NEW DIGITAL METHOD FOR THE DIRECTIONAL DETECTION OF TRANSIENT GROUND FAULTS

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ABSTRACT

This paper describes a new digital sensitive method for the directional detection of ground faults in resonant-grounded or isolated networks. The method evaluates the transient response which occurs due to the state change after the ground fault ignition.

In the past such methods were implemented in an analog way, with disadvantages like limited sensitivity, no fault recordings and others. The analog implementation was caused by the fact that the frequency range of the transient response is large, including frequencies up to approximately 4 kHz (for the charging oscillation). Such high signal frequencies require a respectively high sampling frequency by the protection device which was usually not available in the past. With constantly increasing performance of modern digital protection devices such high sampling frequencies are now possible, allowing the implementation of fully digital algorithms for the directional detection of transient ground faults.

The basis of the direction determination is the evaluation of the discharging and charging oscillation of the networks capacitance to ground, which occurs during the first ms after the fault entry. However, due to the frequency range and the energy content mainly the charging oscillation of the sound phases is taken into account.

The criterion for direction determination is the active energy of the zero sequence system during the transient response. By means of the sign of the active energy the fault direction is determined. Especially for high resistance ground faults the new method shows a significant better sensitivity compared to analog methods which depend only on comparing the signs of neutral voltage and current.

The new method was tested and verified under different conditions. Since static testing is not applicable due to the required dynamic processes, different testing approaches were chosen.

Testing was carried out a) by means of dynamic simulations of the transient response, b) by use of ground fault recordings from the field and c) finally by a prototype application under real conditions in a meshed 110 kV network.

By the integration of this transient ground fault detection method into a modern digital multifunctional protection device all advantages of such a device (e.g. high sampled fault recording) are provided, as well as the option for the integration into an existing communication structure. Due to the high reliability of this new method in combination with the communication facilities a safe fault location at the control station site is achieved.

INTRODUCTION

Various methods are being used for the detection of ground faults in resonant-grounded or isolated networks. The simplest method evaluates the zero sequence voltage U0 (displacement voltage) or the zero sequence current 3I0. With these methods, only the detection of a ground fault is possible. The localization of the fault via the direction is not possible. Extension of the method to include evaluation of the phase difference between U0 and 3I0 makes it possible to obtain the direction of the ground fault; e.g. the watt-metric ground fault detection falls into this category. With such methods it is only possible to determine the ground fault direction under stationary fault conditions, as the direction measurement requires steady state values. In the event of non-stationary ground faults of short duration, it is not possible to obtain the direction by evaluation of the phase angle difference. Consequently, other methods based on the transient ground fault signals are applied, e.g. the transient ground fault method used in the device 7SN60.

During a ground fault in a system with compensated star point grounding, the transient ground fault effect is present during the initial ms of the fault. This is caused by the discharge of the line capacitance in the faulted phase, and the charging of the capacitance in the sound phases [1][2]. These are then followed by the fault extinction or the steady state fault current and voltage. The transient ground fault effect is typically only of a short duration (a few ms to a few network periods). The duration is primarily dependent on the system capacitance, the type of fault (high resistance, low resistance) and the duration of the fault. Low resistance faults are easier to detect than high resistance faults and generally don't present any problems to the measuring methods. The new directional transient ground fault function evaluates this transient ground fault effect within a short interval after the ground fault ignition and determines the fault direction also in the event of high-resistance faults.

The algorithm described here and tested in operation significantly increases the sensitivity e.g. as compared with the device 7SN60. Ground faults with fault resistances up to several kΩ are detected securely. By integrating the function within a multi-function protection device (e.g. 7SJ85), a separate additional transient ground fault protection device is not required. The function is thereby also fully integrated into the existing communication infrastructure. This function in combination with the described measures facilitates localizing the affected feeder section. The algorithm must function very reliably for this purpose. Static test methods are not suitable for the verification. The reliability was therefore determined with tests in the power system and simulation of various networks (e.g. meshed networks) under varied conditions.

MEASURING PRINCIPLE

The measuring principle evaluates the signals in a short interval after the ground fault ignition. At this point, the signal components resulting from charging and discharging the ground capacitance of the network are of particular interest. The discharge oscillation (frequency range 500 Hz to 1000 kHz) in the faulted phase typically ends within the first cycle of the charging oscillation. The charging oscillation (frequency range 70 Hz to 4 kHz) in the sound phases typically terminates within the first power system frequency cycle [3]. The discharge oscillation can therefore not be reliably detected, even with relatively high sampling rates (e.g. 8 kHz). The charging oscillation on the other hand can reliably be measured with higher sampling rates (e.g. 8 kHz). An important feature of these charging and discharging cycles is that they are resistive and dependent on the fault direction. This characteristic was already used by analog transient ground fault relays to determine the fault direction [2]. After detecting the fault ignition, the ground current and displacement voltage are evaluated to determine if they are in-phase or in other words have the same sign or not. This is done in a small time window following the instant of detecting the fault ignition. If the signs are not equal the fault is in the forward direction and alternatively the fault is in reverse direction.

This principle has been applied for a number of decades and provides reliable results for faults with low resistance (see Figure 1). The reason for this is that the resistive current components (charging of the network capacitance) dominate compared to the static ones – in systems with resonant grounded star point these are shifted by approx. 90°. Using this, the co-phase or opposite phase condition of the zero sequence current and zero sequence voltage will reliably determine the fault direction. In the case of high resistance faults (see Figure 2) on the other hand, the static component is dominant. As a result there is only a small phase shift between the charging transient and the static component.

During high resistance ground faults the transfer of charge between the line capacitances is slower, as these take place via the high fault resistance. These high resistance faults only result in a small phase shift away from the purely capacitive range towards the resistive range. This small phase shift must be extracted and used for the evaluation/classification of the direction.

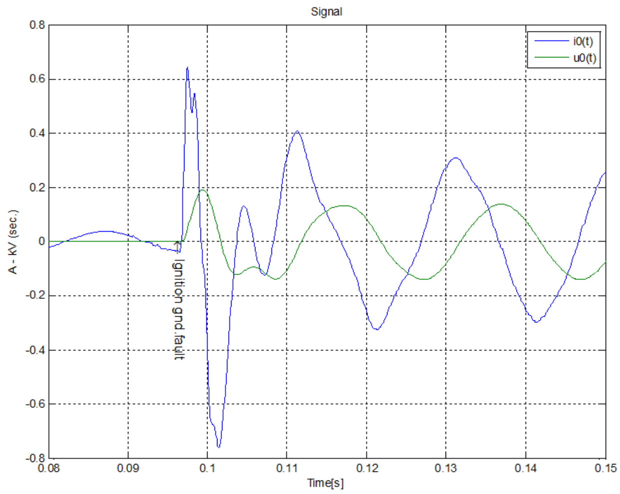

Figure 1 Low resistance ground fault

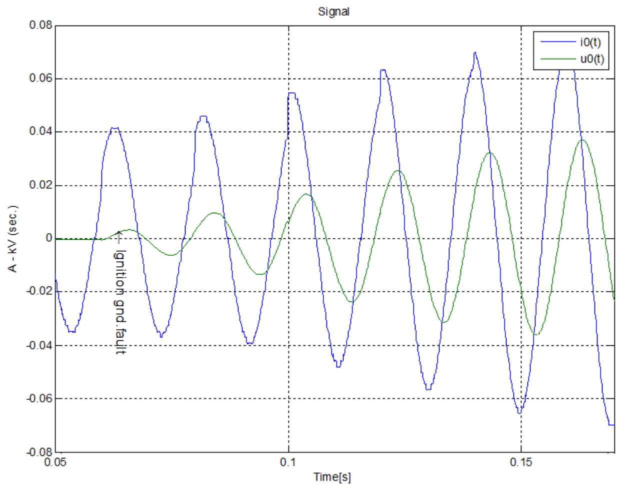

Figure 2 High resistance ground fault

The active power in the zero sequence system has proven to be a good criterion for determining the fault direction of the transient ground fault (Equation 1 and 2). This represents the resistive component of the signal. As the charging takes place over a longer period of time, the resistive component is present during this time. It therefore makes sense to form an integral of this component starting with the ground fault ignition. The result is the active energy in the zero sequence system (equation 3).

$$p_0(k) = u_0(k) i_0(k) \qquad (1)$$

$$p_a(k) = \frac{1}{T} \int_{k-T}^{k} p_0(k) \cdot dt \qquad (2)$$

$$E_0(k) = \int_{0}^{k} p_a(k) \cdot dt \qquad (3)$$

The computed active energy must then only be compared with set thresholds to determine the fault direction. Exceeding the positive threshold indicates that the fault is in reverse direction while dropping below the negative threshold shows that the fault is in the forward direction.

The thresholds required for the direction decision must still be determined. For this purpose a compromise between sensitivity and a correct direction result must be made. Three zones have proven to be effective as shown in Figure 3. The energy thresholds are additionally limited by a time Tmax after which a decision is no longer made as the charge transfer process has been largely completed by this time and the static fault condition will influence the result. The threshold for forward (-E0<) and reverse (+E0>) were determined during the previously mentioned field trials and simulations. An optimization process was applied for this purpose so that all transient ground faults that were available resulted in correct response. The results showed that the resulting two thresholds were suitable for all the transient ground faults. The user therefore does not have to determine the thresholds or set them. Of interest is that the reverse threshold is smaller than the forward threshold (not shown true to scale in Figure 3).

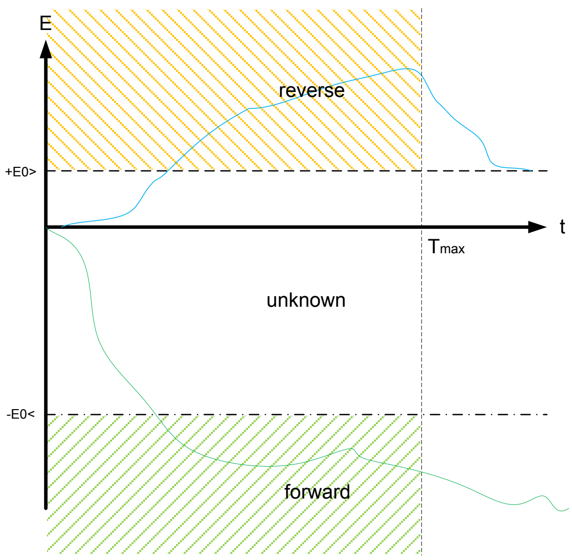

Figure 3 Zones for direction

This is plausible as the transient oscillations from all feeders are summated in the faulted feeder in the event of a forward ground fault. This results in a greater energy result in the faulted feeder (fault in forward direction) as compared with the sound feeders (fault in reverse direction).

The ground fault detection methods have a problem with circulating operational zero sequence currents that occur in meshed or closed ring networks. These currents, that result from a non-symmetry of the phase impedances or systems connected in parallel, cause the phase of the fault current to be shifted. They appear in the computed active energy of the zero sequence system. The direction of these currents does not have any correlation with the actual fault current. As a consequence the direction measurement may yield a wrong result. For correct direction measurement the elimination of these currents is necessary and this is done within the measuring method.

Initially, the simulation tool MATHLAB was used to simulate the measuring method and test and optimize its response to the available fault recordings. This field data was used to create a reference data set for testing with an OMICRON test set. With this setup the device was tested to confirm that the code in the device was working accordingly.

TEST OF THE MEASURING METHOD

Background

Contrary to many other protection functions, it is not effective or even possible to test the transient ground fault function with static test conditions. The "Omicron" test set provides a simple simulation for testing the ground fault function as well as the transient ground fault function. In this case the test corresponds to a simple radial system. This is not sufficient for the intensive testing that is necessary for a newly developed measuring method.

For testing the measuring method data from a number of sources may be used. These are:

- Artificial data
- Data obtained with dynamic simulation
- Field data from real ground faults

A further possibility is the application of prototypes in the real power system.

Apart from the data required for testing the directional ground fault function, the network topology also plays a large part in determining the faulted feeder. The following network topologies need to be considered:

- Radial network
- Meshed network or ring network

Most methods are reliable in radial networks. Experience has shown that meshed or ring networks pose a greater problem for the localization of the faulted feeder. For the tests with data obtained from dynamic simulation, amongst others, 2 topologies that are oriented on real systems were used. This also allowed the comparison of simulation data with real fault recordings, which validated the simulation results. This procedure allowed further testing by modification of the test parameters. These parameters were:

- Fault location
- Fault resistance
- Fault duration
- Point of ground fault ignition
- Degree of compensation (over / under compensated)

Testing Methodology

The new measuring method was developed and tested using approximately 200 fault recordings from a medium voltage ring network N1 (Figure 4) and simulation data from a radial network. The fault recordings have a high sampling rate and were classified according to the fault nature, so that they were suitable for the tests. The implementation was done in a prototype, which had to detect all the faults correctly. The prototype performance was permanently compared with the MATHLAB simulation during the entire testing process. The resulting prototype was then installed in network N2.

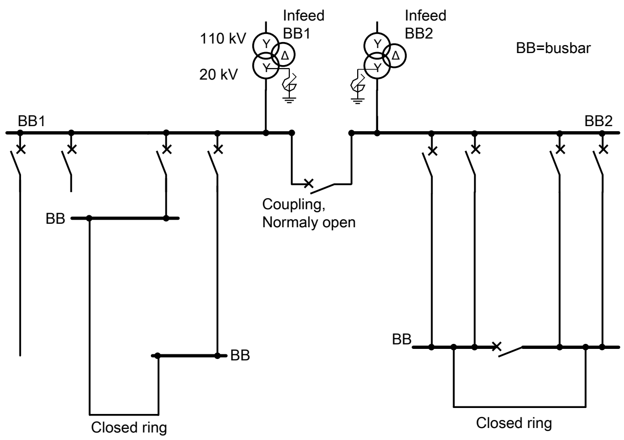

Figure 4: Ring network N1

To collect experience, and to determine the suitability of the new transient ground fault measuring method, a field test was conducted, where four protection devices were applied in a KELAG meshed 110 kV system (Figure 5). In essence, this was a 110 kV parallel line in a high alpine region with a high incidence of thunderstorm activity. Furthermore pump storage generators were connected to one of the parallel lines. The large number of incidents within two years (transient ground faults, switching operations, generation and pumping operation) resulted in a comprehensive data set for further evaluation.

The KELAG network proved to be very well suited for this purpose, as tests for ground fault localization procedures had already been done there before [4], which made accessible experience and infrastructure for the detection and localization of ground faults possible.

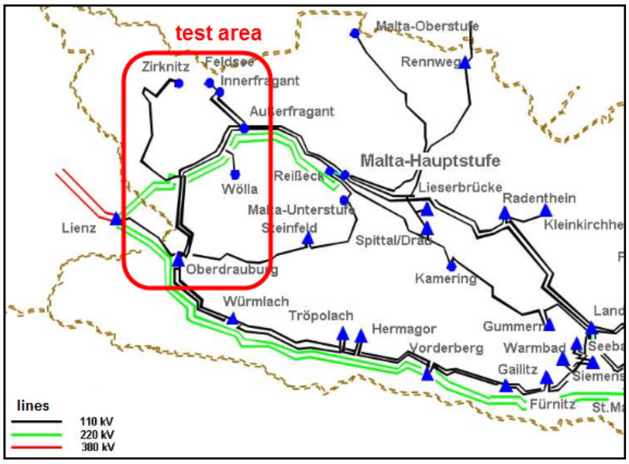

Figure 5: 110kV network N2

The network N2 is schematically shown in Figure 6. The protected parallel line has a length of approx. 40 km. The one line has two T-Offs to the pump storage generators (LG1, LG2additionally. Due to the superimposed ring (lines Ln1, Ln2, Ln3) and the T-Offs LG1 and LG2 the demands on protection functionality are challenging.

Field test of the prototype

The devices were applied to the parallel lines A1-A2 and B1-B2, where they operated in parallel to the already installed ground fault detection devices. The function was applied with a high sensitivity to obtain fault recordings from other influencing conditions, which were not ground faults. All the ground faults on the observed parallel lines were detected correctly. A large number of ground faults in the remaining system were detected. The very sensitive setting of the function resulted in a pick-up during switching operations in the system. With the applied SIPROTEC 5 devices it was possible to register fault recordings with a sampling rate of up to 8 kHz. This wass absolutely necessary for the analysis of the transient ground fault effect. These fault recordings were then used for further optimization of the transient ground fault function and were added to the field record test data base. The modified function was subsequently tested with all the already available test cases and had to provide the same results, as well as remain stable during switching operations. The devices in the KELAG network N2 were then updated with the improved measuring method and remained in operation. Since the inception of the tests with the improved measuring method, approx. 100 new ground faults have occurred. All of these were correctly detected. A pick-up during switching operations no longer occurred.

The close cooperation with the system operator thereby resulted in an improvement and optimization of the algorithm under real operating conditions. These tests are ongoing and will be continued in the future. Consequently the field data base will be increased continuously.

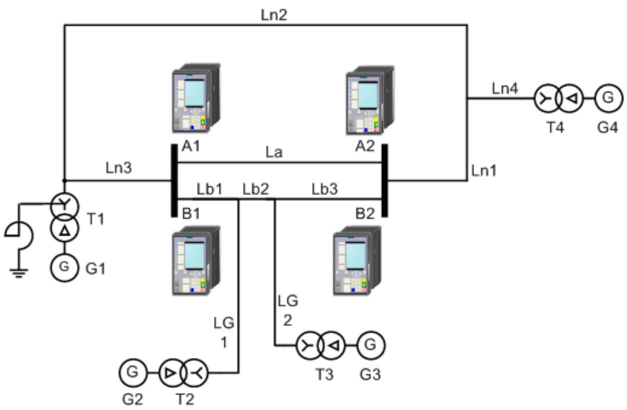

Figure 6 Schematic representation of network N2

Simulation results

The network N2 that was used for testing is shown in Figure 6. It was transferred into a simulation. This allowed further investigation of the transient ground fault function. Of particular interest is the boundary presented by the detection of high resistance ground faults. For this purpose the fault location and the fault resistance can be varied.

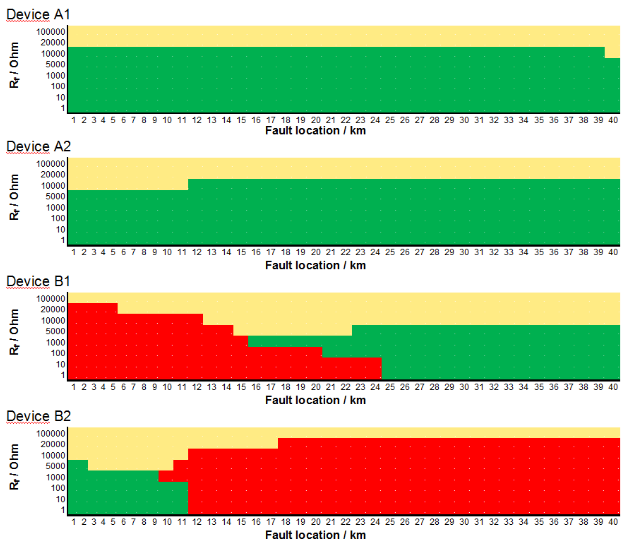

Figure 7 Fault resistance versus fault location for the line La

Figure 7 shows the result obtained with devices A1, A2, B1 and B2 for ground faults on the line La (green = forward, yellow = no decision, red = reverse). Up to 5 kΩ the forward direction is securely obtained. Meanwhile the 5 kΩ sensitivity has been confirmed by customer testing.

Close to the relay location it is even possible to obtain good results up to 10kΩ. On the sound parallel line Lb the direction reverses as expected. This fact however does not result in a measurement where the line Lb is indicated as the faulted line.

SUMMARY

Modern digital protection devices can provide high sampling frequencies (e.g. 8 kHz) which allow measuring the transient response after the ground fault ignition. This was a precondition to develop a new digital and sensitive transient ground fault detection function.

The methodology, whereby algorithms are developed in MATHLAB and the target system in parallel, as well as prototype testing in the field, has proven itself.

The new measuring method has proven to be very dependable. The method is simple and robust and shows significantly improved characteristics during high resistance ground faults, when compared to e.g. the proven 7SN600 transient ground fault relay. A secure detection of ground faults up to 5 kΩ is possible. For testing, approx. 800 fault recordings are available at present. The new measuring method is available in protection devices of the SIPROTEC 5 family provided by Siemens AG. The new function can be applied within one device in parallel to other protection functions like line or overcurrent protection which prevents from applying two physical devices.

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