

David Tomáš
EGE spol. s r.o.
Czech republic
tomasd@ege.cz

Petr Vančata
EGE spol. s r.o.
Czech republic
vancata@ege.cz

ISKUSTVA SA REZONANTNO UZEMLJENIM MREŽAMA

SAŽETAK

Metoda tretiranja neutralne točke jedan je od najvažnijih faktora koji utječu na kvalitetu i pouzdanost napajanja. Najrasprostranjenija metoda u Europi je rezonantno uzemljenje, zbog svog pozitivnog učinka na poboljšanje pokazatelja kvalitete električne energije (SAIDI, SAIFI).

U rezonantno uzemljenoj mreži, prigušnica za samogašenje (ASC, Petersenova prigušnica) spojena je između neutralne točke distribucijskog sustava i zemlje, i podešena je tako da se kapacitivna struja zemljospoja kompenzira induktivnom strujom koja prolazi kroz ASC.

Ovaj referat opisuje prednosti rezonantnog uzemljenja i uspoređuje ga s drugim metodama uzemljenja koje se često koriste u distribucijskim sustavima.

Ovdje su također opisane metode udešavanja prigušnice i zahtjevi za rad tih metoda.

Ključne riječi: Petersenova prigušnica, rezonantno uzemljenje, zemljospoj, neutralna točka

EXPERIENCES WITH RESONANTLY GROUNDED NETWORKS

SUMMARY

The method of neutral point treatment is one of the most important factors influencing power supply quality and reliability. The most widespread method in Europe is resonant grounding because of its positive effect on improvement of the power quality indicators (SAIDI, SAIFI).

In the resonant earthed network, **Arc Suppression Coil** (ASC, Petersen Coil) is connected between the neutral point of the distribution system and ground and it is well tuned so that the capacitive earth fault current is compensated by an inductive current passing through the ASC.

This text describes advantages of the resonant earthing and compares it with other grounding methods often used in the distribution systems.

Methods of arc suppression coil tuning and requirements for operation of this method are also described here.

Key words: Petersen coil, resonant earthing, earth fault, neutral point

1. INTRODUCTION

1.1. Petersen Coil Anniversary

Arc Suppression coil (ASC), also called Petersen coil, celebrated in 2017 hundred years of the invention. Waldemar Petersen, who invented it, was born in 1880 in Athens and died in 1946 in Darmstadt. In 1904 he began his career as a scientific assistant at the Technical University. He received his doctorate in 1907 at the TH Darmstadt. While his colleagues still relied on DC technology, Mr. Petersen dealt with AC high voltage technology, which was still very young those days.

Mr. Petersen had a high pedagogical talent in his lectures. But he was not only a German professor of electrical engineering but also an entrepreneur and from 1926 a member of the board of AEG.

He wrote basic textbooks about high voltage engineering. And therefore, he is considered to be the founder of high voltage engineering in Germany.

Not only the Petersen coil makes him famous, but also a wattmetric earth fault relay, that he developed just one year later in 1918.

The very first and original Petersen coil is still possible to see in Deutsches Museum in Munich.

2. METHODS OF NEUTRAL POINT TREATMENT

2.1. Neutral point treatment

Neutral point of the distribution system is usually considered the neutral point of the power supply transformer (YNyNd). But there are more possibilities. The neutral point can be also formed by an earthing transformer (Zn, Ynd) or by neutral point of a generator.

The distribution network is possible to operate in several ways that are determined by method of grounding. Each method has its own advantages and disadvantages. The most significant difference is network behaviour during the earth-fault: possibility of fault self-extinguishing, earth-fault current value, overvoltage and possibility of network permanent operation during the earth-fault.

It is obvious that the method of neutral point earthing affects the reliability of power supply, safety during an earth fault and of course the costs.

The 4 main relevant methods used for neutral point grounding of multiphase electrical system are: Solidly grounded neutral point, resistance grounding, isolated neutral point and resonant grounding.

2.2. Isolated neutral point

It is the cheapest way of the earthing, the neutral points of all existing generators and transformers in the network are not earthed.

At the first sight there is no way for the fault current to find current loop, but actually each phase has its own capacitance with very small conductance to ground. The fault current can flow through them.

During an earth fault the voltage of sound phases rise $\sqrt{3}$ times with transient phenomenon causing even higher voltage increase with transient peak up to 3 times higher than phase voltage amplitude. The earth fault current has capacitive character in this type of earthing system. That makes self-suppressing of the arc quite difficult.

Depending on network size there could be high fault current and then it is necessary to trip the faulty feeder. Only small networks are possible to operate with permanent earth fault because of low fault current at the fault point. Depending on the country, only networks with capacitive earth fault current under 10 or 20 Amperes are allowed to be operated with isolated neutral point.

Very significant disadvantage of this method of neutral point treatment is the problem with unstable phase voltage and overvoltage caused by transient earth faults. Due to the non-linearity of inductive VTs connected between the phases and the ground, there is a risk of ferroresonance phenomenon.

2.3. Solidly grounded neutral point

This kind of systems has neutral point directly connected to earth through very low impedance. During the earth fault there is a low overvoltage effect but high fault current. That is why it is necessary to trip the faulty feeder immediately when the earth fault occurs and that leads to the loss of supply for the customers supplied by the faulty line.

During the fault conditions, all customers are influenced, even if they are supplied from other MV feeders without the fault, because the line voltages are also affected by the earth fault.

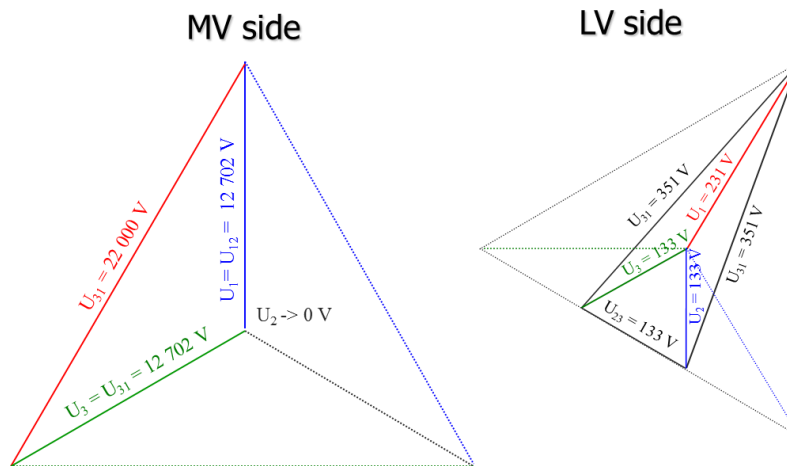


Figure 1: Voltage on distribution transformers Dyn1 in case of solid earth fault in solidly earthed MV system.

On the other hand, only this system enables supply phase-to-earth loads (SWER - single wire earth return lines). The load current loop closes through solidly earthed neutral point.

2.4. Resistance earthing

There is a resistor connected between the neutral point and the earth. It limits the fault current value. The earth fault current is a vector sum of resistive current and capacitive earth current. The fault current is higher than in isolated system and therefore it is necessary to trip the faulty feeder immediately, which causes loss of supply. If earthing resistor with very low resistivity is used, the behaviour of the network is close to the solidly earthed network in case of an earth fault.

The resistor increases an active component of the current during the earth fault, which supports the proper function of wattmetric earth fault protection relays.

2.5. Resonant earthing

Petersen coil is one of the possibilities of neutral earthing in distribution networks. It is commonly used in three phase systems to compensate arcing capacitive currents during the earth fault.

Petersen coil reduces fault current to minimum. Capacitive part of earth fault current is compensated by inductive current passing through the coil and the faulty point. In case of properly tuned coil the residual current has mainly active character. This is the main advantage of this system because of good conditions for self-extinguishing of the arc. Due to this self-extinguishing capability, about 80 % of all earth faults in overhead lines, which are transient earth faults, are cleared. In this case it is not necessary to interrupt power supply compared to the networks operated with different types of earthing described above.

Remaining 20 % of all earth faults in overhead lines are permanent faults. The low value of the fault current enables to operate the network with a permanent earth fault, however, it is suggested not to operate the network for unnecessary long time. During operation with the earth fault, the phase voltage in

sound phases has value of the line voltage and that is why there is higher risk of secondary cross country fault (double earth fault) occurrence.

2.6. Comparison of different methods of neutral point treatment

From the comparison of the different types of the neutral point earthing it is obvious that only the resonant earthing system reduces significantly the number of interruptions of power supply as there is no need for immediate tripping of faulty feeder in case of earth fault.

In cable lines the earth fault has a character of re-striking arc usually. Even if there is a low probability of permanent self-suppressing – resonant earthing has significant advantage as it reduces the fault current value and that is why the touch voltage and damage at the faulty point are significantly lower than in case of another neutral point earthing systems.

If it is required to operate network for longer time with permanent earth fault, combination of Petersen coil and FPE (faulty phase earthing) can be the best solution. FPE reduces residual current and also the faulty phase voltage to minimum. Even in cable lines the faulty point remains without arcing during FPE is switched on.

Even if the faulty phase voltage is close to zero during the earth fault conditions, the LV customers are not affected because phase-to-phase MV voltages are not significantly influenced.

Table No. 1 below presents comparison of various types of neutral point treatment:

Table No. 1

	Solid earthing	Low impedance earthing	Isolated neutral	Resonant earthing
Required Insulation level	Phase-to-earth	Phase-to-phase for short time	Phase-to-phase	Phase-to-phase
Surge arresters and VTs dimensioning	Phase-to-earth	Phase-to-phase for short time	Phase-to-phase	Phase-to-phase
Permanent operation possibility during an earth fault	No	No	Small networks only	Yes
Self-extinguishing of arc	No	No	Very low probability, only in small networks	Yes
Transient overvoltage in case of an earth fault	No	No	High	Low

3. NETWORKS IN EUROPE

As the Europe consists of many countries, the power systems have been developed in different ways. Depending on the country, there are various voltage levels of the distribution networks and also several types of neutral point treatment.

Resonant grounding is typical for many European countries. E.g. Central Europa including all German speaking countries, East Europe, Italy, Scandinavian and Baltic countries, but also Middle Asia or Israel.

Reasons, why the Petersen coil is so often used in Europe, is mostly improvement of power quality parameters thanks to reduced number of power supply interruptions. Figure 2 shows results of pilot project evaluation in certain networks in Italy (1). In January 2001 there were installed Petersen coils in some networks. Before installation the networks were operated with isolated neutral point. The number of power supply interruptions was reduced significantly after the ASC installation (red line) even if the total number of interruptions in the whole area increased (blue line).

It is not necessary to interrupt power supply during the transient earth-faults. Thanks to very low value of residual current, that has active character, there is high chance of self-extinguishing of the arc. In overhead lines that are easily influenced by weather, about 80 % of all earth-faults are just transient

thanks to arc suppression coil. Compared to other types of neutral point treatment, this is a significant reduction of interruptions.

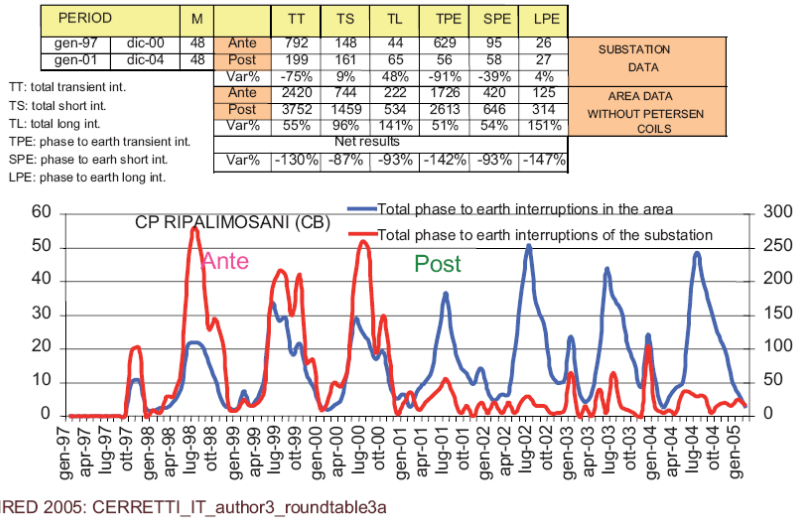


Figure 2: Power supply interruptions before and after Petersen coil installation in the network – evaluation of Italian pilot project (1)

Reliability of the networks with ASC helps to expand this network type around Europe. Extensive research was made in German speaking countries in 2009 organized by technical-scientific association VDE (2). The research shows also statistics about neutral point treatment and number of faults, which are mentioned below. Figure 3 shows that about 97 % of 20 kV and 30 kV distribution networks were operated with ASC in 2009 in Germany. That is an increase in comparison to 1998 statistic, especially for distribution system of 30 kV. It is given by positive experience with the influence of resonant earthing on power quality. Situation about 10 kV networks is different. The relative number of the networks with ASC decreased in 2009. The reason can be that number of these networks with relatively low voltage is generally decreasing, many of them were rebuilt to higher voltage levels. The rest of remaining 10 kV networks are usually old cable grids in towns with problematical insulation conditions. That is why a lot of these networks are no more possible to be operated as resonant earthed networks with permanent earth fault due to the increasing probability of cross country faults.

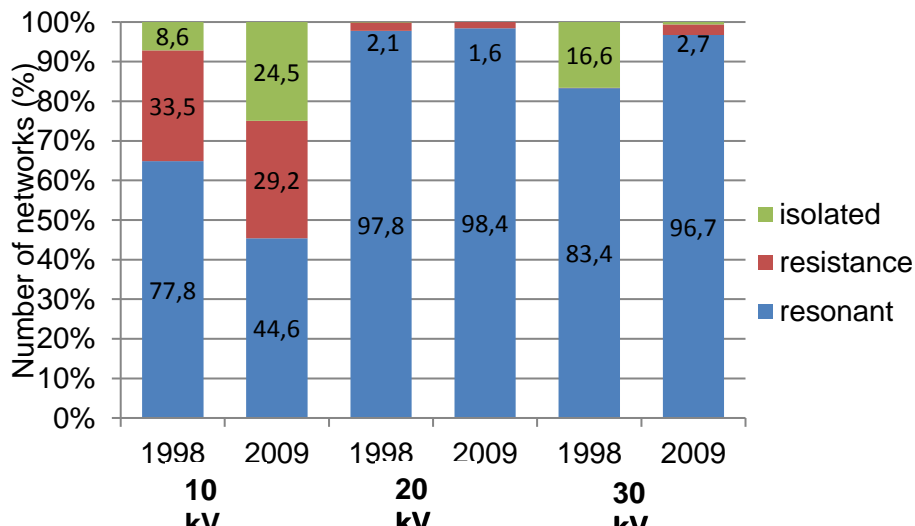


Figure 3: Comparison of neutral point treatment in Germany. (2)

It was found out how many interruptions occurred in distribution networks (2). Figure 4 shows a number of overhead line networks differentiated by the number of earth faults per 100 km. Self-extinguished (transient) faults are not included.

It is evident that almost 70 % of resonant grounded networks had only 0.5 faults per 100 km or less. About 25 % of resonant grounded networks were affected by 0.5 to 1 fault per 100 km. The reason is that the majority of earth-faults self-suppressed in overhead lines.

Earth fault appears more often in isolated networks according to the study. Most of the isolated networks (about 55 %) had more than 2 earth faults per 100 km. More than 2 earth-faults occur in almost 40 % of resistive grounded networks.

This statistic show positive influence of resonant earthing on improving of power supply reliability and power quality.

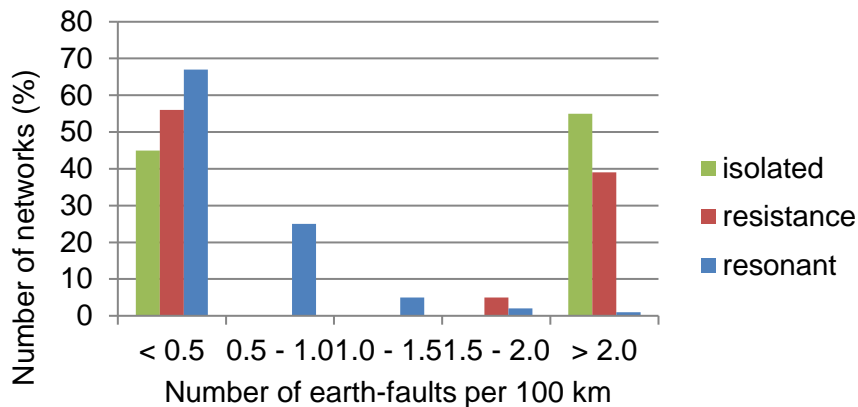


Figure 4: Relative number of overhead line networks with exact number of earth-faults per 100 km. Self-extinguished (transient) faults are not included. (2)

4. PRINCIPLE OF RESONANT EARTHING

One of the most important parameters of the power network is phase-to-earth capacitance that influences the value of the capacitive earth fault current. The value of this capacitance depends mainly on the type of the network – proportion of cables and overhead lines. Generally the capacitance is about 50-60 times higher in case of a cable line compared to an overhead line. Of course the larger the grid (length of the lines) is, the higher value of the capacitance is.

When a solid phase-to-earth fault appears in the network, the faulty phase voltage is reduced to earth potential (≈ 0 V). The voltage of the other two sound phases rises to phase-to-phase voltage ($\sqrt{3}$ times) and voltage between the neutral point of the network and the earth is increased to the value of the phase voltage.

During the earth fault a capacitive current I_c flows from the sound phases through the phase-to-earth capacitances as it was mentioned above. The current flows via the faulty point back to the network. The fault currents can reach high values (hundreds of Amperes).

The main principle of the earth fault current compensation is using an arc suppression coil producing compensation current of inductive character. The ASC is installed between the neutral point and the earth and it is tuned to a specific inductance, that in case of solid earth fault produces the current with nearly the same magnitude like the capacitive earth fault current, but 180 degrees out-of-phase.

The inductance of the ASC and the earth capacitance of the network are in resonance for fundamental network frequency – that is why this method of neutral point treatment is called “resonant earthing”.

Because the reactive part of fault current is very low in case of properly tuned ASC, through the fault point flows almost no reactive current of fundamental frequency. The residual current is then very low, usually about 2-5 % of capacitive charging current. In this case residual current is caused by insulation leakage and coil losses and it has resistive character.

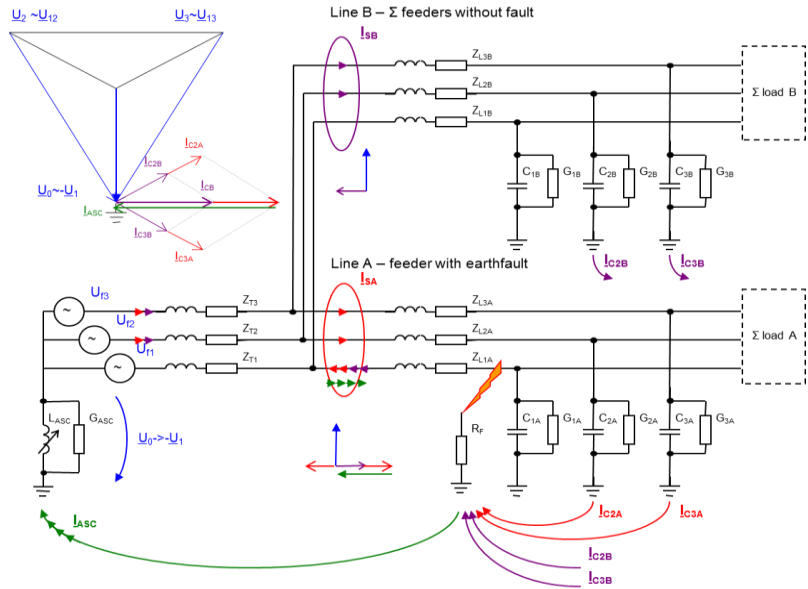


Figure 5: Resonant earthing principle – reduction of earth fault current

Petersen coil is tuned for one specific frequency (usually 50 Hz), any harmonics in the network also increases the residual current.

Resulting residual current is the sum of the active and reactive part of fundamental frequency and higher harmonic components of the current. These higher harmonics are significantly reduced by increasing of earth fault resistivity and do not play important role in practical life especially in overhead lines.

4.1. Tuning of ASC

Arc suppression coil controllers continually monitor zero sequence voltage and look for the resonance where the capacitance and Peterson coil are correctly tuned.

Consider a Petersen coil connected between the neutral point and earth with inductive reactance ωL , then the current I_L flowing through it is:

$$I_L = U_0 / \omega L \tag{1}$$

Where:

U_0 ...Neutral point voltage

LInductance

ω ...angular frequency

To get an effective compensation of the capacitive earth current, I_L has to be equal to the capacitive current of the network I_c :

$$\frac{U_0}{\omega L} = 3U_0\omega C \tag{2}$$

Where:

C ...Total capacitance between the network and the earth

The value of the properly tuned inductance is:

$$L = \frac{1}{3\omega^2 C} \tag{3}$$

If the capacitance of the network changes due to network switching, the coil reactance must be newly adjusted so that the circuit remains tuned.

ASC is usually tuned by changing its inductance under normal conditions. This causes change of neutral point voltage as expressed in figure 6. The peak of the curve indicates the resonance.

The best possibility is to change the coil reactance fluently using steplessly adjustable arc suppression coil, so the finest possible tuning can be reached. Other systems (stepped coils, coils tuned by switching of capacitors parallel to the coil) cannot reach so precise tuning. The tuning process happens in no-fault state. Petersen coil is then tuned and in case of earth fault it compensates the fault current immediately. It is not necessary to rely on a correct reaction of the tuning device at the moment of the earth fault.

When the Petersen coil is tuned properly, the voltage in the neutral point is at its maximum. For this reason it is necessary to have relatively well balanced network (low capacitive unbalance of all three phases to the ground). If the asymmetry is too high, the voltage of neutral point can reach very high value (even higher than the phase voltage). In this situation there are significant differences between the phase voltages and it is necessary to do certain measurements to reduce the differences between the line-to-earth capacitances.

In case of a pure resonance the neutral point voltage is very sensitive to any changes in the network, even to changes of phase unbalanced loads or moving of phase wires in overhead lines caused by wind. That is why Petersen coil is not usually tuned exactly on the top of the resonance curve, but it is a little bit detuned by a few Amps only. This detuning reduces significantly the neutral voltage and excessive sensitivity to changes described above.

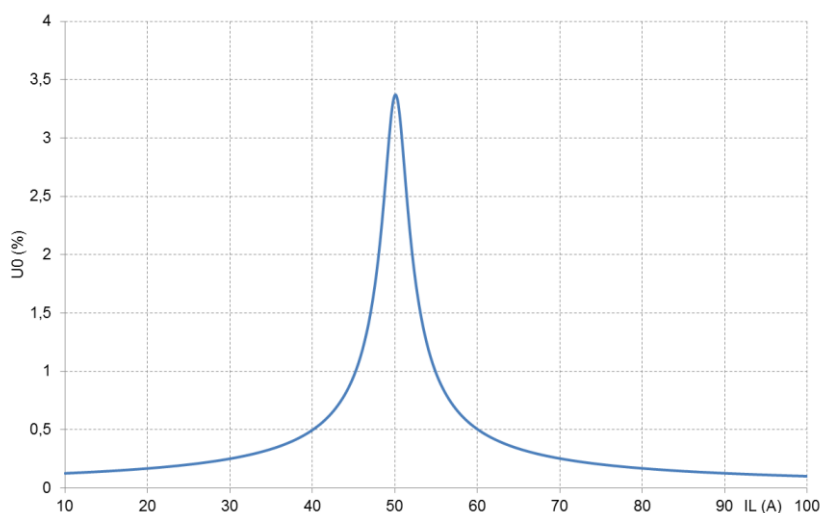


Figure 6: Typical resonance curve. Value of the neutral point voltage corresponding to ASC current (as tuned)

On the other hand, the capacitive asymmetry can be very low or the zero sequence voltage can be very unstable. In these cases it is necessary to use special tuning devices. Using a current injection to the neutral point and sensitive measuring of network capacitance enables proper tuning without necessity of any change of the coil inductivity for measuring and recording the resonance curve. These injection methods of tuning are used as a standard tuning method in some countries, because there is a certainty of reliable tuning even under adverse conditions related to the development of distributed energy sources.

4.2. Why convert to a resonant earthing system?

There are usually three main reasons to convert to a resonant earthing system:

- Reliability improvement: the middle voltage network continues to supply all the loads connected phase-to-phase and the customers supplied on LV side of distribution transformers are not affected by the earth fault in MV system, so there is no loss of supply.
- Safety improvement: Reduction of the fault current in case of the earth fault and creation of good conditions for self-extinguishing of arcs, which significantly reduces not only the number of

interruptions, but also the scope of damage at the faulty point and risk of dangerous increase of touch voltage.

- Sensitivity of high impedance fault detection: Resonant earthed system enables to detect high impedance earth faults in the grid. In case of earth fault, zero sequence impedance and earth-fault impedance create voltage divider. In resonantly grounded networks the resulting zero sequence impedance of the resonant circuit is very high and that is why even relatively high fault resistivity causes significant increase of neutral point voltage (U_0 , NVD), which is detected by protection relays. It is showed in the figure 7. There is shown comparison of resonantly grounded network with slightly undertuned ASC (blue line), overtuned ASC (green line), isolated network (red line) and network with resistance earthing (black line).

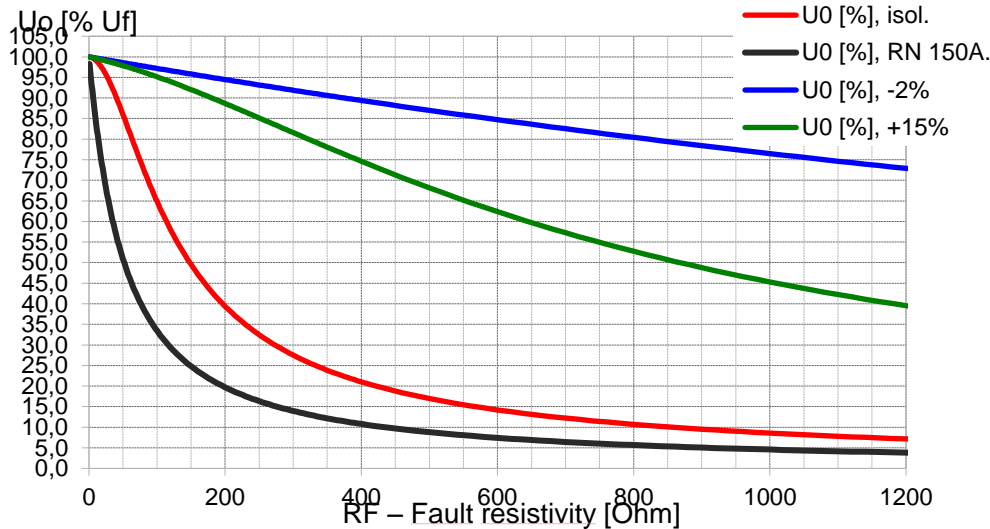


Figure 7: Influence of earth-fault resistivity on the neutral point voltage. Network model: 15 kV, $I_{CE} = 100$ A, 50 Hz, 2 % damping, ASC losses 1 %. Legend: isol.: Isolated neutral point, RN 150: resistance earthing, -2%: resonantly grounded networks with ASC undertuned 2 %, +15%: resonantly grounded networks with ASC overtuned 2 %, %:

4.3. Requirements for conversion to resonant system

In order to operate this type of neutral point treatment, several conditions must be met:

- Low capacitive unbalance of the three phases to ground
- Phase-to-phase insulation level in the network is required
- The surge arresters must be set higher than the line voltage.
- Protection system must be adjusted
- Phase VT must be dimensioned for line voltage

5. EARTH FAULT DETECTION IN RESONANT EARTHED NETWORK

There are several types of protections in resonant earthed networks. Due to the very low value of fault current, sensitive directional overcurrent protections are usually used to detect the faulty feeder. There are also other special methods which can detect the faulty feeder even with higher reliability.

Attempts to find a reliable distance-to-fault method in case of an earth fault have not been successful. Some promising projects using evaluation of traveling waves at the moment of earth fault occurrence were published in the last year, but there is no device for distance measuring of an earth fault on the market yet. For better localisation of the faulty point it is necessary to install earth fault indicators along the line or to divide the line by section disconnectors.

5.1. Protections evaluating static earth fault conditions:

Wattmetric directional earth fault overcurrent protection is the mostly used method of faulty feeder detection. The function is based on measuring of zero sequence current and voltage magnitude and their angle.

The relay reacts to the flow direction of active part of residual fault current. The sensitivity of this method is possible to increase by using of short time wattmetrical current increasing. Therefore, the Petersen coil is usually equipped with secondary resistor.

Admittance methods work on a similar principle, evaluates the zero-sequence admittance of each feeder (method calculates it also from current and voltage magnitude and their angle).

Higher harmonic methods evaluate the flow direction of higher harmonic components of fault current.

5.2. Transient methods

The transient method is used for fast detection of faulty feeder. During an earth fault the faulty phase discharges and healthy phases charge up to line voltage. That appears just once at the beginning of the earth fault. This transient process of charging and discharging has typically much higher frequency than the fundamental frequency of the network. The arc suppression coil does not compensate these (dis)charging currents, so they can be used for faulty feeder detection. The relay evaluates the flow direction of charging currents related to neutral point voltage at the moment of fault occurrence. It is possible to use it for low impedance fault only.

Special improved algorithms “qu” using integration of the current values (calculating the charge “q”) enable to use the transient method even for high impedance faults too.

6. CONCLUSION

All the mentioned types of the neutral point treatment have no influence on the transmission of power as long as the network is in faultless condition.

Differences occur during the earth-fault state. Solidly grounded networks and grids with low resistance grounding are impossible to be operated with permanent earth-fault and it is necessary to trip the faulty feeder immediately, due to high value of fault current. This is also partially true for isolated networks. Only small networks with isolated neutral point can be operated.

The arc suppression coil compensates the fault current flowing through the phase to earth capacitances of the network to a minimum value (usually <5 % percent of the network earth capacitive current). So the resonant grounded system is possible to operate with the earth fault thanks to low value of fault current.

The arc suppression coil limits the fault current and creates good conditions for self-extinguishing of the fault. Low value of residual fault current and its active character causes that about 80 % of all earth-faults are only transient in overhead lines and it is not necessary to interrupt the power supply of the customers. It is an important advantage that improves the power quality indicators (SAIDI, SAIFI) significantly.

Required insulation level for all insulators, cables and the devices connected to the network with resonant earthing is phase-to-phase voltage. Surge arresters and VTs have to be also dimensioned for phase-to-phase voltage. The network must be also balanced (phase-to-earth capacitances of all phases should be almost equal), if there is the arc suppression coil installed and properly tuned, otherwise neutral point voltage would be too high (in resonant point).

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