DETECTION OF SINGLE PHASE EARTH FAULT IN COMPENSATED NETWORK WITH C0 ESTIMATION

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ABSTRACT

Single phase earth fault in compensated network creates faulty current with very small magnitude. The connection of a Petersen Coil in the transformer neutral turns the zero sequence impedance into very high ohmic system. The small faulty current makes the detection of the faulty feeder impossible with simple over current protection. That is why algorithms are using transients.
This paper presents a novel method to detect such earth fault with a strong sensitivity regarding the fault impedance. The algorithm builds a model of the sound feeder behaviour using the zero sequence voltage and current. The healthy feeder can be considered as a zero sequence capacitance. By measuring the deviation of a perfectly capacitive feeder, the faulty one can be detected. Algorithm description and tests are presented with comparison of small impedance fault and high impedance with recordings and simulations.

INTRODUCTION

Several strategies to ground the transformer neutral exist in Europe. The classic technique of connection is the solidly grounded and the isolated. Solidly grounded network creates a very strong faulty current and does not need lot of insulation because single phase earth fault will not rise the phase to ground voltage. The isolated strategy gives relatively mean faulty current depending on the total zero sequence capacitance but it needs higher insulation because single phase earth fault creates voltage increasing on the sound phases. Some Distribution System Operators (DSOs) are placing a resistance in the neutral of the transform which limits the faulty current. The extreme solution to reduce the faulty current is to place an inductance in the transformer neutral to compensate the zero sequence capacitance of the network. The impact of such method is the small faulty current in case of single phase earth fault because the zero sequence system has very high impedance which limits the fault current. This allows the continuous operation of the network even in faulty condition but it makes difficult the detection of the fault.

During faulty operation, the fault must be located to isolate the faulty section and makes the repair. Some locators exist using the transient [1], the travelling wave [2] or the steady state signal [3]. These systems could be very powerful to locate a relatively precise section of the faulty feeder but seems relatively expensive. The most common method is cheaper and is based on a detection method. Measurements are made in the main substation and the faulty feeder is detected. The fault location is not known accurately but the faulty piece of the network is known. Some devices provide the direction of the fault at the main substation. The transient signal is used to make the direction decision. Some devices use the healthy behavior of the feeder to detect if the feeder is healthy or not. This system is based on the capacitance behavior of the sound feeder [4], [5].

This paper presents a new method to determine the faulty feeder in a compensated or isolated network. The presented algorithm assumes the sound feeders act as a zero sequence capacitance and not the faulty feeder. By measuring the deviation from a perfect capacitive model, the faulty feeder can be detected.

The first section presents the phenomena that appear when a single phase earth fault happens in a compensated network. The explanation of why a sound feeder can be assumed to be a capacitance and not a faulty feeder is made. The transient and the steady state are described to valid this assumption.

The second part details the algorithm and how the deviation is computed and integrated. Least squares method is used to estimate the capacitance and an error signal is built to improve the sensitivity regarding fault impedance.

The third section shows some simulations and recordings test of the algorithm. Some figures illustrate the operation of the detection for small impedance fault and the difficulty of detecting high impedance.

THE PHENOMENA DURING EARTH FAULT

A single phase earth fault can be divided in two pieces; the transient that occurs at the beginning of the fault due to a sudden stress on the network and the steady state signal that stays once the faulty state is stable.

The transient appears in case of low impedance fault because the voltage on the healthy phases will increase and the voltage on the faulty phase will decrease. This sudden increasing will oscillate the network and a current flow coming from the fault and going toward the healthy phase is measured. Using the zero sequence system measurement clearly shows an opposite direction of the current from the faulty feeder and the current from the healthy ones. This transient is represented by the big arrows on the figure 1. In case of high impedance fault, the network does not oscillate because the damping is too strong. However, the fault impedance makes the healthy phases charging very slowly and it takes several periods for the voltage to reach the steady state. The beginning of this transient shows also a distinction between the sound and faulty feeder.
Regarding the steady state, once the transient is gone, a current in the zero sequence system is still measured. This

current is proportional to the zero sequence capacitance of the feeder because zero sequence voltage applied creates a circulation of capacitive current in this healthy feeder. The faulty feeder has also capacitive current because no steady state current is flowing through the fault in theory with perfectly compensated network. This is why compensated network has usually intermittent fault, only the transient is going through the fault and then the Petersen coil blocks the fifty Hertz component. If the network is not perfectly compensated, then the measured capacitive current is not equal to the current going to the whole capacitance of the faulty feeder but it is bigger in case of over compensation and smaller in case of under compensation. Over compensation is when the inductance is too high compared to the total zero sequence capacitance of the network. In this case, steady state current will flow through the flow and this is the surplus of inductive current from the Petersen coil absorbs by the capacitance. This inductive current will reduced the zero sequence capacitive current seen from the faulty feeder. This is the opposite for under compensation.

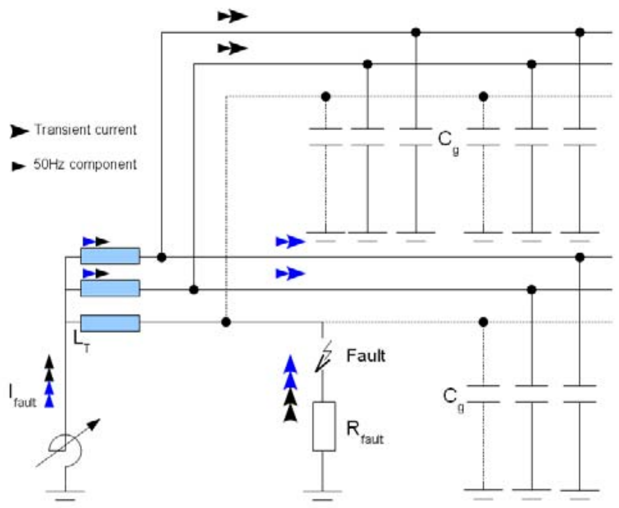

Fig. 1: Current flow creates by the earth fault

In the reality, the Petersen coil is not a perfect inductance because current leaks occur and can be modeled by the connection of a parallel resistance. If such resistance is taken into account in the model, then a non capacitive current will circulate in this resistance and through the fault. Then the faulty feeder is not perfectly capacitive anymore compare to the healthy feeder during the steady state.

The theory presented shows that the zero sequence system makes the sound feeder acts as zero sequence capacitance during transient and the steady state and the faulty feeder does not. The figure below shows the adjusted amplitude zero sequence voltage V0 and the zero sequence current I0 for a sound and a faulty feeder. The transient has a frequency which depends on the network capacitance, inductance and fault distance. This transient is completely opposite for the faulty feeder compared to the sound feeder. However, the steady state has just a small phase angle and makes the faulty feeder not perfectly capacitive. This is due to the imperfection of the coil as stated above.

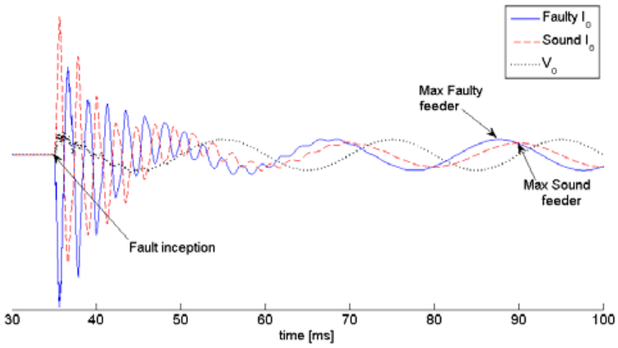

Fig. 2: Difference between the faulty and a sound feeder in a perfectly compensated network (simulation ATP/EMTP)

THE C0 DETECTION ALGORITHM

As the theory described the behavior of a sound feeder, the algorithm presented in this paper is based on the verification of this behavior. A way to quantify the deviation of a perfectly capacitive model has been found.

Using this assumption, the equation below can describe the sound feeder by measuring the zero sequence current $i_0(t)$ and voltage $v_0(t)$.

$$C_0(v_0(t)-v_0(t_0))=\int_{t_0}^{t} i_0(t)dt \qquad (1)$$

C_0 is the feeder capacitance and t_0 is the time when the algorithm starts. This equation cannot be verified because the zero sequence capacitance is usually not known with enough accuracy by the users. However, it can be assumed that the feeder is sound and based on enough sample (e.g. one period or two) a least square method can be applied to estimate a capacitance value. The integral of the current can be computed and results in the amount of zero sequence charge until the sample k; $q_0(k)$. The least square method gives the C_0 estimation of the equation 2 with N the number of samples measured.

$$C_0^{-1}=\frac{\left(N\sum_{k=1}^{N}u_0(k)q_0(k)-\sum_{k=1}^{N}q_0(k)\sum_{k=1}^{N}u_0(k)\right)}{\det A} \qquad (2)$$

$$A=\begin{bmatrix}\sum_{k=1}^{N}q_0(k)^2 & \sum_{k=1}^{N}q_0(k)\\ \sum_{k=1}^{N}q_0(k) & N\end{bmatrix} \qquad (3)$$

Once the algorithm has computed a value of the zero sequence capacitance for one or two periods, an error signal can be computed using the same samples by measuring the deviation from the perfectly capacitive behavior using the equation 4.

$$\varepsilon(k)=u_0(k)-\frac{q_0(k)}{C_0} \qquad (4)$$

This error signal measures the deviation from the perfectly capacitive behavior for the sample k. However, in case of high impedance fault, the deviation might be very small which implies a very difficult detection. An integration of this signal is then suggested to memorize the deviation history.

The integral can be done on the square of the function or an even power factor of the error signal to increase the contribution higher deviation.

For the detection of the faulty feeder, a threshold is set because the noise and imperfection of measurements create small error on sound feeder which must be distinguished of the faulty signal. Once the error signal reaches the threshold, the algorithm considers this feeder as faulty. The computation can still run to detect intermittent earth fault or temporary earth fault.

Limitations of this algorithm will occur for extremely small overhead line. Barely any capacitance exists for such line therefore no zero sequence current is detected if the feeder is sound. The algorithm will not be able to run to indicate that the feeder is healthy. However, if the feeder is faulty strong current will come to charge the whole network zero sequence capacitance and the detection of the faulty feeder will be done correctly.
The conclusion made for the compensated network can also be made for isolated network. The sound feeder acts also as a capacitance therefore the following algorithm can detect the faulty feeder even if the characteristic is different.

SIMULATIONS AND RECORDINGS

This section illustrates the algorithm with a simulation of a small impedance fault and a recording from a German DSO of a high impedance fault.

The small impedance fault

The simulation was made by ATP/EMTP with the simulation of a three feeders network with medium zero sequence capacitance. The figure below shows the voltage signal and the current on the faulty feeder.

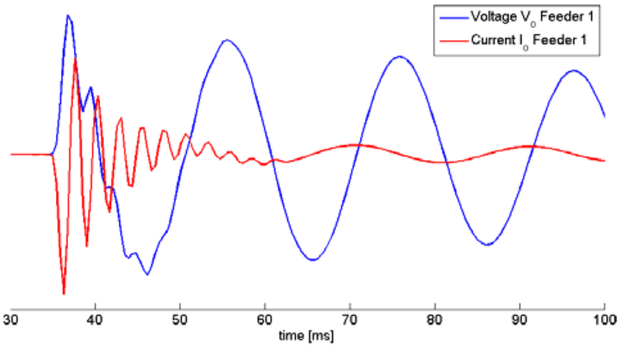

Fig. 3: Signal of a small impedance fault with a compensation factor of 95%

Once the C_0 has been estimated using the least-squares method, the voltage samples are compared to the charge divided by the capacitance computed samples. The next figure shows that the difference with the feeder 1 is very big compared to the feeder 2 which is the sound feeder.

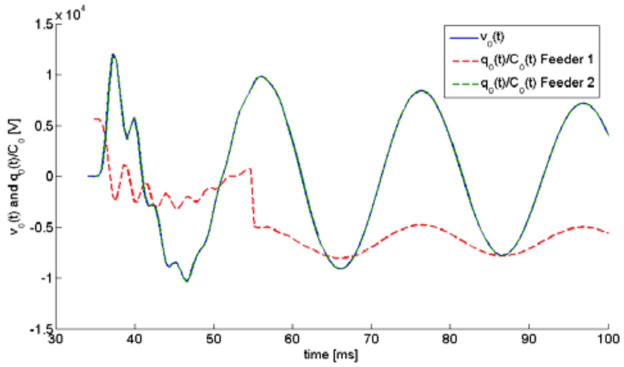

Fig. 4: Voltage signal and charge signal over C0 shows the differences between capacitive sound feeder (F1) and faulty feeder (F2)

The error signal is then very big for the feeder 1, once it is integrated, the distinction between the sound and the faulty feeder can be easily made. The figure 5 shows the results and the threshold for each feeder. The threshold value is automatically computed by the algorithm and depends on the estimated C_0 value. The feeder 1 is clearly detected faulty and the feeder 2 is undoubtedly not detected faulty. The detection is made during the first period of the fault. The estimation of the C_0 needs one period to be done than the tripping time cannot be made earlier.

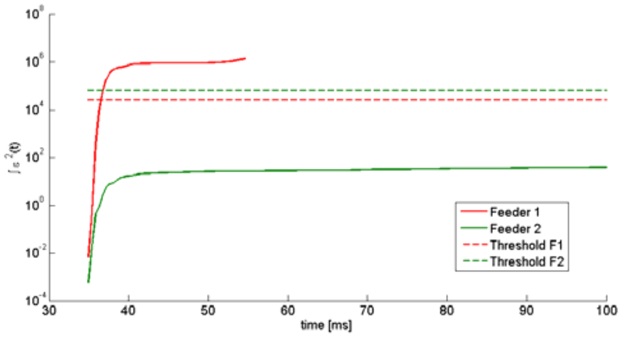

Fig. 5: Integral of the squared error signal and detection of the faulty feeder for a small impedance fault

The high impedance fault

The high impedance fault has no high frequency transient; the detection is then much harder because the major contribution in the fault information does not exist in this case.

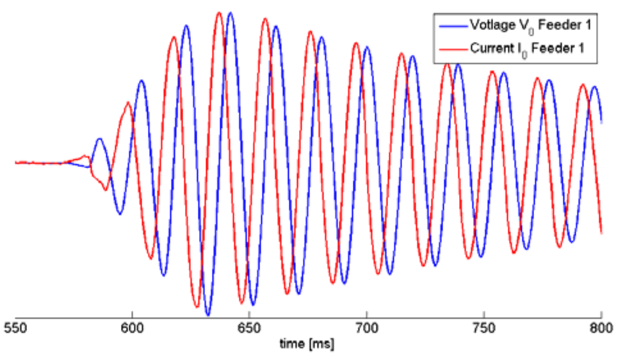

Fig. 6: Signal of a feeder with high impedance fault from a real recording

As the figure below shows it, only the beginning of the fault creates a completely wrong signal for the faulty feeder. The feeder 1 is faulty and the feeder 2 is sound. The C_0 estimated value must be in a specific range, if the estimated value is outside this range, the closest value is set. During the voltage increasing, a small difference can be noticed between the sound feeder and the faulty feeder. When the voltage is decreasing, the fault has disappeared and the faulty feeder is now sound. This small decreasing comes from the high impedance of the zero sequence system and an oscillation between the zero sequence capacitance and the Petersen coil. The frequency of this decreasing voltage depends on the compensation factor.

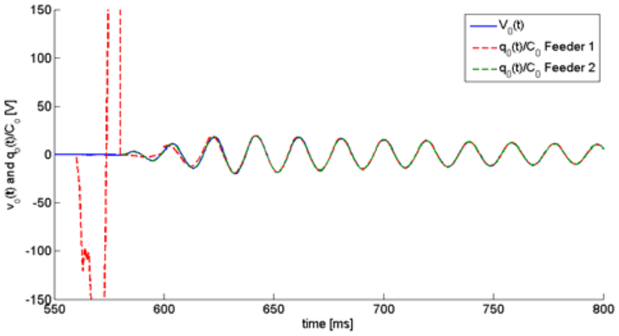

Fig. 7: Voltage signal and charge signal over C0 shows the difficulty to detect the faulty feeder after the inception of the fault

The next figure shows the integration of the squared error signal. The feeder 1 is clearly detected faulty, the algorithm is running continuously and the integration resets every five periods. The feeder 1 is not detected faulty after the reset because the fault is gone. However, if the fault has strong impedance and is continuous, the fault might be not detected because the steady state does not have enough faulty information for the algorithm. Nevertheless if the fault is intermittent, a new fault inception will bring enough energy for a novel detection.

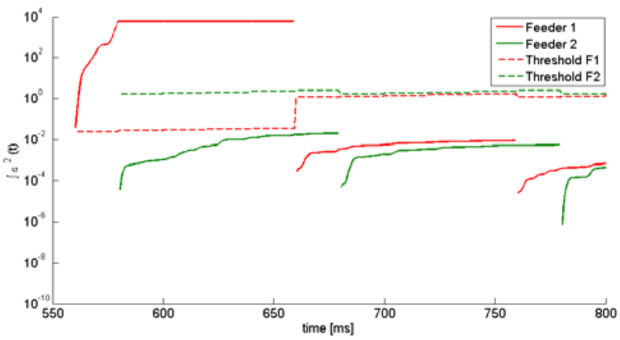

Fig. 8: Integral of the squared error signal and detection of the faulty feeder

CONCLUSION

In conclusion of this paper, an algorithm to detect the faulty feeder in a compensated and isolated network has been proposed. The algorithm uses the transient and steady state information to make its decision. The algorithm takes into account the historic of five periods which brings quite lot of information to differentiate the sound and faulty feeder.

Two electrical phenomena are used by the algorithm and have been described in this paper; the transient which comes from an increasing of the voltage of the two healthy phases and the steady state. The transient has a capacitive behaviour on the sound feeder but looks inductive on the faulty feeder because the flow is in the other direction. The steady state looks capacitive for the faulty feeder but the imperfection of the Petersen coil adds some active energy coming from the fault which differentiates the faulty and the sound steady state signal.3

The algorithm measures the zero sequence current and voltage. It integrates the current and estimates a zero sequence capacitance with a least-squares method. The deviations from this estimated model are integrated and the extremes are emphasized. A threshold is computed and the detection of the faulty feeder is done when this threshold is reached.

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