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Assessment of Fault Location Algorithms in Transmission Grids

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***Abstract*--The increased accuracy into the fault's detection and location make an easier task for maintenance, this being the reason to develop new possibilities to a precise estimation of the fault location. The paper presents the results of the implementation of two fault location algorithms in ATP-EMTP program. Some ATP-MODELS modules were associated to the ATP model of different transmission grids, these modules being developed on basis of Takagi algorithm applied in two-machine systems and on basis of one algorithm processing synchronized positive-sequence phasor quantities on both transmission lines' terminals. DFT and A3 type filters were used to calculate the fundamental frequency phasors of the transient voltages and currents. There are presented some simulations', the considered parameters of the presented analysis being: line's load, fault's type and resistance and fault position along the overseen line.**

***Index Terms*—ATP simulation, double-end data algorithm, fault location, single-end data algorithm, transmission grids.**

I. INTRODUCTION

THE complexity of the actual power grids implies dynamic operative structures leading to more frequent and dynamic changes of the fault currents' levels, in the conditions of an increased importance of the faults' detection and location. The rapid removal of transmission lines' faults is one of the best measures to improve power systems stability. Decreasing the protection operation time is the simplest method for fast fault clearance. In the same time, in a competitive electricity market, the rapid fault restoration on transmission lines is faced with the quality of utility's power service. Following the occurrence of a fault, the utility tries to restore power as quickly as possible because rapid restoration of service reduces customer complaints, outage time, etc. To aid rapid and efficient service restorations, an accurate fault location estimation and fault discrimination technique are needed.

Without neglecting the severe economical losses induced by a fault occurrence, the increased accuracy into the fault's detection and location estimation make an easier task for inspection, maintenance and repair. For the transmission lines, an error into the fault's location of a few kilometers may still be acceptable for impedance relays decision but would represent a hard work for maintenance teams.

Nowadays the trend is to locate faults quickly, reliably and, if possible, without human intervention. This is made directly possible by utilizing fault-generated signals. A fault produces a wide spectrum of signals that contains information about the fault distance. These signals are the power frequency component and the transients.

In the case of widely used power frequency based algorithms, the IEEE Guide for determining fault location on AC transmission and distribution lines–IEEE Standard C37.114™ considers one-ended measurement techniques as well as two-terminal data methods to estimate fault location [1].

The merit of the single-terminal data algorithms is that they need just one terminal measured data, so no data transmission channels between terminals are necessary. In the same time, these algorithms carry some errors due to the variations of sources' power, faults' inception angle, lines' asymmetry, the combined effect of the load current and fault resistance, loading flow unbalance, presence of shunt installations and uncertainty about the line parameters, particularly zero-sequence impedance [1]-[4]. As an example, a 20 % error into zero-sequence impedance can introduce a 15 % error in the calculated fault location [1].

The actual industrial-scale technologies in the computer-aided measurements and in data-transmission make feasible the development of new digital techniques for high-speed transmission lines' protection, based on wide area monitoring. In these conditions, many authors recommend to use the information from both transmission lines' ends for an accurate fault location [2], [4]-[8].

The errors of two-terminal algorithms are smaller than 1 % [1], these ones being able to minimize or eliminate the effect of fault resistance, loading and charging currents. In the same time, their precision can be affected by the presence of the harmonics and the frequency deviation [1]. On the other hand, the transients can be used in fault location for both repair and protection purposes, instead of the power frequency. This is possible because the fault transients develop much faster and are less dependent on network configuration than the power frequency component. Traveling wave based fault locators have already been applied in power systems with success [9], even the traveling waves based fault location algorithms need a high sampling frequency along with special transducer with a wider frequency band and sophisticated electronic devices.

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Similar to the algorithms based on power frequency quantities, the traveling waves based algorithms can be divided into so-called single-ended, double or multi-ended, depending of the measurement type. Irrespective of type, the algorithms that derive from traveling waves principles can cope with high frequency transients [2], improving the faults' locations estimation [1], [10].

II. Fault Location

As a consequence of their relative simplicity, especially as concerning the involved equipment, the majority of the actual distance relays and fault location algorithms process the phasors of voltages and currents. As an example, 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 line's terminal, during the fault's existence and, eventually, before its occurrence, and algorithms like those of Jiang, Brahma, Girgis, Lee, Izykowski process synchronized or unsynchronized voltages and currents measured at both line's terminals.

A. Phasors' estimation

The digital estimation of fundamental frequency voltages and currents, during the fault existence, is fairly accurate only when signals are pure sinusoids, the transients affecting the accuracy of the distance to the fault estimation.

In the case of the steady-sate regime or in the case when transducers and analog low-pass anti-aliasing filters process the transient voltages and currents, the signals are roughly sinusoidal of industrial frequency. In such cases, a possible way to calculate the peak values of the voltage (V_{peak}) and current (I_{peak}) is that of using algorithms as are those of Mann and Morisson, Gilcrest-Rockefeller or Smolinsky.

These algorithms are designed to calculate the apparent impedance, but can be used to calculate the phasors, too. As an example, the peak value of voltages and currents can be calculated as [2]:

$$\begin{cases} V_{peak} = \sqrt{v_k^2 + \left(\dfrac{1}{\omega} \cdot \dfrac{v_k - v_{k-1}}{\tau}\right)^2}, \\ I_{peak} = \sqrt{i_k^2 + \left(\dfrac{1}{\omega} \cdot \dfrac{i_k - i_{k-1}}{\tau}\right)^2}, \end{cases} \tag{1}$$

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 such an algorithm, as Mann and Morrison is, is very rapid and unaffected by oscillations, 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. 1, and the high frequency components are amplified, making such an algorithm inadequate for fault location.

The algorithms based on integral calculus, as are those of McInnes and Morrison, Ranjbar and Cory, Horton, Sleman or Phadke and Ibrahim, have better precision into fundamental frequency phasors estimation.

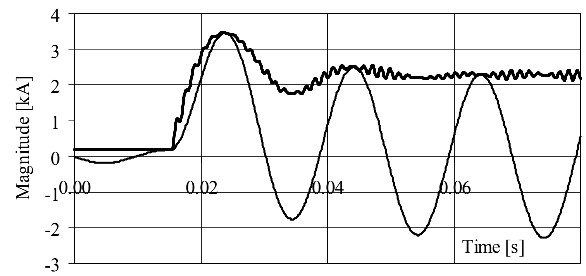

Fig. 1. Results of processing of the fault's current of a 400 kV grid by Mann and Morrison algorithm.

The modern digital relays use Discrete Fourier Transform based algorithms to extract the fundamental frequency voltages and currents, the estimation error being smaller than 2,5 % [11]. 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 [11], 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:

$$\begin{cases} \Re(V_1) = \dfrac{2}{N} \displaystyle\sum_{k=0}^{k=N-1} v_k \cdot \cos\left(\dfrac{2\pi}{N} k\right), \\ \Im(V_1) = -\dfrac{2}{N} \displaystyle\sum_{k=0}^{k=N-1} v_k \cdot \sin\left(\dfrac{2\pi}{N} k\right), \end{cases} \tag{2}$$

where the indices 1 refers to the first order harmonic and *N* is the number of samples within the 20 ms chosen window.

Applying Fourier spectral analysis to transient voltages and currents, the appropriate sampling frequency is established. As an example, in Fig. 2 the results of such an analysis, for a registered single phased fault on a real 220 kV, 130 km line, are presented.

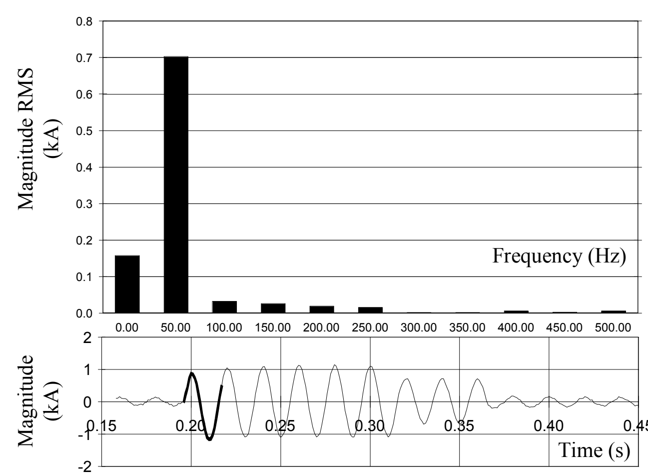

Fig. 2. The frequency spectrum and time-evolution of faulty phase current.

The results of registered faults and those obtained using ATP simulations show that the amplitudes of the components having frequencies higher than 500 Hz can be neglected, so a sampling frequency of 1000 Hz is adequate.

The DFT based filters do not reject the DC component, so in the case of transient current precise values can be obtained only after a time interval equal to the primary circuit's time-constant or processing the signal into a DC-rejection filter.

B. Single-end data algorithm

Takagi's locator algorithm uses the fundamental frequency voltages and currents measured at a line's terminal, before and during the fault, in the case of simple looped grids [2].

In accordance with the equivalent scheme shown in Fig. 3, Takagi introduces the notion of current distribution factor, which is defined as that in (3), where I_f is the fault current 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):

$$\eta = \frac{I_f}{I_f^{'}} = \frac{I_f}{I_{loadS} - I_{fS}}. \tag{3}$$

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 [2]

$$x = \frac{\Im\left(V_S \cdot \left(I_f^{'}\right)^*\right)}{\Im\left(Z_L \cdot I_{fS} \cdot \left(I_f^{'}\right)^*\right)} \cdot \frac{1}{l}, \tag{4}$$

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

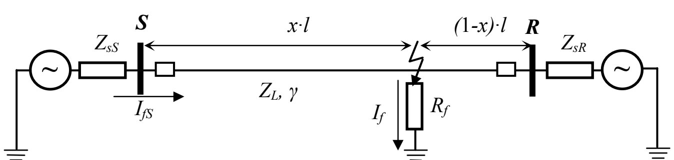

Fig. 3. Equivalent scheme of a two-machine system.

As results from [2], the formula to estimate the fault location is the same irrespective of the fault's type, implying the voltage and the currents of the affected phase.

C. Double-end data algorithm

In the case of a three-phase transmission line, the system of partial differential equations of propagation becomes a system of matrices and, in order to de-couple the phase quantities, a suitable transformation must be used. In modal quantities, the system corresponding to a three-phase single-circuit line is:

$$\begin{cases} \underline{V}_m = \underline{A}_m \cdot e^{\underline{\Gamma}_m \cdot x} + \underline{B}_m \cdot e^{-\underline{\Gamma}_m \cdot x} \\ \underline{I}_m = \dfrac{1}{\underline{Z}_{c,m}} \cdot \left(\underline{A}_m \cdot e^{\underline{\Gamma}_m \cdot x} + \underline{B}_m \cdot e^{-\underline{\Gamma}_m \cdot x}\right) \end{cases}, \tag{5}$$

where V_m and I_m are both 3x1 vectors whose entries are modal components of signals, the subscript m referring to the mode. If the transmission line is fully transposed, the subscript m represents the Clarke components 0, α and β. $Z_{c,m}$ and Γ_m are the modal surge impedance matrix and respectively the propagation constant matrix. A_m and B_m quantities are also 3x1 vectors of modal components, given by:

$$\begin{cases} \underline{A}_m = \dfrac{1}{2} \cdot \left(\underline{V}_{R,m} + \underline{Z}_{c,m} \cdot \underline{I}_{R,m}\right) \\ \underline{B}_m = \dfrac{1}{2} \cdot \left(\underline{V}_{R,m} - \underline{Z}_{c,m} \cdot \underline{I}_{R,m}\right) \end{cases}, \tag{6}$$

where the subscript R refers to the line's receiving end.

Using the solution of (5), for a fault located at the distance $(1\text{-}x)\cdot l$ from the line's receiving end (Fig.3), the so-called fault location index results as [2], [4]-[7]:

$$x_m = 1 - \frac{\ln\left(\underline{N}_m / \underline{M}_m\right)}{2 \cdot \underline{\Gamma}_m \cdot l} = 1 - \frac{\ln\left[\left(\underline{A}_m - \underline{C}_m\right)/\left(\underline{E}_m - \underline{B}_m\right)\right]}{2 \cdot \underline{\Gamma}_m \cdot l}, \tag{7}$$

where m = 0, α, β, and C_m and E_m quantities referring only to the line's sending end (S), and being given by:

$$\begin{cases} \underline{C}_m = \dfrac{1}{2} \cdot \left(\underline{V}_{S,m} + \underline{Z}_{c,m} \cdot \underline{I}_{S,m}\right) \cdot e^{\underline{\Gamma}_m \cdot l} \\ \underline{E}_m = \dfrac{1}{2} \cdot \left(\underline{V}_{S,m} - \underline{Z}_{c,m} \cdot \underline{I}_{S,m}\right) \cdot e^{-\underline{\Gamma}_m \cdot l} \end{cases}. \tag{8}$$

In [4] there are shown the conditions under which the absolute values of the modal fault location index, x_m, can yield the accurate fault location results on three-phase transmission lines, for every fault's type.

In [12] the symmetrical components transformation is used to resolve the coupling effect among the inter-phases, instead of the modal or Clarke transformation. Since the positive sequence quantities appear in all the types of faults, this quantity is used in the fault location algorithm. Operating with positive sequence phasors of voltages and currents, at both line's ends, the fault index results similar as previous, but only in positive sequence quantities:

$$x = 1 - \frac{\ln\left(\underline{N}/\underline{M}\right)}{2 \cdot \underline{\gamma} \cdot l}, \tag{9}$$

where the formulas for the nominator and denominator of the expression under the logarithm are:

$$\underline{N} = \frac{1}{2} \cdot \left[\underline{V}_R + \underline{Z}_c \cdot \underline{I}_R - \left(\underline{V}_S + \underline{Z}_c \cdot \underline{I}_S\right) \cdot e^{\underline{\gamma} l}\right], \tag{10}$$

and

$$\underline{M} = \frac{1}{2} \cdot \left[\left(\underline{V}_S - \underline{Z}_c \cdot \underline{I}_S\right) \cdot e^{-\underline{\gamma} l} - \underline{V}_R + \underline{Z}_c \cdot \underline{I}_R\right] \tag{11}$$

In (9)-(11), l is the total length of the transmission line, Z_c and γ are the positive sequence surge impedance and propagation constant respectively, and V_R, V_S, I_R, I_S are the synchronized positive sequence phasors of the receiving and sending end voltages and currents, respectively.

The nominator and the denominator of the expression under the logarithm in (9) can be used to discriminate between faulty and healthy conditions of the grid, as well as to discriminate between internal and external faults on the overseen line, as result from the following formulas [12]:

- for internal faults

$$abs\left[\arg\left(\frac{\underline{V}_S - \underline{Z}_c \cdot \underline{I}_S}{\underline{V}_R - \underline{Z}_c \cdot \underline{I}_R} \cdot e^{-\underline{\gamma} \cdot l}\right)\right] \neq 0; \qquad (12)$$

- for external faults

$$abs\left[\arg\left(\frac{\underline{V}_S - \underline{Z}_c \cdot \underline{I}_S}{\underline{V}_R - \underline{Z}_c \cdot \underline{I}_R} \cdot e^{-\underline{\gamma} \cdot l}\right)\right] = 0, \qquad (13)$$

where arg($\underline{W}$) denotes the phase angle of the $\underline{W}$ phasor, and *abs* denotes the absolute value of the quantity.

As results from the (9)-(11), the fault's resistance does not appear explicitly in the calculus and if the quantities from both ends are pure-fault data, the effect of the line's loading on the *x* index's accuracy can be eliminated. On the other hand, the influence of the line's parameters on the value of the fault location index is strongly important. This is the reason why the lines' parameters must be accurate estimated, even by techniques based on double-end measured data [4]-[7], [12].

III. ATP LOCATOR'S MODEL

A possible way to implement the two previous described fault location algorithms into a program transposed in the MODELS section of the ATP software is that presented in Fig. 4.

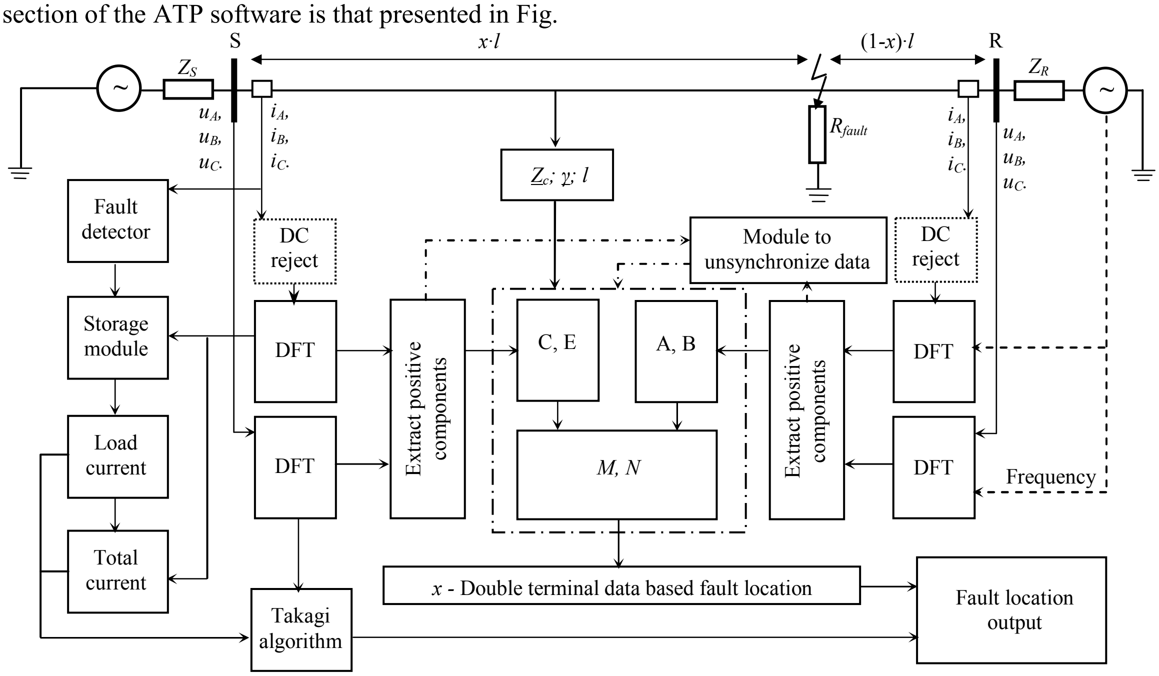

Fig. 4. Block-diagram of an ATP module for fault location based on single and double end algorithms.

The program modules realized in ATP-MODELS section process all the phase voltages and currents from both ends of the transmission line, in the modules associated to Takagi locator being processed only the phase voltages and currents from the line's sending end. In the first stage, the modules realized as recursive DFT based filters give the fundamental frequency phasors of the voltages and the currents at both line's terminals. Before the processing of the transient current into DFT based filters, some numerical filters should reject the exponentially decaying DC component, very good results being obtained when replica impedance principle based filters are used:

$$i_{f,k-1} = F_{u,i} \cdot \left(R \cdot i_{k-1} + L \cdot \frac{i_k - i_{k-2}}{2 \cdot \tau}\right), \qquad (14)$$

where $i_{f,k\text{-}1}$ is the sample k-1 of the filtered transient current, τ is time interval between samples, R and L are the nominal positive sequence parameters of the overseen line and $F_{u,i}$ is a scaling factor between voltage and current, which can be obtained after some simulations. If such DC rejecting filters are used in the locator's model, an additional delay of 2τ must be compensated in the model's software.

If such locator models are designed in the idea to analyze the possibilities to obtain an accurate fault location and not to take a fast tripping decision, then the data can be acquired and processed till the line's disconnection. In such conditions, the filters to reject the exponentially decaying DC component are not necessary, simplifying the locator's model.

The synchronized data two-terminal schemes as well as the programs based on Takagi algorithm do not demand a high sampling frequency. The results of the spectral analysis performed on the signals registered in transmission grids and on simulations' results lead to the observation that the sampling frequency of 1000 Hz is adequate for such studies. So, in the 50 Hz grids the number of samples per cycle in DFT based modules is of twenty, irrespective of the time-step into the ATP grid's model.

However, a time step of 10^{-3} seconds in the simulations can be too big, even in the studies of the transients having internal causes. As an example, when the lines are modeled through distributed parameters elements, the time step of he ATP simulation must be smaller than the waves' propagation time along the line. Thus, the time steps should be different in the grid's ATP model and in the DFT based filters. For instance, the transient voltages and currents should be generated, in the ATP grid's model, every $5 \cdot 10^{-5}$ seconds, the DFT based filters calculating, in a recursive way, only the last twenty values obtained with a sampling frequency of 1000 Hz, when the system's frequency is of 50 Hz.

The results of the transient current processing in a DFT filter, after the rejection of the exponentially decaying DC component, is that presented in Fig. 5. The curves correspond to a single-phased short-circuit on a 400 kV, 300 km overhead line having two conductors in the phase's bundle.

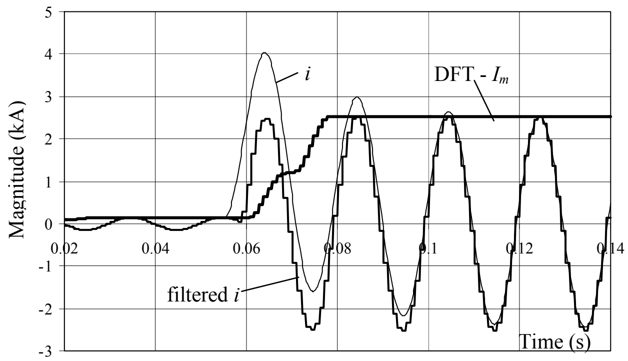

Fig. 5. Time-evolution of faulty phase current, of the DC rejection result and of the output signals of the DFT module.

As one can see, the output of the DFT based module is very stable, having not oscillations, just after the first cycle of data processing. Also, the difference between the two sam-pling frequencies, the one of the grid's model and the other one of the locator's model, is quite evident.

The instantaneous currents coming from the grid's ATP model, as well as the connection-state of the switches which are simulating the occurrence of the fault, are processed in the module of fault detector, the logical output of this one being used to discriminate between healthy and faulty conditions. These logical signals are used to store the pre-fault currents and to calculate the fault current, necessary in the algorithm of Takagi. The phase quantities, the real and imaginary parts of a faulty phase voltage and of load and fault currents are, also, input data for the locator's module based on Takagi algorithm. On the other hand, the output signals of the DFT based filters are processed in modules calculating the positive, negative and zero sequence components of voltages and currents, necessary values in the locating algorithm based on two terminal data.

IV. RESULTS

The presented results are obtained using the previously described ATP models in the case of a two-machine 400 kV grid having one line of 300 km, realized on PAS type towers and having two conductors of 450 mm^2 in the phase's bundle. The line's positive sequence parameters, given by the component named LINE CONSTANTS of the ATP program, are the following: surge impedance, $\underline{Z}_c = 319.58\angle{-5.1^o}$ Ω; atenuation, α = $8.339\cdot10^{-4}$ dB/km; resistance $R = 6.112\cdot10^{-2}$ Ω /km; reactance, $X = 3.396\cdot10^{-1}$ Ω /km.

For a short-circuit power of 2500 MVA of both equivalent sources and for a fault location at $0{,}7\cdot l$ from the line's sending end (Fig. 4) the time evolution of the absolute values of the complement (1-x) of the fault location index and of the M_1 and N_1 quantities are those drawn in Fig. 6.

As results from Fig. 6, the absolute value of the location index converges rapidly to its final value, but always is smaller than the unit. In the same time, the absolute values of M_1 and N_1 quantities increase in the post-fault conditions. Thus, the fault's location must associates, in an AND operation, the value of x index and a bigger than a pre-established threshold value for M_1 or N_1 quantities.

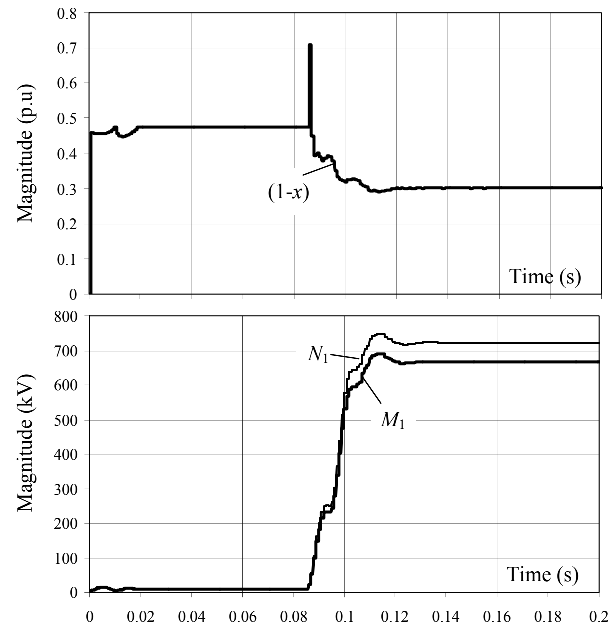

Fig. 6. Time-evolution of the absolute values of (1-x), M_1 and N_1 quantities.

In the same case of the previous described 400 kV grid, the dependence between locating error and fault's position along the line, beginning from its sending end, is that in Fig. 7.

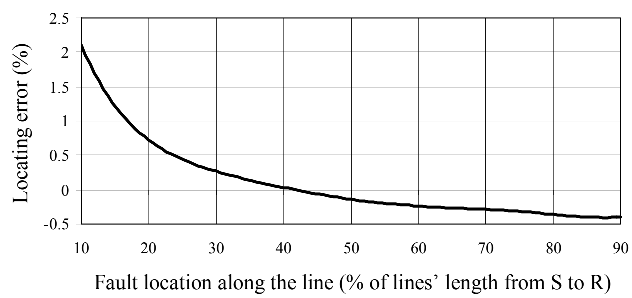

Fig. 7. Locating error of double-end algorithm as a function of the fault's position along the line.

As results from fig. 7, the location error has its minimum value for single-phased faults located from 30 % to 70 % of the line's length, measured from its declared sending end. In the case of the faults located near line's sending end, the location error can reach 2.3 %. On the other hand, in the case of transmission lines having phasor measurement units installed at both line's terminals, the more accurate value of the location index can be considered the smallest value of those two calculated at every line's terminals.

In Table 1 some simulation results, to put into evidence the influence of the distance to the fault on the locating error of the two considered types of algorithms, are presented.

TABLE I
LOCATING ERROR AS A FUNCTION OF THE DISTANCE TO THE FAULT

Distance from line's sending end to fault (%)	Locating error, in %, as a function of the fault's type					
	Single-phased		Two phased		Three phased	
	Single-end alg.	Double-end alg.	Single-end alg.	Double-end alg.	Single-end alg.	Double-end alg.
25 %	+15.38	+0.42	+0.65	+0.56	-0.55	-0.53
50 %	+16.32	-0.13	+1.56	+0.77	-0.76	-0.69
75 %	+16.48	-0.32	+1.83	+0.72	-1.12	-0.62

The distance to the fault's position is given in % from the 300 km length of the considered line, measured from its sending end.

In the case of the single-phased faults the locator based on double-end data is incontestably more precise than that based on single-end data algorithm, these difference being quite small in the case of the multi-phased faults. The location error of single-end algorithm continuously increases with the distance from line's sending end to the fault, this trend being not the same in the case of double-end data algorithm.

The line's load practically does not affect the results of the distance to the fault estimation.

The fault inception angle does not affect the results of location algorithms if the decaying DC component became near zero. If there are used filters rejecting the DC component of the transient currents, the final result is obtained practically after the first cycle.

For the usual range of towers' earthing resistances, the error remains practically the same, both types of locating algorithms giving an increase of locating error with a roughly 0,25 % when the fault's resistance increases from 1 Ω to 50 Ω.

V. CONCLUSIONS

Models of fault locators based on a single-terminal and on a double-end algorithm, were implemented into the MODELS section associated to some power grids' ATP models. The modules of fault locators contain DFT based filters processing the transient voltages and currents, modules calculating the positive and zero components of these and modules calculating the location index and error. Also, there are used modules detecting fault's occurrence and type, which calculate the fault current at the line's sending end, as a difference between the total current and the stored pre-fault one.

As it results from simulations, in the case of the single-phased faults the locator based on double-end data is incontestably more precise than that based on single-end data algorithm, these difference being small in the case of the multi-phased faults. The lines' load, the faults' resistance and inception angle do not essentially affect the locating error.

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