ASSESSMENT OF TWO SINGLE-END FAULT LOCATION ALGORITHMS IN AN ATP APPROACH

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The paper presents the results of the implementation of two single-end data algorithms in ATP-EMTP program, the modules of the algorithm being associated with different power distribution grids. In the ATP-MODELS the algorithm developed by Takagi, but adapted for one-machine systems, and that developed by Das, improved in this approach, are implemented. DFT and replica impedance filters are used to calculate the fundamental frequency phasors of the transient voltages and currents. The considered parameters of the presented analysis are: line's load, fault's type and resistance and fault position along the power grid's lines.

1. **INTRODUCTION**

The transmission and distribution lines are very important components of the power systems that achieve the essential continuity of service from the power plants to the end users. The complexity of the actual power grids implies dynamic operative structures leading to more frequent and dynamic changes of the fault currents' levels and, as a consequence, the sensitivity and selectivity of an entire population of relays must be frequently verified and adjusted. At the same time, these changes into the operating schemes of the power grids, eventually as a result of the distributed generation using unconventional sources, give an increased importance to the detection and the location of the grids' lines faults, not only in the long transmission lines but in the distribution ones, too.

There are researches developed into fault location based on one-terminal measured data, the merit of the resulted algorithms being that no data transmission channels between terminals are necessary, even if these algorithms carry some errors. Two-end algorithms usually process synchronised signals from both lines' terminals having better performances than the one-end approaches [1]. Still, due to the extra costs of the necessary equipment, single-end algorithms attract attention

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and, consequently, they are superior when it comes to the commercial point of view, especially for the distribution power grids that have radial operative schemes.

Algorithms as are those of Snirivasan and St-Jacques or Girgis estimate the location of faults in radial distribution systems, eventually with multiple tapped loads, and algorithms as those of Takagi, Wiszniewski, Erickson, Richards and Tan estimate the fault's location in transmission lines using fundamental frequency voltages and currents measured at one terminal, during the fault's existence and, eventually, before its occurrence [2, 3]. Other fault location algorithms use the transients' analysis [4] or techniques of the artificial intelligence [5] the advantage of the fundamental frequency based ones being that of their relative simplicity.

As a consequence of a short period of time between the fault inception and the distance relays' tripping decision, the saturation of current transformers can be neglected [6], although some authors show that the distance relaying becomes unselective in the case of the current transformers' severe saturation. In the case of fault location, the last processed data can be that collected in a period of time just before the line's disconnection and not immediately after the fault's inception, so the currents processed by the locating algorithms may be distorted by such saturation. Even in the conditions of the previously described changes of the fault currents, the majority of actual studies do not consider such non-linearity.

2. PHASORS' ESTIMATION

The majority of impedance relays and fault location algorithms process the phasors of voltages and currents. The digital estimation is fairly accurate only when both voltage and current signal are pure sinusoids, the transients affecting the accuracy of the apparent impedance and of the distance to the fault estimation.

In the case of analog relays, having as constructive elements transducers and analog low-pass anti-aliasing filters, the voltages and currents processed by the measuring element of the relay are roughly sinusoidal of industrial frequency. Thus, a model of an analog impedance relay and of an associated fault locator can be quite simple; a possible way to calculate the peak values of the voltage (V_{peak}) and current's intensity (I_{peak}), as well as the phase angle (φ) is that of using the Mann and Morisson's algorithm [6]:

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

$$\varphi = \tan^{-1}\left(\omega \cdot i_k \cdot \frac{\tau}{i_k - i_{k-1}}\right) - \tan^{-1}\left(\omega \cdot v_k \cdot \frac{\tau}{v_k - v_{k-1}}\right), \qquad (2)$$

where the k and k–1 are samples of voltage and current, τ being the time interval between the samples and ω the angular frequency of the sinusoidal waveforms.

In steady state regime the response of the Mann and Morrison's algorithm is very rapid and unaffected by oscillations, as results from the time-evolution curves presented in Fig. 1, their average level being smaller than 1 %. In the case of transient signals, the presence of the exponentially decaying component is quite obvious, as results from Fig. 2, and the high frequency components are amplified, making such an algorithm inadequate to model digital relays and to be used in the associated fault locating functions.

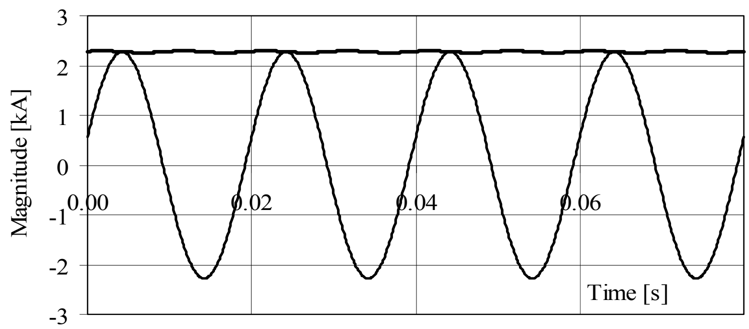

Fig. 1 – Results of the Mann and Morrison's algorithm applied to fault's steady state regime current.

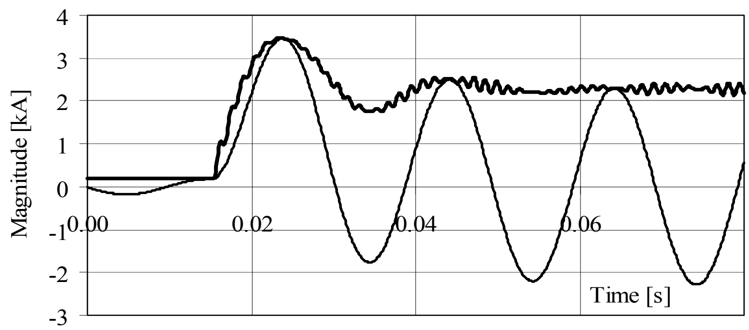

Fig. 2 – Results of the Mann and Morrison's algorithm applied to fault's transient regime current.

The modern filters of the digital relays use Discrete Fourier Transform based methods to extract the fundamental frequency components, especially due to the precision of these methods, the estimation error being smaller than 2.5 % [7]. Even for discrete non-periodic signals, as the transient current is, the Discrete Fourier Transform (DFT) algorithm can be used instead of a Discrete Time Fourier Transform (DTFT) technique [7], which needs long strings of samples. Supposing that the processed signal is a voltage, in order to calculate the real and the imaginary part of the 50 Hz components, the following formulas can be used as Fourier based fundamental component filter:

$$\Re(V_1)=\frac{2}{N}\sum_{k=0}^{k=N-1} v_k\cdot\cos\left(\frac{2\pi}{N}k\right);\quad \Im(V_1)=-\frac{2}{N}\sum_{k=0}^{k=N-1} v_k\cdot\sin\left(\frac{2\pi}{N}k\right),\tag{3}$$

in the above formulas, the indices 1 refers to the first order harmonic and N is the number of samples within the chosen window (here the period of 20 ms).

Working with discrete signals, the appropriate sampling frequency must be established. In this aim, the Fourier spectral analysis should be applied to transient voltages and currents. As an example, in Table 1 the results of such an analysis for a single phased fault on a real 220 kV, 130 km line and on a real 110 kV, 34 km line are presented. The results are given for registered transient parameters as well as for some results of ATP-EMTP simulations. It is quite obvious that the amplitudes of the components having frequencies higher than 500 Hz can be neglected. Thus, in order to satisfy the Nyquist criteria, a sampling frequency of 1000 Hz is adequate. This corresponds to the real digital relays which process the signals of 16 or 20 samples per cycle.

Table 1

Results of the Fourier spectral analysis

Frequency [Hz]	Single phased fault on a 220 kV, 130 km line				Single phased fault on a 110 kV, 34 km line			
	Registered results				Registered results		Simulations' results	
	Current [kA]		Voltage [kV]		Current [kA]		Current [kA]	
	The first cycle	The second	The first cycle	The second	The first cycle	The second	The first cycle	The second
0	0.113	0.015	1.856	0.647	0.2237	0.0298	0.2435	0.0357
50	0.318	0.352	102.048	98.364	0.6162	0.8273	0.6651	0.8930
150	0.015	0.005	5.681	2.619	0.0615	0.0108	0.1012	0.0231
250	0.011	0.005	3.211	1.785	0.0501	0.0047	0.0785	0.0058
350	0.012	0.001	0.894	0.773	0.0139	0.0047	0.0279	0.0025
450	0.011	0.002	1.067	0.521	0.0097	0.0007	0.0436	0.0025
500	0.020	0.001	0.915	0.064	0.0069	0.0004	0.0308	0.0019

In the case of transient voltages, less distorted by a DC component, the results of the DFT algorithm reach the steady-state value immediately after the first cycle, the oscillations near the mean value being smaller than 0.5 %.

The DFT based filters do not reject the D.C. component so when the processed signal is the transient current, precise values can be obtained only after a time interval equal to the primary circuit's time-constant. In the distribution power grids this time-constant is of 25 ÷ 50 ms, the time evolution of the output signal being similar to that presented in Fig. 3.

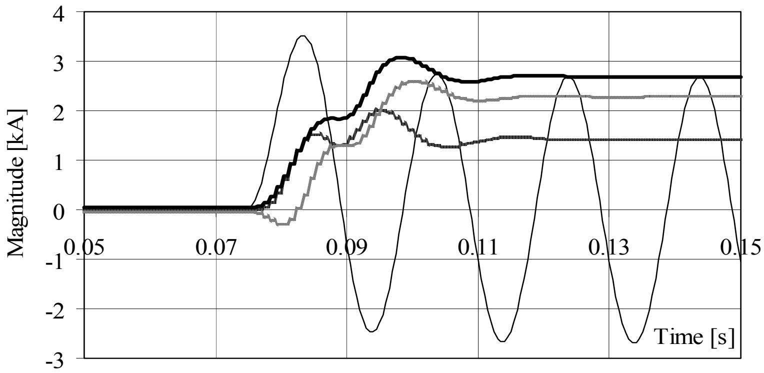

Fig. 3 – Results of DFT based 50 Hz filter applied to fault's transient regime current.

In conclusion, if the aim of a given algorithm is that of tripping decision, when a fast and accurate response of data processing is mandatory, filters to reject the exponentially decaying DC component must be used. A good response gives the filter realised on the replica impedance principle. If the final result of fault location can be obtained just before the line's disconnection, with a long enough time interval, in practice, for a complete attenuation of the exponentially decaying D.C. component, the previously mentioned filters are not necessary.

3. **FAULT LOCATOR**

On the one hand, Takagi's locator algorithm uses the fundamental frequency voltages and currents at a line terminal, before and during the fault, in the case of simple looped grids [3, 5]. On the other hand, more simulations' results show that the locating error is less affected by the grid's type (looped or radial), thus the algorithm can be used as a fault locator in distribution grids, such as that in Fig. 4, the equivalent impedance of the source as well as the electrical and propagation parameters of the line assume being known.

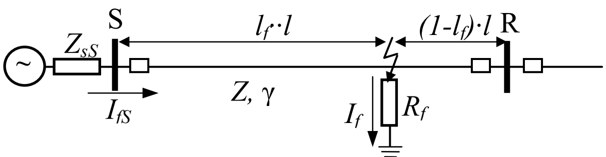

Fig. 4 – Single line diagram of a one-machine system.

The current distribution factor is defined as that in (4), where I_f is the fault current, at its occurrence point and I'_f is the difference between the pre-fault line current (I_{loadS}) and the line current during the fault (I_{fS}) at its sending end (S):

$$\eta = \frac{I_f}{I_f^{'}} = \frac{I_f}{I_{loadS} - I_{fS}} . \tag{4}$$

Assuming that the argument of the current distribution factor is equal to zero, the distance from the line's sending end and fault's position is given by the following formula [3], [5]:

$$l_f = \frac{\Im\left(V_S \cdot \left(I_f^{'} \right)^* \right)}{\Im\left(Z \cdot I_{fS} \cdot \left(I_f^{'} \right)^* \right)} , \tag{5}$$

where Z is the line impedance per unit length, $\Im(X)$ is the imaginary part of the X quantity and $(X)^*$ is the complex conjugate of the quantity X.

As results from [3], the formula to estimate the fault location is the same irrespective of the fault's type, implying the voltage and the currents of an affected phase.

The assumption of load current neglecting is acceptable only in small grids, with short lines. However, the estimates provided by Takagi's algorithm are substantially more accurate than the estimates provided by the reactive component method [5].

In [3] Das presents an iterative algorithm of a fault locator based on apparent reactance (X_{app}) estimation, using symmetrical components and phase components. The apparent impedance seen from the line's sending end (node S in Fig.4) results as follows:

– for phase-to-ground faults (1*phg*)

$$Z_{app}^{1phg} = \frac{V_A}{I_A} = R_{app}^{1phg} + \mathrm{j} \cdot X_{app}^{1phg} ; \tag{6}$$

– for two-phase-to-ground (2*phg*) and phase-to-phase faults (2*ph*)

$$Z_{app}^{2phg} = Z_{app}^{2ph} = \frac{V_B - V_C}{I_B - I_C} = R_{app}^{2phg} + \mathrm{j} \cdot X_{app}^{2phg} ; \tag{7}$$

– for balanced three-phase faults (3*ph*), the positive sequence apparent impedance

$$Z_{app}^{3ph} = \frac{V_1}{I_1} = R_{app}^{3ph} + \mathrm{j} \cdot X_{app}^{3ph} . \tag{8}$$

In the apparent impedances' formulas, V_A, V_B and V_C are the fundamental frequency voltage phasors; I_A, I_B and I_C are the current phasors at the line's sending end toward its receiving end; V_1 and I_1 are the positive sequence voltage and current phasors, at the line's sending end, too.

If the loads are neglected, in the case of the single-phased fault the modified reactance of a small section of the line (l_s), near its sending end, is computed as [3]:

$$X_m = \left(X_1 + \frac{X_0 - X_1}{3} \right) \cdot l_s , \tag{9}$$

where X_1 and X_0 are the positive, respectively the zero sequence reactance of the line.

If the modified reactance is smaller than the apparent reactance then the fault is located beyond the considered section. Thus, in order to estimate the fault's location, the section's length is increased with a small increment Δl. The modified reactance of this new section is then computed, added to the first section and compared with the apparent reactance. The process is repetitive until the value of the modified reactance becomes bigger than the apparent reactance. For the shunt faults implying more than one phase, the modified reactance in the first iteration is equal to the positive sequence reactance of the first section [3].

Similar to Takagi's algorithm, the estimation error was reduced considering the line's load in the calculus of the apparent reactance.

A possible implementation of the above-presented algorithms into a program realized in the MODELS section of the ATP software is that presented in Fig. 5.

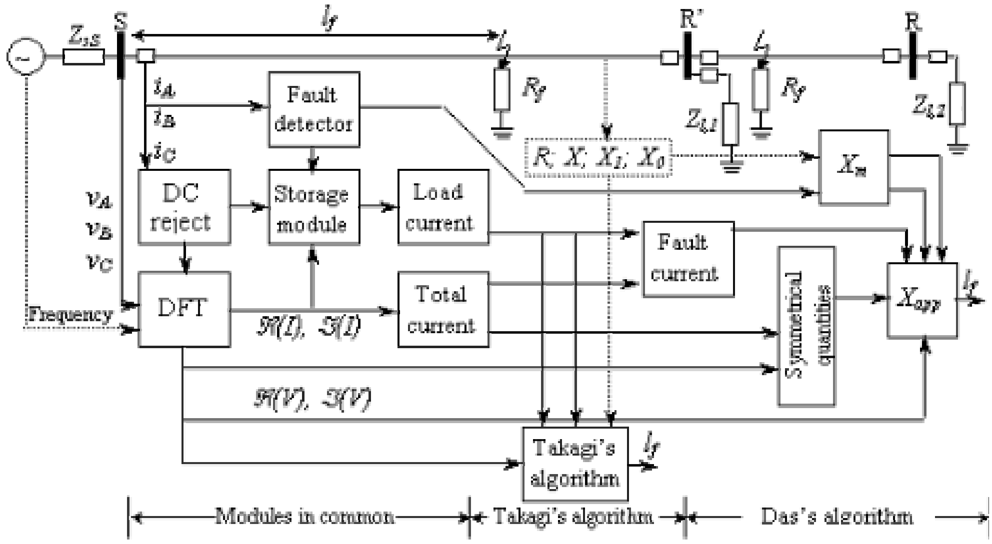

Fig. 5 – Block-diagram of an ATP module for fault detection/location based on single end algorithms.

The locator's model modules process the phase voltages and currents from the line's sending end. A replica impedance principle based filter rejects the exponentially decaying DC component and DFT based filters give the voltages' and the currents' fundamental frequency phasors. The number of samples per cycle is of twenty, irrespective of the time-step into the ATP grid's model.

The instantaneous currents coming from the grid's ATP model, as well as the connection-state of the switches modelling the fault occurrence, are processed in the module of fault detector, the logical output of this one being used to discriminate between healthy and faulty regimes. These logical signals are used to store the pre-fault currents and to calculate the fault current.

The phase quantities, the real and imaginary parts of a faulty phase voltage and of load and fault currents are input data for the locator's module based on Takagi's algorithm. Also, these quantities are processed in a module calculating the positive, negative and zero components of voltages and currents. The signals resulting from the previous modules are processed in the module calculating the apparent reactance. In this one, the apparent reactance is compared with the modified one and an iterative calculus is done until the values become roughly equal.

The ATP locator model is associated to the model of a one-machine system having two lines and an intermediary substation, giving the possibility to analyse both internal and external faults.

4. **RESULTS**

The presented results are obtained using the previously described ATP models in the case of a 110 kV grid with two lines of 80 km and respectively 40 km. In the intermediary substation only a load is considered (Fig. 4).

In Table 2 some simulations' results are presented, the parameters being the fault's type and the lines' load, given as percent from the nominal power of a 16 MVA transformer in intermediary and in the receiving end substations. The internal fault is considered at the 75 % of the line's length.

Table 2

Locating error as a function of the line's load

Line's load	Locating error in [%] as a function of the fault's type					
	Single-phased		Two phased		Three phased	
	Das	Takagi	Das	Takagi	Das	Takagi
0 %	-14.00	+16.52	+3.00	+1.82	+2.83	-2.17
50 %	-13.67	+16.45	+3.07	+1.90	+2.00	-2.00
100 %	-13.65	+16.42	+3.00	+1.83	+2.83	-1.87

In Table 3 some simulation results to put into evidence the influence of the distance to the fault on the locating error are presented. Three types of shunt faults were simulated on the overseen line (internal faults) and on the following line in grid's scheme (external faults).

Table 3

Locating error as a function of distance to the fault

Distance to the fault		Locating error in [%] as a function of the fault's type					
		Single-phased		Two phased		Three phased	
		Das	Takagi	Das	Takagi	Das	Takagi
Internal faults	25 %	-12.00	+15.35	+8.00	+0.65	+5.50	-0.50
	50 %	-13.02	+16.28	+7.23	+1.40	+2.75	-0.68
	75 %	-13.67	+16.45	+3.07	+1.90	+3.00	-2.00
External faults	125 %	-14.60	+17.20	+2.89	+0.95	+4.10	-0.76
	150 %	-14.83	+17.67	+2.17	+0.95	+5.08	-1.49
The distance to the fault's position is given in % from the length of the relay's overseen line, which is of of 80 km in the presented case-results.							

For the single-phased faults, the locator based on Takagi's algorithm always overestimates the distance to the fault and the model based on Das's technique underestimates this distance.

In the case of the single-phased faults the locator based on Das's algorithm is more precise than that based on Takagi's algorithm, the last one being significantly more precise for the multi-phased faults. The location error continuously increases when the distance to fault grows, for internal as well as for external single-phased faults, irrespective of the considered algorithm. The locator based on Takagi's algorithm in the case of multi-phased internal faults manifests the same trend.

For the usual range of towers' earthing grids resistances, supposing that the fault is the result of a flashover through the line's insulators, the locating error remains practically the same. The model based on Das' technique is unaffected by the value of the faults' resistance and the model based on Takagi's algorithm gives an increase of locating error with a roughly 0,2 % when the fault's resistance increases from 1 Ω to 30 Ω.

5. **CONCLUSIONS**

Models of fault locators based on two single-terminal algorithms, that of Takagi's and Das's, were implemented into the MODELS section associated to some power grids' ATP files. The model of fault locators contains DFT based modules calculating the real and the imaginary parts of voltages and currents at the impedance relay's location and modules calculating their positive and zero components. Before processing the currents signals into DFT based filters, the exponentially decaying dc component should be rejected only in the case when a tripping decision is the aim of the algorithm. Also, in the model's structure there are modules detecting fault's occurrence and type, calculating the fault current at the line's sending end, as a difference between the total one and the stored pre-fault one, and modules estimating the fault's location along the lines, irrespective if the fault is internal or external.

As it results from simulations, both locators have smaller errors in the case of multi-phased faults than in the case of single-phased ones. The fault locator model based on Takagi's algorithm always overestimates the distance to the fault and the model based on Das's technique underestimates it, in the case of internal as well as of external single-phased faults.

The lines' load and faults' resistance do not significantly affect the locating error.

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