ADVANTAGES OF THE NEW COMBINATION: PETERSEN-COIL AND FAULTY-PHASE-EARTHING

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ABSTRACT

The results of field tests have shown, that the behaviour of the restriking earthfault in a cable is completely different in isolated and compensated networks.
Due to the different behaviour, there are new possibilities to reduce the current via the fault location. One of these new concepts will also be presented in this paper.
Additionally, this paper will present the influence of travelling waves to limit the maximum current via the fault location and on the self-distinguishing of arcs in case of restriking faults in well-tuned compensated networks. Using new methods and devices, this behaviour enables to reduce the current at the fault location dramatically.
It will be shown that the use of the faulty phase earthing enables a correct tuning of the Petersen-Coil, even during the earthfault. Up to now, the advantages of the Petersen-Coil in cable networks were called into question. In this paper it will be shown that the new combination of Petersen-Coil and Faulty-Phase-Earthing is an ideal combination for linear impedances (stationary earthfaults) and nonlinear impedances (restriking earthfault) at the fault location.

INTRODUCTION

In many European countries the "resonant grounding" is one of the most important options in electrical network design, in order to obtain the optimal power supply quality. The main advantages of an earthfault-compensated network are:

- Self-healing of the system without any intervention of protection systems
- Continuing the network operation during a sustained single line earth-fault
- Improved power quality and reliability for the customer
- Reduction of the current via the fault location to 2% - 3% of the whole capacitive current

The first main advantage of this neutral-point-treatment is the fact, that in most cases the system is self-healing, as the arc distinguishes without any intervention of the protection system. The second main advantage is the possibility of continuing the network operation during a sustained earth fault. As a consequence this reduces the number of interruptions of the customers power supply.

With the increased use of cables the advantages of the Petersen-Coils are called into question, as the fault is always restriking until it becomes a line-to-line-to-ground-fault (LLG-fault) or a cross-country fault.

BASIC OF THE EARTHFAULT

To explain the transient behaviour of a single-line earth fault in more detail, the scheme of a substation (Fig. 1) with three feeders (A, B and C) and an earth fault in line 1 of feeder A will be used [1].

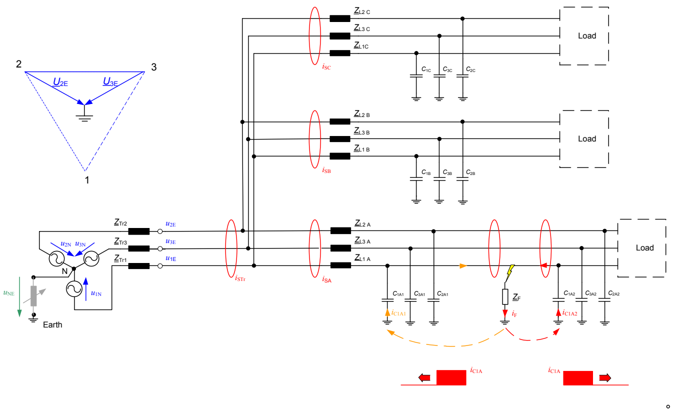

Fig. 1 Discharge of the faulty line via earth

The transient parts of an earthfault cannot be described using "symmetrical components". For the mathematical description either the αβ-components introduced by Edith Clarke [11] or the space-vector description introduced by K.P. Kovács [10] should be used. The second method is widespread, in the reduced form, for the description of frequency converters for motor drives. Reduced, because in these applications there is no zero-sequence in use. A detailed explanation of the space vector theory applied to power systems can be found in [4][5][6]
With the beginning of the earth-fault two different processes can be superposed [1]. The following two processes are starting at the same time, but with different duration:

- discharge of the faulty line over the earth
- charging of the two healthy lines over the earth

The two processes end in the stationary state of the earth fault.

Discharge of the faulty line via earth

The lines can be considered as a distributed lattice network, consisting of a distributed complex serial

impedance and a distributed $\underline{Z}'_{Lxx} = R' + j\omega L'_{Lxx}$ line-to-ground capacitance C'_{Lxx}. The highest probability for the first ignition is near the maximum of the line-to-ground voltage u_{1G}. At this time the line has about the maximum charge. The discharge of the lattice network of line 1 will start at the fault location and it will spread in both directions to the ends of line 1. A reflection of the waves occurs at the end of the line, respectively at every change of the characteristic impedance $\underline{Z}_c$ of the line. These reflections can be detected in form of oscillations at a high frequency in the zero-sequence-current and in the zero-sequence-voltage. The oscillation frequency essentially depends on the serial impedance and the line-to-ground capacity, which are, in a first approximation, inversely proportional to the length of the line. Therefore, the frequency is higher for small networks and it is lower for large networks.
According to the time-domain equations (1) and (2) of a single-conductor line [5]

$$-\frac{\partial u(x,t)}{\partial x} = R'\,i(x,t) + L'\frac{\partial i(x,t)}{\partial t} \quad (1)$$

$$-\frac{\partial i(x,t)}{\partial x} = G'\,u(x,t) + C'\frac{\partial u(x,t)}{\partial t} \quad (2)$$

the velocity for a lossless line can be estimated as

$$v = \frac{1}{\sqrt{L'C'}} = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}} \approx \frac{c}{\sqrt{\varepsilon_r}} \quad (3)$$

with $\varepsilon_r = 1$ for overhead lines and $\varepsilon_r = 2.3 \ldots 3.5$ for cables [9]. For a more accurate modelling of a line, the frequency dependency of the line-parameters must be taken into account The characteristic impedance of the lossless line (surge impedance) is

$$\underline{Z}_c = \sqrt{\frac{L'}{C'}} \quad (4)$$

with a value of about 400 Ohm for overhead lines and about 40 Ohm for cables. **This surge impedance limits the discharge current of the line**.

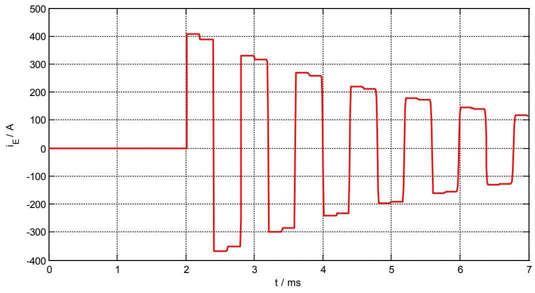

*Fig. 2 Discharge current of a loaded cable (11.5 kV * sqrt(2), 20km, NA2XS2Y 150mm²).*

The simulation with SimPowerSystem using a model with distributed parameters confirms, that the maximum discharge current in a standard 20 kV cable is limited to about 400 A [1], as depicted in Fig. 2.

Charge of the two healthy lines via earth

As a result of the discharge of the faulty line, the triangle of the line-to-ground voltages is destroyed. As the supply-transformer is still delivering a symmetrical three- phase-system, the two healthy lines will be charged to the line-to-line voltage in isolated and compensated networks.

Stationary state of the earth fault

In an isolated network the whole capacitive current of all feeders flows via the fault location.
For compensated networks the situation is different. In this case, the current through the Petersen-Coil superposes and reduces the capacitive current over the fault location. In a well-tuned network the capacitive current over the fault location is completely compensated.
Using a Petersen-Coil, the fundamental current over the fault location can be reduced to the small wattmetric part, which is usually in the range of 2 % to 3 % of the whole capacitive line-to-ground current of the network. During the transient state of the earthfault ignition respectively during the first ms, the Petersen-Coil has no or low compensation effect [1]. But after few periods the capacitive current via the fault location is compensated more or less completely. In a well-tuned network only the wattmetric part flows over the fault location.

RESTRIKING EARTHFAULT IN A CABLE-SECTION

Fig. 3 shows a line-to-ground-fault (LG-fault) in a cable. Due to the fault, an air-channel is developing with higher pressure. The isolation level of the air gap is smaller than the one of the dielectric. In overhead lines (OHL) the air is self-healing after the arc has extinguished [2][3]. The self-healing of the OHL-network is supported by the Petersen-Coil.

In cables the isolation-level of the air gap is too small, so that there will be always a re-ignition of the arc [1].

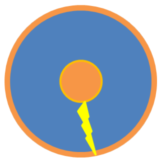

Fig. 3 LG-fault in a cable section.

Fig. 4 shows the behaviour of a restriking fault in a cable-section: During the whole earth fault, the voltage u_{L1} is zero only for very short times. The low current arc extinguishes within few milliseconds at the zero-crossing of the current. As the investigated network is a compensated network, the phase voltage u_{L1} increases slowly. The increase of the voltage in a cable network goes up to the restriking voltage, which is in the range between 2 kV and 6 kV in a 20-kV-network. This restriking voltage depends on different parameters and it is not constant, neither during an earth fault.

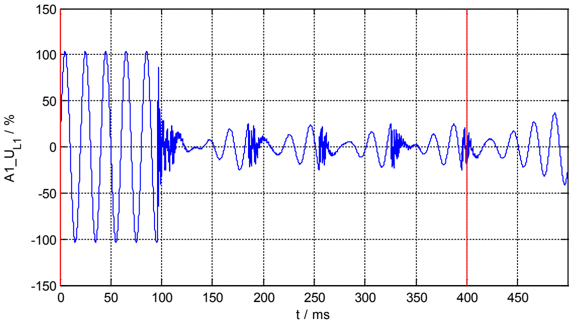

Fig. 4 Voltage u_{L1} measured at the bus-bar

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Fig. 2 shows the behaviour of the fault current in case of a solid earthfault. In this simulation it was assumed, that there is no restriking voltage. Real measurements have confirmed, that in a well-tuned compensated network the following items are valid:

- The arc in a cable-section with a restriking voltage will distinguish after the first zero-crossing of the current via the fault location.
- The length of the pulse depends on the network length. The burning time of the arc is reduced from continuous burning to few ms with a replication of some periods
- The amplitude of the discharge-current via the fault location is limited by the surge impedance of the network (Fig. 6) and is more or less constant during the pulse.
- The time for the next restrike mainly depends on:
  - the detuning of the network
  - the damping of the network
  - restriking voltage of the cable-air-gap
  - pressure, temperature and consistency of the gas in the cable-air-gap
- Due to the limited amplitude of the discharge current, due to the reduction of the burning time and due to the increase of the restriking time, the converted energy at the fault location is reduced to some 100 W.

Fig. 7 shows the behaviour of the restriking for the case of an ideal tuned network. The time in-between the restrikes is increased.

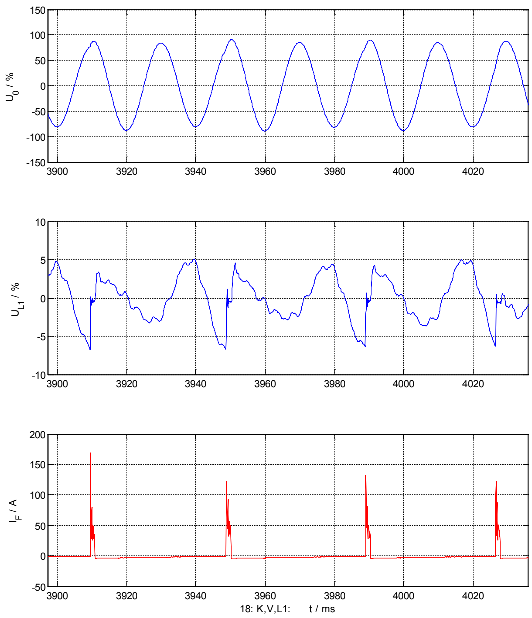

Fig. 5 Restriking fault in a cable section of a well-tuned compensated network

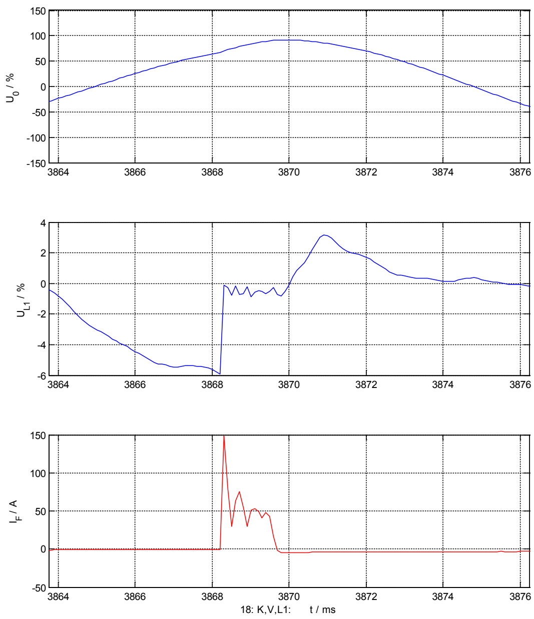

Fig. 6 Zoomed window of Fig. 5

Up to now the classification for the network and the handling auf SL-faults is:

- Networks with OHL (cable / OHL < 10%)
- Mixed networks (10% < cable / OHL < 90%)
- Cable-Network (cable / OHL > 90%)

In the future, we should classify according to the point, where the fault occurs:

- Earth-fault in the cable section => restriking
- Earth-fault in the OHL section => quasi-stationary

In case of restriking earthfaults, it is possible to improve the function of the Petersen-Coil with the faulty-phase-earthing (FPE).

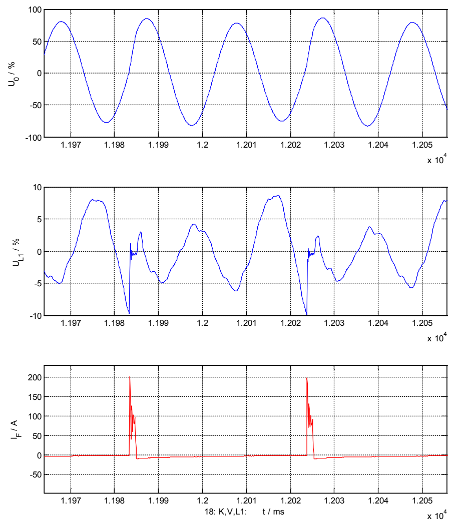

Fig. 7 Restriking fault in a cable section of an ideal tuned compensated network

FAULTY-PHASE-EARTHING (FPE)

Fig. 8 shows the situation in case of a single LG-fault. The not compensated current flows via the fault location.

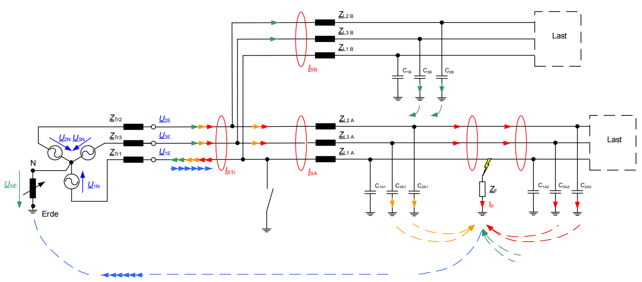

Fig. 8 Faulty-Phase-Earthing (FPE) stand by

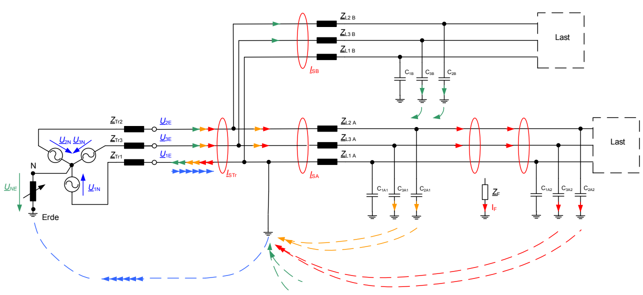

Fig. 9 Faulty-Phase-Earthing (FPE) activated

In Fig. 9 the FPE is activated and the fault current is now flowing via the grounded phase in the substation. Due to the cable, the restriking voltage at the fault location is in the range of 1… 6 kV. This restriking voltage is now the allowed voltage drop from the substation to the fault-location, as a result of the load current. Due to this high restriking voltage of the cable, the arc at the fault location will not re-ignite. High restriking voltage can be find in all faults with an air-gap with constant gap-length like in cable joints, cable sealing end and so on.

The resulting advantages of the FPE are:

- During the active FPE, the earthfault-current is moved from the fault-location to the well-grounded substation. At the point of the damaged cable no current flows to the earth and therefore no power conversion occurs at the fault location
- As there is no current via the fault location, also the touch and step-voltage is reduced
- As there is no current via the fault location, also the often discussed problems with harmonic currents in the residual current are eliminated.
- The positive-sequence-system is not influenced by the earthfault, so that the customers on the LV-network do not see the isolation problem in the MV-system.
- In addition, there is no more a restriking earthfault with corresponding voltage spikes on the two healthy phases.
- Relays for the correct and reliable recognition of restriking earthfaults already exist.
- As already mentioned above: during the active FPE the earthfault-current is moved from the fault-location to the well-grounded substation. Therefore it is now possible, to measure the current via the fault location in the substation and **to make a correct tuning operation with the Peterse-Coil, even during the earthfault.**
- Due to the control of the Petersen-Coil during the earthfault, it is now possible to react on changes in the network size and to move the Petersen-Coil to the correct tuning position. In all actual controllers on the market, the control of the Petersen-Coil is blocked during the earthfault.
- For the localisation of the fault after switching operations the FPE must be reopened to check if the earthfault is removed. In case of a restrike, the earthfault still exists in the compensated network and the FPE will be closed immediately.
- The used vacuum-switch is suitable for short-circuit-currents, so that also cross-country-faults are under control.

- The correct detection of the faulty phase under all possible earthfault scenarios is a challenge, but possible with the new E-FPE controller
- A Petersen-Coil, well-tuned to the resonance-point, supports the functionality of the FPE. The restriking voltage is increased, due to the longer available time to cool down the plasma after the last flashover.

Fig. 10 shows for example a combination of a Petersen-Coil with a ZigZag transformer and an integrated Faulty-Phase-Earthing. The real implementation of this combination is depicted in Fig. 11.

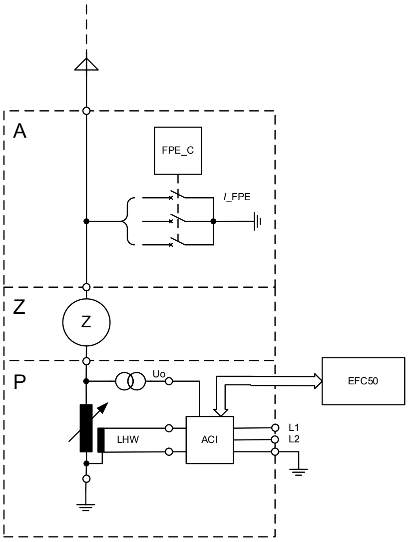

Fig. 10 Petersen-Coil combination with ZigZag-transformer and integrated Faulty-Phase-Earthing (FPE)

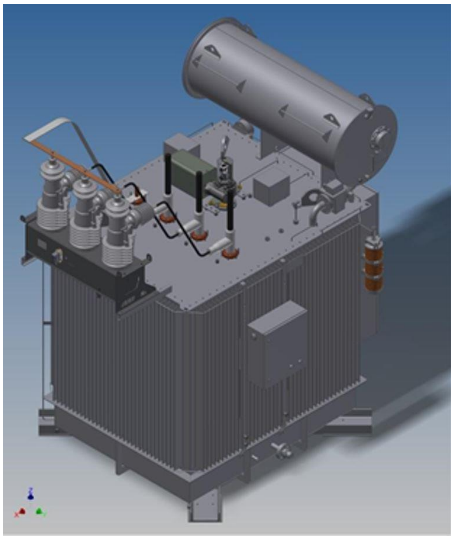

Fig. 11 Combination of Petersen-Coil with ZN-Transformer and Faulty-Phase-Earthing

The advantage of the combination FPE and Petersen-Coil is, that the FPE will be activated by the new relays, when earthfaults occur in the cable-section. If the earthfault is in the range of the OHL all the well-known advantages of the Petersen-Coil remain available.

SUMMARY

Due to the new relays and the new classification of earthfaults:

- Earth-fault in the cable section => restriking
- Earth-fault in the OHL section => quasi-stationary

a different handling of the fault situation can be initiated.

If the fault is in the range of the OHL, the well-known advantages of the Petersen-Coil can be used.

If the fault occurs in the cable-section, the fault can be moved from the faulty cable-section to the substation by using the Faulty-Phase-Earthing (FPE) device. Due to the nonlinearity and the high restriking voltage of the cable-fault, there will be no restriking and therefore no fault-current via the original fault-location.

The FPE ideally complements the advantages of the Petersen-Coil in OHL lines in cases of earthfaults in cable sections.

In addition, using the FPE a tuning of the Petersen-Coil also during the earthfault is possible.

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