$$\dot{Y}^{\nu} = G + jB^{50hz}\nu. \tag{82}$$

On the over hand, for the inductive impedance the ν harmonic component can be represented:

$$\dot{Y}^{\nu} = G - j\frac{B^{50hz}}{\nu} \tag{83}$$

From Equations (82) and (83) it is clear that for ν-th harmonic, the inductive susceptance is ν times smaller than when frequency is fundamental and in opposite the capacitive susceptance is n times bigger. Experimentally it was defined that the dominant harmonic in the earth fault current and voltage is the 5th.An example of the waveforms of the residual current and voltage recorded during actual field tests is shown in Figure 25.[5]

For the ν-th harmonic Equations (79) and (81) can be represented as follows:

Result of admittance calculation when the fault is located outside the protected feeder:

$$\dot{Y}_0^{\nu} = -(\left[G_1 + G_{f1}\right] + \mathrm{j}\cdot\left[\dot{B}_1\nu - \frac{B_{L1}}{\nu}\right]). \tag{84}$$

Result of admittance calculation when the fault is located inside the protected feeder:

$$\dot{Y}_0^{\nu} = (\left[G_2 + G_L + G_{L2}\right] + \mathrm{j}\cdot\left[\dot{B}_2\nu - \frac{B_{L2} + B_L}{\nu}\right]). \tag{85}$$

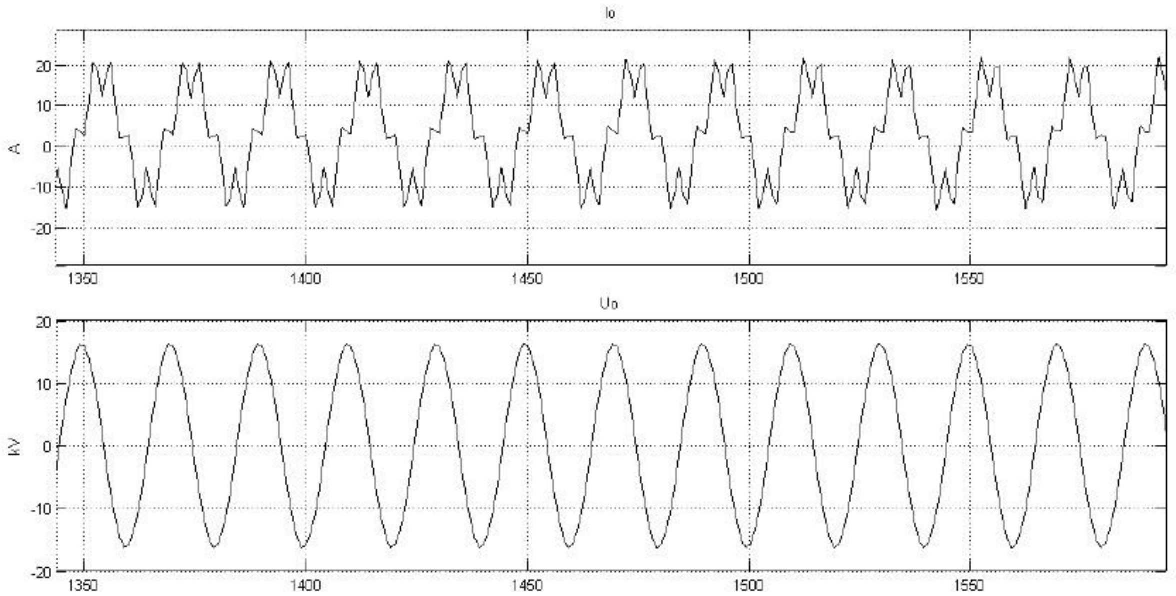


Fig. 25. Example waveforms of residual current and residual voltage recorded during field tests.[5]

From Equations (84) and (85) it is obvious that the measured admittance for the 5th harmonic are always capacitive. Even if the real system is overcompensated for the 5th harmonic the result is not changed. According to this feature it is very simple to distinguish earth fault conditions without any need to increase the earth fault current in purpose to provide specify sensitivity. [5]

There are two possibilities to utilize harmonic admittance principle: it can be implemented in a separate relay protection device or this principle can be integrated with admittance principle. In case when two these methods are implemented together, the operation criterion will be transformed and presented in such way:

$$\dot{Y}_0 = \dot{Y}_0^1 + \sum \dot{Y}_0^\nu \qquad (86)$$

Where

$\dot{Y}_0^1$ - fundamental frequency admittance,

$\sum \dot{Y}_0^\nu$ -harmonic admittances sum of ν-th order.

The idea to merge these principles in one relay protection complex allows increasing the sensitivity of the protection and consequently its effectiveness. For example in case when a high resistance at the fault point appears the method of harmonic admittance works not so good, the principle of fundamental admittance works stable. On the other hand, the harmonic admittance principle significantly improves sensitivity of the relay protection if in $\dot{I}_0$ and $\dot{U}_n$ harmonics are represented at the sufficient level.[5]

The combination of two these principles also leads to so some changes in the operating characteristic, it should include both criteria. In the Fig. 26. operating characteristics for both fundamental admittance principle and merged fundamental + harmonic admittance principle are represented.

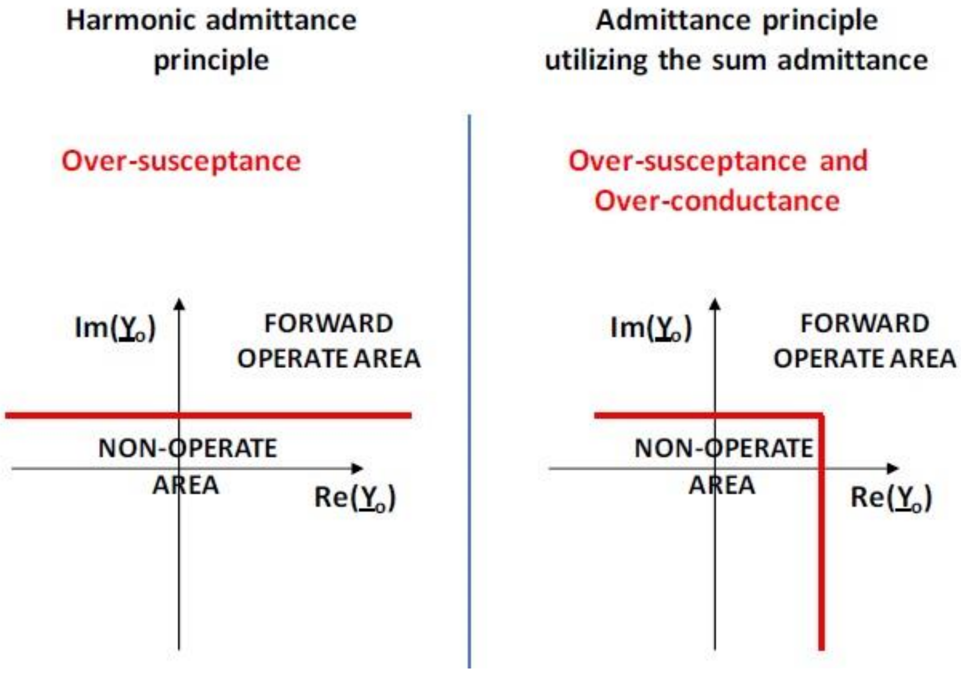


Fig. 26. Operation characteristics of the harmonic admittance principle and the combination of fundamental and harmonic principles.[5]

3.8 Intermittent earth fault protection.

Earth faults can be separated into two types: permanent and intermittent. Because of the replacement of overhead lines by underground cable lines great attention should be also paid to the second type of earth faults. Intermittent earth faults are characterized by the discontinuous form of current with spikes. Earth fault protection of conventional types cannot satisfy requirements applied to the relay protection and can cause an unselective operation. Moreover, in some cases, because of the unselective operation of the back-up protection, disconnection of all feeders is possible. Also it should be mentioned, that even a single intermittent earth fault in a cable line is an evidence of the cable insulation degradation. Thus, cabled feeders with this defect must be disconnected, however disconnection in case of overhead line imperfection does not need. Hence, according to the future situation when underground cables and overhead lines will be represented in medium voltage networks, it is essential to define faulted feeder. All reasons mentioned above accent importance of the intermittent relay protection.

3.8.1 Principle of operation.

In the protection measurements of instantaneous zero sequence currents and voltages are used to define faulted feeder. The principle of operation is based on the fact that in the first moment of the transient earth fault angle between zero sequence voltage U_0 and current I_0 close to 180 in the faulted feeder, whereas in over lines the same angle is equal 0. Monitoring of the instantaneous zero sequence power direction can be executed by comparing signs of the zero sequence current and the zero sequence voltage at a given time or by comparing the signs of residual current and the first derivative of zero-sequence voltage in time. If both U_0 and I_0 values exceed setting values the direction of the instantaneous zero sequence power is measured, which define faulted and healthy feeders. However relay protection based on this principle does not have characteristic of continuous action to permanent earth faults.[22,20]

Novel Cumulative Phasor Summing (CPS) principle allows to solve many problems of mentioned above principles. This method involves the use of the integral value within the operation time of intermittent protection. Cumulative phasor sum is calculated according to the formula 87

$$E_{CPS} = \sum_{i=t_{start}}^{t_{stop}} Y(\mathrm{i}) = \sum_{i=t_{start}}^{t_{stop}} \mathrm{Re}[Y(\mathrm{i})] + j \cdot \sum_{i=t_{start}}^{t_{stop}} \mathrm{Re}[Y(\mathrm{i})] \tag{87}$$

E_{CPS} can be represented by any electrical quantity, which reflects the direction of the zero sequence power flow, time interval of integration is defined by the Uo> criteria. CPS principle is represented in Fig.27.

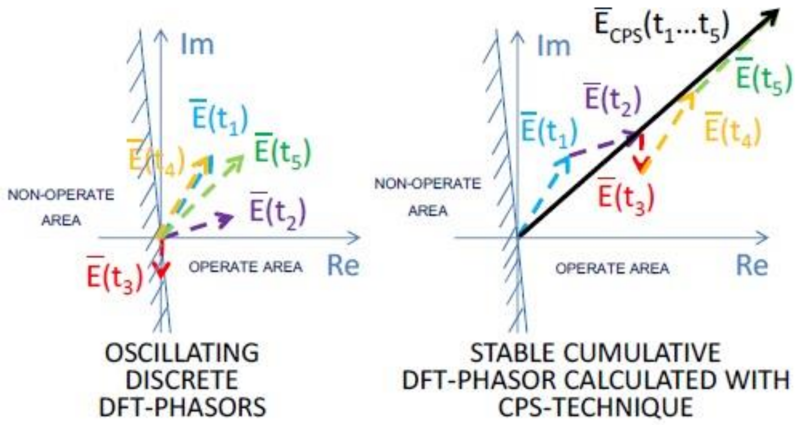


Fig.27. Demonstration of the Cumulative Phasor Summing principle.[23]

CPS principle is advantageous in comparison with conventional principles and allows to:

- stable operation when residual values are highly distorted;
- the utilization of higher harmonics;
- possibility to integrate CPS principle into admittance base protection;
- offset from the possible violations in initial correlation between I_0 and U_0 in compensated networks;
- continuous action. [23,12]

3.8.2 Coordination of intermittent relay protection with back-up protection.

In fully compensated networks, as it can be seen from Fig. 28, back-up protection may not release before the next fault and it will cause an unselective disconnection of all feeders if intermittent protection will not operate fast enough. In order to prevent unselective operation this protection can be blocked by the signal from the intermittent protection.[20,21]

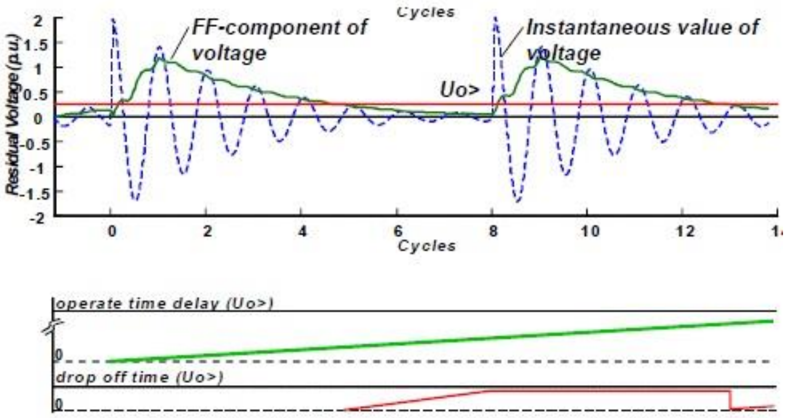


Fig.28. Illustration of a possible nonselective operation of the back-up protection.[21]

3.8.3 Coordination with the directional earth fault protection.

Conventional earth fault protection cannot guarantee reliable operation in case of intermittent earth faults. Behavior of the directional earth fault protection during the fault is represented in Fig.29. As it seen from Fig.29 the measured value in faulted and healthy feeder during the fault do not lay only in operate area or non-operate area, thus it can be the reason of a false tripping.[20,21,22]

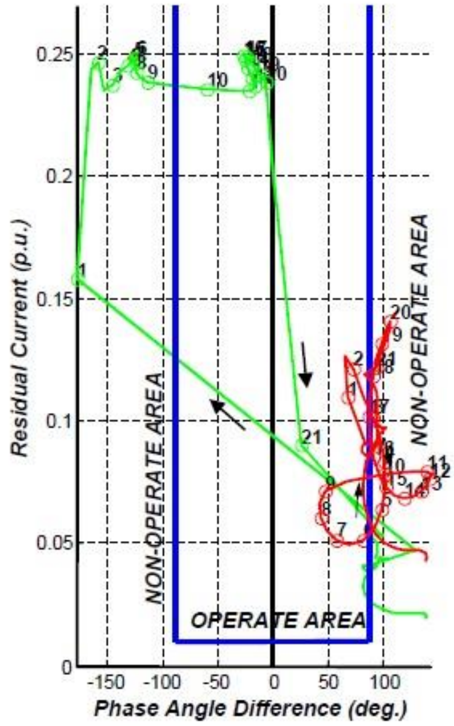


Fig.29. Behavior of the directional earth fault protection during single impulse of the intermittent earth fault protection. Green line-trajectory of the residual current angle measured in a faulted feeder. Red line-trajectory of the residual current angle measured in an intact feeder.[21]

There are two methods to fix this problem. The first variant is to set up turn-on delay of the directional earth fault protection bigger than operation time of the intermittent protection. Another method is to use the starting signal of the intermittent protection for blocking of all conventional protections.[20]

3.9 Conclusion.

Currently, there are more than 15 relay protection manufacturers producing a separate device, or protection against earth faults. Obviously, this diversity of offers complicates the selection of a particular type of protection, and in most cases the final decision is dictated only by the customer's preferences and costs. As the experience of operation, to ensure the selectivity of specific protections against earth faults in isolated neutral or compensated networks is not always possible, even when using expensive devices. Therefore, the problem of determining optimal mode of neutral and selection of the appropriate type of protection requires a comprehensive analysis of earth faults.

It should be noted that some modern earth fault relay protection devices combine several different principles of damaged feeder detection and, with proper configuration, are the most reliable protection.

4 EXAMINATION OF THE NETWORK.

For the purpose of carrying out the comprehensive analysis of distribution networks with long cable lines model with distinctive in the nearest future parameters should be created. As it was stressed earlier the main idea of the work is not to investigate specific medium voltage grid, thus the network with the most common structure and types of conductors is examined.

In this master thesis distribution network with radial structure and power lines, represented by cable lines as well as by overhead lines, is analyzed. Electricity network map without shunt reactors and arc suppression coils is reflected in Fig. 30.

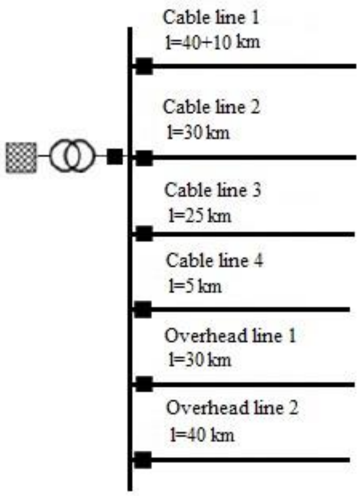


Fig.30. Diagram of the examined network.

In order to provide analysis of earth fault relay protection in a medium voltage network with long cable lines model of this network was created in PSCAD. Due to the peculiar properties of the implemented program cable lines are modeled by geometrical dimensions of conductor and insulator layers, whereas overhead lines can be dimensioned directly by specific parameters. In this electrical greed cabled feeders are represented by cables with cross-linked polyethylene insulation produced by ABB company, overhead lines are represented by lines with Raven 54/9 conductors. Parameters of cabled power lines were obtained from the PSCAD model where they were dimensioned based on the information from the ABB catalogue of power cables [24], while parameters of overhead lines were used the same as obtained during the projects of University of Vassa [10]. In Table 1 and Table 2 main characteristics and parameters of power lines are reflected.

Table 1. Main characteristics of power lines.

Voltage class	Title	Type of a line	Length, km
20kV	Cl1	underground cable+overhead	40+20
20kV	Cl2	underground cable	30
20kV	Cl3	underground cable	25
20kV	Cl4	underground cable	5
20kV	OHL1	overhead	60
20kV	OHL2	overhead	50

Table 2. Main parameters of power lines.

Title	Specific resistance (Om/km)	Specific inductive impedance (Om/km)	Specific capacity (μF/km)	Cross-section (mm^2)
Cl1	0.124	0.192	0.237	150
Cl2	0.153	0.198	0.217	120
Cl3	0.153	0.198	0.217	120
Cl4	0.193	0.203	0.19	95
OHL1	0.543	0.372	0.00438	
OHL2	0.543	0.372	0.00438	

5 REACTIVE POWER MANAGEMENT.

The apparent power consists of two components: active and reactive power and consequently the use the same path from the point of generation to the point of consumption. Reactive power does not execute shaft work, but it generates magnetic fields and provides motor torque, also voltage levels in the network are determined by the reactive power. Thus it is obvious that in order to transfer bigger amount of active power through electric lines, the reactive power should be generated close to the consumption point. Ordinary the reactive power management in distribution lines is performed by the use of shunt reactors and shunt capacitors.[15]

Distribution networks with high cable penetration is investigated in this work is, hence, hereafter will be discussed and represent the influence of cable lines to the reactive power generation and flow in distribution grids. Due to the high capacitance of cable lines in comparison to overhead lines, they generate significantly more reactive power than consume. Consequently, extensive cabling creates new challenges to the distribution networks. In purpose to clearly understand the problem and find economically and technically adequate solution these effects should be estimated based on both distribution system operator point of view and technical constraints.[15]

5.1 Fingrid's policy of reactive power policy.

According to the Fingrid's regulations reactive power generation and consumption of their clients are constrained by certain values for each point of connection. These limitations are presented by so called "reactive power window». The main aim of these requirements is to provide stable main grid operation and maintain voltage balance. Also better reliability, power quality and lower losses are achieved with voltage balance. The allowed voltage deviations according to the Fingrid's regulation are represented in Fig.31.[15]

Voltage level	Lower limit	Upper limit
400 kV	380 kV	420 kV
220 kV	215 kV	245 kV
110 kV	105 kV	123 kV

Fig.31. Allowed voltage levels in the main grid.[15]

5.2 Reactive power control by Fingrid.

For every point where the customer is connected to the main grid Fingrid sets up a reactive power contract. Also Fingrid establishes monitoring area if the location of connection points an electrically close to each over. For the customers in the monitoring are there is a possibility to allocate generation and consumption of reactive power between themselves, due to features of the Fingrid's regulation.[17]

The reactive power limit, which is comprised from the reactive power windows of all the clients in the monitoring area, is defined for the whole monitoring area. Inside these established boundaries the generation and consumption of the reactive power is free of charge. However in case of extra input or output of the reactive power from the monitoring area, financial penalty will be implemented. The measurements of the extra reactive power are done for each hour every month in a year. Fingrid provide some flexibility for clients, as outlined in regulations no more than 10 hours of exceedings during one month are permitted, but the maximum input or output reactive power should be lower than the double maximum volume of allowed reactive power. Nevertheless, all abnormal situations have to be explained and clarified for Fingrid. Furthermore, Fingrid has determined exception condition when there is no fee for the extra reactive power: starting of a generator, faults in the low voltage side, significant starting or stopping process. In case if listed above processes can be predicted, clients have to report it to the Fingrid.[16,17]

The reactive power window is represented in Fig. 32. Q_{S1}-is the reactive power input limit and Q_S is the reactive power output limit. Fig. 32. reflects the dependence of the allowed reactive power in accordance to the consumption of the active power. The input reactive power from the distribution network to the main grid is restricted by the specific value Q_{S1} which is constant for any active power consumption. However, the permitted output reactive power can change from zero to the 16 percentage of the consumed active power. At the example illustrated in Fig. 32. the extra volume of reactive power is shown by arrows and the amount of penalty is marked on the horizontal axe. Formulas (88), (89) and (90) are used to determine reactive power output and input limits.[17]

$$Q_S = W_{Output} \cdot \frac{0.16}{t_k} + \frac{0.025 \cdot W_{Gen}}{5000}, \tag{88}$$

$$Q_S = W_{Output} \cdot \frac{0.16}{t_k} + 0.1 \cdot S_N, \tag{89}$$

$$Q_{S1} = -0.25 Q_S. \tag{90}$$

Where

t_k - peak usage time

- 7000 h for process industry;
- 6000 h for other industry;
- 5000 h for other consumption.

W_{Output} - output active power (MWh);

W_{Gen} - net active power production (if the largest generation is smaller than 10 MVA, than $W_{Gen} = 0$);

S_N -apparent power of the largest generator (if the largest generation is smaller than 10 MVA, than $S_N = 0$).

After the calculation Equations (88) and (89), Q_S is equal to the largest result.[17]

The financial penalty of extra reactive power consists of the usage fee and energy fee. For this calculation is used average value of the reactive power during one hour period which is measured for each connection point. In order to determine usage fee for the specific month, the largest reactive power exceeding should be found for this month. Equations (91), (92) and (93) are used to calculate usage fee. The target value is equal to the difference of the maximum exceeding and the window limit and the result is multiply by 3000 €. For every hour when reactive power exceeds limits, energy fee has to be paid. Energy fee is equal exceeding reactive energy multiply 10 €/MVarh.[17]

- If $P_h \le Q_S / 0.16$ and $Q > Q_S$, the usage fee is

$$(Q - Q_S) \cdot 3000 \text{ €/MVar}. \tag{91}$$

- If $P_h > Q_S / 0.16$ and $Q / P > 0.16$, the usage fee is

$$(Q - 0.16 P_h) \cdot 3000 \text{ €/MVar.} \tag{92}$$

- If $|Q| > |Q_{S1}|$

$$(|Q| - |Q_{S1}|) \cdot 3000 \text{ €/MVar.} \tag{93}$$

Where

$$Q = Q_M + Q_h; \tag{94}$$

Q_M - one hour average reactive power;

Q_h - transformers' reactive power losses, in case when measurements are done in lower voltage side;

P - one hour average active power.

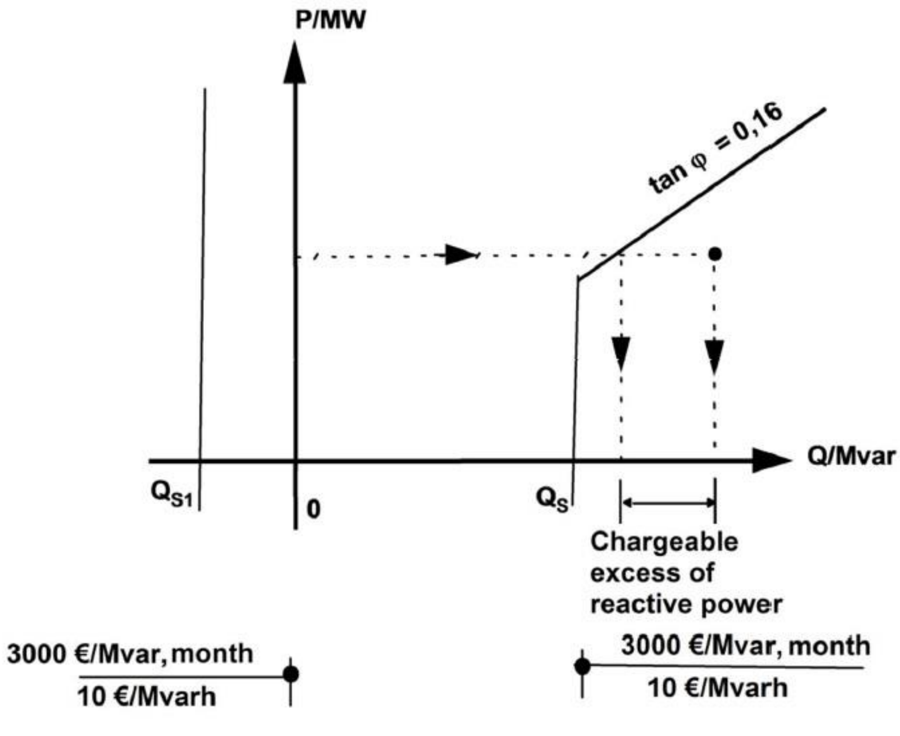


Fig.32. The principle of the reactive power window.[17]

Due to the high cable penetration in distribution medium voltage networks new challenges concerning reactive power balance at Fingrid monitoring areas and connection points are aroused. Ordinary distribution networks are considered as consumers of the reactive power, thus, there was not exceeding of input limits. However because of high capacitance of the cable lines in networks with long cable feeders or significant amount of relatively short cable lines during night periods or other situations with low loads the reactive power balance in connection points can be disturbed. Nowadays in Finland more and more medium voltage cable lines are created every year in order to withstand large climatic disturbances. This method is almost one possible way to prevent extensive and long-lasting interruptions which are caused be storms or blizzards in overhead networks. For this reason the problem concerning reactive power input limits is acute for distribution lines and Fingrid has been asked about possible changes in regulations.[16]

Fingrid does not intend to reconsider working regulations, because according to their results the present method to control reactive power balance is working well. Also, organization announced that there is no plan for further restriction of the reactive power consumption or generation in distribution networks. Fingrid will not follow Central Europe strategy in power regulation in which zero tolerance of reactive power window is accepted.[16]

Ordinary total consumption power of distribution networks in rural areas is close to 20MVA with $\cos\varphi = 0.92$. For the examined electrical grid it is 18MVA, consequently consumption of reactive power is equal:

$$Q = 18 \cdot 0.39 \approx 7M\,\mathrm{var} \tag{95}$$

Thus, maximum allowed value of the reactive power which can be transferred to the transmission network is:

$$Q_{S1} = 0.25 \cdot 7 = 1.75M\,\mathrm{var} \tag{96}$$

Reactive power, generated by cable lines:

$$\begin{aligned} Q_C &= U^2 \cdot \omega \cdot (l^{CL1} \cdot C_{nom}^{CL1} + l^{CL2} \cdot C_{nom}^{CL2} + l^{CL3} \cdot C_{nom}^{CL3} + l^{CL4} \cdot C_{nom}^{CL4} + \\ &+ l^{OHL1} \cdot C_{nom}^{OHL1} + l^{OHL2} \cdot C_{nom}^{OHL2}) = 20000^2 \cdot 2 \cdot 50 \cdot \pi \cdot (40 \cdot 0.237 \cdot 10^{-6} + \\ &30 \cdot 0.217 \cdot 10^{-6} + 25 \cdot 0.217 \cdot 10^{-6} + 5 \cdot 0.1907 \cdot 10^{-6} + 80 \cdot 0.0044 \cdot 10^{-6}) \approx 3.1M\,\mathrm{var} \end{aligned} \tag{97}$$

where

Q_C - charge capacity of cable lines.

Difference between allowed and generated reactive powers are:

$$Q_C - Q_{S1} = 3.1 - 1.75 = 1.35M\,\mathrm{var} \tag{98}$$

According to this calculation it is evident that in the examined network during low load period exceeds of allowed limits in reactive power transfer is possible. In this case if reactive power flow exceeds allowed limit for 500 kVar, than financial penalties FP for one month can be estimated as follows:

$$FP = (Q_S - Q_{S1}) \cdot 3000 \cdot 6 \cdot 30 = 0,5 \cdot 3000 \cdot 6 \cdot 30 = 0,27 \cdot 10^6 € \qquad (99)$$

Obtained amount of money reveals need of utilization shunt reactors in the network. By these calculations for specific medium voltage network should be provided financial justification of shunt reactor implementation.

5.2.1 Compensation of the charge capacitance.

As it can be seen from the represented above calculations that utilization of shunt reactors is economically beneficial in distribution networks with long cable lines. Consequently next questions are arisen:

- what type of shunt reactors should be implemented;
- where should be installed devices;
- permanent or temporary connection of reactors?

In order to solve these tasks they have to be considered all together. In day hours charging capacity increases transmission capacity of lines and decrease voltage dip in the end of a line. During low load period reactive power flow from distribution network to the transmission greed does not lead to losses from distribution company point of view. Also, total amount of charging capacitance is equal 1.35Mvar which allows selection of a shunt reactor with standard rated power in order to realize central compensation of excessive reactive power. Consequently there is no need to utilize distribution compensation of reactive power because it will complicate its operation and increase financial expenditures.

Due to that fact that there is a boundary of reactive power transfer form one system to another, than the task is not to exceed that limit rather than to compensate certain amount of reactive power. Thus, fixed type shunt reactors can be implemented which significantly decrease cost of the device. Charge capacitances of power lines are represented in Table 1.

Total apparent power of consumers connected to each line is 3MVA, thus consumption of reactive power is:

$$Q \;= S \;\cdot \sin\varphi = 3 \cdot 0.39 = 1.18 M\,\text{var} \qquad (100)$$

As it can be seen from Table 3 even for long cable lines charge capacitance is lower than consumption of the reactive power. Evidently, that power flow of the reactive power from the transmission network to the medium voltage consumer will be decreased due to the charge capacitance of a line. Thus compensation of the reactive power should be implemented only during low load periods according to the load curve.

Table 3. Charge capacitance of power lines.

Title	Charge capacitance, Mvar
CL1	1.2
CL2	0.9
CL3	0.8
CL4	0.14

5.3 Ferranti effect and voltage rise in distribution lines.

Ferranti phenomena lead to the situation when during no-load or low load period of a power line the receiving end voltage is higher than the voltage at the sending end. This effect occurs if current determined by the line capacitance exceeds value of the load current. Ferranti phenomena occurs in case when the capacitance of a power line is significant, so it can be observed at medium and long lines with high capacitance per unit of length. The principle of Ferranti phenomena can be explained by the use of Fig.33. and phasor diagram in Fig.34.[15,17]

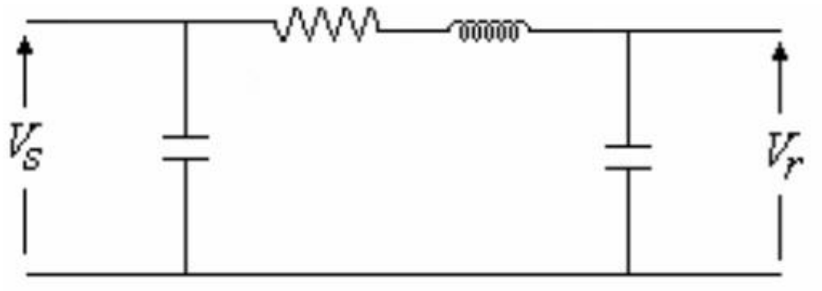


Fig. 33. Equivalent π model of the line.[17]

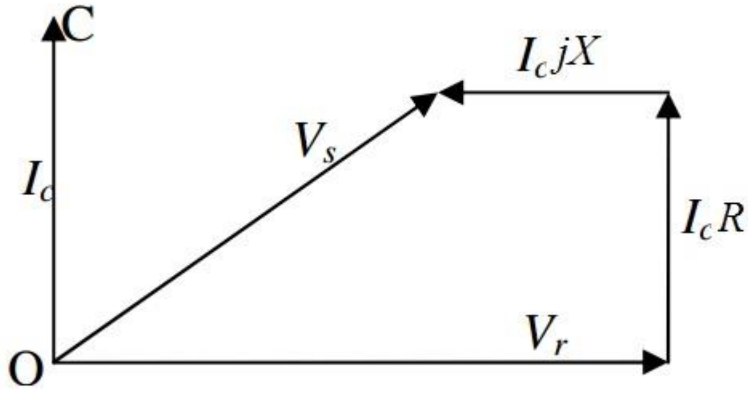


Fig.34. No-load phasor diagram.[17]

On the phasor diagram main electrical values are presented:

V_r - voltage at the receiving end;

V_S - voltage in the sending end;

The capacitive current leads to voltage drop across the line inductor which is in phase with the sending end voltage. This voltage drop keeps on increasing additively as we move towards the load end of the line and subsequently the receiving end voltage tends to get larger than applied voltage leading to the phenomena called Ferranti effect in power system. Equations (101)-(103) reflects the represented theory and allow to calculate the numerical value of the voltage rise.[17]

$$V_r = V_r(1+0j); \tag{101}$$

$$I = j\omega C V_r; \tag{102}$$

$$V_S = V_r + IR + jIX = V_r + j\omega C V_r(r + j\omega L) = V_r - \omega^2 CLV_r + j\omega CRV_r; \tag{103}$$

In medium voltage distribution networks with overhead lines Ferranti phenomena practically does not affect to voltage level. However in case when long cable lines are presented in the electrical grid, because of high capacitive currents during low load conditions, the voltage rise can be observed. The main danger of these phenomena is determined by the constant voltage level at the sending end of the power line. Thus, substation does not observe any changes and in this case voltage at the receiving end of the feeder will not be adjusted by on-load tap changer. Main substation is blind for Ferranti effect and in high voltage networks such phenomena can cause serious breakdown of equipment in the receiving end.[15]

In Pekkala's master thesis simulations of the voltage rise in distribution networks with high cable penetration have been done. The gained data reveal that the maximum increase in voltage occurs when the thirst third of the line is overhead line and other part is presented by cable line. In this situation 4% of voltage rise was achieved, which does not exceed acceptable limits. These results for solely cable line and composite feeder are represented in Fig.35. and Fig. 36 consequently. [13,15]

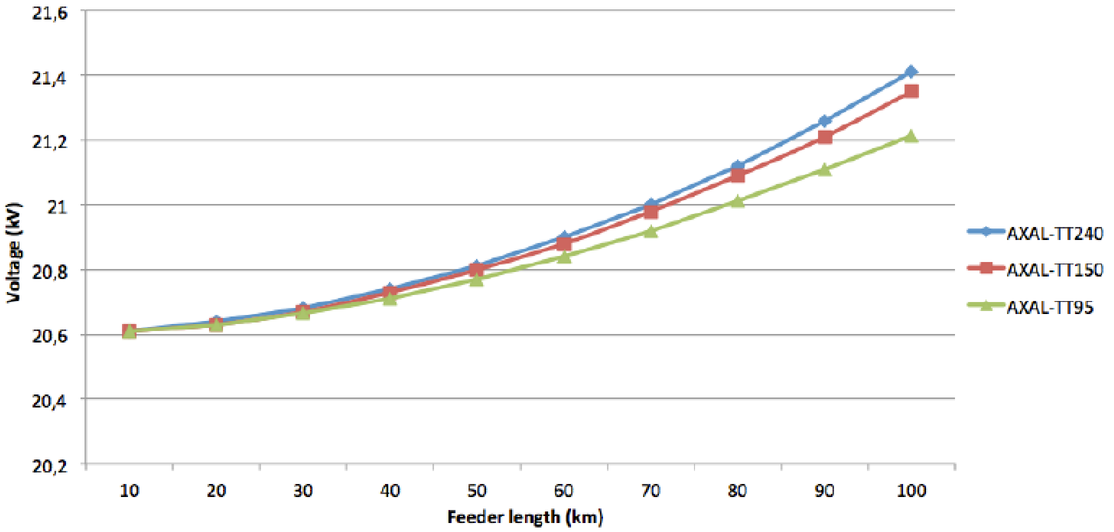


Fig.35. Voltage rise at the receiving end of a feeder.[15]

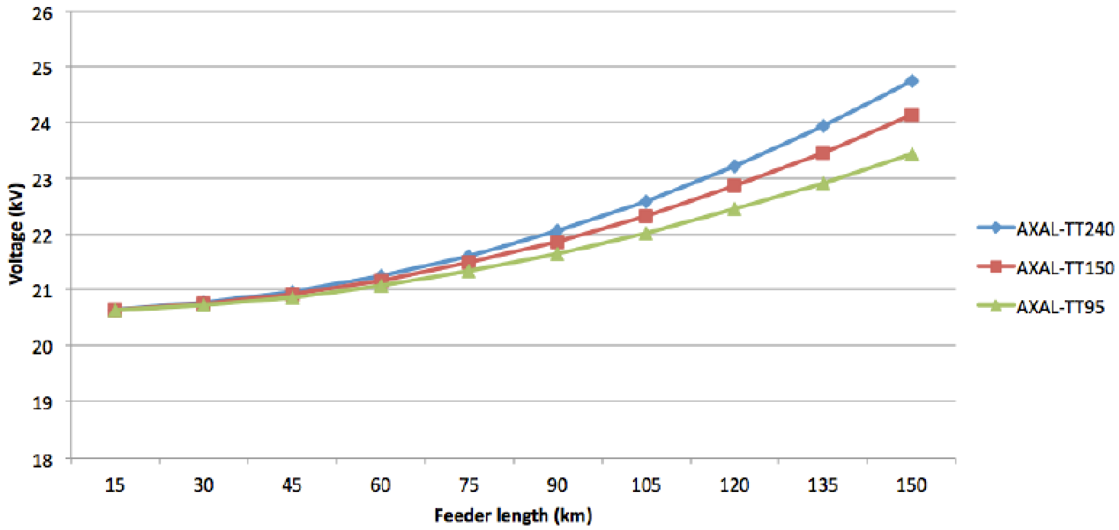


Fig.36. Voltage rise at the receiving end of a feeder which is consist of a cable and overhead lines.[15]

5.4 Shunt reactors

Shunt reactors are compensation devices which are utilized in order to accomplish reactive power management in networks. Reactors consume reactive power and mainly they are used to compensate inappropriate high voltage levels in the end of lines during hours with light load conditions. Also shunt reactors can accomplish other functions such as current limitation and filtering of harmonics. Nowadays these compensation devices are produced for all voltage levels and a high range of reactive powers, thus a shunt reactor can be chosen close to the desired parameters. Shunt reactors can be placed in the tertiary winding of the transformer in order to reduce costs, or can be directly connected to the bus or to the line.[15]

5.4.1 Core and insulation.

The parameters of shunt reactors are defined by their core and insulation. Reactors are produced with a gapped core or with and air core. Due to even increase of the magnetic field density in the air core, the inductance of this reactor type is linear. Such feature allows to dimension reactors relatively simply and makes their behavior easy to predict.

Ferromagnetic materials are used for reactors with gapped core, which leads to saturation of the reactor. Under the influence of certain values of currents due to saturation the inductance of the reactor will be reduced which caused increase in currents. High values of the current are dangerous for this device and in case of protection failure it can be damaged. Implementation of tap changer in order to change amount of circuits in the coil allows to create gapped core reactors with variable inductance.[15]

The most frequently used solution for the compensation of excessive reactive power in Finland high voltage networks is air core shunt reactors. These devices consist of three equal high cylindrical one-phase coils. In order to provide symmetric impedance single phase coils are placed in corners of equiangular triangle. Also due to such composition of shunt reactors the spreading magnetic field is minimized. Nowadays fiberglass insulation is used to protect conductor layers which are separated from each over by special aluminum sticks. Because of the strong Lorentz forces strict demands are putted to the durability of reactors. The decrease in sizes can be gained due to the implementation of oil immersed air core reactors in comparison to dry type reactors. However oil immersed reactors are more expensive and because of the oil weight more.[15]

5.4.2 Connections

In Fig.37 several connection methods for shunt reactors are illustrated. The first two types of connection are wye-connection and delta-connection; these connections can be transformed to each over with wye-delta transformation. The third and fourth types are grounded wye-connection and grounded wye-connection with a neutral reactor which is used in countries, in which the single phase reclosing is used. [15]

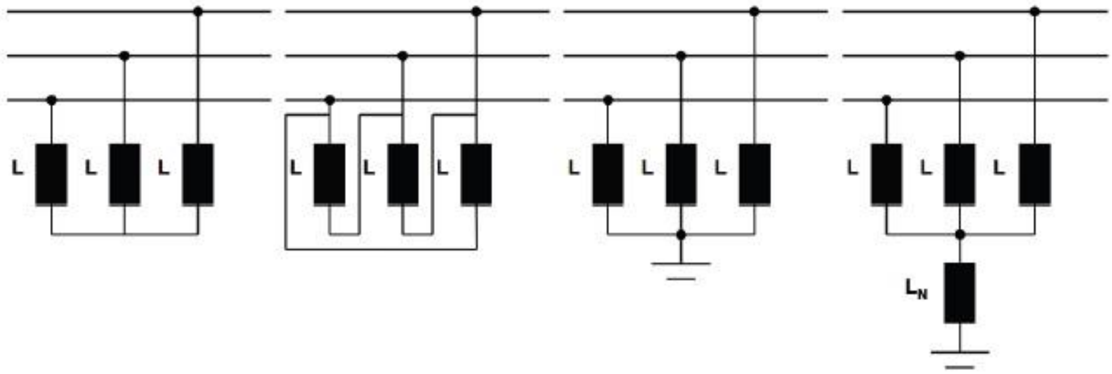


Fig.37. Shunt reactor winding connection.

In fourth case the grounded reactor can be used as an arc suppression coil in order to compensate capacitive earth fault current. However due to this additional function shunt reactors should satisfy some requirements. During solid earth faults (when $R_f = 0$) shunt reactors will be under the influence of line-to-line voltage and should withstand it. Secondly, the positive and zero sequence impedances of the coil have to match in order to behave linearly during the fault. Thirdly, if there is a gapped core, it cannot be saturated so the inductance would not drop.

Equations (104) and (105) represent how the reactance of wye-connected and delta-connected shunt reactors can be calculated:

$$X_{Wye} = \frac{U^2}{S}, \tag{104}$$

$$X_{Delta} = 3\frac{U^2}{S}. \tag{105}$$

Due to the fact that each of one-phase reactors in case of delta connection is under the influence of line to line voltage, the generated reactive power is consequently higher.[15]

5.4.3 Variability of the inductance.

According to the possibility to vary inductance reactors can be separated into three categories: fixed-type, step-type and plunger core reactors. The simplest and the cheapest one are fixed type reactors, their impedance con not changed. These devices are produced with two types of insulation: oil immersed or dry. The second type of reactors is named due to the tap changer which allows changing their inductance manually when shunt reactors are disconnected from the network. The inductance of plunger core reactors can be changed gradually during the operation mode. Such results are gained by the use of electrical motors which are decrease or increase air gap of the core. Fig. 38 represents the principle of work.[18]

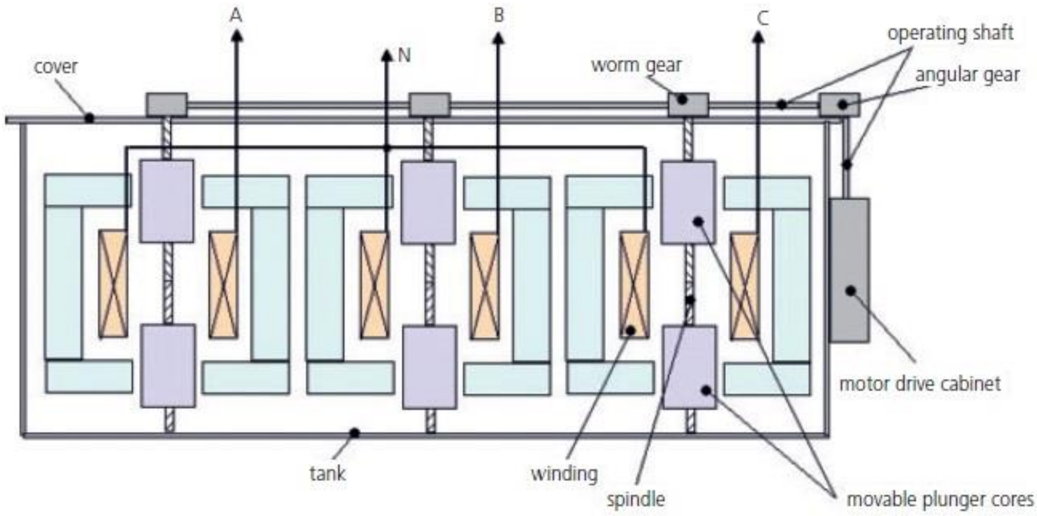


Fig. 38. Variable shunt reactor.[18]

6 EARTH FAULT CURRENT CALCULATIONS

According to the standard SFS-6001 the value of touch voltage is limited, according to the time during which human is under the influence of this voltage. Decision of earth fault compensation is made based on the mentioned above regulation. For the touching voltage calculations are used the value of earthing resistance which is in range of $R_f = 5 \div 20\Omega$.

Therefore, it is possible to determine the limit for the total value of shunt capacitance $C_{\lim}$ in the network. Equation for the maximum allowed shunt capacitance can be obtained from Equations (28) and (73):

$$U_m = I_f R_f = \frac{3\omega C_{\lim} E_{ph}}{\sqrt{1+(3\omega C_{ph} R_f)}} R_f \Rightarrow C_{\lim} = \frac{U_m}{3\omega R_f \sqrt{E_{ph}^2 - U_m^2}}. \tag{106}$$

The result is represented in Fig. 39, if the total value of the network capacitance does not exceed represented values, than this network can operate with isolated neutral.

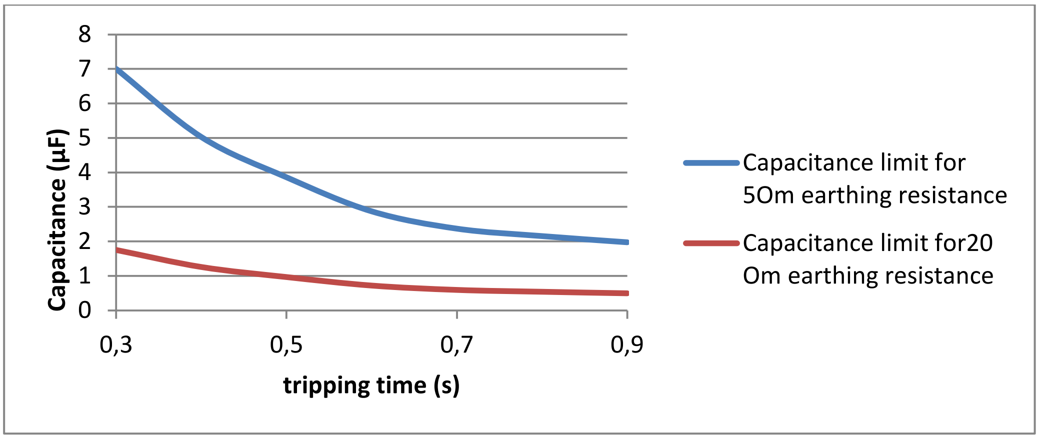


Fig.39. Capacitance limit for networks with isolated neutral.

According to the regulations which are valid in the Russian Federation the compensation of earth fault currents should be utilized when the earth fault current exceeds specific value. For the 20kv medium voltage distribution networks with cable lines earth fault current is limited by 15 A. For this standard capacitance limit can be determined as follows:

$$C_{\lim} < \frac{I_f}{3\omega\sqrt{E_{ph}^2 - I_f^2 R_f^2}} \tag{107}$$

For $R_f = 5 \div 20\Omega$ the result is $C_{\lim} < 1.36\mu F$. It is obvious from Equation (107) that the earthing resistance, when it is no higher 100 Ω, has no strong influence on $C_{\lim}$. Thus, both of these regulations provide relatively close results and for the investigated network, because of the long cable lines, compensation of earth fault currents should be utilized according to the both regulations.

Total capacitance of the network $C_{\sum}$ can be determined by simple summation of capacitances of each cable line.

$$C_{\sum} = \sum_{i=1}^{6} C_i l_i = 0.237 \cdot 40 + 0.217 \cdot 30 + 0.217 \cdot 25 + \\ +0.19 \cdot 5 + 0.00438 \cdot 40 + 0.00438 \cdot 40 = 24.16\mu F. \quad (108)$$

Where C_i - specific capacitance of the feeder i; l_i - length of the feeder i.

Evidently, that this value of total network capacitance leads to the high earth fault currents and, consequently, inacceptable value of the touch voltage. Thus arc suppression coils should be implemented in order to decrease the value of the earth fault current. However, in the theoretical point of view it is also interested to investigate network with isolated neutral and point out the influence of long cable lines. All electrical quantities is defined for the earth fault at phase A through the 500 **Ω** resistance, this particular value of the transient resistance is specified in Finish regulation, also presentation of results for specific earth fault resistance makes it possible to compare electrical quantities with each other for different networks.

6.1 Network with isolated neutral.

Examined network is represented in Fig.30.In order to reveal changes values of earth fault currents were calculated by the use of simplified formula and for the same points PSCAD results are presented. Values of earth fault currents and zero-sequence voltage at the bus-bar, when the earth fault point is at the end of a line in phase A, adopt next values:

- Neutral point voltage

$$\dot{U}_n = \frac{-E_a}{3j\omega R_f \sum_{n=1}^{6} C_i l_i + 1} = \frac{-\frac{20000}{\sqrt{3}}}{3 \cdot j \cdot \omega \cdot 500 \cdot 2.28 \cdot 10^{-5} + 1} = 1011\angle 95° V \quad (109)$$

Results obtained from the model are represented in Table 4 for the earth fault point in the receiving and sending ends of a feeder.

Table 4. Neutral point voltage in the network with isolated neutral.

Title	Calculated zero sequence voltage		Experimental zero sequence voltage		Fault point
	Value (kV)	Phase (degree)	Value (kV)	Phase (degree)	
CL1	1.011	95.0	1	94.4	Sending end
			0.956	90.4	Receiving end
CL2	1.011	95.0	1	94.4	Sending end
			0.938	92.17	Receiving end
CL3	1.011	95.0	1	94.4	Sending end
			0.936	93.14	Receiving end
CL4	1.011	95.0	1	94.4	Sending end
			0.944	93.1	Receiving end
OHL1	1.011	95.0	1	94.4	Sending end
			1	94.5	Receiving end
OHL2	1.011	95.0	1	94.4	Sending end
			1	94.5	Receiving end

In Fig. 40 relative position of phase voltages and neutral point voltage are reflected.

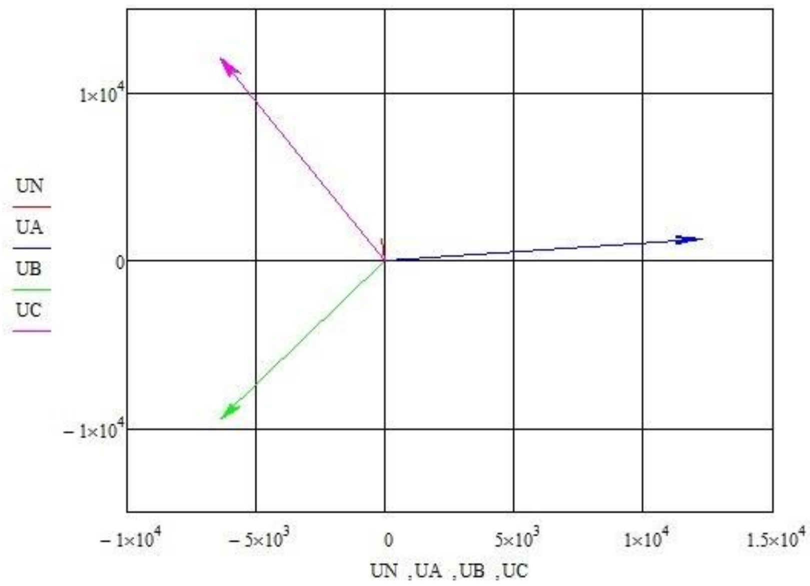


Fig.40. Phasor and neutral voltages during earth fault at phase A through 500 resistance.

- Earth fault current

$$I_f = \frac{(E_a + U_n)}{R_f} = \frac{11547 + 1011\angle 95}{500} = 23\angle 5.0° A. \qquad (110)$$

Results obtained from the model are represented in Table 5 for the earth fault point in the receiving and sending ends of a feeder.

Table 5. Earth fault currents in the network with isolated neutral.

Title	Calculated zero sequence current		Experimental zero sequence current		Fault point
	Value (A)	Phase (degree)	Value (A)	Phase (degree)	
CL1	23.0	5.0	22.7	4.6	Sending end
			23.16	0.04	Receiving end
CL2	23.0	5.0	22.7	4.6	Sending end
			22.77	1.51	Receiving end
CL3	23.0	5.0	22.7	4.6	Sending end
			22.72	2.38	Receiving end
CL4	23.0	5.0	22.7	4.6	Sending end
			22.9	2.21	Receiving end
OHL1	23.0	5.0	22.7	4.6	Sending end
			22.7	4.6	Receiving end
OHL2	23.0	5.0	22.7	4.6	Sending end
			22.7	4.6	Receiving end

Also during modeling of the network with isolated neutral abnormal increase of earth fault currents was observed. In order to represent this phenomenon more clearly model of the network with only one cable line 2 was In Table 6 results of earth fault current for the single cable feeder are represented.

Table 6. Earth fault currents in a single cable line during low load period.

Experimental value of earth fault current (A)	2.5	12.8	25.7	51.8	79	138
Length of the line (km)	1	5	10	20	30	50
Calculated value of earth fault current (A)	2.5	12.5	25	50	75	125

As it can be seen from the Table 6 value of the earth fault current for a cable line with 50km length is $138 - 125 = 13A$ higher than it was calculated. If in the network there are long cable lines the difference can be significant and it will change expected level of compensation. Obviously, if the network operates with under compensation of earth fault currents, than this level will be even lower which can cause an inappropriate value of earth fault current.

The result of such phenomenon is determined by low loads of cable feeders an as a consequence high voltage level at the end of a feeder. In the examined network this can be seen during the night hours. Voltage level at the sending and receiving ends is represented in Fig. 41.

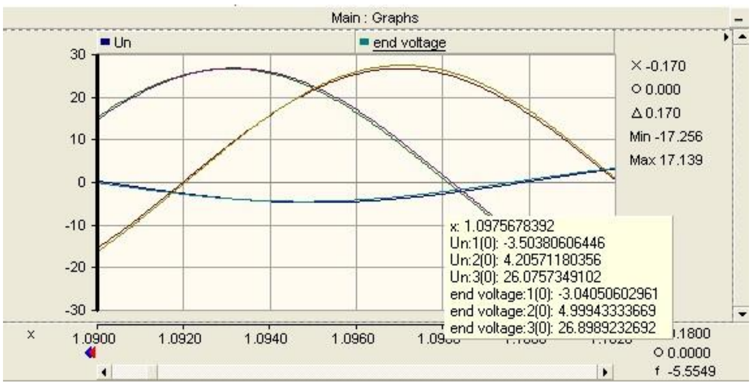


Fig. 41. Voltage level at the sending or receiving ends of a long cable line during earth fault at the low load period.

6.2 Selection of arc suppression coils and transformers for their connection to the network.

From the technical point of view an earth fault is not crucial regime for a network, because ordinary value of the earth fault current does not exceed value of current in normal operating mode. Thus, there is no harmful influence on electrical devices and the electrical grid can operate under this condition for some time. However, earth fault current is a great threat for the people and the value of it should be restricted in order to fulfill safety regulations. As it is presented in previous chapters by the use of arc suppression coils the fault current can be compensated. In order to decrease earth fault current during earth faults arc suppression coil can be utilized. For implementation of Petersen coil in a network the nominal reactive power of it Q_P should be determined. This power is equal to the reactive power generated by the network during earth fault and can be calculated as follows:

$$Q_P = I_{\max} \frac{U_{nom}}{\sqrt{3}} = 262.8 \cdot \frac{20000}{\sqrt{3}} = 3034.5k\,\text{var} \tag{111}$$

As it can be seen from Equation (111) reactive power and consequently inductance of the arc suppression coil depend on the maximum earth fault current in the network. Thus, parameters of the utilized Petersen coil are determined by total length of feeders and their specific parameters. From the Equation (111) can be determined the total reactive power of arc suppression coils in the network.

In case of implementing centralized compensation obtained value of the reactive power is a parameter of a central coil. Thus, the nominal reactive power central arc suppression coil has to be equal or higher than obtained value. Also, because of the possibility of future changes in the network structure it is obligatory to implement adjustable coil, and the nominal power of it should be calculated taking into account future development of the network. Ignoring development of the electrical grid leads to the replacement of the chosen equipment to a higher-power arc suppression coil and as a result excessive investment costs.

When the selection of compensated coils are finished, based on them nominal reactive power, transformers for their connections to feeders should be chosen. In case of implementation special transformers for arc suppression coils rated power of transformers should be at least equal to the nominal power of a connected Petersen coil. For central compensation one large compensation coil is utilized and a transformer for it should also be high powered. Losses of this transformer should be taken into account during utilizing central compensation in order to adjust Petersen coil correctly. Because of the inductive impedance of the transformer, real compensation current can be found according to the following formula:

$$I_{rc} = \frac{I_{\max}}{1+\dfrac{X_t}{3\cdot X_{asc}}} = \frac{262.8}{1+\dfrac{7.5}{3\cdot w\cdot 0.151}} = 248.6A \qquad (112)$$

Where I_{rc} - integral current in the arc suppression coils; X_t -inductive impedance of the earthing transformer; X_{arc} -inductive impedance of the arc suppression coils.

$$\frac{I_{rc}}{I_{\max}} = \frac{262.8}{248.6} = 1.05 \qquad (113)$$

Consequently, real compensation current is lower than required one. The increase of total reactive power of the Petersen coil allows eliminating of this difference. Thus, total reactive power is equal:

$$Q_p = I_{rc} \cdot 1.05 \cdot \frac{U_{nom}}{\sqrt{3}} = 262.8 \cdot 1.05 \cdot \frac{20000}{\sqrt{3}} = 3186k\,\mathrm{var}. \qquad (114)$$

Real compensation current will be:

$$I_{rc} = \frac{I_{rc} \cdot 1.05}{1 + \frac{X_t}{3 \cdot X_r}} = \frac{262.8 \cdot 1.05}{1 + \frac{7.5}{3 \cdot w \cdot 0.143}} = 262.2A \qquad (115)$$

As it reflected by achieved results reactive power of arc suppression coils should be selected with ample of power in order to eliminate the influence of additional inductance of earthing transformers.

However in case of central compensation combination of the fixed type reactors and control reactor can be implemented. This allows to decrease rated power of the control coil and to solve the problem with future development of the grid. Also, in the network with high values of earth fault currents utilization of few coils is economically beneficial, because there is no need to buy nonstandard devices.

Nowadays there are three strategies to utilize Petersen coils: centralized, distributed or hybrid compensation. It is essential to compare this opportunities to utilize arc suppression coils, because they have a significant influence on the network from both technical and economic points of view.

6.3 Network with central compensation.

The examined network is represented in Fig. 42. In order to reflect the influence of the earth fault current compensation earth fault at phase A is investigated. In case of implementation centralized compensation electrical quantities adopt next values:

- Neutral point voltage

$$U_n = \frac{-E_a}{3j\omega R_f \sum_{n=1}^{6} C_i l_i + 1 + \frac{R_f}{i\omega L_t}} = -E_a = 11547\angle 180°V \qquad (115)$$

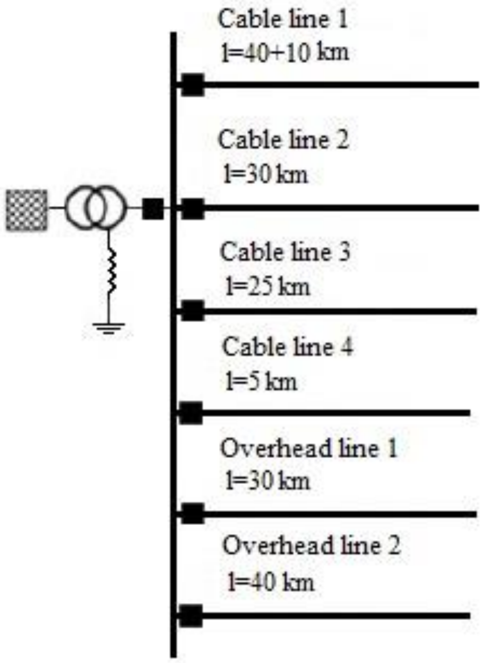


Fig. 42. Diagram of the examined central compensated network.

In Fig. 43 relative position of phase voltages and neutral point voltage are reflected.

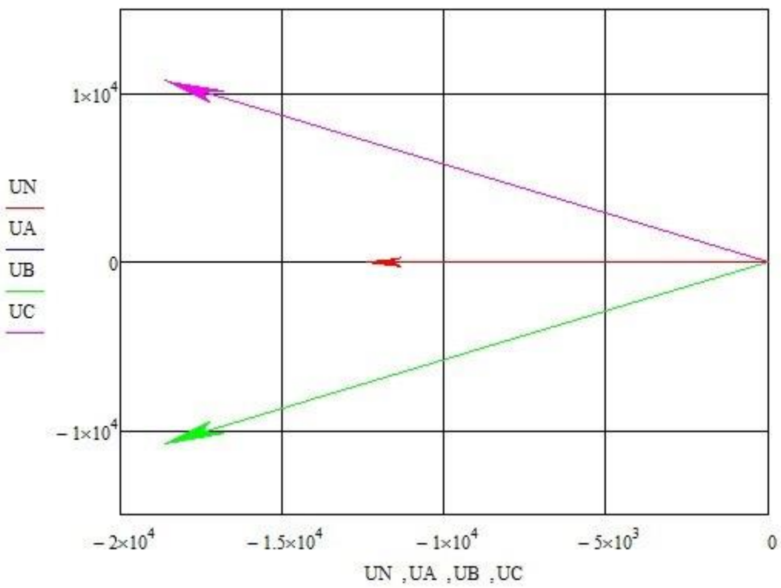


Fig.43. Phasor and neutral voltages during earth fault at phase A through 500 resistance.

Results obtained from the model are represented in Table 7 for the earth fault point in the receiving and sending ends of a feeder.

Table 7. Neutral point voltage in the compensated network.

Title	Calculated zero sequence voltage		Experimental zero sequence voltage		Fault point
	Value (kV)	Phase (degree)	Value (kV)	Phase (degree)	
CL1	11.5	180	9.81	176	Sending end
			9.52	174.5	Receiving end
CL2	11.5	180	9.81	176	Sending end
			11.3	174.7	Receiving end
CL3	11.5	180	9.81	176	Sending end
			11.3	174.8	Receiving end
CL4	11.5	180	9.81	176	Sending end
			11.4	176.4	Receiving end
OHL1	11.5	180	9.81	176	Sending end
			11.5	176.8	Receiving end
OHL2	11.5	180	9.81	176	Sending end
			11.5	176.9	Receiving end

As it can be seen from Equation (115) neutral point voltage, when the total line capacitance is precisely compensated by Petersen coil, are equal to the phase voltage of a faulted phase with opposite sign for any value of earth fault resistance R_f . This feature of a fully compensated network guarantees location of earth faults by measuring zero-sequence voltage at the bus-bar of the substation.

However, as it can be seen from the results of simulation, neutral point voltage differs from calculated values and it depends of the earth fault point. Such behavior can be explained by active and inductive impedances of feeders which cannot be compensated by arc suppression coil.

- Earth fault current

$$I_f = \frac{(E_a + U_n)}{R_f} = 0A. \qquad (116)$$

Taking into account that $U_n = -E_a$ it is obvious that earth fault current is equal to 0 for any value of earth fault resistance. Thus, in case of zero value of the earth fault current the value of a current measured by a summation current transformer at the sending end of any feeder is determined only by own shunt capacitance of the feeder. Results obtained from the model are represented in Table 8 for the earth fault point in the receiving and sending ends of a feeder.

Table 8. Earth fault currents in the compensated network.

Title	Calculated zero sequence voltage		Experimental zero sequence voltage		Fault point
	Value (A)	Phase (degree)	Value (A)	Phase (degree)	
CL1	0		6.7	-2	Sending end
			6.5	-0.5	Receiving end
CL2	0		6.7	-2	Sending end
			6.2	-1.5	Receiving end
CL3	0		6.7	-2	Sending end
			6.4	-1.9	Receiving end
CL4	0		6.7	-2	Sending end
			6.6	-1.6	Receiving end
OHL1	0		6.7	-2	Sending end
			5.4	-1.9	Receiving end
OHL2	0		6.7	-2	Sending end
			5.2	-1.9	Receiving end

As it was expected, in the model the earth fault current are not equal to zero, due to uncompensated admittance of the network. Also it should be mentioned, that results represented in Table 6 and Table 7 for the model are obtained for the different value arc suppression coil inductance. Utilization of a calculated inductance for the central compensation coil may lead to the udercompensation in the low load regime. Thus, results, which are represented above, stress the importance of measurements in a real network in purpose to define real parameters.

- Earth fault current in relay protection

$$I_{ri} = -3j\omega C_i l_i E_a \qquad (117)$$

Where I_{ri} earth fault current measured by relay protection of i-th feeder. Values of earth fault currents in relay protection are represented in Table 9.

Table 9. Erath fault currents in summation transformers.

Title	Calculated zero sequence voltage		Experimental zero sequence voltage		Fault point
	Value (A)	Phase (degree)	Value (A)	Phase (degree)	
CL1	37	-90	25.6	-83.1	Sending end
			24.4	-84.6	Receiving end
CL2	25.4	-90	17.6	-86.3	Sending end
			16.9	-87.5	Receiving end
CL3	21.2	-90	14.7	-87.15	Sending end
			14.2	-88.5	Receiving end
CL4	3.9	-90	3.9	-54.6	Sending end
			3.8	-55.9	Receiving end
OHL1	0.5	-90	047	-34.6	Sending end
			0.46	-39.8	Receiving end
OHL2	0.63	-90	0.55	-34.6	Sending end
			0.55	-39.8	Receiving end

Theoretically directional earth fault protection cannot operate in the compensated network. Current measured by summation current transformer of intact or faulted feeder is equal to the own earth fault current of the feeder, due to this fact, relay protection which is based on directional principle cannot differ faulted feeder.

However in the investigated network long cable lines are represented and the influence of them on currents is represented in experimental results. Based on obtained results from the model in PSCAD it is evident, that earth fault current, measured by summation current transformer in a faulted feeder, is not solely capacitive. Though, the value of an earth fault current argument is strictly determined by the length of the faulted feeder and, consequently, tripping of the relay can be unstable for different network topologies. For cable line number 1 measured current and angle practically equal to the calculated values, but for overhead lines number 1 and 2 results are significantly differ from calculated one. However, for operation under this condition directional earth fault protection should react on active component of the current, which means that tripping area should be limited by angles $-80° \le \varphi \le 80°$.

To reflect behavior of directional earth fault protection more vividly values of the zero sequence current measured in the cable line 1 for $R_f = 500 \div 3000\Omega$ can be represented on operation area of it. Setting value for the relay protection is calculated by following equation:

$$I_{1tr} = \frac{I_{01}}{K_S} = \frac{103.5}{2} = 51.8A \quad (118)$$

Where I_{01} - zero sequence current in the line during earth fault in the cable line 1; K_S - sensibility factor. Operating area with zero sequence currents depicted on it is represented in Fig.44.

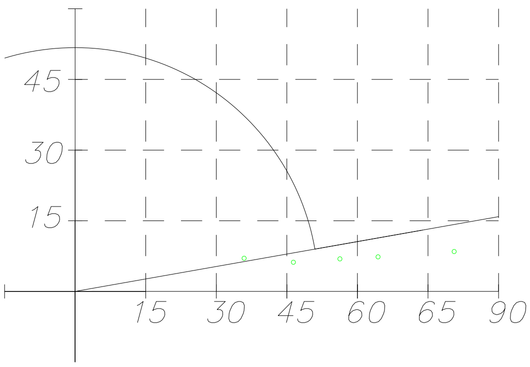


Fig.44. Operating area of the directional earth fault protection.

Such results reveals that directional earth fault protection will be at the boarder of the tripping, thus any disturbances can cause failure to operate, which is inappropriate. Thus directional earth fault protection will not detect faults in long cable lines and detect in short cable lines or overhead lines. This phenomena is explained by different values of the own zero sequence current in lines during earth fault. In the real network current measured by summation transformer consists of two parts: own capacitive zero sequence current and real zero-sequence current determined by the active resistance of all lines in the network. Thus phase of the measured current differs according to the correlation of active and capacitive parts.

As it can be seen from forecited results utilization of earth fault protection based on measurements of fundamental frequency quantities in networks with central compensation is inappropriate. This fact is a reason why method of central compensation does not widely used for compensation of earth fault currents in distribution networks. In this case there are two possibilities to ensure operation of directional protection:

1) to over or under compensate network;
2) to add in parallel to the central arc suppression coil additional resistance.

In this work will be investigated only second case because it consists of the first method of compensation plus high-ohmic resistor.

6.4 Selection of arc suppression coils for operation in parallel with resistance.

6.4.1 Central compensation.

In order to increase earth fault currents in parallel to the arc suppression coil can be added resistor. Ordinary value of the resistor is determined in amperes and common values of it are 5 or 10 A. For the examined network is utilized 5A resistor, its value in Ohms can be gained as follows:

$$R_l = \frac{U_{ph}}{I_R} = \frac{20000}{\sqrt{3}\cdot 5} = 2309\Omega \qquad (119)$$

In case of central compensation utilization of this method is restricted by the own value of the earth fault current of a line, in other words by the length of the line. This can be demonstrated following calculations for the 1st and 4th cable lines. Neutral point voltage in case of earth fault through the transient resistance is equal:

$$U_n = \frac{-E_a}{3j\omega R_f \sum_{n=1}^{6} C_i l_i + 1 + \frac{R_f}{R_l} + \frac{R_f}{i\omega L_t}} = \frac{-20000\frac{1}{\sqrt{3}}}{1+\frac{500}{2309}} = 9491.6\angle 180V \qquad (120)$$

Earth fault current is equal:

$$I_f = \frac{(\mathrm{E}_a + U_n)}{R_f} = \frac{(\frac{20000}{\sqrt{3}} - 9491.6)}{500} \approx 4{,}1\angle 0^\circ A. \qquad (121)$$

Current in summation transformer in the 4th line:

$$I_{04} = Y_4 \cdot U_n + I_f = j\cdot 3\cdot w\cdot 0.1907\cdot 10^{-6}\cdot 5\cdot(-9491.6) + 4.1 = 10.2\angle -65.9A \qquad (122)$$

Obviously, that this value of a current and a sufficient margin in angle guarantee stable operation of conventional earth fault relay protection.

Earth fault current in summation transformer in case of earth fault in the 1st line:

$$I_{01} = Y_1 \cdot U_n + I_f = j \cdot 3 \cdot w \cdot 0.237 \cdot 10^{-6} \cdot 40 \cdot (-9491.6) + 4.1 = 92.4\angle -87.4A \qquad (123)$$

As it follows from obtained results directional earth fault protection cannot detect earth fault under this conditions. In such a manner maximum allowed length of a line can be found. Taking into account that operation are is limited by angle +- 80 degrees, the length can be calculated as follows:

$$ctg(\varphi) = \frac{I_f}{3 \cdot w \cdot c \cdot l \cdot U_n} = \frac{\dfrac{G_f \cdot G_L \cdot E_a}{G_f + G_L}}{-3 \cdot w \cdot c \cdot l \cdot \dfrac{G_f E_a}{G_f + G_L}} \qquad (124)$$

After simplification:

$$ctg(\varphi) = \frac{G_R}{-3 \cdot w \cdot c \cdot l} \qquad (125)$$

As it can be seen from the formula the argument of earth fault current depends on the length of the line and it's specific admittance upon condition $G_R = const$.

For the $C = 0.237 \cdot 10^{-6} \Phi$ $l_{\lim}$ can be determined as:

$$l_{\lim} = \frac{G_R}{-3 \cdot ctg(\varphi) \cdot w \cdot c} = \frac{\dfrac{1}{2309}}{-3 \cdot ctg(80) \cdot w \cdot 0.237 \cdot 10^{-6}} = 10.2km \qquad (126)$$

Thus, maximum allowed length of the line with specific capacitance $C = 0.237 \cdot 10^{-6}$ F/ km is 10km which is 4 times shorter than length of cable line 1.In order to reveal possibility of relay protection, based on measurements of fundamental frequency quantities, detects earth faults in long cable lines following experiments have been done. In the examined network for the longest cable line have been obtained values of zero sequence current and neutral point voltage during permanent earth fault in cable line1 through the transient resistance $R_f = 500 \div 3000 Ohm$. Based on these results on operation areas of directional and admittance based earth fault protections corresponding dots are flagged. Setting values for the directional earth fault protection can be calculated according to the next formula:

$$I_{trip1} = \frac{I_{01}(\mathrm{R}_f = 0)}{K_S} = \frac{92.4}{2} = 46.2A \qquad (127)$$

Operation area of the directional earth fault protection with plotted results on it is represented in Fig. 45.

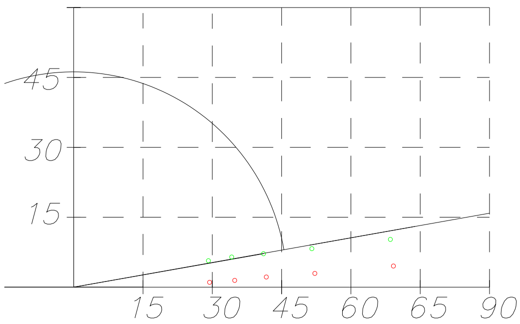


Fig.45. Operation area of the directional earth fault protection .
Green dots – results obtained during inside faults.

Red dots-results, obtained during outside faults.

As it can be seen from Fig. 45. this type of relay protection cannot guarantee detection of earth faults under these specific conditions.

Setting values for the admittance base earth fault protection can be calculated as follows:

Outside fault:

$Y_{01} = -Y_1 = 3\angle -90° mSm$

Conductance forward: $G_L \cdot 0.2 = \dfrac{0.2}{2309} = 0.087 mSm$

Conductance reverse: -0.2mSm

Susceptance forward: 0.1mSm

Susceptance reverse: $1.5 \cdot Y_{01} = -1.5 \cdot 3 = -4.5 mSm$

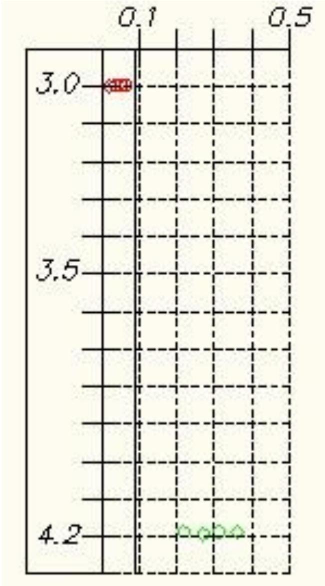


Fig.46. Operation area of the admittance based earth fault protection .

Green dots – results obtained during inside faults.

Red dots-results, obtained during outside faults.

From Fig.46. it is evident that admittance based earth fault protection operate reliable for all transient resistances in this network for the longest cable line. This can be explained by more precise selection of setting values in comparison with directional earth fault protection. Thus, advantageous of admittance based protection is evident.

6.4.2 Hybrid compensation.

In case of hybrid compensation earth fault currents are compensated by arc suppression coils connected at to the bus bar of a substation as to feeders. Own earth fault currents of lines and the required reactive power of Petersen suppression coils:

$$I_{01} = 3wC_1 l_1 E_{ph} = 3 \cdot w \cdot (0.237 \cdot 10^{-6} \cdot 40 + 0.00438 \cdot 10) \cdot \frac{20000}{\sqrt{3}} = 110.9A \tag{128}$$

$$Q_1 = I_{01} \cdot \frac{U_{nom}}{\sqrt{3}} = 110.9 \cdot \frac{20000}{\sqrt{3}} = 1377k\,\text{var}. \tag{129}$$

$$I_{02} = 3wC_2 l_2 E_{ph} = 3 \cdot w \cdot 0.217 \cdot 10^{-6} \cdot 30 \cdot \frac{20000}{\sqrt{3}} = 76.2A \tag{130}$$

$$Q_2 = I_{02} \cdot \frac{U_{nom}}{\sqrt{3}} = 76.2 \cdot \frac{20000}{\sqrt{3}} = 945.4k\,\text{var}. \tag{131}$$

$$I_{03} = 3wC_3 l_3 E_{ph} = 3 \cdot w \cdot 0.217 \cdot 10^{-6} \cdot 25 \cdot \frac{20000}{\sqrt{3}} = 63.47A \tag{132}$$

$$Q_3 = I_{03} \cdot \frac{U_{nom}}{\sqrt{3}} = 63.4 \cdot \frac{20000}{\sqrt{3}} = 787.8k\,\text{var} \quad (133)$$

$$I_{04} = 3wC_4 l_4 E_{ph} = 3 \cdot w \cdot 0.1907 \cdot 10^{-6} \cdot 5 \cdot \frac{20000}{\sqrt{3}} = 11.2A \quad (134)$$

$$Q_4 = I_{04} \cdot \frac{U_{nom}}{\sqrt{3}} = 11.2 \cdot \frac{20000}{\sqrt{3}} = 138.5k\,\text{var}. \quad (135)$$

Hybrid compensation is organized by installation of arc suppression coils with fixed reactive power along feeders and controlled coil is connected to the bus bar of the substation.

Based on obtained results Petersen coils for each line and for the connection to the bus bar of the substation can be chosen. Nowadays on the market a lot of different companies producing arc suppression coils are represented. In order to avoid excessive financial expenditures it is assumed to utilize standard coils rather than custom-made equipment. After the analysis of the market standard nameplate power of Petersen coils were found, so arc suppression coils installed at lines are represented in Table 10.

Table 10. Arc suppression coils installed in the network.

Title	Nameplate power, kvar	Number
CL1	840	2
CL2	840	1
CL3	840	1
CL4	100	1

That way, because of the limited range of arc suppression coils on a substation should be installed the Petersen coil which is allowed to compensate the rest of earth fault currents. Reactive power of this reactor can be found as:

$$\begin{aligned} Q_{nc} &= Q_1 - Q_{1comp} + Q_2 - Q_{2comp} + Q_3 - Q_{3comp} + Q_4 - Q_{4comp} = \\ &= 1377 - 1377 + 945.4 - 840 + 787.8 - 787.8 + 138.5 - 100 = 143.9k\,\text{var} \end{aligned} \quad (136)$$

Consequently coil with nominal reactive power more than 143.kVar should be installed at the bus bar. Also this arc suppression coil should be able to compensate earth fault current in case of malfunction or repair works of the most powerful distributed coil. Thus 1500 Mvar arc suppression coil have been chosen for connection to the bus bar of the substation. Inductance of arc suppression coils can be found as follows:

$$L_1 = \frac{E_{ph}^2}{w \cdot Q_{comp1}} = \frac{(\frac{20000}{\sqrt{3}})^2}{w \cdot 1377000} = 0.356H \quad (137)$$

$$L_2 = \frac{E_{ph}^2}{w \cdot Q_{comp2}} = \frac{(\frac{20000}{\sqrt{3}})^2}{w \cdot 840000} = 0.584H \quad (138)$$

$$L_3 = \frac{E_{ph}^2}{w \cdot Q_{comp3}} = \frac{(\frac{20000}{\sqrt{3}})^2}{w \cdot 787800} = 0.623H \quad (139)$$

$$L_4 = \frac{E_{ph}^2}{w \cdot Q_{comp4}} = \frac{(\frac{20000}{\sqrt{3}})^2}{w \cdot 100000} = 4.905H \quad (140)$$

$$L_{cc} = \frac{E_{ph}^2}{w \cdot Q_{nc}} = \frac{(\frac{20000}{\sqrt{3}})^2}{w \cdot 143900} = 3.41H \quad (141)$$

Let's calculate earth fault currents and displacement of the neutral point voltage for this case. Displacement of the neutral point voltage:

$$U_n = \frac{-E_a}{3j\omega R_f \sum_{n=1}^{4} C_i l_i + 1 + \frac{R_f}{R_l} + \frac{R_f}{i\omega L_{nc}} + R_f(\frac{1}{jwL_1} + \frac{1}{jwL_2} + \frac{1}{jwL_3} + \frac{1}{jwL_4})} =$$

$$= \frac{-20000\frac{1}{\sqrt{3}}}{1 + \frac{500}{2309}} = 9850.4\angle 180V \quad (142)$$

Earth fault current:

$$I_f = \frac{(\mathrm{E}_a + U_n)}{R_f} = \frac{(\frac{20000}{\sqrt{3}} - 9850.4)}{500} \approx 4,2\angle 0°A. \quad (143)$$

As it seen from formulas, listed above, the earth fault current and neutral-point displacement voltage are not reliant on method of compensation (place of arc suppression coils installation). Zero sequence earth fault currents in the lines when the fault is located inside or outside of a protected feeder:

Internal fault:

$$I_{01} = U_n \cdot (\frac{1}{j \cdot w \cdot L_1} + 3\,\mathrm{j} \cdot \mathrm{w} \cdot \mathrm{c}_1 \cdot \mathrm{l}_1) + \frac{1}{R_f}(\mathrm{E}_a + \mathrm{U}_n) =$$

$$\mathrm{U}_n \cdot 0 + \frac{1}{500} \cdot (\frac{21500}{\sqrt{3}} - 10332) = 4.162\angle 0°A \quad (144)$$

External fault:

$$I_{01} = U_n \cdot (\frac{1}{j \cdot w \cdot L_1} + 3\,\mathrm{j} \cdot \mathrm{w} \cdot \mathrm{c}_1 \cdot \mathrm{l}_1) = 0A \tag{145}$$

Calculated zero sequence current in other lines with distributed coils is represented in Table 11.

Table 11. Zero sequence current in cable lines measured by summation transformer during permanent internal or external fault.

Title	Internal fault,(A)	External fault,(A)	Reactive power of a Petersen coil,(kvar)	Reactive power of a power line,(kvar)
CL1	4.2	0	1377	1377
CL2	$8.2\angle -59.5°$	$7.1\angle -90°$	840	945.4
CL3	4.2	0	787.8	787.8
CL4	$4.9\angle -31.8°$	$2.5\angle -90°$	100	138.5

However, when making the selection of power and number of Petersen coils, malfunction, take-down for repairs of the most powerful one or disconnection of a part of a line should be foreseen. Also, as it seen from this case, that only 10% of reactive power of the arc suppression coil, connected to the bus bar of the substation, will be used during earth faults. Consequently, nominal reactive power of the most powerful distributed coil should be decreased in order to increase the efficiency of use of central coil. Following calculations revel aftermath of the wrong selection of Petersen coils.

In case of malfunction of the most powerful coil connected to the line zero sequence current measured by relay protection of the line is changed. Zero sequence current in the cable line 1 in case of coil disconnection can be calculated as follows:

$$L_1 = \frac{E_{ph}^2}{w \cdot Q_{comp1}} = \frac{(\frac{21500}{\sqrt{3}})^2}{w \cdot 840000} = 0.584H \tag{146}$$

$$I_{01} = U_n \cdot (\frac{1}{j \cdot w \cdot L_1} + 3\,\mathrm{j} \cdot \mathrm{w} \cdot \mathrm{c}_1 \cdot \mathrm{l}_1) + \frac{1}{R_f}(\mathrm{E}_a + \mathrm{U}_n) = -10332 \cdot (\frac{1}{j \cdot w \cdot 0.584} +$$
$$+3\,\mathrm{j} \cdot \mathrm{w} \cdot (0.237 \cdot 10^{-6} \cdot 40 + 0.00438 \cdot 10)) + \frac{1}{500} \cdot (\frac{21500}{\sqrt{3}} - 10332) = 36.2\angle -83.6°A \tag{147}$$

From the Equation it is evident that directional earth fault protection may not detect earth fault because of the low sensitivity in angle.

For each line can be found maximum permissible value of distributed coils inductance which allow operation of relay protection, based on measurements of fundamental frequency electrical quantities. In order to guarantee reliable tripping of relay protection maximum permissible angle of operation can be accepted 5 degrees higher than bottom boundary of operation.

Allowed inductance of distributed arc supersession coils for 1 cable line is:

$$L_1 = \frac{1}{w(\frac{I_f \cdot \tan(-75)}{U_n} + 3\mathrm{wc}_1 \mathrm{l}_1)} = \frac{1}{w(\frac{4.162 \cdot \tan(-75)}{-10332} + 3\mathrm{w} \cdot 0.237 \cdot 10^{-6} \cdot 40)} = \qquad (148)$$

$$= 0.428H$$

Consequently, in case of malfunction of one coil total inductivity of distributed coils should not exceed calculated value. On that basis reactive power of a single Petersen coil can be defined on condition that total number of arc suppression coils is known. In the examined network is expected existence of branch lines every 2 km with transformer 20/0,4kV where distributed arc suppression coils are connected. Number of installed coils is restricted economically and by possibility of overcompensation in case of disconnection part of the line.

Comparison of configurations when 6 or 9 Petersen coils were installed in the network.

When 9 coils are connected reactive power of a single coil is:

$$L_1^9 = L_1 \cdot (\mathrm{n} - 1) = 0.428 \cdot (9 - 1) = 3.424H \qquad (149)$$

When 6 coils are connected reactive power of a single coil is:

$$L_1^6 = L_1 \cdot (\mathrm{n} - 1) = 0.428 \cdot (6 - 1) = 2.14H \qquad (150)$$

In case of utilization 9 coils the distance between two neighbor’s is 4 km, while when 6 coils are connected to the line the distance is 6 km. Nine arc suppression coils can compensate earth fault current generated by a line which length is:

$$l_1^9 = \frac{n}{3 \cdot w^2 \cdot c_1 \cdot L_1^9} = \frac{9}{3 \cdot w^2 \cdot 0.237 \cdot 10^{-6} \cdot 3.424} = 37.5km \qquad (151)$$

Thus, if the 2km section of the line will be disconnected distributed coils will not cause overcompensation and due to the controlling of the central coil level of compensation can be matched to the required.

Six arc suppression coils can compensate earth fault current generated by a line which length is:

$$l_1^6 = \frac{n}{3 \cdot w^2 \cdot c_1 \cdot L_1^6} = \frac{6}{3 \cdot w^2 \cdot 0.237 \cdot 10^{-6} \cdot 2.14} = 39.9km \tag{152}$$

Consequently, disconnection of any section of the line will cause overcompensation of earth fault currents in this line which cannot be eliminated by the use of central coil.

Current generated be distributed Petersen coils:

$$I_L = \frac{U_{ph}}{w \cdot L_1^6} = \frac{20000 \cdot 6}{\sqrt{3}w \cdot 2.14} = 103.1A \tag{153}$$

Earth fault current of a cable line 1 without a section of 2 km:

$$I_C = 3w \cdot (\mathrm{C}_1 \cdot \mathrm{l}_1) \cdot \mathrm{U}_{ph} = 3w \cdot (0.237 \cdot 10^{-6} \cdot 38 + 0.00438 \cdot 10) \cdot \frac{20000}{\sqrt{3}} = 98.01A \tag{154}$$

Degree of overcompensation will be:

$$k = \frac{I_L}{I_C} = \frac{103.1}{98.01} = 1.05 \tag{155}$$

In this context degree of compensation is 5 percentages, which is close to the allowed level of overcompensation for the whole system. Thus, installation of 6 coils will complicate selection of distributed coils in over lines. Consequently, this amount of Petersen coils is not optimal for cable line 1 and 9 coils should be connected.

Conclusively, the reactive power of a single arc suppression coil which is connected to the cable line is:

$$Q_{comp1} = \frac{E_{ph}^2}{w \cdot L_1} = \frac{(\frac{21500}{\sqrt{3}})^2}{w \cdot 3.424} = 143k\,\mathrm{var} \tag{156}$$

For the cable line 4 reactive power of a single Petersen coil is:

$$L_4 = \frac{1}{w(\frac{I_f \cdot \tan(-75)}{U_n} + 3\mathrm{wc}_4\mathrm{l}_4)} = \frac{1}{w(\frac{4.162 \cdot \tan(-75)}{-10332} + 3\mathrm{w} \cdot 0.1907 \cdot 10^{-6} \cdot 5)} = $$
$$= -5.2H \tag{157}$$

Negative value of an inductance indicates that earth fault protection, which is based on measurements of fundamental frequency electrical quantities, will operate on the cable line 4 even without installation of the arc suppression coils.

Petersen coils selected for installation on cable line are represented in Table 12.

Table 12. Distributed arc suppression coils.

Title	Nameplate power, kvar	Number
CL1	190	9
CL2	115	7
CL3	115	6

6.5 Hybrid compensated network with 5A neutral resistor.

In case of implementation of hybrid compensation earth fault current of each feeder is compensated locally by distributed arc suppression coils. For local compensation is utilized not adjustable Peterson coils with standard nominal values. Thus, own earth fault current of each power line does not fully compensated which has an influence on the current measured by relay protection. It is evident, that the bigger value of the uncompensated earth fault current, the bigger is current in summation transformer and the angle between earth fault current and zero-sequence voltage at the bus-bar. The examined network is represented in Fig. 47.

- Neutral point voltage

$$U_n = \frac{-E_a}{3j\omega R_f \sum_{n=1}^{6} C_i l_i + 1 + \frac{R_f}{R_l} + \frac{R_f}{i\omega L_{centr}} + R_f \cdot \left(\frac{1}{i\omega L_1} + \frac{1}{i\omega L_2} + \frac{1}{i\omega L_3}\right)} = 9492\angle 180 V \quad (158)$$

In Fig. 49 relative position of phase voltages and neutral point voltage are reflected.

Results obtained from the model are represented in Table 13 for the earth fault point in the receiving and sending ends of a feeder.

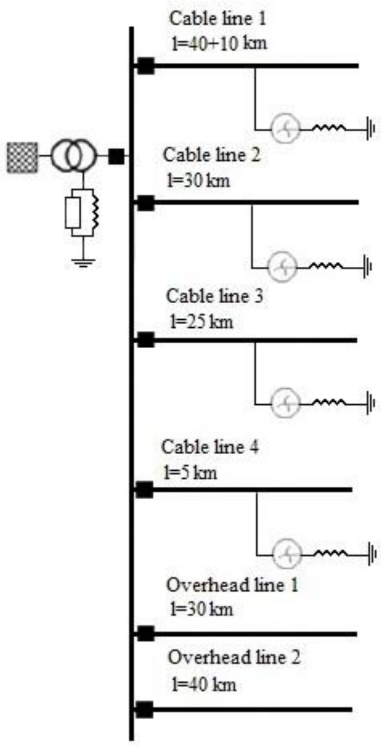


Fig. 47. Diagram of the examined hybrid compensated network with 5A neutral resistor.

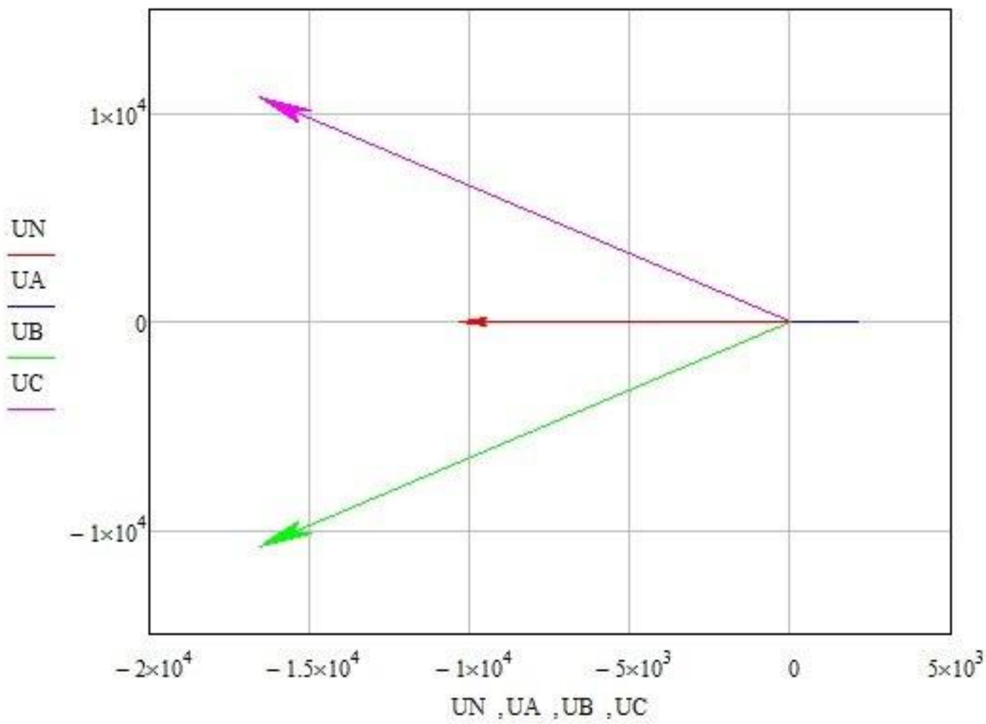


Fig.48. Phasor and neutral voltages during earth fault at phase A through 500 resistance.

Table 13. Neutral point voltage in the hybrid compensated network with 5A neutral resistor.

Title	Calculated zero sequence voltage		Experimental zero sequence voltage		Fault point
	Value (kV)	Phase (degree)	Value (kV)	Phase (degree)	
CL1	9.5	180	9.41	178.2	Sending end
			8.22	174.5	Receiving end
CL2	9.5	180	9.41	178.2	Sending end
			8.2	174.7	Receiving end
CL3	9.5	180	9.41	178.2	Sending end
			8.3	174.8	Receiving end
CL4	9.5	180	9.41	178.2	Sending end
			8.25	176.4	Receiving end
OHL1	9.5	180	9.41	178.2	Sending end
			8.31	178.1	Receiving end
OHL2	9.5	180	9.41	178.2	Sending end
			8.31	178.1	Receiving end

As it can be seen from Table 13 neutral point voltage did not significantly decreased in case of the earth fault through 500Ohm fault resistance, which as in networks without high-ohm resistor provides high sensitivity of earth fault relay protections. However, due to the adding of active impedance in to the zero sequence circuit, there is the increase in the earth fault current. Consequently, safety regulations should be taken into account when making a selection of high-ohm resistor.

- Earth fault current.

$$I_f = \frac{(E_a + U_n)}{R_f} = \frac{11547 - 9492}{500} = 4.1\angle 0^\circ A. \quad (159)$$

Results obtained from the model are represented in Table 14 for the earth fault point in the receiving and sending ends of a feeder.

Table 14. Earth fault currents in the hybrid compensated network with 5A neutral resistor.

Title	Calculated zero sequence voltage		Experimental zero sequence voltage		Fault point
	Value (A)	Phase (degree)	Value (A)	Phase (degree)	
CL1	4.1	0	9.2	-1.4	Sending end
			6.5	-0.5	Receiving end
CL2	4.1	0	9.2	-1.4	Sending end
			6.8	-1.5	Receiving end
CL3	4.1	0	9.2	-1.4	Sending end
			7.3	-1.9	Receiving end
CL4	4.1	0	9.2	-1.4	Sending end
			8.6	-1.6	Receiving end
OHL1	4.1	0	9.2	-2	Sending end
			5.4	0.3	Receiving end
OHL2	4.1	0	9.2	-2	Sending end
			5.2	0.1	Receiving end

From results of Table 14 it is evident that values of earth fault currents, obtained during modeling, is higher than calculated one. It can be mentioned, that the biggest values of the earth fault current is observed when the earth fault point is close to the bus bar of the substation. However, this value does not used by relay protection, thus deviations from calculated values should be estimated in amplitude to satisfy safety regulations.

Earth fault current in relay protection.

In the faulted feeder earth fault current can be calculated as follows:

$$I_{ri} = I_{fi} + I_{f} = (3j\omega C_i U_n + \frac{U_n}{j\omega \cdot L_i}) + \frac{(E_a + U_n)}{R_f} \tag{160}$$

Results obtained from the model are represented in Table 15 for the earth fault point in the receiving and sending ends of a feeder.

As it clear from Table 15 values of zero sequence current obtained during experiments differ from calculated ones. Because of the significant length of cable lines active impedance increases active component of zero sequence current, it’s total value and decrease angle between zero sequence current and voltage. Thus, utilization of engineering simplified formulas for calculating earth fault currents, in which active and inductive lines’ impedances is not taking into account, is possible in purpose of relay protection.

Table 15. Erath fault currents in summation transformers.

Title	Calculated zero sequence voltage		Experimental zero sequence voltage		Fault point
	Value (A)	Phase (degree)	Value (A)	Phase (degree)	
CL1	6.3	-52.7	11.2	-29.2	Sending end
			8.3	-37.8	Receiving end
CL2	13.7	-72.6	16.1	-54.2	Sending end
			14.7	-62.5	Receiving end
CL3	13.2	-71.8	15.6	-53.8	Sending end
			14.5	-59.8	Receiving end
CL4	10.87	-67.8	13.6	-47.6	Sending end
			13.3	-49.5	Receiving end
OHL1	4.3	-15.9	10.7	-7.4	Sending end
			8.1	-11.2	Receiving end
OHL2	4.4	-20.9	9.3	-9.6	Sending end
			7.9	-15.4	Receiving end

However it should be stressed, that in PSCAD model ideal compensation of earth fault currents were provided for the network, which can be gained in the real network only due to utilization of arc suppression coil with automatic tuning control. If only uncontrolled Petersen coils are installed in the network, then accurate calculations needed in order to estimate total capacitance of the grid and also the control of connected feeders to guarantee certain level of compensation.

In order to reveal possibility of relay protection, based on measurements of fundamental frequency quantities, detects earth faults in the examined network experiments have been done. For calculations of setting values will be used simplified formulas to reveal its' "reliability" in networks with long cable lines. Thus, for the cable line 1 setting values for directional and admittance based protections is calculated.

Trip current can be defined as follows:

$$I_{01}(\mathrm{R}_f=0)=\left|U_n\cdot\left(\frac{1}{j\cdot w\cdot L_1}+3\,\mathrm{j}\cdot\mathrm{w}\cdot\mathrm{c}_1\cdot\mathrm{l}_1\right)+5\right|= \\ =\left|-11547\cdot\left(\frac{1}{j\cdot w\cdot 0.38}+3\,\mathrm{j}\cdot\mathrm{w}\cdot 0.237\cdot 10^{-6}\cdot 40\right)+5\right|=8.64A \tag{161}$$

$$I_{1tr}=\frac{I_{01}(\mathrm{R}_f=0)}{K_\mathrm{S}}=\frac{8.4}{2}=4.2A \tag{162}$$

Operation area with plotted zero sequence currents on it is represented in Fig. 49.

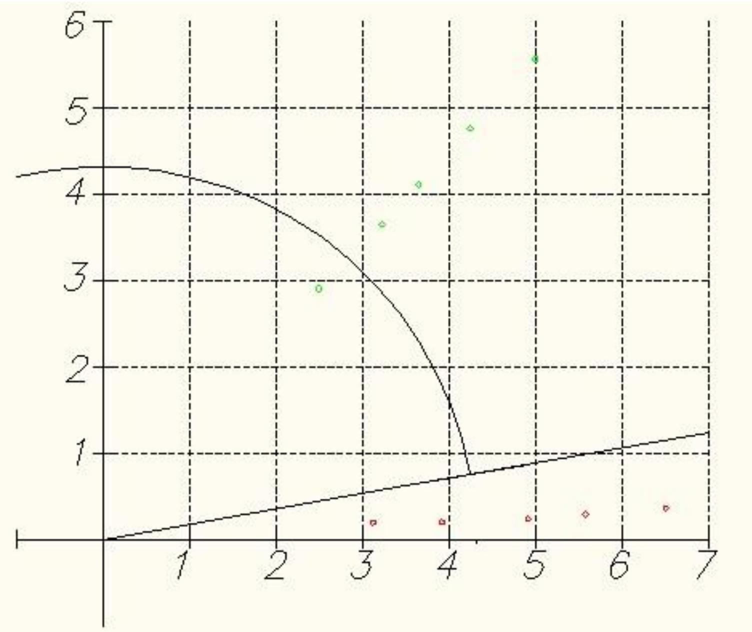


Fig.49. Operation area of the directional earth fault protection .

Green dots – results obtained during inside faults.

Red dots-results, obtained during outside faults.

As it can be seen from Fig. 40 results, obtained during external fault, are located inside operation are with significant margin in angle, which guarantee reliable operation of directional earth fault protection. In case of internal earth fault protection does not operate according to the represented data.

Setting values for the admittance base earth fault protection can be calculated as follows:

Internal fault:

$$Y_{01} = -(\mathrm{Y}_1 + B_{L1}) = -(\mathrm{jw}\cdot(\mathrm{C}_1^{CL1}\cdot l_1^{CL} + \mathrm{C}_1^{CL1}\cdot l_1^{OHL}) + \frac{1}{jw\cdot L_1}) =$$
$$= -(\mathrm{jw}\cdot(0.237\cdot 10^{-6}\cdot 40 + 0.00438\cdot 10^{-6}\cdot 10) + 1\frac{1}{jw\cdot 0.38}) = -j0.5mS \quad (163)$$

Conductance forward: $G_L \cdot 0.2 = \frac{0.2}{2309} = 0.087mS$

Conductance reverse: $0.5\cdot Y_{01} = -0.5\cdot 0.5 = -0.25mS$

Susceptance forward: 0.1mS

Susceptance reverse: $1.5\cdot Y_{01} = -1.5\cdot 0.5 = -0.75mS$

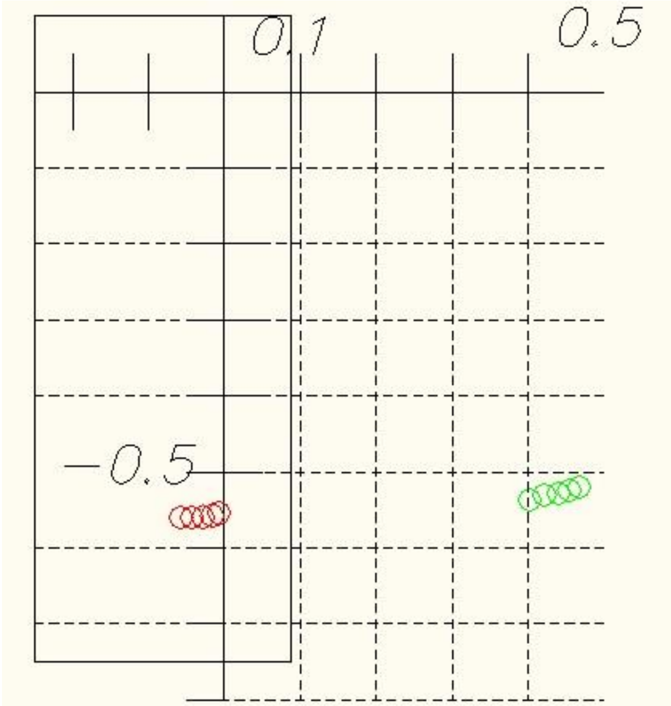


Fig.50. Operation area of the admittance based earth fault protection .

Green dots – results obtained during inside faults.

Red dots-results, obtained during outside faults.

It is obvious from Fig.50. that in case of external fault admittance based relay protection operates reliably for all values of resistances in place of earth fault. Thus, only values of zero sequence current and voltage that can be measured by transformers are restrictions for this type of protection. These results once again emphasize advantage of admittance based protections in comparison with directional earth fault protections.

In order to reveal influence of neutral resistor on relay protection results obtained from the compensated network and values calculated for this network. The most important difference for relay protection in these cases is angle. For hybrid compensated network it lays inside allowed limits with significant merge for all cable lines independent from their length.

6.5.1 Operation of the intermittent earth fault protection.

In the examined network with hybrid compensation oscilloscope records of zero sequence voltage and currents were taken during intermittent earth fault. In Fig.1 total zero sequence currents and voltage are represented in the first moment of the intermittent earth fault in the cable line 1.

As it seen from Fig.51. the residual current in the damaged line is in antiphase with zero sequence voltage and residual currents of over feeders. It is obvious that intermittent relay protection can reliably detect faulted feeder.

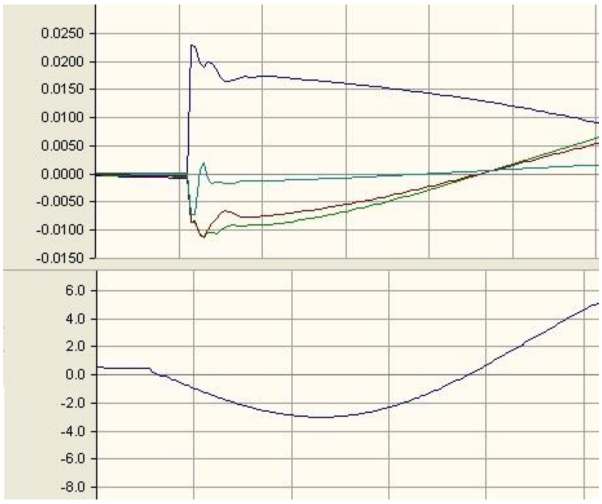


Fig. 51. Total zero sequence currents and voltage at the bus bar during impulse of the intermittent earth fault in cable1. (On the upper fig. total currents are depicted, zero sequence current in the line 1-blue. On the bottom figure zero sequence voltage is represented.)

In the relay protection of the examined type quantities of fundamental frequency as quantities of higher harmonics are used in order to guarantee reliable operation. In Fig.52. fundamental frequency zero sequence currents in cable lines 1 and 2 during single impulse of the intermittent earth fault are represented. From Fig.52 it is evident that expected phase correlation between residual current in the faulted feeder and zero sequence voltage at the bus bar can be observed only at the first moment of the fault. This fact emphasizes the importance of the quick operation of the intermittent relay protection.

In Fig.53. is illustrated CPS principle of the intermittent relay protection when integral quantity is represented by zero sequence admittance. As it seen from Fig.53the end of blue line (integral quantity of the faulted feeder is represented by the blue line) is in the first quadrant and others are out of the operation area - second and fourth quadrants. Also it is important to note that red line crosses first quadrant (operation area) which is an evidence of distortion, however due to the CPS principle it was eliminated. In case of conventional comparison of signs of residual current and zero sequence voltage at bus bar this distortion may lead to the trip failure.

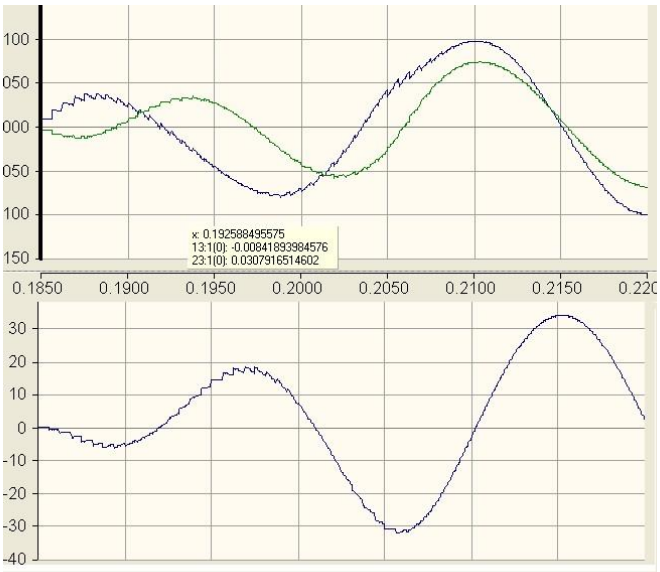


Fig. 52. Fundamental frequency residual currents and zero sequence voltage at the bus bar during single impulse of the intermittent earth fault in the cable line1. On the upper figure residual currents are depicted, the current in the feeder 1-blue. On the bottom figure is represented voltage at the bus bar.

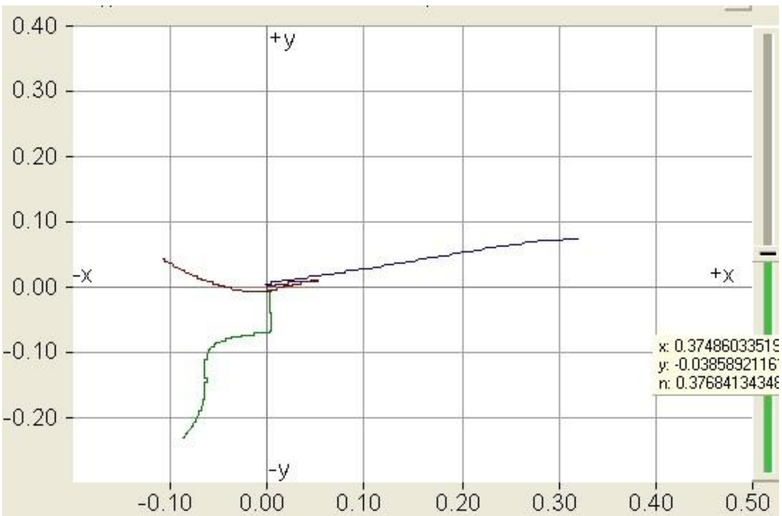


Fig.53. Oscilloscope record of CPS principle.(Integral value of the faulted feeder is represented the by blue line.).

Due to the time delay in intermittent relay protection offset from the regimes without earth fault is accomplished. As an example, which emphasizes the importance of time delay, can be examined connection of a line with asynchronous close in of breaker phases. According to the regulations allowed time difference of breaker phases close in is 2,5ms. Fig. 54 shows the waveform of the currents and the residual voltage when the phase A close in by 2.5ms later than phases B and C.

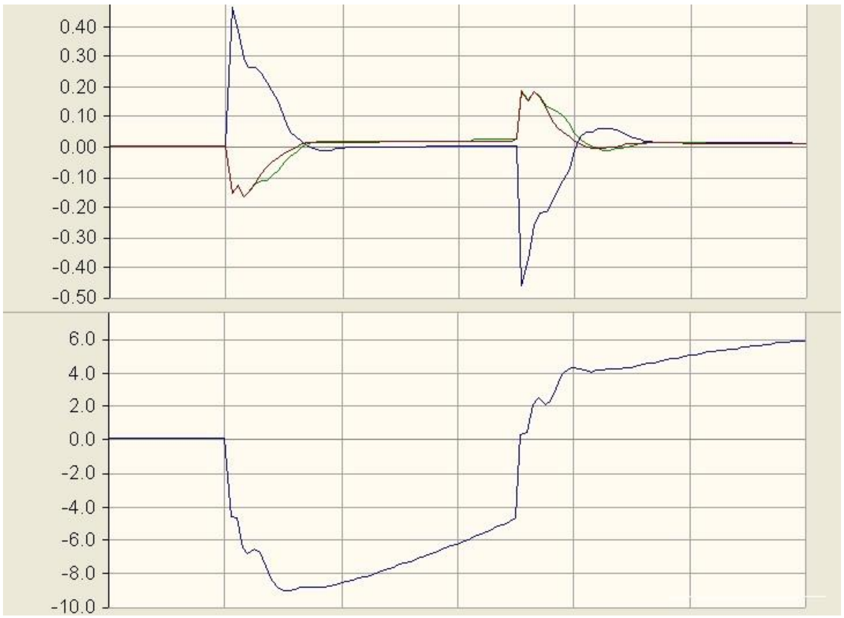


Fig. 54. Zero sequence currents and voltage in case of asynchronous close in of breaker phases.

As it can be seen from Fig.54 pikes of residual voltage and currents which can be a reason of intermittent protection triggering. However due to the time delay in the intermittent earth fault protection it will not operate.

7 RESULTS

The main goal of this work was to assess influence of the long cable lines on the distribution network. In this master thesis is presented theory bases and calculations which allow to estimate:

- voltage rise at the receiving end of a long cable feeder determined by Ferranti effect;
- reactive power flow which defined by excessive charge capacity and allowed power limits for a connection point;
- optimal compensation method and location of arc suppression coils for distribution networks
- influence of long cable lines on setting values of earth fault protection.

Ferranti phenomenon lead to the situation when during no-load or low load period of a power line the receiving end voltage is higher than the voltage at the sending end. This phenomenon occurs in case when the capacitance of a power line is significant, so it can be observed at medium and long lines with high capacitance per unit of length. In Chapter 5.3 Ferranti phenomenon explained by the use of phasor diagram in Fig. 34. The main danger of these phenomena is determined by the constant voltage level at the sending end of the power line. Thus, substation does not observe any changes and in this case voltage at the receiving end of the feeder will not be adjusted by on-load tap changer. According to the result of the work /13/ it was established that maximum possible voltage rise in medium voltage distribution network is 4% which is not dangerous for network equipment and this value is in allowed limits. In purpose to do results more evident in Fig. 35 and Fig. 36 voltage rise for networks with only cable lines and for mixed networks are represented.

According to regulations of Fingrid for every connection point to the transmission network is set reactive power contract. Ordinary, distribution networks in rural areas are supposed to be the consumer of a reactive power, however for networks with long cable lines totally opposite situation can be observed. It was calculated that charge capacity of the examined distribution network is equal 3.1 Mvar, when allowed limit for the transfer of reactive power from it to the transmission network is 1.75 Mvar. Thus, during low load period charge capacitance may exceed allowed limit established for specific connection point, than distribution system operator has to pay penalty. In order to represent this situation the next case have been investigated: if for 6 hours in a day charge capacity is higher than the limit for 500 kVar than financial penalty for one month will be approximately 0.25 million of euro. This result reflects need in implementation of shunt reactors in the network in order to avoid huge penalties.

In Chapter 5.2.1 answers for the main questions about charge capacitance compensation are represented. It was explained that there is no need to utilize distribution compensation of reactive power and central compensation of excessive reactive power can be implemented. Total amount of charging capacitance allows to select a shunt reactor with standard rated power. It was stressed that the aim of reactive power compensation is not to exceed allowed limit, rather than to compensate certain amount of charge capacitance. Based on all these conclusions compensation of charge capacitance can be realized by the use of standard fixed type shunt reactor which is connected to the bus bar of the substation during low load periods according to the load curve.

For distribution networks Russian and Finnish standards, which determine when earth fault currents should be compensated, were compared. Maximum level of allowed capacitance of power lines was calculated based on these requirements. For both regulations when earthing resistance is in range $R_f = 5 \div 20\Omega$ the result according to both regulations is approximately $C_{\lim} < 1.36\mu F$.

For the earth fault compensation central and hybrid compensation methods have been analyzed. According to calculations implementation of relay protections, which are based on measurements of fundamental frequency quantities, is not possible. Consequently this type of compensation is undesirable, because utilization of the central compensation decreases probability of earth fault detecting.

In order to guarantee reliable operation of relay protections, which are based on measurements of fundamental frequency quantities, implementation of high-ohmic resistor was suggested in parallel with central arc suppression coil. In Chapter 6.4.1 equation which determine maximum allowed length of a cable line when implementation of conventional earth fault protection have been represented. According to calculations was found that maximum allowed length of a cable line is 10 km, consequently, implementation of high-ohmic resistor with central compensation in the examined network will not allow directional earth fault protection detect earth faults in long cable lines.

In case of utilization hybrid compensation question of location distributed arc suppression coils was discussed in Chapter 6.4.2. It is suggested to utilize large number of low powered noncontrolled Petersen coils than small amount of high powered coils as distribution compensators of earth fault current. This suggestion was obtained by the invention of method which allows to select number and rated power of arc suppression coils. Finally, connection of distributed coils is assumed to the branch substation every 4 km. This decision allows to repair one of distributed Petersen coils without any harm for operation of conventional earth fault protection. In the substation arc suppression coil arc suppression coil with automatic tuning control should be implemented in order to match level of compensation to the wanted one.

In the created PSCAD model analysis of relay protection operation have been carried out. During experiments for the network with central and hybrid compensation estimation of directional and admittance based protection was undertaken. According to the results of experiments it was shown that admittance based protection allows to detect even high-ohmic earth faults and it operates reliably in the network where central compensation in parallel with resistor is implemented. The advantages of this type of protection are represented in chapter 6.4 and 6.5. Also in these chapters advantages of implementation of high harmonics for detection of a faulted feeder in networks with earth fault compensation is represented.

It should be stressed that in all cases for the calculations of setting values for the relay protection simplified equations were used. According to the obtained results it is obvious that utilization of these formulas do no lead to significant errors or false operation of protections.

It is concluded that in order to provide reliable protection of a network with long cable lines from permanent and temporary earth faults should be implemented complex approach to the relay protection. Relay protection device should include as conventional type of protection as intermittent earth fault protection.

8 DISCUSSION AND CONCLUSIONS

In this work was carried out comprehensive analysis of medium voltage distribution network with long cable lines. Main goal of the thesis was to estimate influence of long cable lines on a network in general, rather than provide solution for the particular case. Consequently in order to conduct experiments and for some calculations some simplifications and generalizations were made. In this chapter author tried to explain what questions should be considered in the future to create finished and reliable engineering approach.

It should be stressed that all experiments were carried out in PSCAD, this program allow to create a network with strictly specified parameters of electrical devices. For these purpose parameters from official catalogues and other sources of information were used and in the program the most realistic models of cable lines, transformers and other equipment were implemented. However all these steps do not guarantee accurate results which can be significant in some regimes. In the following paragraphs cases which were not taken into account are briefly represented.

Modeling of the earth fault and especially of the intermittent earth fault is a complicated task which was simplified in this work. In the networks with cable lines grate attention should be paid to the intermittent earth faults and thus intermittent earth fault protection should be tested more carefully in order to evaluate behavior of it in certain conditions.

Also in the experiments influence of the weather were not reflected, however this can be crucial for operation of conventional type relay protection. In the situation when distribution network will be represented as by cable lines as by overhead lines significant influence on the zero sequence current will cause active conductivity between ground and overhead lines. It can change considerably because of the weather conditions. Consequently during periods with high moisture protection of this type may operate falsely.

According to the experiments it is possible to utilize central compensation with parallel connection of the high-ohmic resistor with admittance based protection. In comparison with hybrid compensation this method is considerably cheaper and the maintenance of it is much more simple. However some questions are arisen in this case. During low load periods because of the voltage increase in the receiving end of a long cable line degree of earth fault compensation can be changed. Secondly, real parameters of cable lines can be estimated only by measurements in the real network and thus, it is difficult to guarantee reliable and selective operation of relay protection.

Consequently, field tests with real terminals of relay protection should be carried out. This will allow to take into account all mentioned above factors.

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