Circulating currents in closed loop structure, a new problematic in distribution networks

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Abstract-- **Loop operation of distribution networks is more and more common. The increasing penetration of distributed generation and higher power quality requirement are making the loop structure more interesting. We study the impact of the unbalanced phase impedances. Measurements and simulations show that it creates a mutual coupling between the positive sequence and the zero sequence system. Balanced load creates a zero sequence voltage between two feeders. Their connection of the both ends to form a loop results in circulation of a zero sequence current. In case of an earth fault this current will be added to the fault current and can negatively influence the protection devices. Healthy lines do not have active current in the zero sequence system because there is only capacitance connection with the earth but the circulating current change this hypothesis. We propose a study of this problematic current for simple and multi loop in distribution networks.**

Index Terms-- **Circulating current, earth fault, isolated network, compensated network, closed loop**

I. INTRODUCTION

Distribution networks in Europe have been changing since several years. The increasing demand for distributed generation systems is changing the philosophy of the distribution network use. The previous passive contribution of the network is turning into a more active one with a real contribution in the electricity production [1]. Generally, most of the distribution networks are operated in open loop due to security and protection limits. However the increased demand for a better power quality makes the distribution networks operate more and more in closed loop mode instead of open loop mode [2], [3], [4].

In Europe, the use of three phases transformers and their connection in delta creates no or a very small zero sequence current during healthy operation. However, the closed loop structure might produce circulation of zero-sequence current because of unbalanced serial impedance in the line [1], [5] or coupling with parallel lines [6]. State of the art earth fault protection algorithms could malfunction due to such zero sequence currents. Lot of protection algorithms dealing with the zero sequence measurement supposes that there is no interaction between the load and the zero sequence system. For example, some devices measure the active zero sequence current level to detect if the feeder is faulty. They consider that there is only capacitive current on the sound feeder in the zero sequence system. But in case of circulating current, active current will be measured on sound feeder too.

This paper explains the phenomena of unbalanced serial impedance that could produce such circulating current. Firstly, we present the theoretical context of the circulating current and explain how they are produced in a simple loop and multi loop systems. Recordings of earth fault in 20kV nominal voltage in distribution network in Germany are presented. This network is a compensated network with a Petersen coil; also known as resonant network. This network has a loop of two feeders and a loop of four feeders. Then simulations have been made with the ATP/EMTP software. Based on a distributed line model of overhead lines and cables, the coupling between the positive and zero sequence system has been reproduced. The network studied is based on the real network parameters. Finally, some solutions to avoid the malfunctioning are suggested in the topic of transient relays in isolated and compensated networks [7].

II. DISTRIBUTION NETWORKS WITH CLOSED LOOP STRUCTURE

Networks can have different kinds of loop. The more common one is the loop made of two feeders. Generally, there are two feeders feeding the same area and connected at their both ends. The others loops are called multi loop and contains more than two feeders. These feeders are also connected at their both ends and are built to increase the power capacity of the line. This paper investigates these two kinds of loop and their differences.

A. Closed loop distribution networks

In Germany, distribution network voltage is between 6 kV and 30kV. Usually they are operated in radial mode or with loop. In such networks, underground cables are often replacing the overhead lines. These cables are usually buried in trefoil position or in flat position. The impedance of a three phase feeder can be expressed by the equation (1) with the matrix Z^{abc}.

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$$Z^{abc} = \begin{bmatrix} Z_{L1} & Z_{M12} & Z_{M13} \\ Z_{M21} & Z_{L2} & Z_{M23} \\ Z_{M31} & Z_{M32} & Z_{L3} \end{bmatrix} \tag{1}$$

The matrix Z^{abc} represents the impedance series and mutual coupling of a three phase conductor. Z_{M12} represents the impedance between the phase L1 and the phase L2. Z_{L1} represents the impedance of the phase L1. This impedance can be described in the symmetrical component with the transformation of the matrix with the matrix A.

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \tag{2}$$

with the symbol a; a phase angle of 120°.

$$a = e^{j2\pi/3} \tag{3}$$

The impedance matrix of the symmetrical components is calculated with equation (4):

$$Z^{012} = A^{-1} Z^{abc} A \tag{4}$$

Usually, the mutual coupling between the phase impedance is considered as the same for every phase. With such assumptions, the matrix Z^{012} is diagonal and there is no coupling between the symmetrical systems.

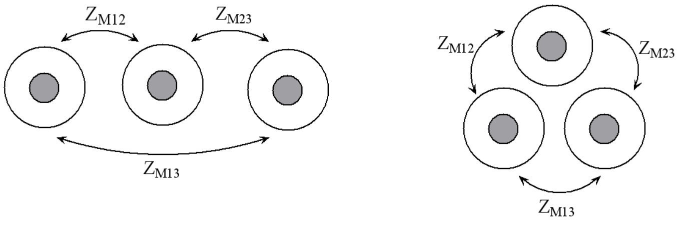
$$Z^{012} = \begin{bmatrix} Z0 & 0 & 0 \\ 0 & Z1 & 0 \\ 0 & 0 & Z2 \end{bmatrix} \tag{5}$$

where Z0, Z1 and Z2 are respectively the zero-sequence impedance, the positive sequence impedance and the negative sequence impedance

The position of the cables influences the serial impedance of the feeder. The mutual coupling between the phases is the same if the cables are laid in a trefoil position as shown in Fig. 1 b). This is obviously not the same in case of Fig. 1 a) where the cables are laid in a parallel position. They have an unbalanced impedance matrix. The same problem can occur on overhead lines but usually the phases are transposed [8], [9].

The unbalance in the serial impedance of the feeder creates a mutual coupling in the matrix impedance. The zero sequence and the positive sequence systems are connected even during healthy condition. Generally, the symmetrical component impedance matrix is diagonal as in equation (5) but if it is assumed that Z_{M12}, Z_{M13} and Z_{M23} are different a coupling between the systems appears. The matrix Z^{012} is not diagonal anymore as stated by equation (6).

$$Z^{012} = \begin{bmatrix} Z0 & M01 & M02 \\ M10 & Z1 & M12 \\ M20 & M21 & Z2 \end{bmatrix} \tag{6}$$



a) b)

Fig. 1: a) Single conductors in trefoil
b) Single conductors in parallel

If the mutual coupling is not neglected as in equation (6), then equation (7) proves that a positive sequence current will create a zero sequence voltage. This coupling is represented in Fig. 2 by M01.

$$\begin{bmatrix} U0 \\ U1 \\ U2 \end{bmatrix} = Z^{012} \begin{bmatrix} I0 \\ I1 \\ I2 \end{bmatrix} \tag{7}$$

Fig. 2 illustrates that even in sound operation a zero sequence voltage can be measured only because a perfectly balanced load current is supplied.

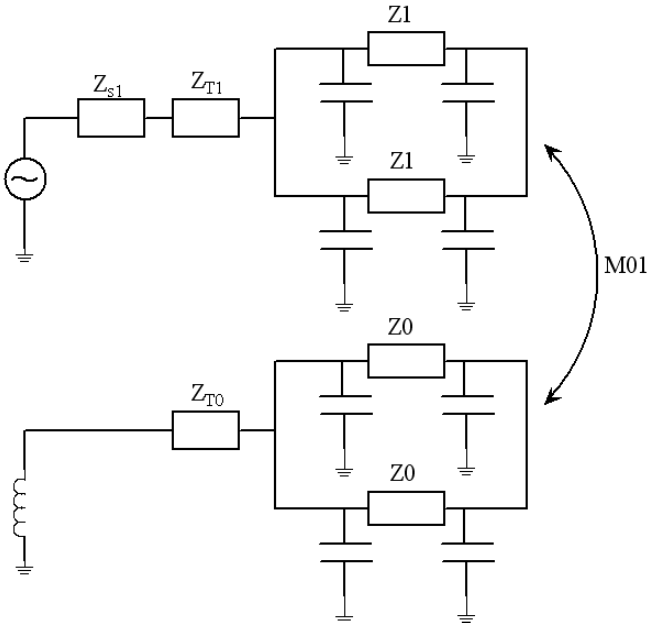


Fig. 2: The positive sequence system and the zero sequence system are connected by mutual impedance. Zero sequence voltage is measured during healthy operation.

During healthy operation, the zero-sequence voltage and current are very small in European distribution networks because of the use of three phase transformers in the MV/LV. A lot of protection devices use the zero-sequence components to detect an earth fault. Presence of zero sequence voltage (U0) can be a criterion for the detection of an earth fault in the network. The unbalance of the phases is creating a small zero sequence voltage that is not very high. In radial networks, only a small capacitive current is produced because U0 applied on the phase to earth capacitance of the feeder.

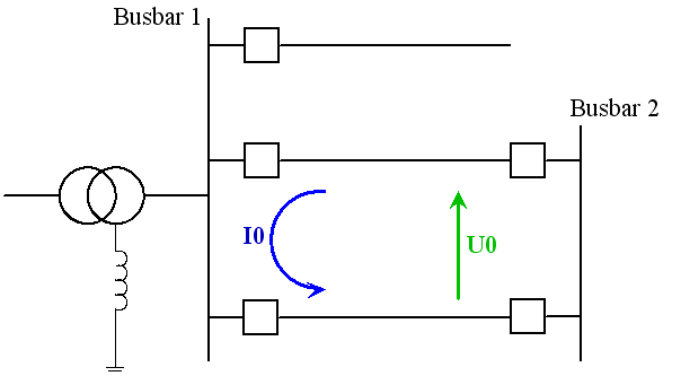


Fig. 3: Connection of two feeders with unbalanced phase impedance causes circulating current.

In case of loop structure caused by e.g. connecting two feeders, a zero sequence voltage is applied between the two feeders and a zero sequence current can circulate in the loop in addition to the capacitive current. This explanation is illustrated on Fig. 3 for a closed loop of two feeders in a compensated network. Only because of the serial impedance of the lines, such currents may show amplitudes up to several Amps primary. Such values are enough to negatively influence fault detection algorithms.

Fig. 2 and Fig. 3 prove that even a perfect positive sequence system with balanced load can produce zero sequence current, which is usually considered as an indicator for earth faults.

The circulating current depends on the positive sequence load and the unbalance of the serial phase impedances. The unbalance does not change during the life of the network and the load is generally very stable; it does not change within a short period of time. The amplitude of this current will be relatively constant compared to the evolution of an earth fault.

B. *Multi loop networks*

Loop structures are more and more used; some distribution system operators now have loops of more than two feeders. This is sometimes due to a needed increase of the power capacity. E.g. several feeders are contained in the loop and connected to the same underlying busbar. In case of underground cables, the feeder cables can be placed in the same trench. The cables of different feeders might be placed in parallel for kilometers with a distance of around half a meter to each other. The mutual zero sequence coupling between the loops is no more negligible. The current circulating in a ring has an impact on the other rings. Higher amplitudes of the current can be expected in case of such multi loop systems.

The Fig. 4 illustrates this mutual coupling between the feeders of the same loop and the coupling with the positive sequence system in a compensated network.

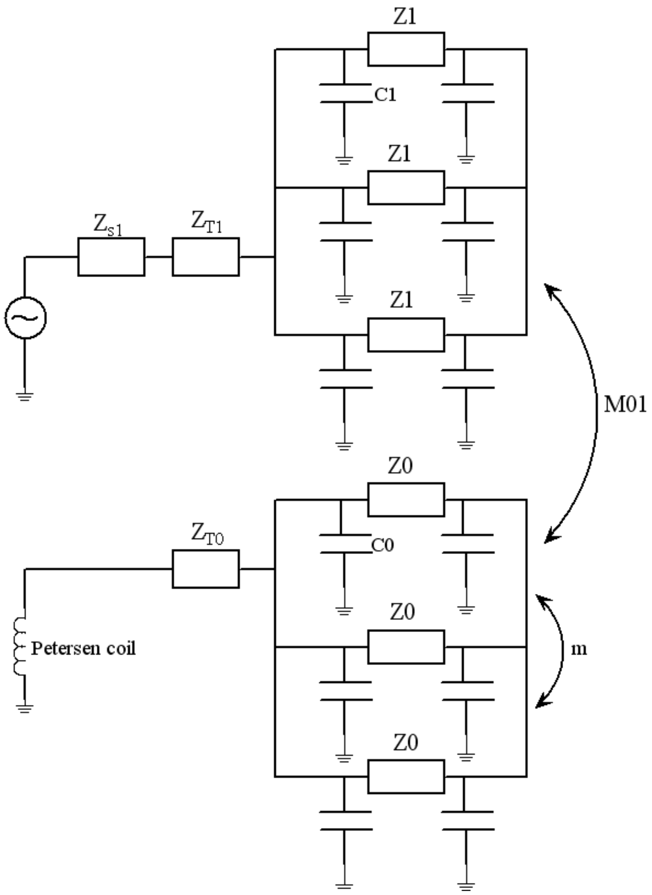


Fig. 4: In addition to mutual coupling between the positive sequence system and the zero sequence system, a mutual coupling in the zero sequence system itself is also to consider in the multi loop system.

III. FIELD MEASUREMENTS

Measurements in a German compensated network have been recorded in the purpose to obtain data for single phase earth fault. There circulating currents have been measured. Some results are shown in this paper. The aim of the recordings was to record fault information but circulating currents are clearly visible before the fault inception.

The recordings have been done by a digital fault recorder SIMEAS-R. The recordings of the zero sequence voltage show no voltage before the fault. The SIMEAS-R has a threshold level and if the voltage is below the threshold no recording takes place. According to the simulation, the voltage is small (around 20V primary) before the fault inception which is below the recording level of the SIMEAS-R. The current is circulating only in the serial impedance of the loop which is small. A very small voltage is then needed to make the current circulate.

A. *The network*

The network is a compensated distribution network operated by Pfalzwerke Netzgesellschaft GmbH. The nominal voltage is 20kV. The network consists of two busbars, each supplied by a distribution transformer. A scheme of this network is shown in Fig. 5.

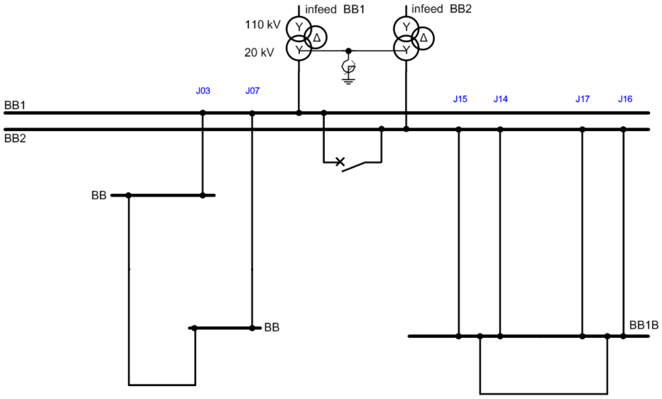


Fig. 5: Network builds with a loop of two and four feeders where the field measurements have been recorded.

The two transformers have their neutral point connected to a Petersen coil which compensates the capacitive current in case of an earth fault. This method is greatly reducing the fault current.

Feeder J03 and J07 form a closed loop and they are a mix of underground cables and overhead lines. Feeders J14, J15, J16 and J17 are completely underground cables and are connected to form one loop. According to the distribution system operator (DSO), the cables are placed in parallel for 2 kilometers with to distance of approximately 40 cm to each other.

B. *The measurements*

A trigger on the zero sequence voltage started the recorder. This trigger is reached only during a single phase earth fault because this phenomenon produces high voltage. Therefore the circulating currents are only observable alone during the pre-fault records.

Circulating currents are measured in both loops. The proof that they are circulating is that the sum of the four currents is approximately zero. The remaining current is mainly the capacitive current created by the small zero sequence voltage. In the loop of two feeders, the circulating current is around 1 A primary. In the loop of four feeders, circulating currents are between 2 A and 3 A primary. The voltage shows the presence of a fault in the network because the voltage produced by the unbalanced impedance seems to be too small. For a fault, the amplitude is varying at each period and the signal is not as stable as the circulating current.

Around 20 earth faults have been recorded from this network, most of them were temporary. The circulating current has always been measured on the loop of four feeders with different but very stable amplitude. These measurements seem to consolidate the idea of a coupling between the load or positive system and the zero sequence system. On the loop of two feeders, the circulating current was not always measured and the amplitude was always smaller than on the multi loop.

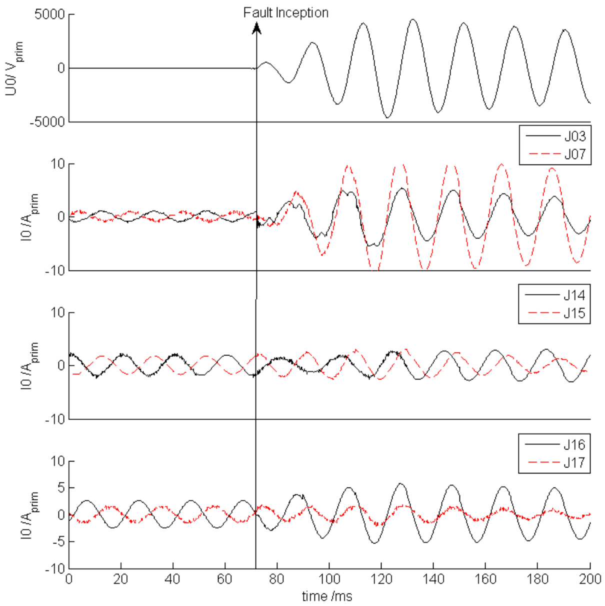


Fig. 6: Field measurement shows circulating current before a single phase earth fault on feeder J03 and J07.

Due to this circulating current, the earth fault signal is corrupted by a current that does not have specific behavior - i.e. capacitive or inductive. In compensated or isolated networks, several protection devices are using the capacitive behavior of the sound feeder as reference for sound feeder. Anything that has a non capacitive behavior will be considered as a faulty feeder. For example, an algorithm evaluating the active current as a fault indicator will measure an active current on every healthy loop. This can lead to wrong fault detection.

The recording presented next on Fig. 7 is even worse regarding the need of secure fault detection. On feeders 14, 15, 16 and 17, the magnitude of the current during the fault is not higher than the pre fault value. The detection of the faulty feeder is much more difficult in this case because the information from the circulating current is more dominant than the zero sequence current due to the fault.

As stated before, under healthy operation no zero sequence current or only a very small one can be observed. Thus the detection of high impedance faults is not the biggest challenge in distribution networks in Europe. However, the detection is more difficult in case of closed loop structure because the circulating current amplitude is the same order than the current caused by the fault.

Field measurements show that the zero sequence current can be even decreased during a single phase earth fault because of such a circulating current. In case of high impedance faults, the current of the faulty feeder can have smaller amplitude than the circulating current. If the phase angle of the faulty current is 180° relative to the circulating current, the sum of the two will result in a small zero-sequence current. If a protection device tests the sound behavior of the feeder, the circulating current will lead to a completely wrong result.

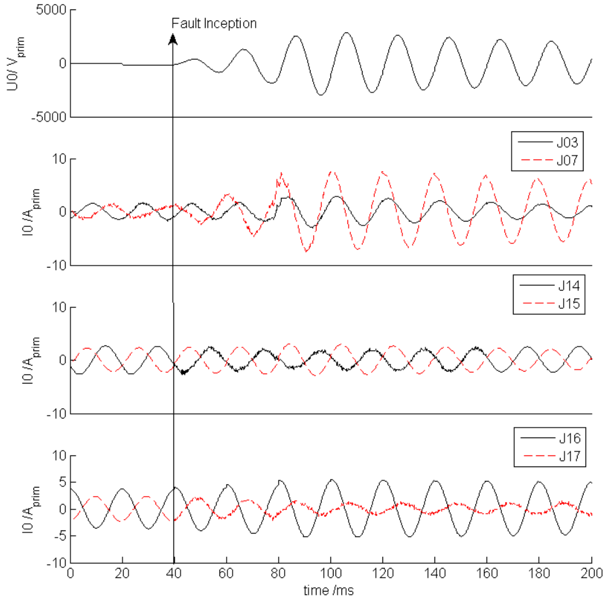


Fig. 7: On some recordings, circulating currents are higher than the fault current for the four feeders loop. Fault occurs on J03 and J07.

Some protection devices are using only the transient part of the signal and they filter the 50 Hz component. These devices should not be disturbed by the circulating current because it affects mainly the fundamental component. However, these devices have not a good sensitivity regarding the fault impedance.

IV. ANALYSIS BY SIMULATION

Influenced of the unbalanced in the matrix impedances have been studied. We have also analyzed the coupling between several feeders in case of multi loop system and the impact on the circulating current amplitude. This section describes the simulated network and the results of the simulations.

Simulations have been made with the ATP/EMTP software. The models used are distributed overhead lines and underground cables. Cables are based on a Bergeron model and overhead lines are simulated with a JMarti model. In the simulated network, we have tried to obtain the same zero sequence capacitance than the real network.

A. The network studied

A network with a loop of two feeders and a loop of four feeders has been simulated trying to reproduce the real network from the field measurement with the data available. Underground cables have been studied; the feeders are in parallel for 2 kilometers with to distance approximately 40 cm to each other. The length of the lines has been adapted to match the zero sequence capacitance of each feeder of the real network and its serial impedances. The position of the cables has been set in the way to obtain a difference of impedance in the phase impedance and consider the mutual coupling between the loops. However, the flat position has not been implemented because the distribution system operator had indicated that the cables were laid in a trefoil position. A trefoil position has been implemented without symmetrical position to obtain a mutual coupling between the systems.

There are two different busbars connected to their own transformer but these transformers have the same neutral and the Petersen coil is compensating both networks with an overcompensation of 10%. Each transformer has a nominal power of 10 MVA.

The four feeders loop consists only of cables and the two feeders loop consists of a mix of overhead lines and cables.

B. Influence of the load power on the amplitude of the circulating current

On Fig. 8, the position of the single core cables in ATP are illustrated. The characteristic of the single core are encoded and the software is computing the symmetrical component parameters based on the Bergeron method.

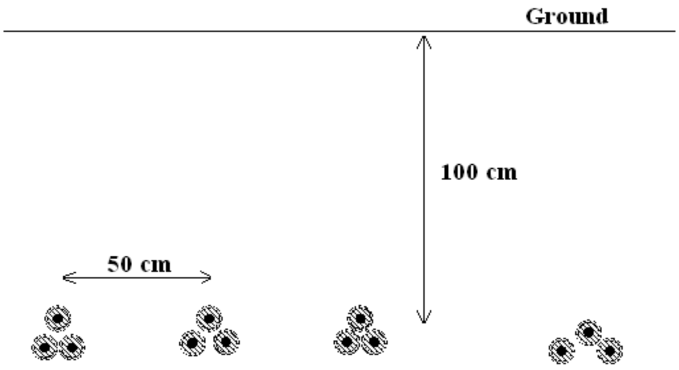


Fig. 8: Position of the single core cables in the soil. Simulation of the four feeders loop in ATP/EMTP

The simulations have been performed, simulated for different value of the perfectly balanced load from 0 to 50% of the nominal power of the transformer.

The zero sequence voltage remains very small and does not disturb the protection devices. Its maximum amplitude has been measured to 0.5% of the nominal voltage. This voltage is measured on the both busbar and the radial feeder will produce zero sequence current which is not circulating. However, this zero sequence current measured on the radial feeder is caused by the voltage on the zero sequence capacitances of the line. This current is a sound one for the protection devices that protect the network.

The circulating current amplitude is proportional to the load because the positive sequence current is directly influencing the zero sequence system. The zero sequence current can represent 6% of the nominal current of the network.

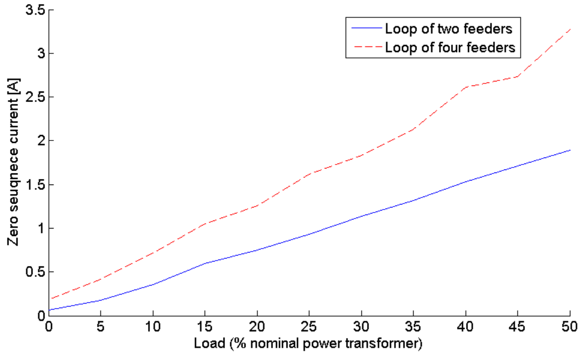


Fig. 9: Influence of the load power on the zero sequence circulating current in case of loop of two and four feeders.

Simulations have proved the link between the positive sequence system and the zero sequence system due to unbalanced serial impedance in loop. This current can have a big impact on protection because this current does not have the expected behavior for a proper detection of the faulty feeder. In case of high impedance fault it can be observed that the zero sequence current caused by the fault is smaller than the zero sequence circulating current.

However, this circulating current is probably stable during the whole fault because the load is not disturbed by a single phase earth fault in such network. The phase to phase voltage does not vary in case of single phase to earth fault. This current is then stable if the consideration that the load is constant during the time window for the earth fault detection. Estimating the phase angle and the amplitude of this current during the pre fault state could allow filtering this component without filtering the 50Hz component produced by the fault at least for the first 100 millisecond after the fault inception. Active filter and non linear filter could be solution.

Another solution is to consider the loop as a single feeder. The sum of the current of each feeder from one loop makes the circulating current equals to zero. The effect of this current is not measured anymore and the detection of an earth fault can be done as usual. This solution could have the disadvantage to not detecting the faulty part of the loop anymore. As a consequence a fault would be cleared unselective.

V. Conclusions

This paper presents a problematic of the more and more common closed loop structure in distribution network. The position of the cables and overhead lines can create unbalance in the matrix impedance. This unbalanced system has a mutual coupling between the positive sequence and the zero sequence system which could be neglected in radial structure. A zero sequence voltage is induced on both feeder and if they are connected at both ends, a circulating current will flow in the loop. Multi loops structures are also studied and show that the circulating current can be even bigger in this case due to mutual coupling between the zero sequence systems.

This circulating current can negatively influence state of the art protection devices because it creates randomly active or reactive current measurement. Some devices are measuring the active current on each feeder and if this current is too high, the feeder is considered as faulty. Such relays could not work when circulating currents are measured on the loop.

Because these currents depend on the load power, the amplitude and phase of this current is supposed to be stable during the faulty process. Estimating this current during the pre fault state and filtering it for the faulty state with active or non linear filter could allow a correct detection of the fault. Another method could be to consider the loop as a single feeder by summing the current of each feeder. This sum will eliminate the circulating current part of the signal and keep only the faulty information.

VI. Acknowledgment

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VIII. Biographies

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Prof. Jean-Claude Maun Jean-Claude Maun received the M.Sc degree in mechanical and electrical engineering in 1976 and the Ph.D. degree in Applied Sciences in 1981, both from the Université Libre de Bruxelles (ULB), Brussels, Belgium. He joined the Electrical Engineering Department of this university in 1976 and he is now professor and Dean of the ULB Engineering School.

He has been leading research projects in the field of the design of digital protections for Siemens as a consultant. An emeritus member of the Société des Electriciens et Electroniciens français and a recipient of many academic awards, Prof. Maun is an recognized expert in electrical networks' safety and protection systems as well as, more generally, in power transport and distribution networks and in decentralized electricity generation.