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Research Article

Increase of Accuracy of the Fault Location Methods for Overhead Electrical Power Lines

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The high-voltage power lines are quite often damaged parts of the energy system. Line outage is always accompanied by undersupply of energy and decrease of reliability, cost, and quality of electric supply. That is why one of the important tasks of line maintenance is quick looking for location of the damage and organization of the rehabilitation. The main part of this work includes development and research of the methods and algorithms for fault location based on one-sided measurement and the ways to increase their accuracy. This type of measurement uses signals from digital current and voltage transformers as input. The influence of the basic distorting factors on the accuracy of the fault location determination methods is also considered.

1. Introduction

Fault location determination on the electrical power lines is an indispensable function of the modern substation automation systems [1–3]. There are wide-spreading methods of fault location based on measurement of the emergency mode parameters (EMPs) [4]. Power lines currents and voltages received from the primary converters are used as input information in the fault location methods based on EMP. These methods and means of the fault location, including the methods based on EMP, can be subdivided into one-sided or two-sided measurement methods. The latter use the information from both sides of the power lines and also use the special communication channel between the subsets of the devices for the data exchange [4]. The one-sided methods are still practically interesting because of their cheapness and maintainability. Besides, the usage of the two-sided methods is limited by some technical abilities (e.g., lack of the static current and voltage sensors on such objects in the medium voltage grids as downward transformer stations in the system of urban electrical supply) [5, 6]. In this case, the fault location determination can be made only at the beginning of the branching cable lines plume—in power supply centers or distribution substations.

The advantages of these methods are simplicity of usage, absence of generating equipment, and possibility of usage on every kind of lines [6–10]. Also distant fault location, which is based on measuring EMP, has large (about 10–20%) error caused by errors of current and voltage sensors [4, 11].

The traditional electromagnetic sensors (current and voltage transformers) have the limited frequency range and the error caused by core saturation [12]. Increasing the accuracy of the fault location methods became possible because of the invention of new innovative digital current and voltage transformers [13–15]. Its usage helps to improve the accuracy of the fault location determination, thanks to such advantages as high accuracy of the measurement (current and voltage error ≤0.1%), wide frequency range of the measurement including the direct current measurement, and absence of the saturation caused by short-circuit current and aperiodic component.

Ivanovo State Power Engineering University (Russia) conjointly with Scientific and Production Enterprise “digital measuring transformer” developed current and voltage converters using such nontraditional sensors as measuring bypass and Rogowski coil for current measurement and divider for voltage measurement.

In [16–20], the application of the Rogowski coils in relay protection in low, medium, and high-voltage grids is described. In this case, they are used for organization of the differential protection of such objects as busses, overhead and cable lines, generators, transformers, and so on. Usage of Rogowski coils improves the technical characteristics of differential protection through high reliability (sensitivity and efficiency in cases of low fault currents in the zone). Also it improves reliability in failure in cases of short circuits out of the zone. Protection algorithms are simplified because Rogowski coils are not saturated. Besides, the existence of several inclined sections of the tripping characteristic is not required. Protection settings can be chosen lower for the providing of sensitivity in comparison with the decisions for ordinary electromagnetic current transformers. But there is almost no experience of the Rogowski coil application, and it is poorly described in the available sources.

The focus of the work is development of the fault location methods based on one-sided measuring of EMP with higher accuracy using digital current and voltage transformers that are based on nontraditional current and voltage sensors.

2. Statement of the Targets

Such one-sided fault location methods based on EMP are as follows [21]:

(i) The methods based on overflows of power

(ii) The methods using the effective value of EMP

(iii) The methods using the instantaneous value of EMP.

The one-sided fault location methods using the instantaneous value of EMP are based on solution of the short-circuit "loop" equation. The basis of this algorithm lies in distant fault location determination—calculation of the inductance to the fault place in the moments of zero crossing by the current of the damaged phase (or phases).

Look at the equivalent circuit for the case of the two-phase (A-B) short circuit when $i'_{AB} = 0$. The power line has a single supply (Figure 1) [22].

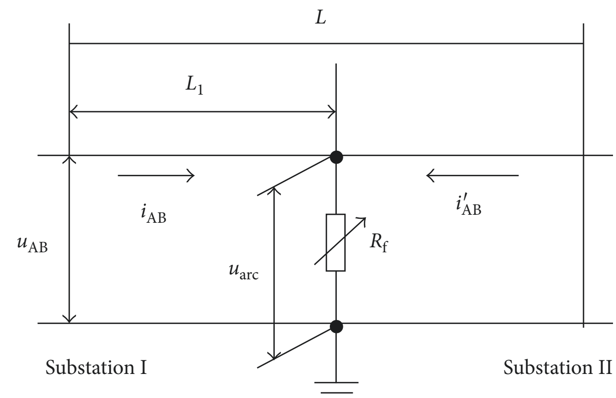

Figure 1: Equivalent circuit for the case of the two-phase (A-B) short circuit.

According to Figure 1, at any moment there can be an appropriate expression as follows:

$$u_{AB} = u_A - u_B = lL_{PU}\frac{di_{AB}}{dt} + lr_{PU}i_{AB} + R_f i_{AB}, \quad (1)$$

where u_{AB} is the instantaneous value of phase-to-phase voltage, $i_{AB} = i_A - i_B$ is the difference between instantaneous values of damaged phase currents from the measuring side, L_{PU} is the unit inductance of the power line (for the case of phase-to-phase short circuit—positive (reverse) phase-sequence inductance), r_{PU} is the unit resistance of the power line, l is the distance to the fault location, and R_f is the fault resistance.

In the moments of zero crossing by i_{AB} in (1), there will not be elements including resistances (resistance of the power line and fault resistance) in u_{AB}. If $i_{AB} = 0$, there can be such an appropriate expression for the distance to the fault location:

$$l = \frac{(u_{AB})_{i=0}}{L_{PU}\,(di_{AB}/dt)_{i=0}}. \quad (2)$$

This way of the one-sided fault location on the lines with duplicate supply will have the best accuracy if the feed to the fault from the source in the opposite side of the power line is taken into account. If it is not, there will be a methodical error caused by a fall of voltage on the fault resistance generated by the current from substation (source) 2 (Figure 1).

The algorithm is considered for the line with a single supply for simplification. The possibilities of this way usage on the lines with duplicate supply will be considered separately.

3. Methodology of the Research of the Fault Location Determination Methods

For the research of the transient processes during the short circuit and the development of the fault location algorithms, the models of the grids 110–330 kV simplified (containing models of ideal current and voltage meters) and integrated were developed in the system Matlab + Simulink [13].

The simplified model was used for the research of the effects caused by some confounding factors. These factors were supposed to be independent. In this model, the primary converters are represented by the ideal current and voltage meters.

The circuit of the real part of the grid with a single supply was modelled for the complex research [13]. There are taps (downward transformation stations) on the modelled power lines. The circuit is realized in Matlab and includes models of the real current and voltage converters (electromagnetic current and voltage transformers, nontraditional converters depending on the researched object or algorithm [23]).

The relative error of the ways of fault location δ (%) was determined according to the following equation:

$$\delta = \frac{l_m - l_{real}}{l_{real}} \cdot 100\%, \quad (3)$$

where l_m is the measured (calculated) distance to the fault location (km) and l_{real} is the real distance to the fault location (km).

Different types of short circuits in cases of different distances to the fault were considered on these simulation models. Also, attention was given to the influence on the fault location accuracy of such factors:

(i) Error of primary current and voltage converters [24, 25]

(ii) Transient fault resistance (in the range of 1 to 50 ohm)

(iii) Electrical load on the power line (in the range of 25 to 125% of the transmission power limit [26])

(iv) Existence of the input frequency filters (cutoff frequency was taken in the range of 200 to 5000 Hz).

Different methods of current derivative calculation and a physical receipt of this derivative from a Rogowski coil were applied for the research of the instantaneous values algorithms (distant fault location).

Amplitude-frequency and phase-frequency characteristics of the Rogowski coil samples were received by an experimental way [27]. Also were taken the coil errors when converting the current values in the wide ranges (to 15 kA) and when transmission of the short-circuit currents containing an aperiodic component with the amplitude to 4 kA. Experimental research of Rogowski coils was made with the help of the equipment included in the unique scientific installation "multifunctional test complex for the study of primary current and voltage converters, digital substation devices, and relay protection and automation equipment."

4. Research of the One-Sided Fault Location Based on Measuring the Instantaneous Value

4.1. Usage of the Signals from Digital Current and Voltage Transformers. In this method, the algorithm of the calculation of derivatives in the moments of current zero crossing is of interest because of the fact that the usage of nontraditional sensors (e.g., a sensor included into the current transformer based on a Rogowski coil) allows to get the derivative value physically, not mathematically. Besides, the absence of the saturable core allows reproducing the value of the primary current in the wide range accurately [28].

In Table 1, there are the results of the error calculation in case of one-sided fault location when the derivative was calculated in the first moment after 2-phase fault current appearance (the moment of the first i_{AB} zero crossing). In these circumstances, the traditional electromagnetic current transformer model based on the T-circuit [24, 25] and operating in the rated load mode was applied. The derivative was calculated based on the double-sided difference method.

From Table 1, it is seen that the electromagnetic current transformer provides significant errors to the fault location ways. So the algorithm further was researched taking into account the usage of the current signals from the digital current transformer (current signal from measuring precision bypass with the following derivative calculation or current derivative signal from a Rogowski coil).

The different methods of derivative calculation were researched. It was shown that the greatest errors could appear during the current inrush. The influence of these methods on the first-moment fault location calculation was researched separately.

Table 1: Fault location error in cases of different distances to the fault and application of the real electromagnetic current transformer.

$L_{\mathrm{f\ real}}$ (km)	25	50	75	100
δ (%)	20.57	65.07	21.02	14.62

Such ways of derivative calculating in the grid model were considered as follows:

Method 1. Double-sided difference method.

"Derivative" unit calculating the increment of the signal in last two points in Matlab was used:

$$y(t) = \frac{\Delta u}{\Delta t} = \frac{1}{\Delta t}\left(u_k - u_{k-1}\right), \quad (4)$$

where Δt is the time interval between present and previous points and u_k and u_{k-1} are the values of the function in these points.

Method 2. Usage of the real differentiator.

Modelled real differentiating sections with such transfer function were as follows:

$$W(p) = \frac{k(p)}{T_{\mathrm{D}}p + 1}, \quad (5)$$

with different values of the time constant T_{D}.

Method 3. Approximation of the current line using math function $i(t)$ and usage of the analytical function $di(t)/dt$ (Figure 2).

The equivalent circuit of the network segment was made up to receive the analytical dependence of the fault current on time (Figure 3).

From Figure 3, the expression for i_{L} in general terms is as follows:

$$i_{\mathrm{L}}(t) = i_{\mathrm{AB}}(t) = \frac{E}{\sqrt{R^2 + (\omega L)^2}}\left(\sin(\omega t + \alpha - \varphi) - e^{-(t/T)}\sin(\alpha - \varphi)\right), \quad (6)$$

where $E = U_{\mathrm{AB}}$ is the source EMF, R is the real line resistance, L is the line inductance, ω is the radial current frequency, α is the source phase, φ is the line angle, and T is the transient process time constant.

Method 4. Usage of the Rogowski coil (RC) or its mathematical model for the derivative calculation.

4.2. Influence of the Distorting Factors on the First-Moment Fault Location. Derivative calculation in the moment of the fault appearance (in the moment of first current inrush) can provide overvalued result of fault location based on (2)

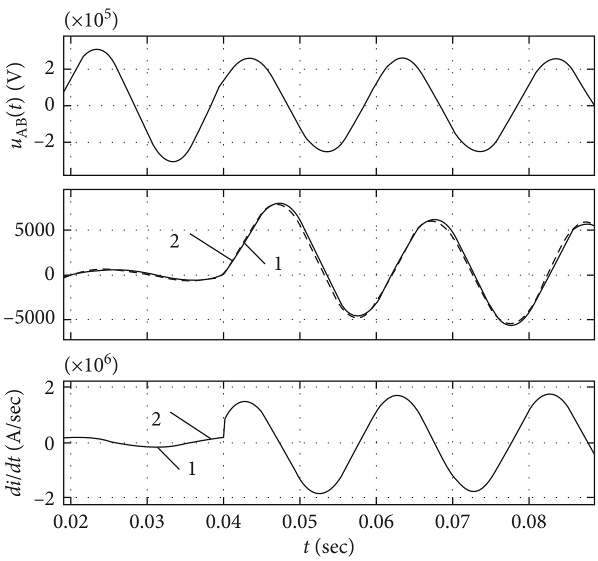

Figure 2: Oscillograms of the electrical units in case of 2-phase fault: (1) current and its derivative received on the model and (2) analytical current and its derivative functions received based on (6).

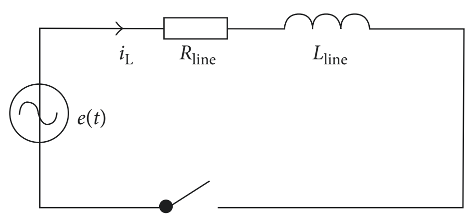

Figure 3: Equivalent circuit of the considered network.

(e.g., $l_F = 100$ km and $l_F = 10$ km in Table 2), depending on the calculation method.

The influence of transient fault resistance on the first-moment fault location accuracy in case of different derivative calculation methods was researched (Table 3). Existence of the transient resistance does not almost influence the fault location accuracy.

Changes in the electrical load also do not almost influence the first-moment fault location accuracy. The results of the evaluation of the distant fault location method accuracy in case of using Method 1 are given in Table 4.

The influence of low-pass filters (LPFs) on the method accuracy was researched. It is shown that, for the fault location in the first-moment current zero crossing (in the moment of first current inrush), the cutoff frequency should be at least 2000 Hz. These conditions provide transmission of the leading edge slope (as derivative) of the current (Table 5).

4.3. Influence of the Distorting Factors on the Further Fault Location. The fault location determination in the moments of further current zero crossing gives some different results. In the quasisteady mode, there are more accurate results of the fault location. Also in this mode, the way of derivative calculation does not almost influence the accuracy of the fault location (Table 6). Here, l_F is taken as the arithmetic mean (average result) of the fault location determination in the moments of current zero crossing except the first one.

Existence of the transient resistance has a little effect on the average fault location result accuracy for every calculation method (Table 7). In this condition, the errors more

Table 2: Influence of the different methods of derivative calculation and different distances to the fault on the first-moment fault location error.

Calculation method	Method 1	Method 2	Method 3	Method 4
δ (%) ($L = 100$ km)	0.042	32.21	3.02	−1.21
δ (%) ($L = 10$ km)	0.667	51.39	15.44	4.07

Table 3: Influence of the transient resistance on the first-moment fault location error, $l_{real} = 100$ km.

R_f (ohm)	1	5	10	20	50
Method 1	0.125	0.461	0.878	1.71	4.29
Method 2	32.29	32.5	32.84	33.4	35.1
Method 3	3.02	3.085	3.17	3.33	3.8
Method 4	2.29	3.89	5.7	7.68	9

Table 4: Influence of the different electrical load values and different distances to the fault on the first-moment fault location error.

Load in % of limit power	25	50	75	100	125
δ (%) ($L = 100$ km)	0.026	0.047	0.053	0.042	0.045
δ (%) ($L = 10$ km)	0.017	0.43	0.285	0.667	0.17

Table 5: Influence of the cutoff filter frequency on the first-moment fault location error, $l_{real} = 100$ km.

f_c (Hz)	200	500	1000	2000	5000
Method 1	60	49.28	24.28	3.43	2.78
Method 2	77.85	80.71	62.14	42.85	32
Method 3	102.1	70.71	34.28	7.14	0.44
Method 4	60.7	57.14	21.42	7.1	−1.2

Table 6: Influence of the different methods of derivative calculation and different distances to the fault on the error of average fault location result.

Calculation method	Method 1	Method 2	Method 3	Method 4
δ (%) ($L = 100$ km)	2.86	3	2.14	−1.64
δ (%) ($L = 10$ km)	1.25	1.357	0.364	3.74

Table 7: Influence of the transient resistance on the error of average fault location result, $l_{real} = 100$ km.

R_f (ohm)	1	5	10	20	50
Method 1	3.14	0.628	0.293	1.09	6.18
Method 2	3.71	0.607	0.393	1.2	6.28
Method 3	3.21	3	3.57	7.14	14.28
Method 4	−1.25	−2.47	−1.28	−1.06	−1

Table 8: Influence of the cutoff filter frequency on the error of average fault location result, $l_{real} = 100$ km.

f_c (Hz)	200	500	1000	2000	5000
Method 1	0.035	0.062	0.071	0.72	0.071
Method 2	0.14	0.09	0.058	1.02	0.14
Method 3	0.51	0.5	0.428	1.05	0.5
Method 4	−1.51	−2.34	−1.42	−2.34	−1.6

Table 9: Influence of the different electrical load values and different distances to the fault on the error of the average fault location result.

Load in % of limit power	25	50	75	100	125
δ (%) ($L = 100$ km)	0.143	2.78	2.64	2.86	2.64
δ (%) ($L = 10$ km)	0.14	0.128	0.035	1.25	0.178

Table 10: Method error in the case of the power line with a duplicate supply.

R_F (ohm)/power transfer angle γ (electrical degree)	1	5	10	20
5	1.71	4.5	3.14	4.79
10	0.57	5.29	6	12
30	2.86	3.03	18.57	48.86
50	2.57	15.3	31.07	89.3

than 5–10% may appear only in cases of the existence of great (tens of ohms) fault resistance.

It is considered how input filters influence the fault location accuracy (Table 8). LPFs with $f_c \leq 5000$ Hz do not affect on further fault location results (after the first one).

The electrical load value also does not almost influence the average fault location result accuracy. In Table 9, there are results of the evaluation of the distant fault location method in the case of using Method 1 and 2 different distances to the fault.

The accuracy of the method also was assessed in the case of the power line with a duplicate supply (Table 10). The example is given for the case of usage of the "ideal" differentiator.

This method demonstrates a reasonable accuracy only for the cases of dead short circuit. If there is a line with a duplicate supply (especially with a great power transfer angle), it is necessary to take feed current into account (i'_{AB} on Figure 1).

5. Conclusions

This work demonstrates the possibility of the usage of the algorithm of the one-sided fault location based on measurement electrical units in the instantaneous value. For the case of one-sided fault location, the main sources of error are identified.

In addition, it is shown that usage of nontraditional current sensors (Rogowski coils) included to digital current transformers allows to increase the accuracy of the calculation of the primary current and its derivative even in the moment of current inrush. Small errors of Rogowski coils, absence of saturation in the modes of great primary currents, and in case of existence of the aperiodic component, linearity of amplitude-frequency, and phase-frequency characteristics allow finding the exact current derivative value and displaying its leading edge without distortion. Application of Rogowski coils excludes the errors caused by the methodology of current derivative calculation.

There is the evaluation of the fault location algorithm in cases of different transient fault resistances, distances to the fault, electrical load values, and applied input filters. The fault location method is persistent to the influence of the distorting factors.

It is obligatory to take the feed current into account for the cases of the line with a duplicate supply (e.g., using synchronized or unsynchronized two-sided fault location determination). These methods require the setting digital current and voltage transformers in the both sides of the power line.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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