WATTMETRIC EARTH FAULT PROTECTION – INNOVATION FOR COMPENSATED DISTRIBUTION NETWORKS

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ABSTRACT

A new enhanced technique to detect the earth fault in a compensated network (Peterson coil) is presented in this paper. The proposed innovative protection algorithm has been developed to comply with the French NF C13-100 norm. The NF C13-100 norm requires the application of PWH2 function (wattmetric directional earth fault protection function for ERDF). The algorithm performance and selectivity allows operation to be precisely deterministic for any kind of fault. This innovative algorithm did not require additional sophisticated hardware and software, and it has been implemented into the compact intelligent electronic device.

INTRODUCTION

FRENCH NF C13-100 NORM REQUIREMENT

The electric power utility in French has the NF C13-100 norm which states one of the relay requirements as the zero sequence active power detection PWH2. This function must work with impedance or compensated neutral network, and must be able to detect a fault with a very small value of fault current, with ring core CT as in Fig 1.

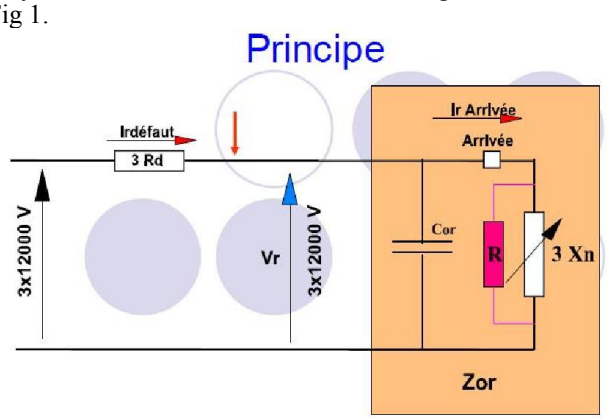

Fig. 1: Typical NF C13-100 scheme

It also require the protection relay to have fast capability of detecting a forward fault in a half period as the phase angle between residual current and residual voltage (opposite) values stays for a maximum of 20ms only when a fault appears as shown in fig. 2. The protection relay should be capable to discriminate a forward fault and a backward fault for a variety of fault signals.

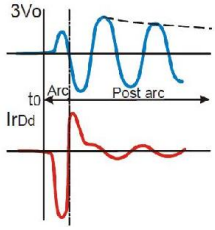

Fig. 2: Fast fault detection must be done on first cycle of the fault

The fault could be permanent as show in fig.3. It is the non-arcing fault (i.e., Earth connection not removed before closing the feeder). In this case, it is not necessary to define the direction of the fault quickly. By measuring the active power, it's easy to define a forward fault. This part is a complement of the protection to detect the entire forward and backward fault efficiently.

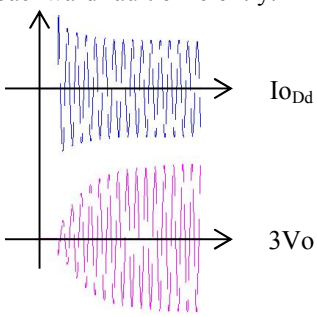

Fig. 3: Permanent resistive fault, low evolution of the voltage

BACKGROUND

The neutral un-earthed system has higher reliability in the power system compared to the system with neutral directly grounded. This is particularly true and beneficial to the system which suffers from high incidence of transient faults and mainly consists of the rural overhead lines. This is because there are no fault circuit formed when a neutral un-earthed system has a single-phase-to-earth fault. Hence, the phase-to-phase voltages should still be symmetrical and have no fault current flow. This creates no impact on the loads except the phase-to-earth voltage of healthy phase which rises to 1.732 times of the nominal voltage [1].

The fault type normally happen in the power system is arcing fault. A single-phase-to-earth arcing fault occurs on the power system with neutral un-earthed has no circuit formed in theory, however practically a closed

fault circuit is formed as to the equivalent phase-to-earth capacitance of each line. This capacitive current will sustain the arc faults. Therefore, in practical, an inductive coil is designated on the neutral to compensate the capacitive current so that the system extinguishes the arc faults. This coil is called “Petersen coil” or “arc suppression coil” [2]. The Petersen coil compensated systems are widely used in distribution power grids, especially in Europe.

Petersen coil earthed system is high impedance earthing scheme. The network is earthed via a reactor with the reactance designed to nominally equal to the total system capacitance to earth. While it is beneficial, the system also does not result in any earth fault current in steady state conditions. The effect is similar to having an insulated system. The effectiveness of the method is dependent on the accuracy of tuning the reactance value – changes in system capacitance (due to system configuration changes for instance) require changes to the coil reactance. In practice, perfect matching of the coil reactance to the system capacitance is difficult to achieve, so that a small earth fault current will flow.

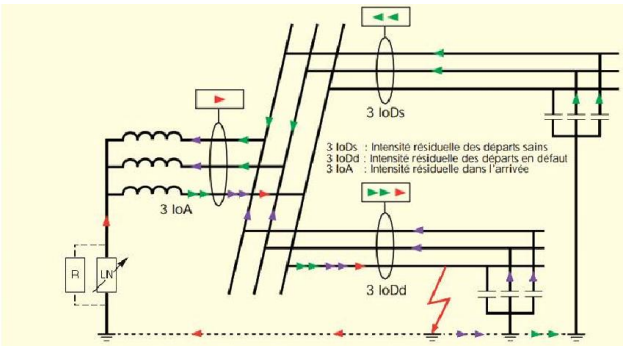

Fig. 3: Single phase fault current flow on the Petersen Coil earthed system

THE CHALLENGE

The challenge is the feeder relay should be able to detect and determine the fault especially the fault direction although the single phase-to-earth fault does not generate any effect on the load. The fault direction can be easily determined by the zero-sequence steady state reactive power directional relay in the neutral un-earthed system. However, the fault direction is hard to be determined in neutral compensated systems by using the traditional technique which is based on the power frequency components [3]. There are two parts of current, capacitive and inductive, decomposed from the current flows via the faulty phase of the faulty line. The capacitive current flows via the phase-to-phase capacitances between non-faulted and faulted phases shunted with the phase-to-ground capacitances of non-faulty phases to the faulty phase. The inductive current is generated by the unbalanced neutral voltage, flows from neutral point of transformer via the fault branch and Petersen coil back.

The current measured by the relay is the mixture of both the inductive and capacitive currents. Therefore, the measured current might be zero because the inductive current may compensate the capacitive current when the fault goes to the steady state. However, the relay measured current could be even over compensated to be inductive, therefore there is no characteristic discrimination between the faulty line and the healthy line. This is the reason why the traditional directional relay based on the power frequency component will give mal-decision. Here comes the challenge for the protective relaying to detect the correct fault direction.

Fig. 4 below shows the challenge to characterize the fault direction. The currents and voltages are in the same direction for a reverse fault and opposite direction to a downstream fault in 3ms. Some products use a technique with fast sample rate, but this technique may not yield satisfactory results over the entire range of scnarios.

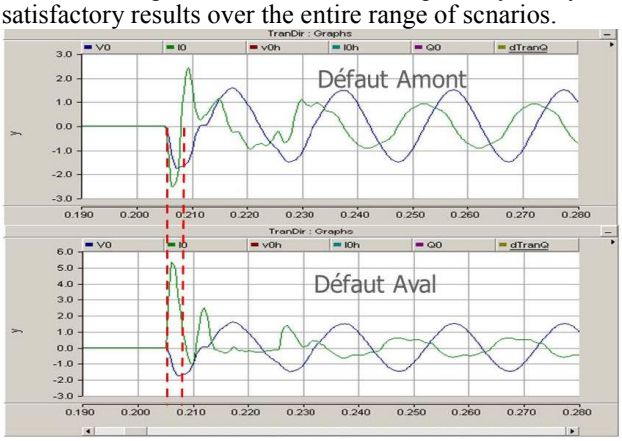

Fig. 4: The directionality must be detected in the short 3ms window

Fig. 5 below shows the residual voltage and residual currents of an actual fault waveform BANQ0358. The waveform demonstrates that the Petersen coil cancels quickly the fault current and caused the circuit to have minimum fault current flowing.

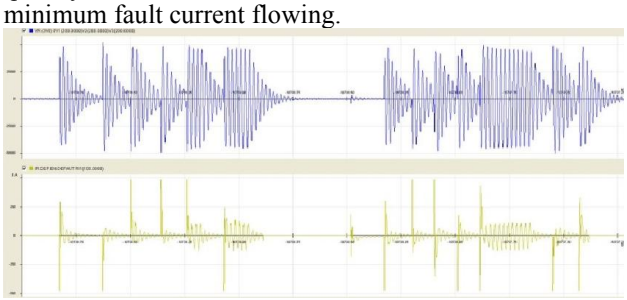

Fig. 5: Actual fault waveform BANQ0358

MATERIAL AND METHOD

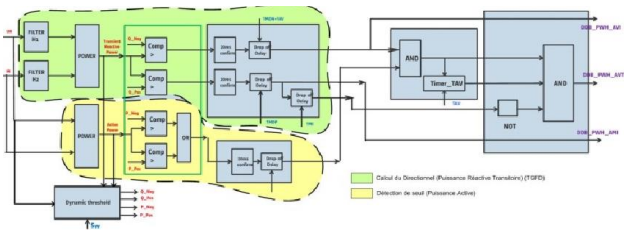

Fig. 6: Logic diagram for the new enhanced technique on the wattmetric directional earth fault protection function

A new enhanced technique on the wattmetric directional earth fault protection function to detect the earth fault in a compensated network (Petersen coil) to comply with French NF C13-100 is presented in this paper. The algorithm performance and selectivity allows operation to

be precisely deterministic for any kind of fault. The innovative algorithm consists of 2 parts:

* Threshold detection (active power) - Helps to keep the selectivity
* Directional Computation (transient reactive power at 220Hz) which is to tackle the transient directional challenge discussed above.

DIRECTIONAL COMPUTATION (TRANSIENT REACTIVE POWER AT 220Hz)

Although the capacitive current could be fully or even over compensated, the active part of the current (both in transient and steady state) never could be compensated. Based on this fact, the measured active power or the conductivity, which are respectively called "Wattmeter" and "Conductivity relay", can be employed to determine the fault direction [4-6]. This technique has already been implemented into few other relays. However, the active current or the conductivity is too small as shown in the fig. 7 below. It is not possible to be measured by common CTs, unless special CTs with higher accuracy are employed as measurements.

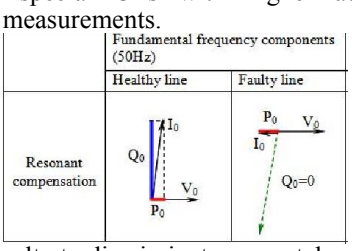

Fig. 7: Difficulty to discriminate accurately an upstream failure of a downstream fault working at 50Hz from P0 and Q0

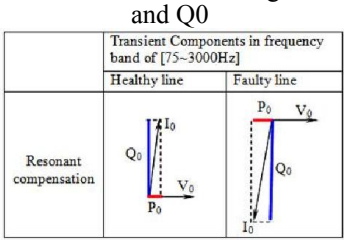

Fig. 8: A 220Hz, transient reactive power (Q0) makes it easy to distinguish an upstream failure of a downstream fault.

Employing transient components for the fault direction determination could be a good idea. Some of the feeder relays have the first-half-wave method implementation, which is actually based on the travelling wave theories, for the fault direction determination [7]. The transient high frequency components with the frequency of 1500~3000Hz are captured for direction determination and obviously require the higher frequency sampling technique. Therefore, a special hardware with high frequency sampling function is designated in the feeder relay. Therefore, a special hardware with high frequency sampling function is designated in these feeder relays.

The feeder relay uses the instantaneous reactive power for fault direction detection. The instantaneous transient reactive power is obtained from the Hilbert transform. Obviously, this technique does not match the neutral compensated system.

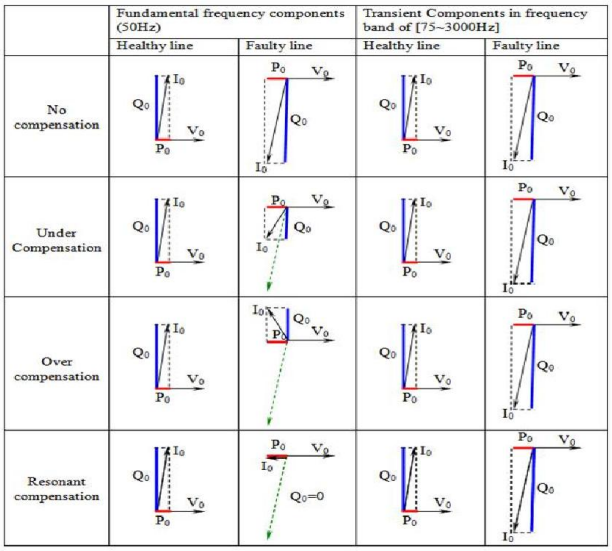

Fig. 9: The Petersen coil earthed system has little if not no effect on transient signals to 220Hz.

A new technique for detecting single-phase-to-earth direction, which can be implemented in a common feeder relay with lower frequency sampling rates that neither any special hardware nor more accurate measurements are required, for neutral compensated power system is proposed in this paper. During the transient stage of a single phase-to-earth fault, the current flows only due to the phase-to-phase capacitances and phase-to-earth capacitances from the non-faulty line to the faulted line back. The direction of the transient current of faulted line is opposite to that of healthy line. However, as the fault goes into steady state, the current consists of not only the capacitive current (first part) but also the current flowing via faulted line and back through the neutral coil. The second part current might change the direction of faulted line current. Based on this fact, a band-pass filter which central band selected to be 220Hz is designed for eliminating the power frequency component and at the same time amplifying the 220Hz component, and then the transient reactive power after eliminating the power frequency component is obtained to determine the fault direction. Fig. 8 below shows the significant difference compared to Fig 7, on the directionality detection on the 220Hz transient reactive power. This technique has already been implemented into the feeder relays and the test result shows that the technique can give the right decision of fault direction. Fig. 9 show the Petersen coil earthed system has little if not no effect on transient signals to 220Hz.

Directional Computation

Bandpass filters that extract the signals at 220Hz are used and they perform a phase shift of 90° for the current in order to calculate a reactive power and maintain the transient characteristic of the defect (fig. 10). The Directional Computation (Transient Reactive Power at 220Hz) is shown in fig. 11.

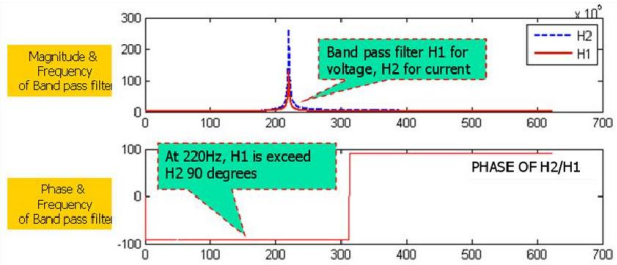

Fig.10: The 220Hz bandpass filter and phase shift of 90° for the current

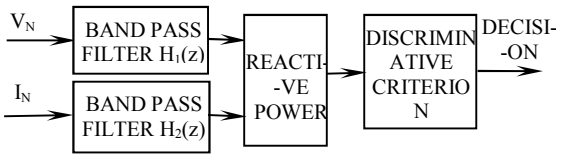

Fig.11 Directional Computation Logic

The measured residual voltage and current is processed respectively by band pass filters H_1 and H_2, which eliminate the fundamental frequency signal and amplify the signal in the special frequency band. Subsequently, the reactive power in per-unit value is obtained by passing through the sign filter, the relay will make a decision that the fault is in forward or reverse direction.

Band-pass filters for voltage and current

The special frequency which is extracted is selected to the range with the frequency centre 220Hz. The reason for such a frequency is that this frequency can avoid the 4th and 5th harmonics which are rich in the system.

The designed digital band-pass filter is shown below.

$$\begin{cases} H_1(z) = \dfrac{(1-z)(1-z_0 z^{-1})(1-\bar{z}_0 z^{-1})}{(1-z_1 z^{-1})(1-\bar{z}_1 z^{-1})} \\ H_2(z) = \dfrac{(1+z)(1-z_0 z^{-1})(1-\bar{z}_0 z^{-1})}{(1-z_1 z^{-1})(1-\bar{z}_1 z^{-1})} \end{cases} \quad (8)$$

where, $z_0=\exp(-\omega_0 T_s)$ is the zero point for fundamental frequency components, $z1=\exp(-\omega_0 T_s)$ is the pole point for 220Hz components which is required for amplifying, Ts is the sampling period. The difference between the two filters is that there is phase difference of 90°, in which filter H_2 is 90° lag to H_1.

Normalised reactive power

Reactive power can be obtained by directly multiplying the voltage and current after passing through the band pass filters H_1 and H_2. However, the threshold of the reactive power is difficult to set due to the very large value range. For example, if the minimum voltage and current are 0.1 p.u, then the minimum reactive power should be 0.01 p.u; if the maximum voltage and current is 10.0 p.u, then the maximum reactive power should be 100.0 p.u.. The range of the power is from 0.01 to 100.

The voltage and current signals pass the sign filter first before the reactive power is obtained.

$$y = \begin{cases} 1 & x \geq X_{set} \\ 0 & -X_{set} < x < X_{set} \\ -1 & x \leq -X_{set} \end{cases} \quad (9)$$

Subsequently, by multiplying the voltage and current which had passed through the band-pass filter and the sign filter, the normalized reactive power obtained can be limited into the range of [-1,1].

$$Q_{TRAN}(k) = \frac{1}{N}\sum_{k=1}^{N} \hat{u}(k-n+1)\hat{i}(n) \quad (10)$$

Where, QTRAN is the normalized reactive power, $\hat{u}$ and $\hat{i}$ are respectively output voltage and current after passing through the band-pass and sign filters.

After such processes, the value of reactive power is limited into the range of [-1,1].

Discriminative Criteria

The analysis in the previous sections shows that the character discrimination exists in the reactive part of current in the frequency region of [f2,f1]. That is, in such frequency band:

(1) Residual voltage LEADS residual current for 90° for a forward fault. So that the normalized reactive power should be negative as the voltage is shifted 90°.

(2) However, voltage LAGS current for 90° for a reverse fault. So that the normalized reactive power should be positive as the voltage is shifted 90°.

Therefore the discriminative criteria are shown as follows:

$Q_{TRAN} < -0.1$ Forward fault (11a)

$Q_{TRAN} > 0.1$ Reverse fault (11b)

Otherwise
a) No decision for backward fault
b) Use Active Power and angle to define forward fault (11c)

Wattmetric directional earth fault protection

As shown in Fig. 6, this innovative PWH2 algorithm consists of 2 parts:

* Threshold detection (active power) - helps to keep the selectivity and define a permanent fault

* Directional Computation (transient reactive power at 220Hz) to tackle the transient directional challenge discussed above.

The active power detection is simple threshold detection where it monitors the system active power.

These 2 criteria must be fulfilled before the relay could make a go on the earth fault protection in the Petersen coil fault for transient fault.

The active earth power and the angle criteria make a go on the earth fault protection for permanent fault.

RESULT

The technique and algorithm had been tested with all ERDF FIDERE fault library file replays. The results are

good and no error identified on the playback. This confirms that this innovation technique will improve significantly the accuracy of the PWH2 protection. The test results below show the directional detection on the typical forward and reverse fault.

Typical forward and reverse fault

Case 1:An internal arc fault occurs on the resonant compensated system, the waveforms can be seen in fig 12

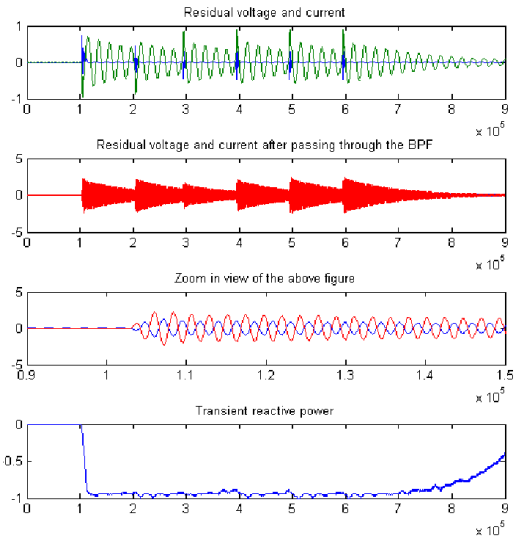

Fig.12 waveforms during the processing for forward fault on resonant compensated system.

One can easily see from figure 11, after passing through the band-pass filters, the output voltage and current of the filter are in opposite direction. After the sign filter, the normalized reactive is nearly -1.

Case 2: An external arc fault on resonant compensated system, the waveforms are shown in figure 13.

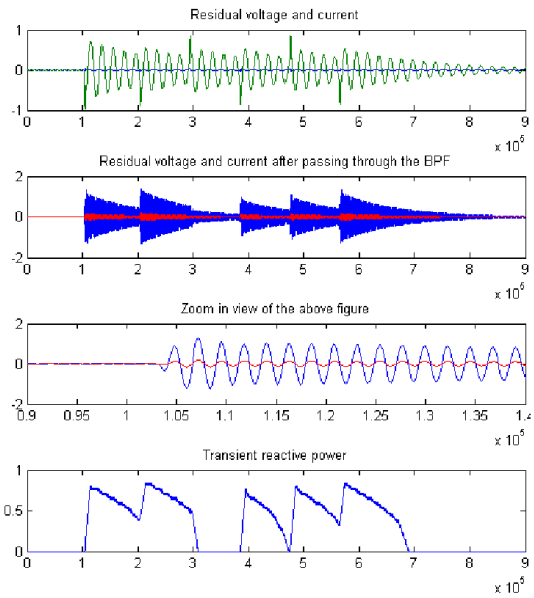

Fig.13 waveforms during the processing for reverse fault on resonant compensated system.

One can see that the voltage and current after passing through the band-pass filter are in same direction, the normalized reactive power is positive.

CONCLUSION

Principal advantages of the new technique are:

• No specific hardware, high frequency sampling or high performance earth sensor is required

• Can be implemented in standard feeder management relay products

• Improves significantly the accuracy of the function - no error identified on all ERDF FIDERE fault library file replays

• Improves the speed of detection of reverse faults, improving the selectivity between products on the same feeder busbar

• Reliability of detection even in the presence of high capacitive currents

• Significant reduction of unexpected trip compared to existing products and algorithms

• One single relay takes care of the PWH2 (wattmetric power) and PVH (neutral displacement voltage) functions. It gives cost savings, less hardware, less maintenance and greater scheme availability for utilities.

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