NEW SOLUTION FOR DETECTING SINGLE PHASE-TO-GROUND FAULTS IN RESONANT-GROUNDED SYSTEMS

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ABSTRACT

The compensation of the earth fault current in resonant-grounded systems is an effective method to increase the chance of clearing the most frequently occurring faults, the single phase-to-ground faults. The closer the value of the inductive reactance of the Petersen coil to the value of the zero-sequence capacitive reactance of the network, the higher the chance for the arc suppression. As a consequence of this tuned near-resonance state, the earth fault current is negligibly small compared to the load current. Therefore, it presents real challenges for the protection devices to detect this type of fault, as the zero-sequence fault current is too small, and the positive sequence impedance cannot be measured correctly between the fault location and the protection device.

This paper gives a brief overview of the different earth fault protection methods used on resonant-grounded systems all over the world and introduces a new method for earth fault detection. It also demonstrates the results of its successful real-life application.

EARTH-FAULT PROTECTIONS IN RESONANT-GROUNDED SYSTEMS

There are many solutions based on different principles which are well-known all over the world today. The commonly used protections for detecting single phase-to-ground faults are:

- wattmetric earth fault protection,
- transient (Wischer) earth fault protection,
- earth fault protection using temporary grounding resistor.

Figure 1 shows the simplified symmetrical component schema for earth fault calculation in compensated networks. The positive- and negative-sequence impedances are concentrated in one-one impedance (Z1, Z2). The zero-sequence equivalent network is detailed: it shows the healthy feeders (Feeder 1 in the schema), the feeder with earth fault (Feeder 2 in the schema) and the Petersen coil. The dotted arrows indicate the positive direction of the current transformers and the solid arrows show the current flow in case of earth fault.

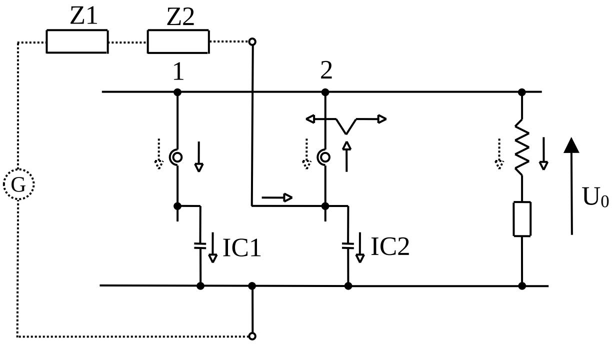

Figure 1. Modelling of a single phase-to-ground fault

Wattmetric earth fault protection

Wattmetric earth fault protection measures the real component of the complex power. The main difference between the healthy lines and the faulty line is that the dissipated real power of the Petersen coil can only be measured in the faulty line, as the current of the coil flows through the CT of the faulty line (Feeder 2).

It presents a correct solution; however, there is a major drawback. The resistance of the Petersen coil is becoming lower and lower as the coil manufacturers try to reduce its power loss. Hence the real power component can be so small that the relay cannot select the faulty line. Therefore, this relay type may face more application problem in the future.

Transient (Wischer) earth fault protection

Transient (Wischer) earth fault protection compares the polarity of the first zero-sequence current peak to the polarity of the first zero-sequence voltage peak when the single phase-to-ground fault ignites. In the healthy feeders the polarity of the zero-sequence current pulse is the same as the polarity of the voltage. In the faulty feeder the current transformer measures the zero-sequence current pulse of the healthy feeders in reverse direction. The transient earth-fault protection detects the polarity of the current pulses and finds the faulty feeder using this principle.

This principle is suitable when there is a low fault resistance. However, if the fault resistance is high, then the zero-sequence voltage increases very slowly, so there is a high chance that the protection relay will not be able to find the first voltage peak. The reason for the gradually increasing voltage is that the high fault resistance does not allow charging the capacitors rapidly. *Figure 2* shows an example of an earth fault with high fault resistance. In *Figure 2* the first channel shows the zero-sequence voltage, then the second channel shows the zero-sequence current of a healthy feeder, and the third channel shows the zero-sequence current of the faulty feeder.

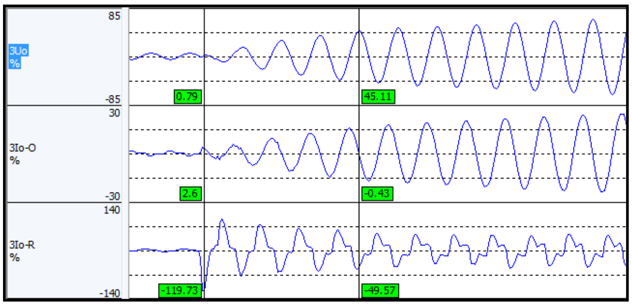

Figure 2. Earth fault with high fault resistance

The zero-sequence voltage reaches 30% of the nominal voltage after 4 cycles (30% is a general setting for the earth fault protections to start the relay). The voltage is very low when the fault occurs, so the relay is not able to compare the peak values, and thus, the relay cannot select the faulty line.

Earth fault protection using temporary grounding resistor

This protection method has a very basic concept: a grounding resistor is switched parallel to the Petersen coil during the earth fault. The switched resistance decreases the impedance of the zero-sequence network (it is a shunt impedance), so the fault current increases in the faulty line. The value of the resistance can be low or high, and depending on this value, the used protection method can be different:

1. If the value of the resistance is **low** (primary 50-100Ω), then the increased zero-sequence fault current is high. In this case an overcurrent protection can select the faulty line. The main problem with this solution is that earth faults with high fault resistance (>100-200Ω) cannot be detected as the fault resistance decreases the level of the fault current. If the fault resistance is high, then the current increase will not be sufficient. The other problem is that high earth fault current can cause dangerous step and touch voltage around the fault location. The step and touch voltage also depends on the natural grounding resistance.

2. If the value of the resistance is **high** (primary 500-2500Ω), then the real power component is increased. In this case the wattmetric protection can select the faulty line. This can be a possible solution for the fault detection. However, it still has some disadvantages: even a small current increase hugely decrease the chance of arc self-extinction. Another problem is that the method is sensitive to the error of the current transformers: the error can significantly decrease the real power component. So instead of the simple Holmgreen-connection of the current transformers, a special ring-type current transformer must be used in order to eliminate the current transformer error.

THE NEW EARTH FAULT PROTECTION

To overcome the drawbacks of the above-mentioned protective principles, Protecta has been developing a new type of earth fault protection (called as “earth fault protection based on admittance change detection”) for years [1]. The main idea is to switch on an additional coil (with known reactance) parallel with the Petersen-coil and to detect its influence on the measured zero-sequence admittance of the feeders. *Figure 3* shows the zero-sequence network for admittance calculation.

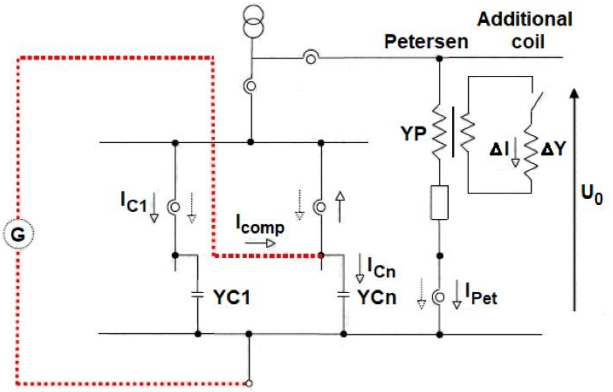

Figure 3. Zero-sequence network with the additional coil

The dotted red line represents the fault circuit, where the positive- and negative-sequence impedances are neglected. All the feeder protection relays measure the zero-sequence admittances of the feeders ($Y_0 = I_0 / U_0$). When a single phase-to-ground fault occurs, the relays measure these admittances:

1. At the healthy feeders, relays measure the own capacitive admittances:

$$Y_1' = \frac{I_{C1}}{U_0} = Y_{C1}$$

2. At the faulty feeder, relay measures the total zero-sequence admittance added to the own capacitive admittance:

$$Y_2' = \frac{-(I_{comp} - I_{Cn})}{U_0} = Y_{tot} + Y_{Cn}$$

After one second the transformer protection switches on the additional coil, which is connected to the power winding of the Petersen coil. The measured admittances will be the following:

1. Relays at the healthy feeders measure the own capacitive admittances again, so the measured admittances do not change:

$$Y_1^{"} = \frac{I_{C1}}{U_0} = Y_{C1}$$

2. Relay at the faulty feeder measures the total zero-sequence admittance added to the own capacitive admittance, plus the admittance of the additional coil:

$$Y_2^{"} = \frac{-(I_{comp} - I_{Cn} + \Delta I_{pri})}{U_0} = Y_{tot} + Y_{Cn} + \Delta Y_{pri}$$

The relay evaluates the measured admittances after a defined time:

1. If the admittance does not change, the relay identifies the feeder as healthy one, and there will not be any operation,
2. If the admittance changes with the admittance of the additional coil, the relay identifies the feeder as faulty one, and there will be operation.

Advantages

This concept is very simple and reliable as the relay expects a determined admittance change during the earth fault. The main advantages of this new method:

- the fault current remains low, so the step and touch voltage at the fault location is significantly decreased,
- if the network is undercompensated, the additional coil can set the compensation of the network near to resonance (called as "adaptive compensation"), so the chance of clearing earth faults is significantly higher,
- the reconstruction work related to the new method is minimal: primary work is not needed, only an installation into the secondary network (power winding of the Petersen coil) is required,
- this new type of earth fault protection can work with other traditional protections as well: the additional coil is switched on after one second, and there is enough time before that for other earth fault protections to operate if necessary,
- there are no such angle setting problems as in case of wattmetric protections,
- protection relays can be used with current transformers connected in Holmgreen-connection,
- intermittent earth faults and earth faults with high fault resistance can be also detected,
- it is possible to differentiate between faults with low and high fault resistance. The relay can calculate the fault resistance,
- it is possible to operate fast (under 100 msec.) when there is a live working on an energized line (see below).

EXPERIENCES

This new earth fault protection has been already installed to several Hungarian substations, and it has been under test for almost 5 years. The device gets the zero-sequence currents from the feeder and of course, it measures the common zero-sequence voltage, which is provided from the delta side of the voltage transformer.

The additional coil switching was controlled from the substation and the coil was built to the power winding of the Petersen coil. *Figure 4* shows how the coil was placed into a marshaling box.

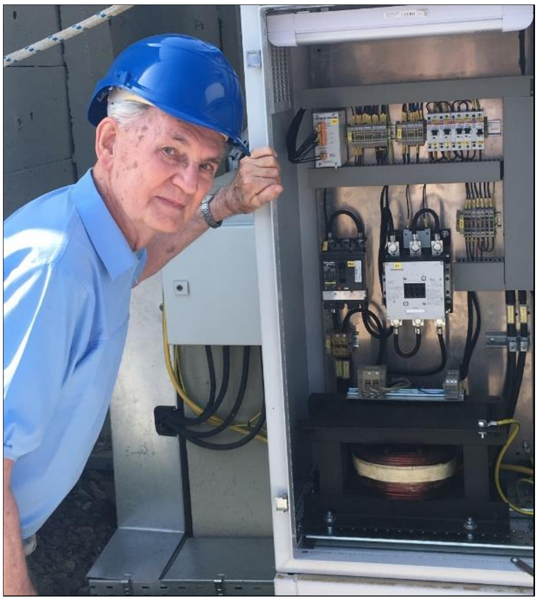

Figure 4. The installed additional coil

During the 5 years of testing the devices recorded many events:

- in hundreds of cases the earth faults were naturally cleared by the Petersen coil,
- around 54 recorded earth faults occurred on the affected feeders,
- the protective relays detected all the low, high resistance and intermittent faults correctly.

Recorded faults

Earth faults with low fault resistance

Figure 5 shows a typical earth fault with low fault resistance. In *Figure 5* the first channel shows the zero-sequence voltage, the second and third channels show the zero-sequence currents of two healthy feeders, and the last one shows the zero-sequence current of the faulty feeder.

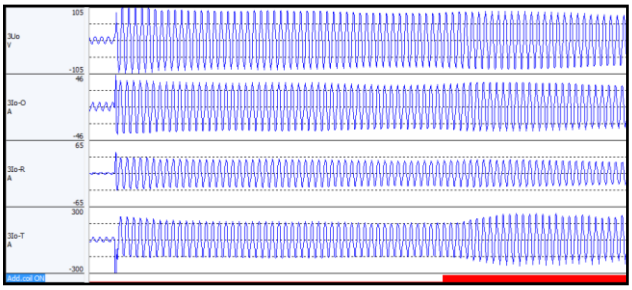

Figure 5. The influence of the additional coil during an earth fault (with low fault resistance)

When the value of 'Add. coil ON' (the coil is switched ON) turns to logical '1', the zero-sequence current starts to increase in the last ("3Io-T") channel, but on the other two channels there are no significant changes. It means that the current of the additional coil flows through only the current transformer of the faulty feeder, and this can be seen on the measured admittance as well (*Figure 6*).

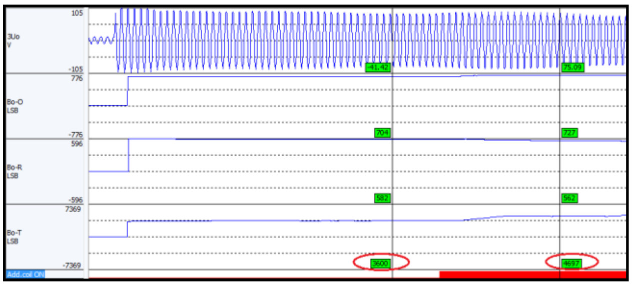

Figure 6. The measured admittances during the earth fault

The admittance of the additional coil can be calculated by:

$$\Delta Y_0^{sec.} = \left[3 * X_{\text{add.}} * \left(\frac{U_{Pet}^{prim.}}{U_{Pet}^{sec.}}\right)^2\right]^{-1} * \frac{N_{VT}}{N_{CT}} =$$

$$= \left[3 * 1{,}8\Omega * \left(\frac{13300\text{V}}{425\text{V}}\right)^2\right]^{-1} * \frac{346{,}41}{60} = 1091\mu\text{Siemens}$$

And this equals the admittance change on the last channel: 4697–3600 = 1097 µSiemens. The measured admittances in the two other feeders do not change significantly even when the additional coil is switched on. The reason for small admittance changes on these two feeders is that there are small error currents in the current transformers.

Earth faults with high fault resistance

The installed test device registered many earth faults with high fault resistance (*Figure 7*) as well. The main attribution of high resistance earth faults is the slow rise of the zero-sequence voltage.

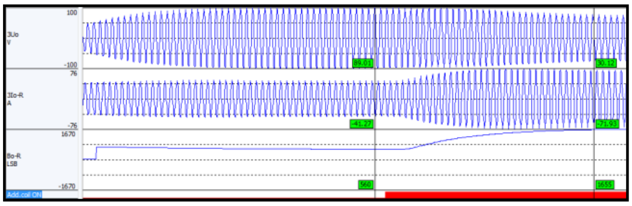

Figure 7. The influence of the additional coil during an earth fault (with high fault resistance)

The admittance of the additional coil equals the admittance change on the last channel: 1655 – 560 = 1095 µSiemens. The protective relay correctly selected the faulty feeder.

Intermittent earth faults

Most of the registered earth faults were intermittent faults. An intermittent earth-fault is a 0.05-1 millisecond self-extinguishing flash-over fault from phase to ground causing heavy transient spikes into the electric network (*Figure 8*). The frequency of the spikes can vary between 1-2 cycles and 15-20 cycles.

Figure 8. The influence of the additional coil during an intermittent earth fault

The admittance of the additional coil equals the admittance change on the last channel: 2331 – 1246 = 1085 µSiemens. The protection relay can select the feeder as a faulty one.

This example underpins the fact that the new earth fault protection method can correctly detect those intermittent faults where the earth fault is almost continuous. The frequency of the spikes increases when the additional coil is switched on, so the relay can measure higher current (which means higher admittance). But when the frequency of the spikes is low and the fault is quite unstable, then the switching of the additional coil has no significant impact on the faulty feeder. For these intermittent faults another detection method must be used (however, this is not outlined in this paper).

High-voltage live working operation mode

During the live working on an energized line, it is very important to operate quickly when an earth fault occurs on the line itself. However, for that purpose the additional coil cannot be switched on permanently because the coil must be used for the protection relays of the other feeders. Therefore, a special preparation phase is used to achieve the required fast operation during live working. The process is the following:

1. The relay of a feeder gets the request for the live working operation mode (through a binary input), so the relay can measure the own admittance of the complete feeder. The relay stores this admittance.
2. The numerical Petersen coil controller gets the command for the live working operation mode, so the controller sets the Petersen coil to 20A overcompensation or (if this cannot be achieved) to 20A undercompensation.

After this preparation phase the affected line is ready for live working. If an earth fault occurs on the network, the relay can select the faulty line using the following method:

1. If the measured admittance does not change, it means there is no earth fault on the line:

$$Y_1' = \frac{I_{C1}}{U_0} = Y_{C1}$$

2. If the measured admittance change equals the total zero-sequence admittance, it means there is an earth fault on the line, and the relay operates fast:

$$Y_2' = \frac{-(I_{comp} - I_{Cn})}{U_0} = Y_{tot} + Y_{Cn},$$

where $Y_{tot} = \frac{-I_{comp}}{U_0} = \frac{20A}{U_n/\sqrt{3}}$

During the development of the new earth fault protection, there was a testing day when one of the distribution operators of Hungary induced direct and intentional phase-to-ground faults. Protecta was able to check and verify the fast operation. The earth fault was induced as it can be seen in *Figure 9*.

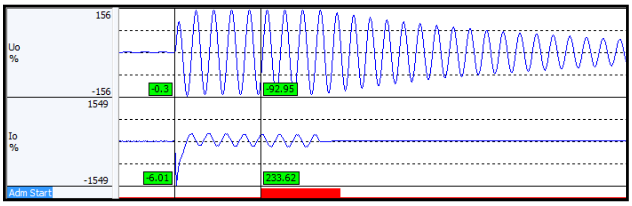

Figure 9. Earth fault during live working operation mode

The change in the binary channel called "Adm Start" means that the new earth fault protection correctly selected the line. The time between the beginning of the fault and the selection (time between the two markers on the figure) was 97 msec. So, this principle was proven by this practical test, and it can be used for earth fault protection during live working in the future.

The complete protection system

Let's see the complete protection system and how this new earth fault protection can work in a substation:

- There is a feeder protection relay with the new earth fault protection function, which measures the zero-sequence voltage and zero sequence current of the feeder. This relay protects the feeder.
- There is a transformer protection relay with the new earth fault protection function as well, which measures the zero-sequence voltage and the current of the Petersen coil. This relay can clear earth faults between the transformer and the current transformers of the feeders and can also provide a remote back-up protection for earth faults on any feeder. The relay is responsible for the switching of the additional coil as well.
- There is a numeric Petersen coil controller which has a key role in the preparation phase of the live working operation mode.

This complete system can be seen in *Figure 10*.

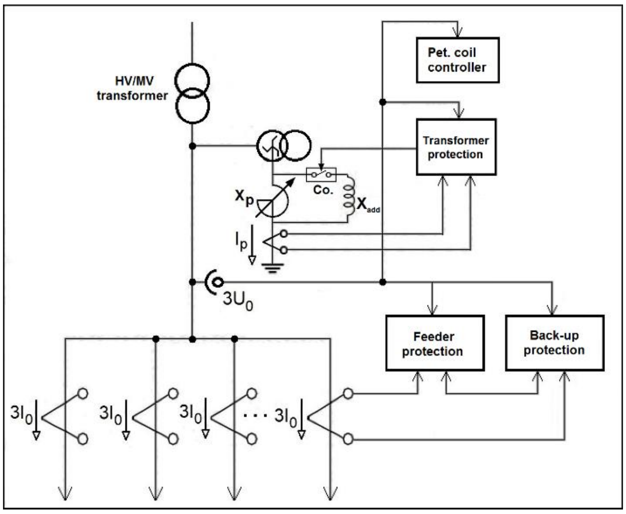

Figure 10. Complete protection system

SUMMARY

The new earth fault protection method has been successfully installed and tested in the practice. The use of additional coil increased the effectiveness of the Petersen coil. The protection devices correctly detected any type of earth fault, and it was even possible to differentiate between the three types of earth faults: the low and high resistance earth faults, and the intermittent faults. The high-voltage live working operation is also a well-functioning and suitable method. Therefore, the new earth fault protection gives an innovative and practically proven solution for detecting single phase-to-ground faults in resonant-grounded systems.

REFERENCES

[1] Dr. Kornél Petri, 2012, "Adaptive earth fault compensation and faulty line identification in distribution networks", *PACWorld conference*