Using the EMTP and the Omicron to Design a Transients Based Digital Ground-Fault Relay for Isolated or Compensated Networks

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Abstract: **Protection engineers have been thinking about transients based protection algorithms for decades, but have always been slowed down by the capabilities of state-of-the-art protection hardwares. Today, digital technology provide the engineers with powerful electromagnetic transients programs to study and design new algorithms, but also with high sophisticated relays hardwares to implement them and finally with good test systems like the Omicron to check them. This paper presents new methods that could be used to determine the direction or even the position of earthfaults occuring in isolated or compensated networks and briefly describes some requirements for accurate transients simulations.**

I. INTRODUCTION

The advantages of compensated or isolated networks compared to conventional earthed networks are well-known: most faults are self-extinguishing single-phase to ground faults which induce such a small fault current that the network can be kept in operation. While this reduces the number of power outages, the drawback of the small fault current is the difficulty to protect the network. Conventional protection relays working with algorithms based on the fundamental wave of the measured voltages and currents can indeed be inappropriate to the protection of isolated or compensated networks since the steady-state fault current can be very small. In such cases, using the mid-frequency range electromagnetic transients generated by the fault provides a better solution to determine the fault direction or even its position.

For studying new transients based protection algorithms, we have to accurately simulate the frequency, initial amplitude and damping of the fault-induced transients, so that the EMTP has extensively been used for this duty.

The frequency range of interest being only a few kHz, such algorithms could easily be implemented in today's digital protection devices and could as easily be tested by ~~users thanks to existing real-time or quasi real-time digital~~ simulators such as the OMICRON CMC-56.

The OMICRON test system is indeed well appropriate to this duty since it can be used in two different ways :

- Its "Ground-Fault Relays Testing" feature can be used to check for proper directional decisions of transient ground fault relays.

- Its "Transient" software module allows the user to replay fault recordings coming either from real fault measurements or from non real-time electromagnetic transients simulation software such as the EMTP. It is then of course very simple to test the protective relay for both directional and distance functions by playback of many different fault cases.

II. FAULT INDUCED TRANSIENTS

When an earth fault occurs in an isolated or compensated network, the electromagnetic transients which last during a few milliseconds after the fault inception provide the only available information for estimating the fault position or direction. Two kinds of transient components can roughly be distinguished : the discharge components and the charge components.

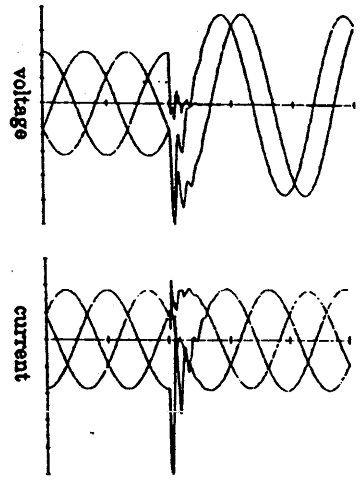

Fig. 1 : Typical voltage and current waveforms during an earth fault

1) High frequency components of current and voltage are due to multiple reflections of travelling waves in the network; they are highly damped due to the line and fault resistances and often disappear rather quickly so they can hardly be used with state-of-the-art digital relay hardware. These components are often referred to as the discharge components because they are due to the quickly falling to zero of the faulted phase voltage, hence removing the charge stored in its capacitances. Consequently, this component is more observable on the faulted phase signals than on the sound phases ones.

2) Medium frequency components (generally in the range 200-2000Hz) are due to oscillatory exchange of energy between the distributed capacitances and inductances of the network; these components are often referred to as the charge transients because they are due to the rapid increase of the sound phase voltages, hence increasing the charge stored in their capacitances. Unlike the discharge transients, they are more present in the sound phases than in the faulty phase signals.

A rough prediction of their main frequency can be computed by solving the equivalent LC oscillatory circuit obtained by considering the network as lumped impedances and by connecting in series the zero-, positive- and negative-sequence networks at the fault point. It is almost impossible to find a theoretical formula leading to that "resonance" frequency since it depends on the whole inductances and capacitances of the network : transformers, lines, ... However we can say that the smaller the network, the higher the associated resonance frequency.

The initial amplitude of the charge and discharge transients is mainly dependent on the fault inception angle; indeed, the fault inception can be seen as a superposed voltage step applied at the fault point with a magnitude equal to the instantaneous value of the voltage at this moment. If the fault occurs near the voltage peak, high-amplitude transients will be induced; on the contrary a fault arising at the zero crossing of the faulted voltage will almost not excite the network. Fortunately, a fault arising at the zero-crossing of the voltage is very unlikely, unless some worker accidentaly cut a conductor with his crane. According to Warrington, we can assume that 95% of all faults of transmission systems occur within 40° of the phase voltage maximum.

The induced transients are more or less damped, depending on the resistances of the lines, loads and fault. Since the time constant L/R is lower at high frequencies (the inductance goes down with frequency whereas the resistance goes up by skin effect) discharge components are usually more damped than the charge components which often carry the most energy in the recorded transients and hence will solely be used for our directional and fault distance purposes.

III. SIMULATION REQUIREMENTS

In order to simulate close to reality fault-induced electromagnetic transients, much attention must be paid to the lines model, but also to the other network elements such as transformers, loads, ... each one having to be valid at medium frequencies (several hundreds Hz). During this study, the emphasis has been set on the modelization of overhead lines.

Conventional distance protection algorithms normally use very simple models for the network lines : each mode can be represented by a π model, hence concentrating the capacitive current at the beginning and the end of the line; the distributed model, characterized by hyperbolic sine and cosine functions is generally introduced for long lines or for very accurate fault location purposes. For overhead lines, the capacitive current is generally rather small so that even a simple RX model gives satisfactory results. This is the state-of-the-art for nominal frequency representation, but for broad frequency range representation, one has to take into account the influence of frequency on the electrical parameters of the lines. Indeed, frequency plays a double role :

○ it increases the equivalent conductor resistance by skin effect,

○ it modifies the equivalent impedance of the current return path.

When frequency goes higher, the capacitances are less neglectable since they offer a lower impedance path $[Z=1/(2\pi fC)]$ to current circulation, while resistances are less important compared to reactances. Thus, in order to avoid appreciable errors that could appear with lumped parameters models, it seems clear that distributed parameters models are advised.

Taking into account the influence of frequency on the line parameters greatly influences transient waveforms, as can be seen in the following figure which compares the faulted currents when simulated with a conventional distributed model and the J. Marti line model [2], the main differences being the amplitude and damping of the fault induced transients :

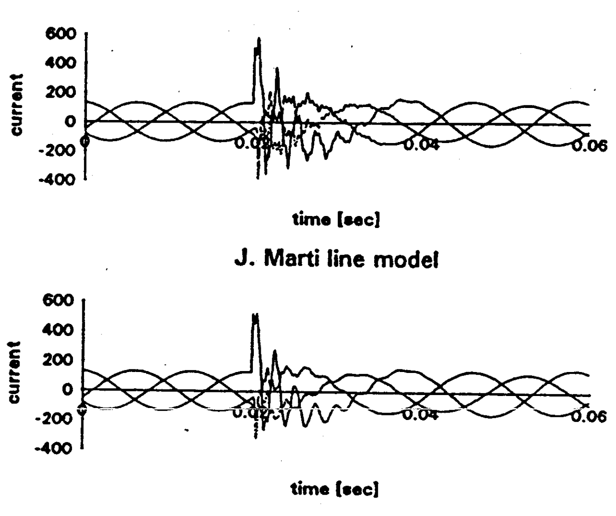

Fig. 2 : Model comparison

The J. Marti line model has thus obviously been selected for all our earthfault simulations.

Unfortunately, it is very difficult to determine the accuracy of EMTP simulations since only a few digital recordings of earthfaults in compensated or isolated networks have been obtained so far : in some cases, no transients have been found while in some others coil saturation generated a lot of fifth harmonics. Field measurements are now planned to investigate the amount of fault transients generated in MV and HV networks and to test the proposed transients based algorithms.

While it is necessary to accurately predict the fault transients in order to determine whether an estimator is applicable, the directional and distance functions have lower modelling requirements, due to their principle and to the desire of keeping settings simple enough.

IV. DIRECTIONAL FUNCTION

A transients based directional function is already available in SIEMENS 7SN71 relay. The behaviour of this static non digital relay can be summarized as follows :

- startup condition : a fault is detected if 50Hz zero-sequence voltage is present for more than 70 milliseconds.
- directional checking : basically, the directional function relies on the transient behaviour of the zero-sequence voltage and current after the fault inception; indeed, the fault direction is determined by the sign of the power flow $I_0(t)*V_0(t)$ during the first alternance of the induced transients.

Though the behaviour of this "wischer" relay is very good, today's digital techniques have led to the development of a more robust algorithm relying on the zero-sequence source angle computed from the measured transients which last a few milliseconds after the fault inception; this angle can be extracted from phasors identification at the frequency which carries the most energy in the measured voltages and currents, under the assumption that this frequency corresponds to a charge component. for a forward fault, the impedance seen in the back of the relay must be almost capacitive and of course, the contrary for a backward fault; this agrees with the "Ground-Fault Relays Testing" feature of the OMICRON test device which represents the faulted feeder in the form of a π equivalent circuit diagram and the remaining system (numerous feeders in parallel) as a concentrated capacitance.

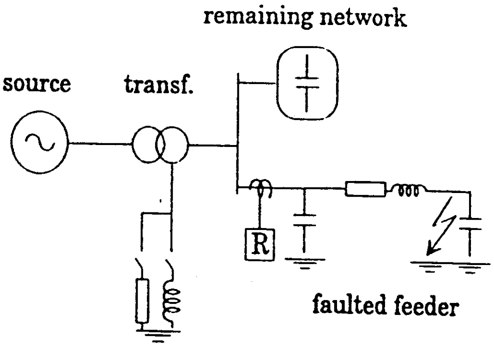

Fig. 3 : OMICRON network model

By principle, this method can be applied in both radial and meshed networks, for both isolated or compensated grounding conditions; indeed, the presence of a Petersen coil is not a problem, since even if the tuning is perfect at the nominal frequency of the network, it cannot be at the charge frequency (several hundreds Hz) where the coil, in parallel with the zero-sequence capacitance of the whole network can be neglected :

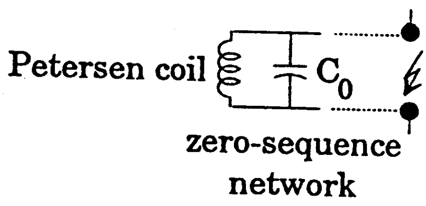

Fig. 4 : Compensated networks

The criterion used for the fault direction estimation can be summarized by the following figure :

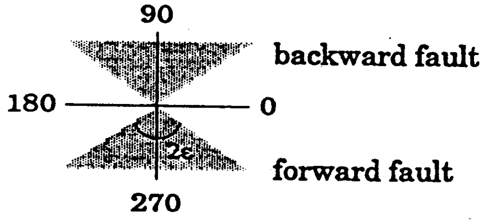

Fig. 5 : Directional decision scheme

In practice, the estimated angle can be slighly different from the theoretical value of plus or minus 90° since a real part can be present in the measured zero-sequence current due to the fault resistance (if any) and to the load.

The above described principle cannot of course apply to discharge components which lead to a virtual computed source angle not solely determined by the fault direction.

Several thousands of EMTP simulations have been performed in order to validate the above algorithm, leading to the conclusion that the backward source angle computed at the charge transient frequency is always rather close from the theoretical value of ±90° (a maximum deviation angle of 20° has been observed); it seems also that the computed source angle is relatively stable in a large frequency band around that charge frequency, what ensures the robustness of the proposed method.

As the function only needs the zero-sequence current and voltage to detect the fault direction, it can easily be implemented in a cheap hardware. A sampling rate of 10kHz should be sufficient for this purpose since only medium frequency transients are involved in the algorithm.

With the latest program delivered with the OMICRON test system, a special module designed for checking for proper directional decisions of transients ground fault relays is already included. The module contains a network calculation program for computing transient signals which approximate the voltage and current waveshapes that appear for ground-faults at the relay location. The model used for this task has already been presented in fig. 3.

Since the feeders are not represented by distributed parameter models, but by π circuits, the travelling waves are not modelled by the software, and thus, the discharge component will not appear in the simulated transients. Signals up to a frequency of 2.5kHz using at least 4 sampling points per period can be represented so far by means of this test device, what covers a wide area of networks where the charge transient frequency is below that limit.

V. FAULT DISTANCE ESTIMATION

A stand-alone relay located at the beginning of a transmission or distribution line in an insulated or compensated network may be able to estimate the distance to a single-phase to earth fault on base on transient signals [1].

The following equation applies to the Clarke components at the fault point, during a phase-R to earth fault :

$$V_{f0}+V_{f\alpha}=3I_0R_f$$

Of course, values at the faulted point are not available so that we need a relation between $V_{f0}, V_{f\alpha}, I_{f\alpha}$ and the voltages and currents at the measurement point (relay). This is obtained by introducing a mathematical description of the faulted line, under the assumption that all the fault current flows through the relay (no infeed current from the remote end of the line), which is also the startpoint of classical distance relaying. Indeed, without this assumption, it is not possible to express I_{f0} as a function of the mere measured signals. However, it is well known that an infeed current in phase with the measured fault current will not disturb the estimation of the fault position if it relies only on the reactive part of the impedance seen from the relay.

The equations of fault and line lead to a complex relation depending only on the measured voltages and currents, the fault resistance and the distance to the fault, id est a system of 2 real equations with 2 unknowns (fault resistance and fault position). These equations are linear or nonlinear, depending on the selected line model :

$$f(V_a,I_a,R_f,x,\text{parameters})=0$$

where x is the fault position, R_f the fault resistance, V_a and I_a are the 3 voltages and phase currents measured by the relay.

This last equation asks for digital integration, which can be carried out eiher in the time domain or in the frequency domain. In the first case, the whole spectrum of the measured signals is fed into the estimator (unless some kind of prefiltering is applied) while the second approach makes it easy to focus on the charge component, hence eliminating most of the disturbing noise.

Since we focus on the charge transient, the parameters of the faulted line required to find the fault position are thus the ones corresponding to that particular frequency; indeed, we know that the resistances and inductances of overhead lines are not constant but functions of frequency, what has been illustrated hereunder by means of the LINE CONSTANTS FREQUENCY option of the EMTP :

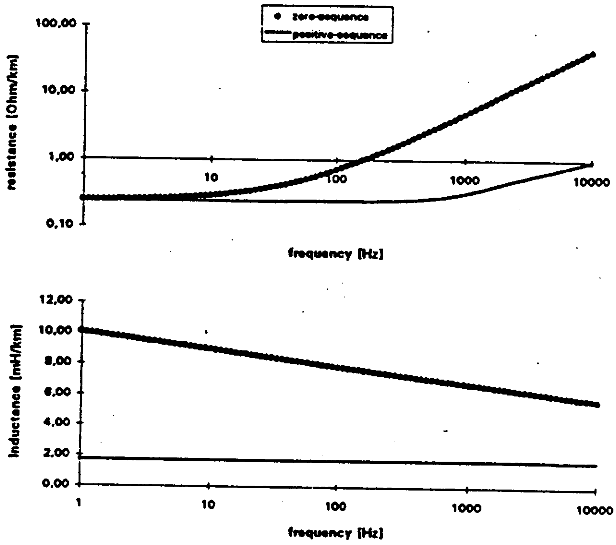

Fig. 6 : Influence of frequency on the line parameters

It is clear that the zero-sequence inductance and resistance are the most subjected to this influence; since the inductance is more important than the resistance (especially at the charge frequency where ωL>>R), only that parameter has to be adjusted. Though only 50Hz parameters of a line are usually known, Carson's equations [4] allow us to predict the value of the zero-sequence inductance knowing its 50Hz value thanks to some kind of correction factors. While the zero-sequence inductance is a linear function of *log f* for overhead lines without ground wires (Fig. 6), this is no longer the case if one or several ground wires are present; however, a rough correction can still be made on the 50Hz inductance value if one knows the general line topology.

Since the proposed method relies only on a model of the faulted line, the distance to the fault can be determined on base on any sinusoidal current component flowing from the measurement point to the fault, the best accuracy being of course achieved with signal components which carry a lot of energy in the induced transients, id est with charge transient components. The most important limitations to the applicability of the described principle are :

- the fault resistance must be small, otherwise the damping will be so high that only a few transients periods are available, which is of course a difficulty for accurate identification.

- the problem of infeed current is also critical, however it arises totally differently than for conventional 50Hz based devices; indeed, the infeed current which can come from the remote end of the line is not generated by a real voltage source, but by capacitances which are after the fault point :

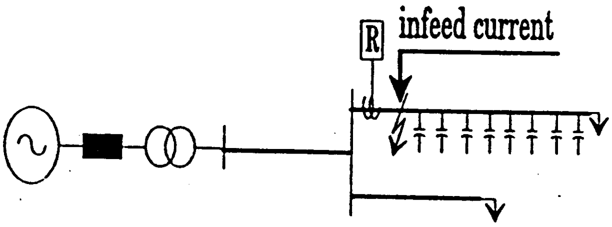

Fig. 7 : Infeed current process

As a consequence, the application area of this method is not restricted to pure radial networks, but rather to networks where most of the capacitances are in the back of the measurement point. This is illustrated by the following example which compares 2 kinds of situations :

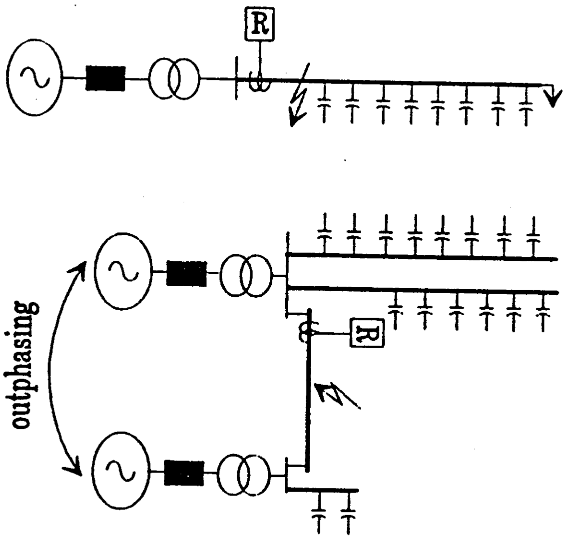

Fig. 8 : Application area

A. the first network is purely radial, and its topology is thus ideal for 50Hz based devices. However, since the fault is very close from the measurement point, most of the capacitances are located after the fault point and will result in a transient infeed current.
B. the second network is meshed, however it will lead to a good behaviour of our method since most of the capacitances are in our back.

Of course, if the fault is a perfect short-circuit, the infeed current has no influence since the equation to solve resumes in :

$$V_{f0}+V_{f\alpha}=0$$

Another problem which could deteriorate the results of such transient based distance function is the error introduced by current and voltage transformers due to their limited bandwidth, especially for the voltage transformers which transient behaviour is very construction dependent. While conventional magnetic transformers are still used today all over the world, a lot of study is achieved by electrical manufacturers in order to develop the next generation of reducers, being aware that new protection principles could be developed with high bandwidth transformers.

Encouraging results have been obtained with EMTP simulations when attempting to locate the position of single phase to earth fault in compensated or isolated networks. Though the algorithm behaves correctly in simulations, tests on real fault measurements are however necessary to conclude about the accuracy which can be reached.

VI. TRANSIENTS ESTIMATION

A mathematical model for the faulted-state voltages and currents can be written as follows :

$$x(t)=A_0\cos(\omega_N t+\phi_0)+\sum_i A_i e^{-\alpha_i t}\cos(\omega_i t+\phi_i)$$

The conventional methods used for the estimation of signal components can be classified into :

- Fourier theory based tools which assume stationary signals (Discrete Fourier Transform _DFT_, Modified Fourier Transform _MFT_, ...),
- Least squares methods,
- Autoregression signal analysis.

Our identification process being non-linear (not only the initial amplitudes, but also the transients frequencies and dampings are unknown), least squares methods often lead to ill conditioned problems.

Autoregression signal analysis has proven to be suitable for estimating sinusoids and damped sinusoids but requires a high computation burden.

The assumption of stationary signals is of course not fulfilled here, however, since the damping of each measured voltage and current is the same at a given frequency, if only linear equations or ratios of signal components at a given frequency are used, one can be content with using the Modified Fourier Transform without taking into account the damping time constant which will result in a same error on each computed frequency component; the MFT allows us to compute a "zoom" discrete Fourier transform, increasing the frequency resolution in the range of interest [3] and hence providing a good way to determine accurately the frequency which carries the most energy in the measured signals.

VII. CONCLUSIONS

A lot of simulations performed with the EMTP and the OMICRON have proven that a stand-alone relay located at the beginning of the faulted line should be able to locate the direction and the position of most single-phase to earth faults happening in isolated or compensated networks using previously described principles.

Close to reality transient simulations can only be performed by using powerful mathematical models taking into account, for instance, the influence of the frequency on the electrical line parameters. However, some questions must still be answered by means of field tests : is there always enough transients to avoid sensitivity problems ? Is the bandwidth of conventional voltage and current transformers high enough to avoid large measurement errors ?

The autors gratefully acknowledge the support of SIEMENS, which took to the decision of performing field measurements in several isolated and compensated networks : digital recorders will be installed in order to answer all these remaining questions and to validate the proposed directional and distance computation algorithms.

VIII. REFERENCES

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