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ASPECTS OF THE POWER GRIDS' IMPEDANCE RELAYING IN AN ATP-MODELS APPROACH

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Abstract **– The coexistence of analog and digital relays in the power grids' impedance protection make difficult the approach of relays' coordination. This is the main reason why in this paper some aspects regarding the modeling of the impedance analog and digital relays are presented. Because a function of distance relays is that to estimate the fault impedance and to compare it with the tripping diagram, in the first part of the paper there are presented some algorithms to estimate the fault impedance adequate for analog and for digital relays. Some aspects regarding the function of fault locator are presented too. Some aspects of transposing these models into an ATP program are emphasized.**

Keywords: *impedance relaying, power grids, ATP-MODELS simulation.*

1. INTRODUCTION

The actual dimensions and complexity of the power grids imply dynamic operative structures leading to more frequent changes of the fault currents' levels, so the sensibility and selectivity of an entire population of relays must be frequently verified and adjusted. In the same time, in the conditions of synchronous functioning of the complex interconnected grids the protective systems have a major importance into reducing the risk of appearance of major damages.

Modern digital relays offer a great variety of protection algorithms and functions, but the complexity of their functions lead to difficulties into finding their optimal settings. In addition to the variety of digital impedance relays' behaviour and parameters, the coexistence of digital and analog ones in the same grid leads to increased difficulties to establish theirs optimal settings. In such conditions, in the aim to obtain an appropriate coordination of the impedance relaying and to set the best tripping levels one possible solution is that to use databases containing apparent impedances' parameters, for the impedance relays of an entire grid.

The ATP simulations of the transients' sequences in some models containing modules dedicated to grid's impedance relays can be an appropriate approach of impedance relaying coordination due to software's precision and adequate modeling possibilities.

Irrespective of the relays' type, the logical modules of the grid's impedance relays can be pictured as an on-line or off-line application. The algorithms having on basis the on-line applications are suitable for digital relays modeling and the off-line approaches are more adequate for the analog relays modeling.

The coexistence of analog and digital distance relays implies combined approaches of both modeling ways even in the protective system's coordination studies due to some possible maloperations of the digital relays as is the voltage instability, especially for their third tripping zone.

As a consequence of a short period of time between the fault inception and the digital relays' tripping decision, the saturation of current transformers can be neglected, although some authors show that in the case of current transformers' severe saturation the distance relaying becomes unselective [1]. Anyhow, the majority of studies do not consider the current transformers' nonlinearity, this observation being sustained by the fault currents' time evolutions, as is that logged from a real 400 kV grid (Figure 1).

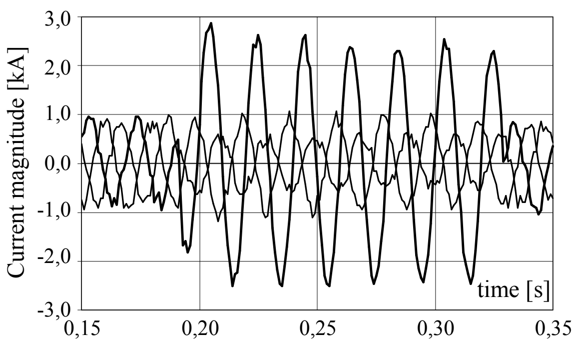

Figure 1: Time evolution of a single-phase fault current on a 400 kV, 230 km overhead line.

2. ATP MODELS OF THE DISTANCE RELAYS

2.1. Analog relays

In the case of the analog relays, the voltages and currents processed by their measuring elements are roughly sinusoidal, of industrial frequency, so a model of such a relay can easy calculate the apparent impedance on the basis of quite simple algorithms, as the Mann and Morisson algorithm is. This algorithm gives the peak values of the voltage (V_{peak}) and of the current (I_{peak}) and the phase angle (φ) between them, using the following formulas, transposed into the digital domain [2]:

$$V_{peak} = \sqrt{v_k^2 + \left(\frac{1}{\omega}\cdot\frac{v_k - v_{k-1}}{\tau}\right)^2} \; ; \qquad (1)$$

$$I_{peak} = \sqrt{i_k^2 + \left(\frac{1}{\omega}\cdot\frac{i_k - i_{k-1}}{\tau}\right)^2} \; ; \qquad (2)$$

$$\varphi = \tan^{-1}\left(\omega i_k \frac{\tau}{i_k - i_{k-1}}\right) - \tan^{-1}\left(\omega v_k \frac{\tau}{v_k - v_{k-1}}\right), \quad (3)$$

where ω is the angular frequency of the sinusoidal waveforms, k and $k-1$ are indices for the samples of voltage and current and τ is the time interval between the samples of the digitized signal.

In the fault's steady state regime, the response of the previous algorithm is very rapid and unaffected by some oscillations, the amplitude of oscillations being smaller than 1 %. In the case of transient signals, containing both exponentially decaying dc-offset and high frequency components, the response of the algorithm is distort, as one can see in Figure 2.

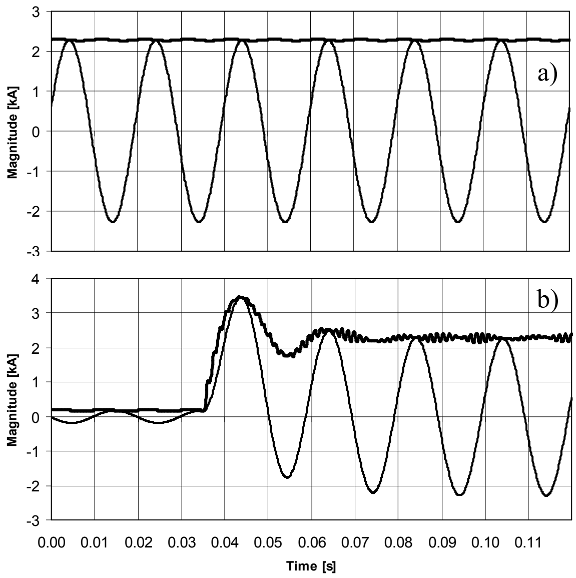

Figure 2: Results of Mann and Morrison algorithm applied to fault's current for a 400 kV, 300 km overhead line: a) – in fault's steady-state regime; b)-in single-phase fault's transient regime.

In the case of transients, the presence of the exponentially decaying component is quite obvious and the high frequency components are amplified. When the sampling frequency increases the numerical noise increases too. A possible solution to reduce the numerical noise is that to calculate the average value for the last few values, in a recursive way. The effect of dc-offset and subnormal frequency components can be reduced using the Gilcrest's algorithm [2]:

$$V_{peak} = \sqrt{\left(\frac{dv}{dt}\right)^2 + \left(\frac{1}{\omega}\cdot\frac{d^2 v}{dt^2}\right)^2} \; ; \qquad (4)$$

$$I_{peak} = \sqrt{\left(\frac{di}{dt}\right)^2 + \left(\frac{1}{\omega}\cdot\frac{d^2 i}{dt^2}\right)^2} \; ; \qquad (5)$$

$$\varphi = \tan^{-1}\left(\omega\cdot\frac{di}{dt}/\frac{d^2 i}{dt^2}\right) - \tan^{-1}\left(\omega\cdot\frac{du}{dt}/\frac{d^2 u}{dt^2}\right), \quad (6)$$

the notations being the same as in (1) ÷ (3) formulas. Transposing this algorithm into an ATP-MODELS program, the results are those shown into Figure 3.

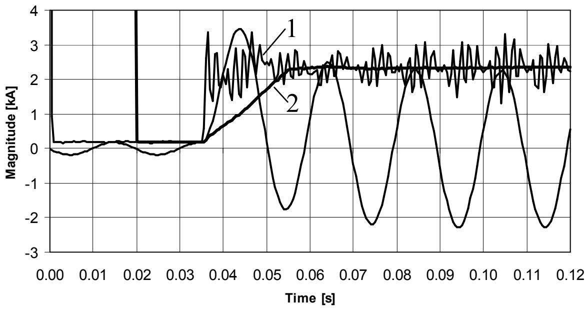

Figure 3: Results of Gilcrest's algorithm applied to fault's current on the same 400 kV, 300 km line.

The introduction of the second order derivative into formulas eliminates the influence of the exponentially decaying component into the output signal, but the algorithm gives some numerical oscillations when the signal is generated and processed in the same simulation (the curve 1 in Figure 3). A solution to reduce the oscillations is that of calculating the mean value of the output signal, in a recursive way, for a cycle corresponding to the period of the fundamental component (the curves noted with 2 in Figure 3).

A block diagram of an ATP analog impedance relay can have the structure shown in Figure 4.

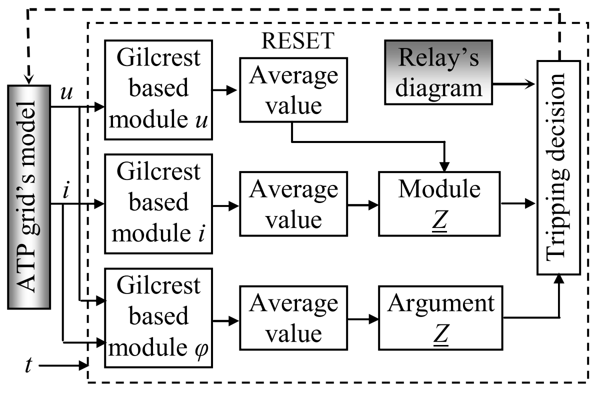

Figure 4: Analog impedance relay's ATP model.

2.2. Digital relays

In the case of digital relays, the high frequency and exponentially decaying dc-offset components must be rejected from the transient signals through numerical algorithms. A good enough rejection of the high frequency components is obtained using a low-pass Butterworth second order filter. The least square filters or Kalman filters are other methods for signal processing, but the modern relays' filters use Discrete Fourier Transform (DFT) based methods [3]. For discrete non-periodic signals, the algorithm of the Discrete Time Fourier Transform (DTFT) is precise, but, in order to avoid long strings of samples, the DFT algorithm can be used [4].

DFT algorithms do not reject the dc-offset, so algorithms based on presented Gilcrest's formulas, or algorithms based on Gilbert's or Lobos' formulas [2] as well as algorithms based on the principle of replica impedance [3] must be applied in signals processing.

Irrespective of the relays' type, analog or digital, the ATP transients' simulation is a numerical approach, so the sampling frequency must be discussed. A Fourier spectral analysis of transient voltages and currents of the faulty phases shows that the amplitudes of bigger than 500 Hz components are quite small, as results from data given in Table 1, for a single-phased shortcircuit on a 400 kV, 300 km line, part of a looped power grid.

Freq. [Hz]	Transient current $[kA_{ef}]$		Transient voltage $[kV_{ef}]$	
	First cycle	Second cycle	First cycle	Second cycle
0	4.27	1.64	7.7	5.94
50	3.64	3.83	178.7	152.72
100	0.55	0.21	25.1	0.76
150	0.22	0.02	15.6	0.06
200	0.21	0.10	8.7	0.34
250	0.07	0.20	5.4	0.37
300	0.13	0.08	6.9	0.32
350	0.05	0.07	5.4	0.05
400	0.11	0.06	4.6	0.12
450	0.06	0.17	3.3	0.65
500	0.09	0.06	4.9	0.12

Table 1: Fourier spectral analysis of transient signals.

The 500 Hz component being practically negligible, to satisfy Nyquist criteria, a sampling frequency of 1000 Hz is adequate.

Considering a number N = 20 of samples within the 0,02 seconds window (a full cycle) of the 50 Hz fundamental sinusoid, the real and the imaginary parts of the current's phasor results from the following DFT particular formulas:

$$\Re(I_1) = \frac{1}{10}\sum_{k=0}^{k=19} i_k \cdot \cos\left(\frac{\pi \cdot k}{10}\right); \tag{7}$$

$$\Im(I_1) = -\frac{1}{10}\sum_{k=0}^{k=19} i_k \cdot \sin\left(\frac{\pi \cdot k}{10}\right); \tag{8}$$

$$I_1 = \sqrt{\Re(I_1)^2 + \Im(I_1)^2}\ ; \tag{9}$$

$$\varphi_{I1} = \tan^{-1}\left[\frac{\Im(I_1)}{\Re(I_1)}\right], \tag{10}$$

quite similar formulas being used for the transient voltage signal.

For a 400 kV, 300 km overhead line realized on PAS 400 type towers and having two conductors of 450 mm^2 in the phase's bundle, the positive sequence parameters are R_1 = 61 Ω and X_1 = 342,6 Ω, resulting the response of DFT as that in Figure 5, when the filter for the dc-exponentially decaying component is based on the replica impedance principle.

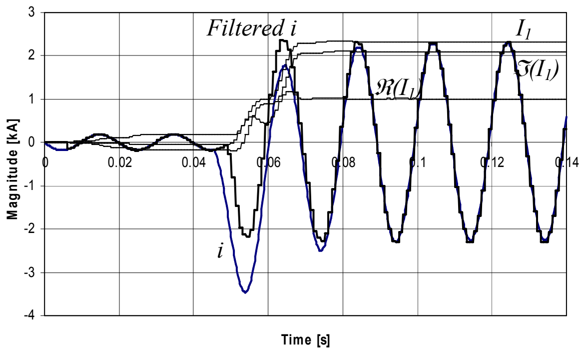

Figure 5: Time evolution of unfiltered and filtered currents and DFT outputs for the filtered current.

As it can be observed in Figure 5, the time step used in the filter designed to reject the exponentially decaying dc-offset is bigger than the time step of the simulation in the grid's model. The time step of this filter results from the sampling frequency used in the DFT based filter and the time step in the ATP grid's model must be small enough to obtain precise results. The dc-offset is practically rejected after a half-cycle corresponding to the fundamental component of the transient current.

For transient analysis of impedance relaying and to model digital impedance relays the model must contain modules to reject the high frequency components, both in voltages and currents signals and modules to reject the dc-exponentially decaying component of the transient currents. To obtain a more complex ATP model of an impedance relay, its function of fault locator can be modeled.

The simplified block scheme of an ATP model for digital distance relays is that drawn in Figure 6.

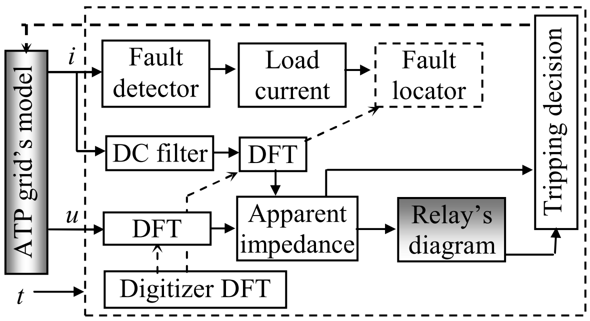

Figure 6: Digital impedance relay's ATP model.

3. RESULTS

The presented results are obtained using the previous described ATP models for the case of a 400 kV grid with two lines of 200 km and respectively 100 km, in the intermediary substation existing the possibility to simulate a load. These lines are energized through 400 MVA self-transformers in the both terminal substations. The overhead lines are realized on PAS 400 towers and they have two conductors of 450 mm^2 in the phase bundle.

Some of the simulations' results for a fault located at 80 % of the previous 400 kV line's length, from its left end an in the conditions of zero load in the intermediary substation, are those given in Table 2.

The line's model type	Numb. of cycles	Module $\underline{Z}$		Argument $\underline{Z}$	
		Value [Ω]	Error [%]	Value [deg]	Error [%]
Traveling wave model	1	194.90	47.43	87.90	13.42
	1.5	131.80	0.70	76.50	1.29
	2	131.40	0.41	77.50	0.00
Nominal Π lumped three-phase circuits	1	193.40	46.29	85.90	10.84
	1.5	135.20	2.27	77.10	0.52
	2	133.60	1.06	77.00	0.65
Error is calculated by report to the steady-state value obtained in the traveling wave model.					

Table 2: ATP simulations' results as concerning apparent impedance's parameters.

As results from the simulations, irrespective of the line's model, immediately after the first cycle from the fault's occurrence the impedances' parameters reach theirs steady-state values, with an error smaller than 2,5 %. The estimation error became of roughly 1%, when the distance from the relay's position to the fault's occurrence one is of 20 % from the line's total length.

The time evolution of the apparent impedance's phasor in the Z plane, for a single-phase shortcircuit is that shown in Figure 7.

The use of the replica impedance algorithm to process the fault's current gives the final value practically after the first cycle, and the response of the algorithm is very stable.

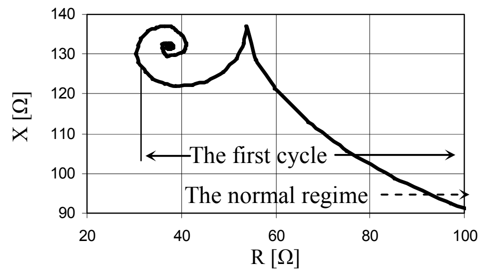

Figure 7: The evolution of impedance in Z plane.

4. CONCLUSIONS

In grids with analog impedance relays, algorithms like Gilcrest's gives good simulations results, only in the conditions of calculating an average value of processed signals.

In the case of an entire population of digital relays or in the case of coexistence of the both types of relays, the DFT based algorithms are precise but only in the conditions of rejecting the exponentially decaying dc-offset component, using a n A3 type algorithm, as the Gilcrest's one is. When relay's model is based on the principle of replica impedance, the final result is obtained practically after the first cycle.

Such relays' models associated to any ATP grid model leads to flexible programs, usable in the grids' protection coordination studies.

Acknowledgments

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