Earth-fault detection in a compensated earthed network, without any voltage measurement : a new protection principle

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In compensated earthed networks, the detection of phase-to-earth faults is currently achieved by a zero-sequence directional relay.

This well-known principle needs the residual voltage to be measured, either with three voltage transformer (VT), either with capacitive dividers, or with an electrical field sensor. The two last sensors are specifically used for fault locators in order to get a cost effective solution. But these sensors are not very accurate, and an additional data processing must be added in the fault locator.

The new principle described here processes the three phase currents only. It allows to detect a phase-to-earth fault located downstream from the relay while being insensitive to a fault located upstream.

Such a fault detection device will give significant cost reduction when located in the MV system, where no residual voltage measurement is needed for another purpose, which is merely the case in MV/LV substations. It can also be installed in HV/MV substations, as a backup for zero-sequence directional protections, useful in case of VT fuse blown.

The principle used for fault detection, which will be fully described in the final paper, is based upon the comparison between the residual current and each of the phase currents. When a phase-to-earth fault occurs downstream, the device detects the "similarity" between the residual current and the current in the faulty phase.

After several years of research, the algorithm is now finalized. It allows proper detection of earth-faults up to 1.5 kΩ. The implementation in a device will be planned soon.

Détection des défauts à la terre dans un réseau à neutre compensé sans mesure de la tension : un nouveau principe de protection.

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Dans les réseaux à neutre compensé, la détection des défauts à la terre est réalisée actuellement par un relais directionnel.

Ce principe éprouvé nécessite la mesure de la tension résiduelle, obtenue soit à partir d'un jeu de 3 transformateurs de potentiels (TP), soit à partir de diviseurs capacitifs, soit par mesure du champ électrique. Ces deux dernier types de capteurs sont utilisés pour la réalisation de détecteurs de défauts directionnels dans le but de réaliser un dispositif moins coûteux. Un traitement particulier doit être effectué dans le détecteur de défauts afin de palier à la mauvaise précision de ces capteurs.

Le nouveau principe présenté ici permet de détecter un défaut phase-terre situé en aval de l'appareil à partir de la seule mesure des courants dans les trois phases, et de la distinguer d'un défaut situé en amont.

L'intérêt économique d'un tel appareil est évident lorsqu'il doit être installé en un point du réseau où aucune mesure de tension résiduelle n'est nécessaire par ailleurs (poste MT/BT par exemple). Nous envisageons également son utilisation au poste source, en secours des protections directionnelles, en cas de défaillance de la mesure de tension (fusion fusible).

Le principe du dispositif, qui sera complètement décrit dans l'article, repose sur la comparaison du courant dans chaque phase avec le courant résiduel. Lorsque le défaut est situé en aval de la protection, le relais détecte la "ressemblance" entre le courant résiduel et le courant dans la phase en défaut.

Après plusieurs années de recherches, l'algorithme est maintenant au point. Il permet la détection certaine de défauts jusqu'à 1,5 kΩ. Son implémentation dans un produit industriel sera prévue prochainement.

EARTH-FAULT DETECTION IN A COMPENSATED EARTHED NETWORK, WITHOUT ANY VOLTAGE MEASUREMENT : A NEW PROTECTION PRINCIPLE

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INTRODUCTION

In a compensated earthed network, the detection of phase-to-earth faults is currently achieved by a directional earth-fault protection. Such a protection can be based either on the residual active current or on the residual active power, but it always requires the residual voltage to be measured.

An Artificial Neural Network (ANN) can be used for an alternative approach. When adequately designed and trained an ANN based algorithm is able to recognise different network conditions and thus it can make a correct fault diagnosis.

This powerful concept has already been used in order to improve the performances of a distance protection, for instance in Coury et al. (1) or to reduce the number of settings of a transformer differential protection, in Bertrand et al. (2).

In the application described in this paper, the ANN is used in order to reduce the number of the relay inputs. An algorithm has been developed, which detects phase-to-ground faults in a Petersen-coil earthed network, without any voltage measurement ; only the three phase currents are processed.

BASIC PRINCIPLE

In case of a fault, it is well known that capacitive currents flowing in sound feeders can reach important levels in case of underground networks, due to the zero-sequence capacitance of cables. There are two conventional solutions to distinguish fault currents from capacitive currents. The first one consists in increasing the current setting of the relays. This is inefficient in the case of Petersen coil earthed networks, where the residual current flowing through the sound feeder may exceed the fault current. The second one consists in using a directional relay. This solution is efficient, but quite expensive, due to the cost of voltage sensors.

To describe our innovative algorithm, let us consider a radial distribution network, with a phase-to-earth fault occurring on one feeder, and let us make a qualitative description of the various currents from a given simulation.

The visual analysis of the phase currents flowing in the feeders during the fault suggests that these waveforms contain enough information in order to distinguish fault currents from capacitive currents.

As shown in Figure 1, on the faulty feeder, the residual current (I0) "looks like" the current flowing in the faulty phase (Ia). On a sound feeder, the residual current "is not very different" from the currents flowing in the two sound phases (Ib and Ic).

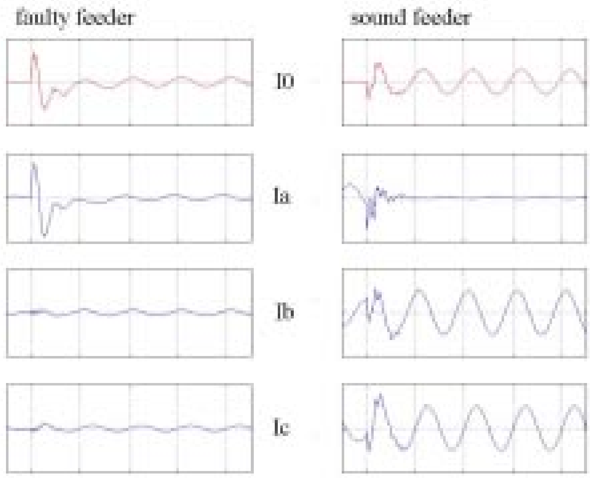

Figure 1 : Phase currents contain enough information to make the difference between a sound and a faulty feeder

This basic principle was first highlighted by Assef et al. (3). Since that time, considerable work has been carried out, in order to improve the principle and make it adapted to industrial relay applications.

MAIN IMPROVEMENTS

General scheme of the protection relay

Our experience in developing ANN based algorithms has convinced us that a unique ANN cannot simultaneously process the samples of the input signals and make the tripping decision. ANN techniques may be used either for signal processing or for classification ; in the former case, the network processes the samples, as a standard filter would do ; in the latter, the inputs of the ANN are made with already processed significant quantities, but the output of the ANN is close to the tripping output of the relay.

In our application, the ANN is used as a classifier. Its 6 inputs are computed from the sampled phase currents through classical signal processing, as explained in figure 3

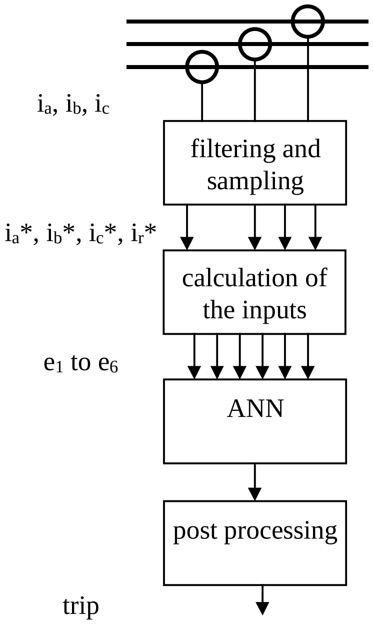

Figure 2 : general scheme of the protection relay : only the 3 phase currents are measured and the ANN is used as a classifier

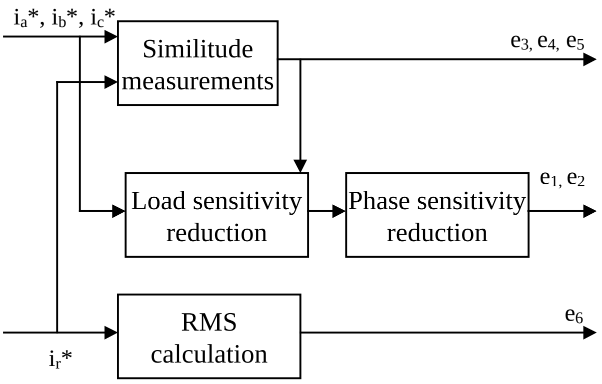

Figure 3 : the computation of the 6 inputs of the neural network is the keystone of the algorithm.

Filtering and sampling the phase currents

For the present application, it is important to properly filter the phase currents before sampling : phase-to-earth faults on compensated networks give heavy transients, the frequency of which may be high when capacitive currents in the network are low.

If no analogue filtering is provided, especially in order to cut costs, then the behaviour of the algorithm during the transient may not be satisfactory. A post-processing logic can take this case into account, but the tripping time of the protection is then likely to increase.

Similitude measurement of two current waveforms

This function processes the samples of two current waveforms (one phase current and the residual current), in order to report on a similitude degree between the two waveforms.

On tuned coil earthed networks, low resistance faults can lead to transients of several hundreds ms on the short-circuited phase. Hence, the similitude measurement must be significant during the transient and the comparison of phasor quantities is not satisfactory.

Notwithstanding the long duration of the transient, the fault situation should be diagnosed quickly, for example in less than two cycles (40ms). For that reason, the depth of the signal processing was fixed to one cycle.

The first similitude measurement function tested was the scalar product (Assef et al. (2)). Finally, we got better results with the quadratic distance.

Making the protection insensitive to load current

As shown in figure 1, the similarity between the faulty phase and the residual current may be clearly established at no load and low resistance fault.

However, the current comparison becomes inefficient for important values of the fault resistance R_d and full feeder load, as the residual fault current looses its impact (figure 4) both in amplitude (small compared with the phase current one) and in form (transient quasi-sine wave). It was one of our main improvements to get good behaviour of the algorithm in case of full load and high fault resistance.

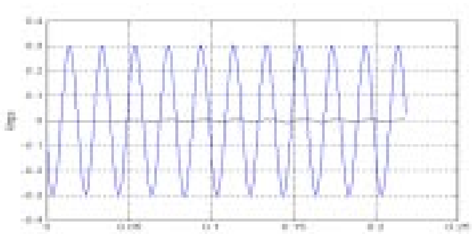

Figure 4 : in case of high fault resistance (5 kΩ), the similarity between the faulty phase current and the residual current is not obvious.

The performance of the protection was improved by adding some load correction factors to the output of the similitude function. These correction factors are simply based on the maximum and minimum rms value of the 3 phase currents.

Phase sensitivity reduction

This problem is common to all ANN based protective relays : if there is only one neural network for all the three phases, having one input per phase, a phase A-to-earth fault won't be identical to a phase B-to-earth fault.

Training the neural network with each fault combination increases unnecessary the size of the training base and may lead to a dead end.

In order to overcome this problem, the most powerful solution is to imagine ANN inputs which are not "phase-sensitive". In the present application, we have selected for inputs e3 and e4 the maximum and minimum values of the corrected similitude measurements.

Post-processing the output of the ANN

In order to make the ANN easier to train and to reduce the relay's computation, the number of inputs was reduced to six. All of these are computed from the same time window of one cycle.

This means that the ANN has no information about what happened before this one cycle window. Thus, very simple functions such as confirmations cannot be performed with the ANN.

When directly analysed by the ANN algorithm, the transient on the sound feeder may sometimes lead to a brief unwanted trip. Thus, it has been necessary to implement a logical processing, following the ANN computation, in order to delay the trip in case of hard transient. This processing implies the increase of the tripping time, but it is mandatory to avoid unwanted trips.

For the simulation with a 600Hz data sampling, the strategy adopted for the protection was to validate a short circuit after the reported fault has been confirmed by sixteen consecutive ANN's output data, one system period taking twelve samples. In the case of an industrial device where data may be processed for instance only once every eight samples, we would require three consecutive fault confirmations.

SIMULATION

When a protection algorithm has to be developed, the first step is to get sufficient knowledge about the fault and no-fault transients which may appear in the network. This is especially the case when ANN are intended to be used : a large number of fault conditions have to be simulated in order first to train the ANN and second to check that good generalisation is obtained.

Two radial distribution systems were simulated with EMTP (Figure 5) : the first one with 5 feeders and a 10MVA 33/10kV power transformer and the other one with 9 feeders and a 36MVA 63/20kV power transformer. The neutral point of the low voltage side of the transformer is grounded through a Petersen coil giving variable active residual current and assuming variable compensation of the total capacitive current (Petersen coil out-of-tune dispersion). The feeders are composed partly of very capacitive cables (underground system) partly of overhead lines with low capacitance. The feeders loads vary between no load and full load with a power factor of 0.82 to 1.

In order to increase the variety of the training base, a certain amount of random has been introduced. For instance, the line parameters are randomly set with a tolerance of +/-30% around their rated values.

The feeders lengths vary in the limits giving a capacitive current per feeder up to 100A for the high power system. In both cases the fault resistance varies from 1Ω to 5000Ω.

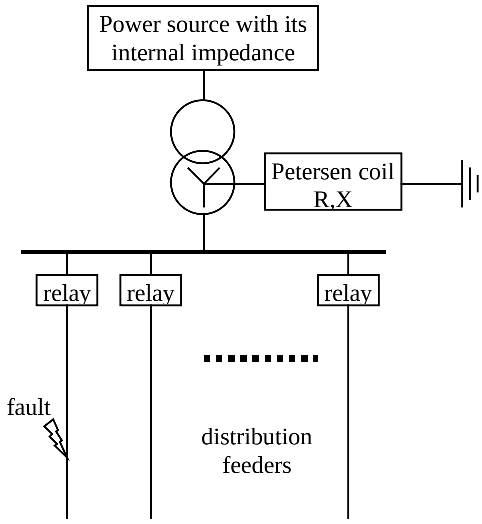

Figure 5 : The simulation network used for training the ANN and testing the algorithm allows a large variety of situations to be examined.

TRANING THE ANN

The Neural Network giving the best results is a 6-3-1 multilayer perceptron with the Levenberg - Marquardt backpropagation training function as implemented in Matlab.

When the network and fault parameters vary in large proportions, the learning base should be calculated lavishly. We have assembled a base of 400 cases covering both simulated power systems (10 MVA and 36 MVA) with 38 000 entries. The initial training values have first been calculated for restricted data sets and the calculated intermediate weights and bias values have then been applied to the final training base. The final weights and bias set has led to a very low mean error.

RESULTS

As an example of our ANN based protection principle, let us describe the results for a simulation of the 10MVA five feeders radial distribution network with a 80% tuned Peterson coil earthing and a phase-to earth resistive (3000 Ω) fault. In about 40 ms after the fault installation the correct diagnose is given on all the feeders.

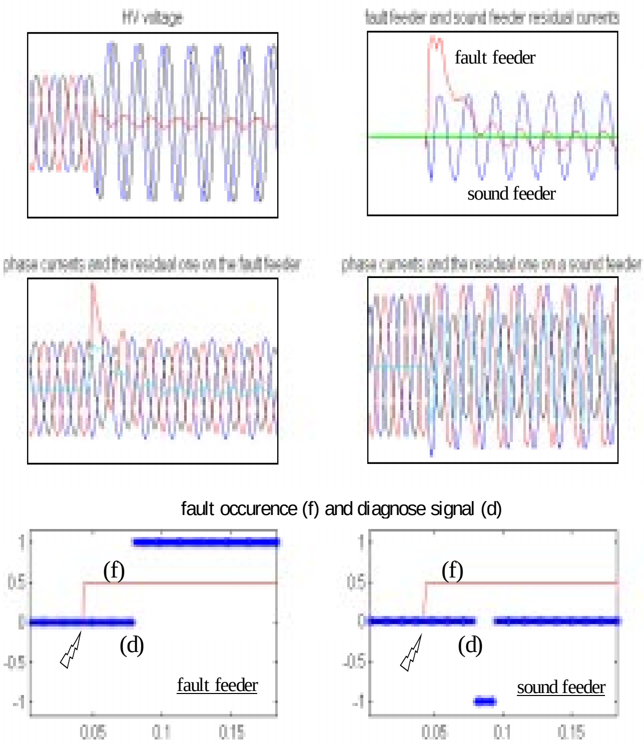

Figure 6 : Results of simulation : the diagnose signal (d) is 0 when no fault is detected at all, +1 when a fault is detected on the protected feeder, and –1 when a fault in the network is suspected, but not on the protected feeder.

We have simulated a line-to-earth short circuit in both low and high power systems (10MVA and 36MVA) with the ANN protection on all the feeders. The error was diagnosed if either the fault feeder was not detected or any of the sound feeders was given a false fault signalling. In the examination of 432 cases the mean error rate was of 1.6% :

Table 1 - The ANN protection error rate

R_d	1-100Ω	1-1500Ω	1-5000Ω
10MVA	0%	1.4%	2.3%
36MVA	1.4%	0.7%	0.9%

CONCLUSION

Thanks to ANN, the short-circuit detection in Petersen-coil earthed networks has been improved : residual voltage measurement is no longer necessary to select the faulty feeder.

This principle allows a cost-effective relay design and thus its extensive use in the distribution networks, in substations where no VTs are available.

In primary substations, where directional earth-fault protection is already used, this protection may also be of interest as backup protection, when VT fuses are blown.

The principle used is based on waveform comparison between zero-sequence current and phase currents. As the ANN has to be trained with many fault conditions, one of the key factor is to get accurate network simulations.
The robustness of the ANN algorithm is the other key factor. It has been extensively tested with important parameter ranges, including 1Ω to 5000Ω fault resistance and variable power network topology.

The result obtained appears to be satisfactory. Real-time implementation will now be the next step.

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