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Neutral Point Connections in Mv Power Networks With Grounding Zigzag Transformers — Analysis And Simulations

SUMMARY

Treatment of transformer neutral point in middle–voltage (MV) networks become an important issue with increasing proportion of MV cables in power networks. As consequence, overall capacitance of MV network is increased and moreover earth fault currents magnitudes. In MV networks with feeding transformer winding in delta connection (isolated networks), that earth fault current increase requires forming of artificial ground point — a neutral connection point on a three–phase ungrounded power system. Grounding transformer use, in zigzag or delty–wye connection, is common, well–known solution for constructing neutral connection in power systems. Physical characteristics of grounding transformers, protection principles, short–circuit calculations with symmetrical components and simulation techniques are presented in this paper. Characteristical operational modalities of MV power networks are also reviewed on practical examples.

KEYWORDS

Neutral point, grounding transformer, earthfault, simulation, PSCAD

INTRODUCTION

Depends on neutral point treatment of feeding transformer in MV networks (isolated, grounded, grounded with resistance or petersen coil), fault with ground means earth fault or one–phase short circuit [1]. Basic criterion for transformer neutral point grounding is magnitude of capacitive earth fault current. Boundary values of earth fault currents [2] are (until quoted values arc fault can extinguish without relay tripping of faulted feeder):

Ic = 20 A (Un = 10 kV)
Ic = 15 A (Un = 20 kV)
Ic = 10 A (Un = 35 kV)

If capacitive earth fault magnitudes exceed this values, establishing a neutral connection point is necessary. In practice, change of neutral point treatment of feeding transformer leads to common problem with grounding resistance of neighbouring substations in means of allowed touch and step voltages. Magnitudes of earth fault currents are determined with capacitances of MV power network, i.e. with length of MV cables in the power network.

Criterions for neutral point treatment of feeding transformer are:

- magnitude of capacitive earth fault currents
- voltage level
- magnitudes of inner overvoltages
- relay protection efficiency and selectivity
- possibility of decreasing equipment isolating level

- conditions of earthing components in power network
- specific soil resistance
- reliability of supply

If feeding transformer winding is delta connected, neutral connection point i.e. artificial neutral — is constructed with grounding transformers usually in zigzag connection. Such grounding point is usually carried out in combination with earthing resistor as short–circuit limiter. Advantages in such operation modality of MV power networks are:

- Limiting of inner overvoltages
- Elimination of intermitent earth faults
- Limitation of 3rd harmonics of magnetic flux in earthing transformers
- Efficient work of relay protections for single phase earth faults

Fault elimination is facilitated in MV network with neutral connection point but bigger magnitudes of earth faults (single phase short circuits) causes danger potentials and unallowable touch and step voltages in substations.

GROUNDING TRANSFORMERS FOR NEUTRAL CONNECTIONS IN MV POWER NETWORKS

Earthing transformer construction

A grounding transformer is usually zig–zag transformer without secondary winding, used for establishing a neutral connection to the ground in a three phase ungrounded power systems [1]. Earthing transformer for neutral connection is positioned near the power feeding transformer in the substation, directly connected on MV busbars. Usually, grounding transformer is builted in zigzag connection. Basic principle of connecting earthing transformer in substations is presented on Figure 1.

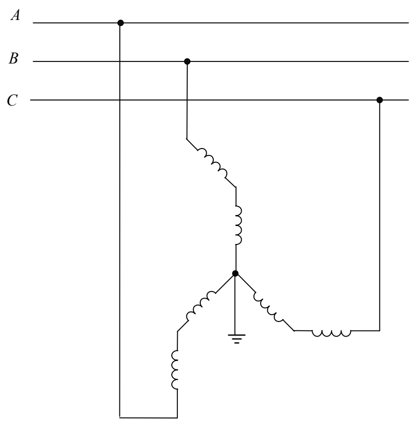


Figure 1: Principle of zigzag earthing transformer connection

Earthing transformer construction and winding connections should ensure following properties: small impedance in steady state (without faults in power network or big load impedance asymmetries) when small magnetising currents flows through the windings. When ground fault occurs in power network, grounding transfomer impedance should be small in order to easily conduct fault current into the ground. Every phase turn consist of two parts in which phase shifted voltages are induced. Six equal half–windings are spooled on three limbs such that every winding spans on different limb with half–windings spooled in opposite direction (Figure 2). Thus, amperturns in phase half–windings are mutually balanced and earthing transformer divide single–phase fault current on three equal components. These currents are equal, not just on magnitudes, but in phase angles [1]. Spooling and construction of earthing transformers are outlined on Figure 2. Connections of half–phases tends to cancel currents of 3rd harmonics — practicaly there is not 3rd harmonics of magnetic flux. Flux can be closed between zigzag turns with big magnetic resistance and considerable amount of ampere–turns would be nedeed i.e. magnetizing primary current must have big magnitude.

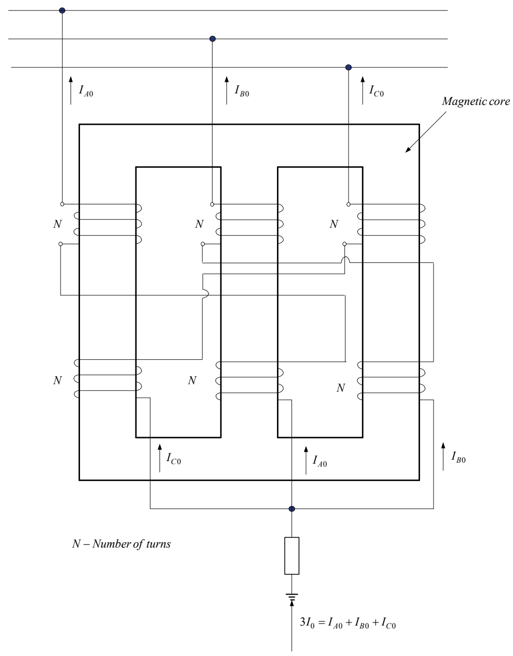


Figure 2: Winding connections of the zigzag grounding transformer

After grounding transformer installation, single phase to ground fault in power system means one–phase short circuit. In order to limit short–circuit currents a grounding resistor usually is connected on neutral leads of grounding transformer. Resistor limits fault currents up to 400 A [1], in praxis most often up to 300 A. Single phase to ground short–circuit distribution inside the grounding transformer is outlined on Figure 3.

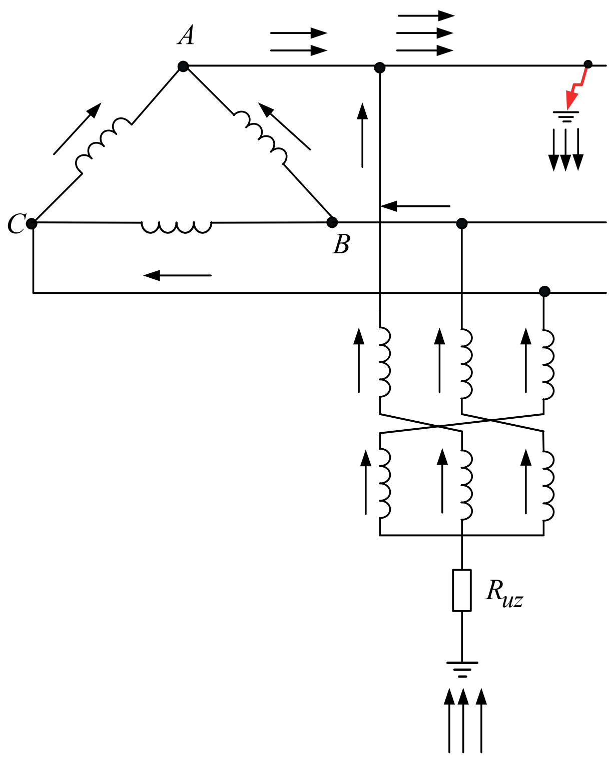


Figure 3: SLG short–circuit distribution inside the grounding transformer

Evidently from Figure 3 is that overall fault current flows through earthing resistor *R*. Fault current divides in manner that one third of fault current flows through every winding of earthing transformer. Characteristic for SLG faults in power networks with grounding transformers for ground path connection is that two thirds of fault current flows through one phase while remain flows through other phases.

Protection of the Grounding transformers for artifficial neutral connection in substations

Grounding transformer for neutral point connection is installed usually in vicinity of feeding transformers in substations. Consequently, overall configuration is protected with differential protection (Figure 4). Depend of speciffic applications, current transformer is added with earthing resistor with independent overcurrent protection. In protection parametring fault current distribution should be considered as presented on Figure 3. Protection principle of characteristic feeding transformer 110/2x10.5/36.75 kV, 20 MVA, YNyn0d5 is outlined on Figure 5.

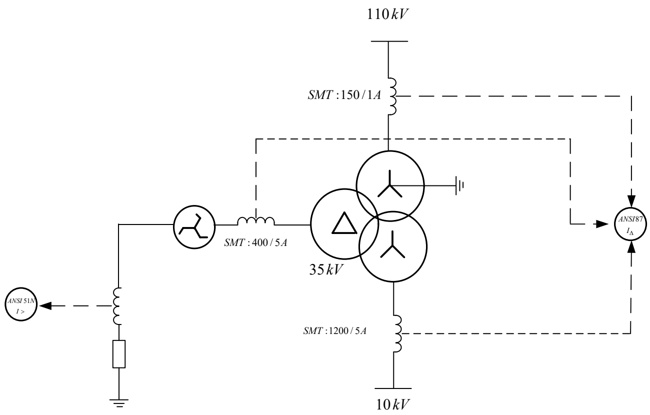


Figure 4: Protection principle of characteristic feeding transformer

Fault currents have much bigger magnitudes then earth fault currents in unearthed networks and overcurrent protections efficient trips the circuit breakers in small time intervals — in order of magnitudes of short circuits. That is safer operational mode of power MV networks, especially from from the point of operational personell safety with consideration of equations for calculation of allowed step and touch voltages in substations [4].

Short circuit calculations with symmetrical components in power networks with earthing transformers

For the analysis with symmetrical components of MV power networks with grounding transfomers, sequence networks should be determined along with calculations of impedances of network elements. Construction of symmetrical components networks will be illustrated on MV power network configuration presented on Figure 5, with SLG fault on 35 kV busbars.

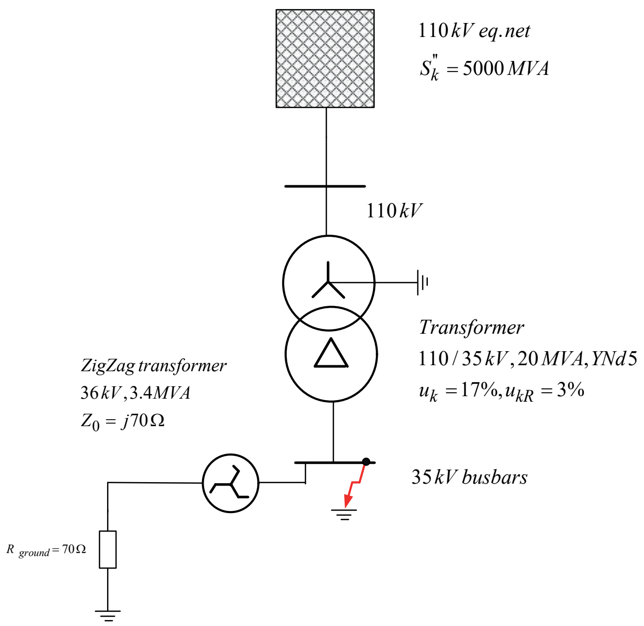


Figure 5: Typical MV power network with zigzag grounding transformer for example of short–circuit calculation with symmetrical components

Configuration for neutral connection of ungrounded MV network consist of grounding transformer with resistor for limiting short circuit currents and allows flow of SLG fault current to the ground. Consequently, equivalent zero sequence network of grounding transformer with resistor have connections as presented on Figure 6.

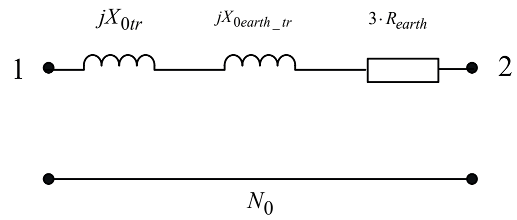


Figure 6: Zero sequence connection of grounding transformer in combination with short circuit limiting resistor

Considering Figure 6 schematic, connection of direct, inverse and zero sequence networks for SLG calculation for MV power network from Figure 5 is outlined on Figure 7:

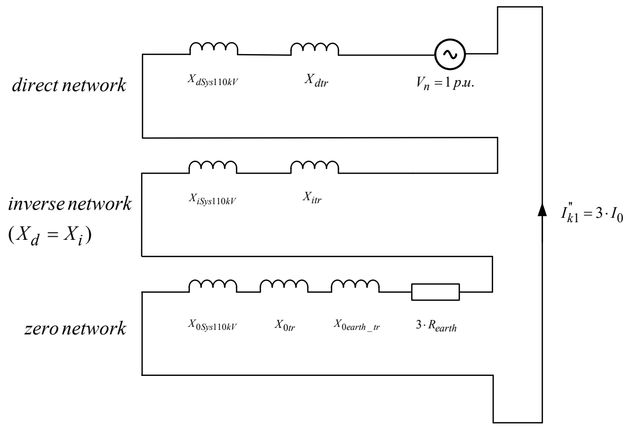


Figure 7: Connection of direct, inverse and zero sequence networks for SLG calculation for MV power network from Figure 5

According to the Figure 7, short circuit current calculation is carried out for MV power network from Figure 5. Impedances of network elements are determined and calculations are performed according to the IEC 60909 standard [7]:

Active 110 kV power network:

$$Z''_{110kV} = \frac{c \cdot U_n}{S''_k}$$

$$X_{110kV} = 0.995 \cdot Z''_{110kV} = j0.842765\,(35kV) \quad (1)$$

Feeding transformer 110/35 kV, 20 MVA:

$$Z_{tr} = \frac{u_k}{100} \cdot \frac{U_n^2}{S_n} = j10.4125\,\Omega$$

$$R_{tr} = \frac{u_{kR}}{100} \cdot \frac{U_n^2}{S_n} = 1.837\,\Omega$$

$$X_{tr} = \sqrt{Z_{tr}^2 - R_{tr}^2} = 10.24908 \quad (2)$$

With correction factor for transformer:

$$K_T = 0.95 \cdot \frac{c_{\max}}{1 + 0.6 \cdot x_T} = 0.984461$$, calculated on 14 MVA (3)

Feeding transformer reactance is:

$$X_{tr} = K_T \cdot X_{tr} = j10.08924\,\Omega \tag{4}$$

:

Single line to ground short circuit is:

$$I_{k1} = 3 \cdot I_f = \frac{\sqrt{3} \cdot c \cdot U_n}{\left| X_{eqd} + X_{eqi} + X_{eq0} + 3 \cdot R_{earth} \right|} = 285.20\,A \tag{5}$$

Simulation model of SLG on power network from Figure 5 is presented ON Figure 8:

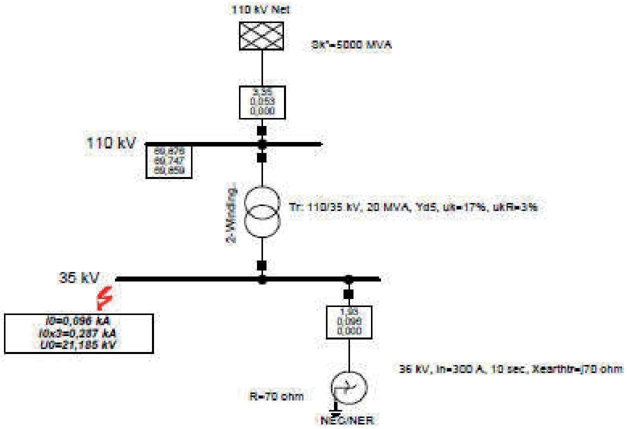


Figure 8: Computer simulation — SLG fault on 35 kV busbars

It is evident that difference between calculation and simulation case is under 1%

Earthing transformer dimensioning

Earthing transformer dimensioning is carried out on a way that rated voltage is equal or bigger with feeding transformer winding in power network where artifficial ground point is builded [1]. In typical sample substation, common feeding transformer rated data are: rated volteges 110/2x10.5/36.75 kV, rated power 20 MVA, winding connections Y0yn0d5. For such rated data, earthing transformer rated voltage is choosen. Rated power of earthing transformer is determined with phase voltage and short–time allowed current. In most of the practical application, that fault current is limited on 300 A for 10 seconds time period.

$$S_n = \frac{38kV}{\sqrt{3}} \cdot 300A \cdot \frac{1}{\sqrt{3}} = 3.8\,MVA \tag{6}$$

Grounding transformer in zigzag connection have bigger number of turns. That allows that phase voltage can be for smaller and as consequent decreasing rated power cost saving can be accomplished.

MODELING OF MV NETWORKS WITH ARTIFICIAL GROUND POINT

Grounding transformer in zigzag connection modeling

Model of MV ungrounded power network with grounding zigzag transformer for ground connection is built in order to demonstrate physical characteristic of such networks. Figure 9 represents a principle of modeling grounding zigzag transformers. Model is built from three monophase transformer with connections in half–windings which corresponds with physical connections on Figure 2.

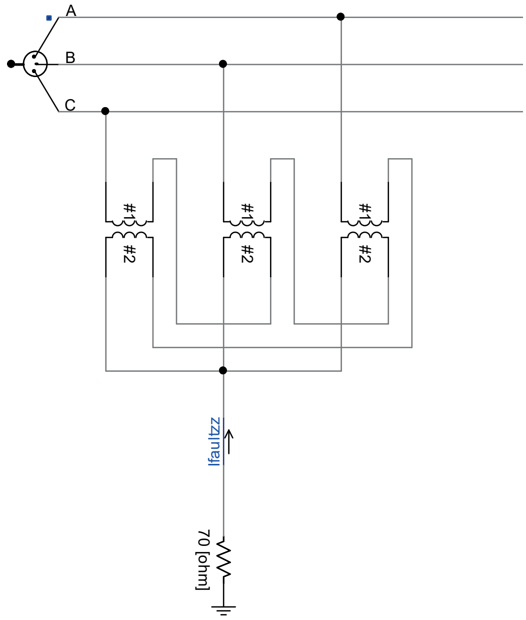


Figure 9: Model of grounding zigzag transformer for artifficial ground point

Based on formed grounding transformer simulation model, simulations for characteristic operational modalities of MV power networks are carried out. For every operational mode analysis of grounding configuration is performed.

Normal (symmetrical load) operation of MV power network

For the illustration of physical principles of artifficial ground point connection operation, simulation model [5] of 35 kV power network is developed based on typical 110/35/10 kV substation equipment data taken from [6]. Underground power cables capacitances are simulated with concentrate capacitances connected on MV busbars. In considered substation, 36.75 kV winding of feeding transformer is delta connected, earth fault currents reached the allowed maximum values and ground connection for this isolated network must be formed. Artifficial ground connection point is formed with grounding transformer (Figure 9) along with grounding resistor for limiting short circuit currents. Normal operation of 35 kV power network without faults and with symmetrical loads is modeled according data taken from [6] and presented on Figure 10.

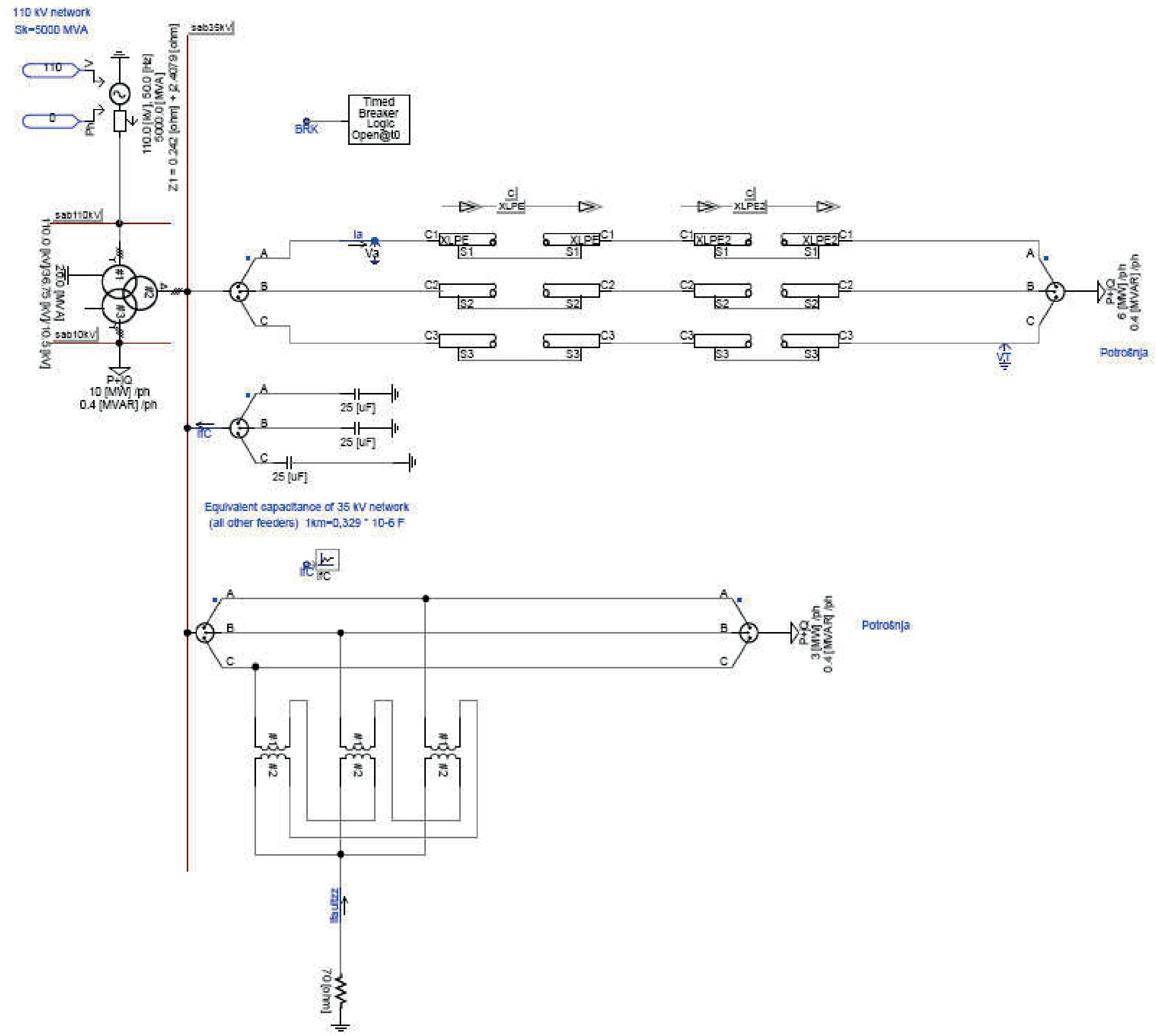


Figure 10: Simulation model of 35 kV power network with grounding transformer neutral point connection — symmetrical loads

Current through earthing resistor in normal operation of MV power network without asymmetrical loads and faults is presented on Figure 11. Magnitude of current through earthing resistor is under 1A (caused with stray capacitances) which prove correctness of simulation model for assumpiton — small magnetising current and big impedance of earthing zigzag transformer in normal network operation.

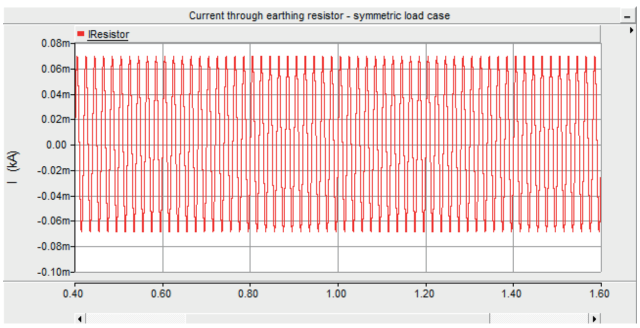


Figure 11: Current through earthing resistor — normal operation of MV power network

Asymmetrical load in MV network

In practice is very rare to find symmetrical loaded MV power network. That's reason for installation of higly asymmetric load in observed MV network (different load phase resistances) in order to examine grounding transformer in such operational mode (Figure 12).

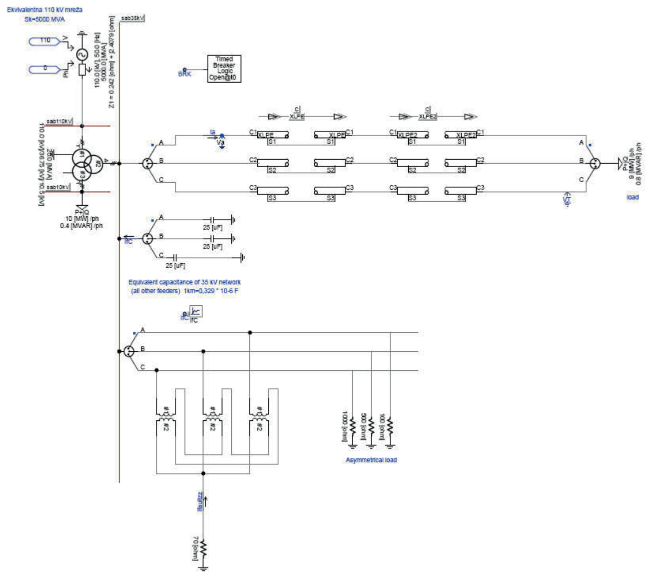


Figure 12: Simulation model of 35 kV power network with grounding transformer neutral point connection — asymmetrical loads

Current which continuously flows through grounding resistor is presented on Figure 13.

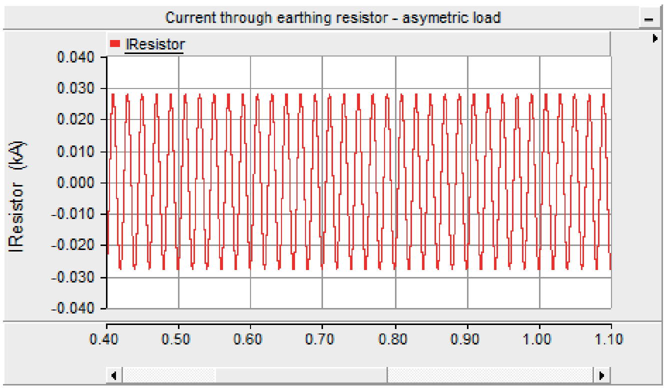


Figure 13: Current through earthing resistor of artifficial ground point — higly asymmetrical loads

For high asymmetric load current magnitude is 26 A which is permitted continous current for earthing resistor. Phase currents in grounding transformer for the asymmetrical load case are presented on Figures 14 — 16.

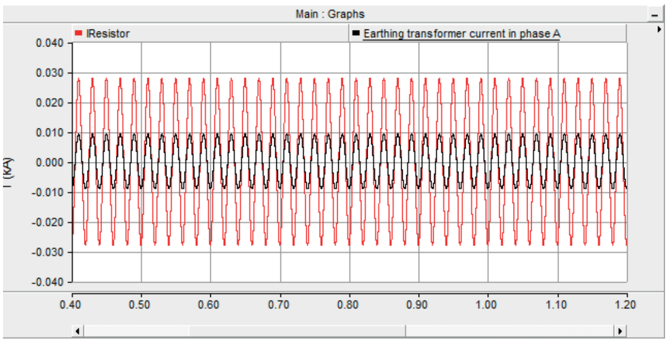


Figure 14: Earthing resistor current of artifficial grounding point connection and grounding transfomer phase A current

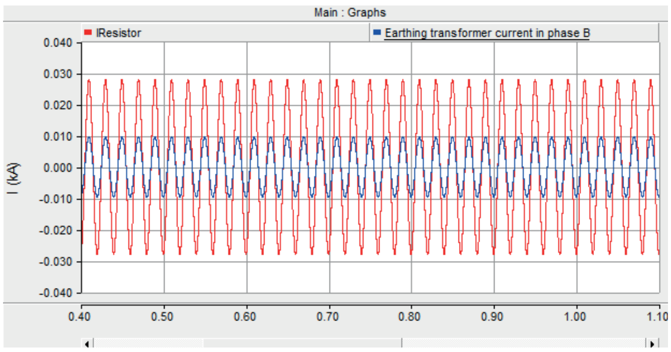


Figure 15: Earthing resistor current of artifficial grounding point connection and grounding transfomer phase B current

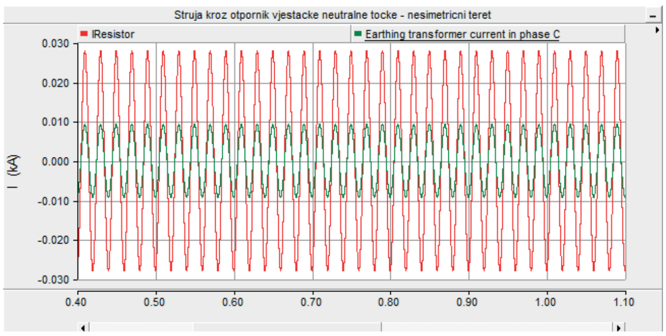


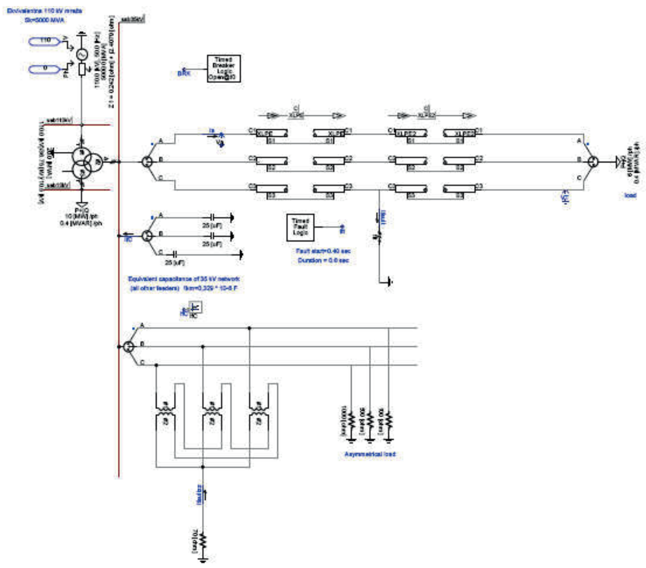
Figure 16: Earthing resistor current of artifficial grounding point connection and grounding transfomer phase C current

Current distribution per phases of grounding transformer is evidently uniform, current magnitudes and phases are equal, which proves of another assumption for grounding transformer characteristics. Also, magnitudes of phase currents through earthing transformers are under 10 A which is permitted rated value.

Single–phase to ground (SLG) fault in 35 kV network

Earth fault or single–phase to ground (SLG) fault (depend on network grounding type) is the most common fault type in MV power networks. For assumed SLG fault is simulated in sample substation with configuration outlined on Figure 17. SLG fault is apllied on one phase of underground power cable, at 0.4 seconds at distance of one kilometer from 35 kV busbars.

Figure 17: Simulation model of 35 kV power network with grounding transformer —



SLG fault on underground power cable

Simulation results are presented on Figures 18 — 20.

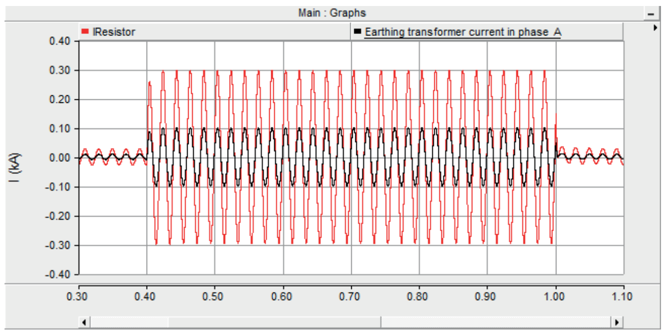


Figure 18: Earthing resistor current of artifficial grounding point connection and grounding transfomer phase A current — SLG fault

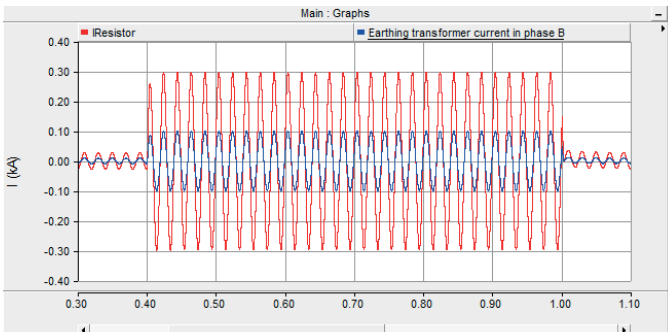


Figure 19 Earthing resistor current of artificial grounding point connection and grounding transfomer phase B current — SLG fault

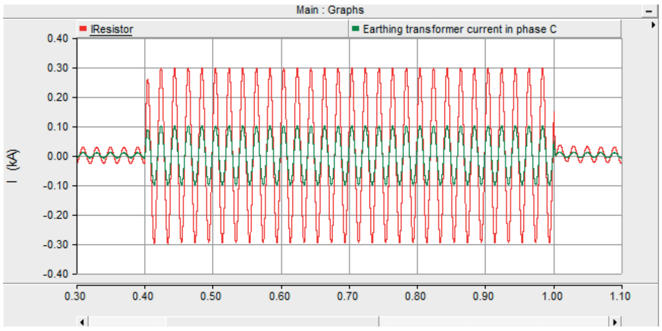


Figure 20 Earthing resistor current of artificial grounding point connection and grounding transfomer phase C current — SLG fault

Even for the case of SLG fault, current distribution per phases of grounding transformer is evidently uniform. Furthermore, current magnitudes and phases are equal, which is another prove of grounding transformer characteristics. With Fourier analysis harmonic decomposition contribution of third harmonic of magnetic flux in earthing transformer is obtained and presented on Figures 21 (Fourier's decomposition of phase C flux) and Figure 22 (detailed view of flux oscillations by harmonics in magnetic core of earthing transformer during the SLG fault).

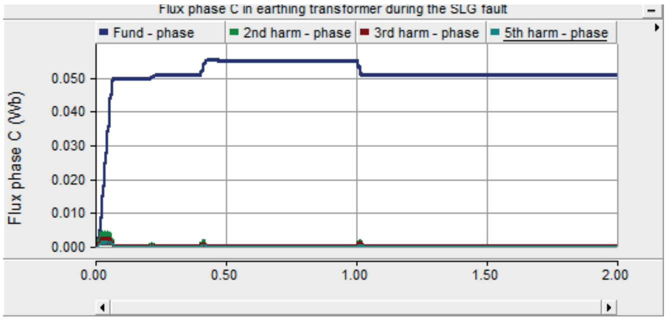


Figure 21: Harmonic decomposition of magnetic flux of grounding transformer

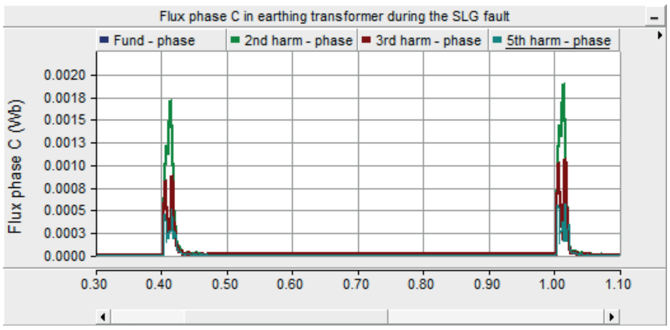


Figure 22: Detailed view of flux oscillation by harmonics during the SLG fault

As quoted, connections of half–phases tends to cancel currents of 3rd harmonics — practicaly there is not 3rd harmonics of magnetic flux.Fourier analysis of magnetic flux in grounding transformer shows that 3rd flux harmonic minor which is another confirmation of grounding transformer characteristics.

CONCLUSION

Use of grounding transformer is common in everyday practice. With increasing proportion of underground cables in MV power networks overall network capacitance is increasing and moreover earth fault currents magnitudes. In MV isolated networks that earth fault current increase requires forming of artificial ground point — a neutral connection point on a three–phase ungrounded power system. Grounding transformers physical characteristics along with their acting in the power networks protection principles and modeling are examined and presented in this paper. Also, characteristical operational modes of MV networks with artificial ground connection (MV power network with symmetrical and asymmetrical load, single–phase to ground fault) necessary for understading of working principles of MV networks are elaborated with detailed simulation cases.

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