NEW DEVELOPMENTS IN EARTH FAULT PROTECTION OF NON-SOLIDLY EARTHED NETWORKS

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SUMMARY

Most existing earth fault protections in non-solidly earthed networks are based on steady state signals. In practical applications their reliability is not satisfactory due to weak fault currents and unstable fault arcs. A new fault earth protection method, based on the measurement of the direction of the transient capacitive current, is introduced. Earth fault detection and recording system has been developed to evaluate the new method. Field trial results are presented which have proved the effectiveness of the new method. Another benefit is that a feeder, which has a temporary insulation breakdown, can be identified by the new technique that provides early indication to the development of a possible permanent fault.

1 INTRODUCTION

Most Chinese distribution networks employ a non-solidly earthed neutral (i.e. fully isolated or Peterson coil compensated) to reduce outages caused by single phase to earth faults. In the absence of a more reliable method many utilities are obliged to use manual switching to identify an earthed feeder. There is therefore an urgent requirement to develop an earth fault detection technique to increase supply reliability and prevent networks from damage due to long duration over voltages.

Protections using power frequency zero sequence current and voltage have low sensitivity, and cannot be applied in compensated networks due to the influence of the inductive current produced by Peterson coils. Projections based on the 5th, or higher harmonic, are not affected by Peterson coils. Their sensitivity, however, is even lower, as the harmonic components are only a small portion of the fault signal. Both these methods are based on steady state components and may fail to give correct faulty feeder selection during the unstable arcing faults that frequently occur on real networks. Faulty feeder selection methods based on detecting injected signals have successfully been put into practical application in China, but this technique needs signal injection equipment that is not always reliable or convenient. Moreover, the technique cannot be applied to detect a fault with an unstable arc since no stable path exists for the injected signal.

Protections using transient signals have better sensitivity and are free from the influence of Peterson coils as the transient fault current is dominated by high frequency components. A directional relay based on comparing the polarity between the initial transient zero sequence voltage and current was developed in the early 1950s. A feeder whose initial fault voltage and current have opposite polarities is identified as the faulty feeder. This relay has not been successful in practice because the time interval in which the polarity between the zero sequence voltage and current is right changes with the fault inception angle and network conditions, and may become wrong a few microseconds after the fault occurs. Modern microelectronics make high speed data acquisition and processing possible, and provide an opportunity to develop a new transient protection technique for earth fault detection in non-solidly earthed networks. A new earth fault protection method based on measurement of the direction of the transient capacitive current is introduced in this paper. Earth fault detection and recording system, developed to evaluate the new
method is described. Almost one year of field trials have proved that the new technique can select faulty feeders with high reliability. In the new technique a feeder that has a transient insulation breakdown can be identified before a permanent fault develops. Thus it provides valuable condition monitoring information of the network insulation.

2 NEW PRINCIPLE OF EARTH FAULT PROTECTION USING TRASIENT SIGNALS

2.1 Characteristics of transient signals

For high frequency transient signals the feeder can be modeled as a π circuit, as shown in Fig.1, where $L_0$ and $C_0$ are the inductance and capacitance of the feeder, respectively. The impedance seen from the busbar varies with frequency, and is capacitive up to the frequency when the first series resonance occurs. Therefore each feeder can be modeled as a capacitor within the Selected Frequency Band (SFB) from DC to the lower of the first series resonance frequencies of any of the connected feeders. The corresponding equivalent zero sequence circuit for an earth fault in a network with an isolated neutral is shown in Fig.2, where $U_f0$ is the superimposed zero sequence voltage source at the fault point, $L_{0k}$ and $C_{0k}$ are the zero sequence inductance and capacitance of feeder $k$, respectively, and $C_{0s}$ is the capacitance of the source.

From Fig.2 it can be seen that the zero sequence capacitive current flows towards the busbar in the faulty feeder and away from the busbar in the healthy feeders. For the faulty feeder $n$, the relationship between the measured SFB zero sequence voltage $u_{0n}(t)$ and current $i_{0n}(t)$ at the busbar is

$$i_{0n}(t) = -C_{0n} \frac{du_{0n}(t)}{dt} \tag{1}$$

where $C_{0n}$ is the equivalent capacitance of the whole network, excluding the faulty feeder, while for the healthy feeder $k$:

$$i_{0k}(t) = C_{0k} \frac{du_{0k}(t)}{dt} \tag{2}$$

where $i_{0k}(t)$ is the measured SFB zero sequence current in the healthy feeder $k$, $C_{0k}$ is the equivalent capacitance of the healthy feeder $k$.

In a compensated network, as shown in Fig.3, the current in the Peterson coil flows through the faulty feeder and affects the relationship described by equation (1). As the network is usually tuned near to the power frequency fundamental the inductive current components that are higher than, say the 4th harmonic of the power frequency, are negligible. The lower frequency of the SFB is selected to be the 4th harmonic instead of DC as used in un-compensated networks. The relationship between the measured SFB $u_{0}(t)$ and current $i_{0n}(t)$ still holds.
2.2 Earth fault protection based on measurement of the direction of the capacitive current

As the capacitive current, i.e. the current components within the SFB, has a different direction in the faulty and healthy feeders, the faulty feeder can be identified by measuring the direction of the capacitive current. The direction of the capacitive current can be determined by examining the polarity of the product of the zero sequence SFB current and the derivative of the zero sequence SFB voltage, defined as:

\[ q(t) = i_{0n}(t) \cdot \frac{du_{0s}(t)}{dt} \]  

(3)

First, the transient zero sequence voltages and currents are filtered using a band pass filter before further processing to get the SFB components \( u_{0s}(t) \) and \( i_{0s}(t) \). The lower cut off frequency of the filter is chosen as DC in isolated networks and the 4th harmonic in compensated networks. The upper cut off frequency of the filter is selected to be lower than the lowest resonance frequency of any of the feeders in the network.

The quantity \( q(t) \) can be physically interpreted as the instantaneous capacitive power of feeder \( k \).

From equation (1) and (2) we can see that for the faulty feeder \( n \):

\[ q_n(t) = -\frac{i_{0ns}(t)^2}{C_{0h}} \]  

(4)

While for a healthy faulty feeder \( k \):

\[ q_k(t) = \frac{i_{0ks}(t)^2}{C_{0k}} \]  

(5)

Therefore a feeder can be identified as faulty if the calculated \( q(t) \) has negative sign.

The discrete form of eq. (3), suitable for digital processing is:

\[ q[j] = i_{0n}[j](u_{0s}[j] - u_{0s}[j-1]) / \Delta t \]  

(6)

where \( j \) is the sample sequence and \( \Delta t \) is the sample interval.

Though the fault direction can be determined from the polarity of any \( q[j] \), the average value of \( q[j] \) over a quarter cycle is used to make the algorithm more reliable

\[ Q_a[j] = \frac{1}{N} \sum_{i=1}^{N} q[j-i] \]  

(8)

where \( N \) is the number of samples in a quarter cycle, which can be considered as the average capacitive power of a feeder.

In practice the fault direction is determined from the polarity of \( Q_a[j] \).

Since the calculation of \( Q_a[j] \) requires a data window length of a quarter of a cycle the calculation actually starts a quarter cycle after fault inception. The feeder is considered to be faulty if any sample of \( Q_a[j] \) is less than a negative threshold, otherwise the feeder is considered to be healthy. This is very useful in coping with unstable arcing faults.

The actual algorithm is illustrated in Fig.4.

3 TRIAL Systems

An earth fault detection and recording system was developed to evaluate the new technique. The system consists of two parts: a transient data-acquisition unit (DAU) and a data storage and processing PC (host). The three phase voltages, zero sequence voltage (3u0) at the busbar and zero sequence current (3i0) of each feeder are fed into the DAU. When a fault occurs and the zero sequence voltage exceeds a preset threshold, the DAU is triggered and fault data within a preset time period are recorded. The DAU transmits the fault data to the host for long-term storage and processing. The host identifies the faulty feeder using the algorithm described above.
and reports the result to the control centre via SCADA. The host provides a Human Machine Interface (HMI) capability to enable manual analysis of the transient waveforms. The transient data in the host can also be remotely retrieved using a dial-up communication link. A block diagram of the system is shown in Fig.5, and the actual hardware used is shown in Fig.6.

![Diagram of the system](image)

**Fig.5.** Fault detection and recording system

4 TRIAL RESULTS

A total of 401 earth fault transients were captured from Dec. 2001 to Nov. 2002 of which 12 were permanent faults and the others were self-extinguishing temporary faults. The faulty feeder was identified correctly for 11 of the permanent faults, i.e., with 91.7% reliability.

![Waveform graphs](image)

**Fig. 7.** The waveforms of 3U0, 3I0s, q(t) and $Q_a(t)$ of a stable fault

Two experimental systems have been installed in two 110kV/10KV substations at Dahuai and Fengshan in Quanzhou Power Utility, Fujian, China, as a technology project sponsored by the Power Bureau of Fujian Province. Each substation has two segments of busbar connected through a normally open tiebreaker, which form two separated networks. Each network has a compensated neutral and more than 10 feeders, including overhead lines and cables. The earth fault current is about 50A.
results are shown in Figs. 7 & 8. Fig. 7 is a stable fault on 5th July 2002, in the Liushi feeder of Dahuai substation. It can be seen that the faulty feeder has significant negative average capacitive power flow. Therefore the faulty feeder can be selected reliably by checking the value of the average transient capacitive power.

The fault shown in Fig. 8 is a fault with an unstable arc on 12th May 2002, in the Haibin feeder of Dahuai substation. The unstable fault arc generated a long duration transient signal. The average transient capacitive power is therefore higher in amplitude, and longer in duration making identification of the faulty feeder even easier.

It is interesting to note from the phenomena shown in Figs. 7 & 8 that the value of the steady state power frequency current of the faulty feeder approaches zero and is less than that in the healthy feeder. This explains why methods based on steady state signals cannot give correct indications of a faulty feeder.

The system failed to give a correct faulty feeder indication for a fault on May 22, 2002 in Fengshan substation. The recording showed no significant current transient. A possible explanation is that the fault was caused by slow deterioration of the network insulation resulting in an observed slow rise of the zero sequence voltage. Further investigation of this situation is needed. However the possibility of this slowly changing fault appears to be rare in real networks.

Final statistics show 6 out of a total of 12 faults were natural insulation breakdown, while the rest were caused by external damage, e.g. road construction. It was observed that temporary earth faults appeared before a permanent fault developed. As an example, for the permanent fault on 3rd September 2002 in the Yonghong feeder of Fengshan substation, a total of 3 temporary faults were captured before the fault became permanent. The first temporary fault, shown in Fig. 9, was early on 1st September. It can be seen that the zero sequence voltage decays as the insulation at the fault point recovers.

With the new technique a feeder that has a transient insulation breakdown can be identified before it develops into a permanent fault. Thus it provides valuable early indication of possible permanent faults.

Fig. 9. The zero sequence voltages (3U0s) of a temporary fault

6 CONCLUSIONS

An earth fault protection method for non-solidly earthed networks using fault-generated transients within a selected frequency band has been developed. The new technique is more sensitive and reliable compared to conventional methods. It is free from the influence of Peterson coils and unstable fault arcs. Temporary self-extinguishing arcing faults can be detected using the new method, which provides valuable network insulation monitoring information. Recorded data from real faults has validated the method. The new technique marks a significant breakthrough in earth fault protection on non-solidly earthed networks.

References: