SMART GRID: MONITORING OF CABLE FAULT LOCATION

K. V. Suslov, N. N. Solonina and A. S. Smirnov
Irkutsk State Technical University, 83, Lermontov street, Irkutsk, Russia

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Abstract: Modern viewpoint suggests that Smart Grid is the network based on "smart technologies"; it is highly reliable, self-controlled, and capable to receive energy from any source and transform it into a final product without man's participation. Changes that occur in the energy sector require higher speed of receiving and processing the data on current state of power system. At the same time increasingly stricter requirements are imposed on accuracy and validity of measurements of circuit parameters. The paper is devoted to solving the problem of promptly determining the coordinates of short circuit location on transmission line, which can be done by digital processing of information about currents in transmission lines and use of Rogowski coil as a primary transducer.

1 INTRODUCTION

Nowadays there are different ways of providing the required reliability of power system operation. However, despite high reliability of power equipment and control systems there can be failures in operation, for example short circuits in supply and distribution networks which can be caused by unforeseen circumstances. Reduction of time for search of the short circuit location on lines is a direct way of improving the reliability of power systems. There is a great variety of methods for detecting location of overhead and cable line faults. We will enumerate them in brief.

The pulse method is based on measuring time intervals between the moment of transmitting a probe pulse of alternating current and the moment of receiving a reflected pulse from the fault location. To make measurements by the method of oscillation discharge the voltage supplied to the faulted cable conductor is gradually raised to the voltage of cable fault. The loop method is based on measuring resistances by the direct current bridge. The capacitance method is suggests measuring capacitance of a broken conductor by measuring bridges. The acoustic method supposes creation of a spark discharge at the fault location and listening to sound vibrations that occur above the fault point. There is also the induction method and others. The main flaw of these methods from the viewpoint of promptness is the fact that their application requires preparatory work and a lot of time.

2 MAJOR PRINCIPLES OF THE APPROACH

The method suggested by the authors allows one to timely detect the place of transmission line fault on-line. The main idea of the method lies in the fact that knowing circuit configuration and line parameters we can obtain an equivalent circuit for calculation of short-circuit currents at different points of transmission line. Depending on the required accuracy we choose a certain interval between the calculated points. The points calculated theoretically are then compared with measured short- circuit currents.

Let us first consider the simplest case where the short-circuit current is created by one source. Figure 1 shows a scheme of determining the location of short circuit on transmission line for the considered case.

There are primary current transducers at the beginning of the line in all phases. Their instantaneous values are processed and effective current values are calculated. At the time of short circuit this effective value will correspond to the initial effective value of the short-circuit current. Based on the relationship between phase currents the logical circuit determines the type of short circuit.

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This makes it possible to compare real short-circuit currents with those previously calculated and thus determine the coordinate of l , i.e. the beginning of section on which the short circuit occurred.

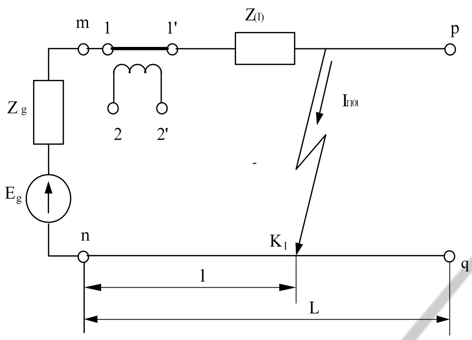

Figure 1: The scheme of detecting the cable fault point. *L* – cable length, *l* – distance from the beginning of the line to the point of short circuit, E_G – system EMF, Z_G – internal resistance of the system, *Z(l)*- resistance of the line section from its beginning to the short circuit location.

Simultaneous accurate measurement of voltage at the point of connection allows the result to be adjusted considering the difference between the real voltage and calculated one. If to continuously measure currents and voltages (updating memory) the said values can be fixed at the moment of short circuit. This, in particular will make it possible to determine the point of self-clearing fault. This is important since similar short circuit can occur in the future. The identified location should be examined and the reason for a potential short circuit - eliminated.

Let us consider a general case where a short-circuit current on the line is considerably affected by several sources.

The number of sources depends on network configuration. Therefore, the calculations should be made for different possible network configurations. From calculation made for each circuit configuration at a rated value of voltage we obtain a matrix of current values for different types of short circuit at specified values of *l*. An example of the matrix is given in Table 1.

It is supposed that there are primary transducers of current and voltage at the beginning of the line and effective values of current and voltage are continuously measured. The indicated values are stored in the data concentrator and constantly updated. The location of line fault is detected in two stages: preliminary and final.

The algorithm for preliminary detection of coordinates of the short-circuit current location is as follows: knowing the short-circuit currents of different phases we determine the type of short circuit, namely: if currents of three phases are almost equal, this is a three-phase symmetrical short circuit; if two currents are equal and considerably exceed the third current, this is a two-phase asymmetrical short circuit; if current of one of the phases considerably exceeds the currents of other phases, this is a one-phase short circuit. Knowing the value of voltage at point “a” at the time instant preceding short circuit, we adjust the data of matrix, supposing that the calculated currents are linearly related to the voltage. Knowing the type of short circuit we find an interval from the matrix, within which the measured initial effective value of short-circuit current lies.

Table 1: An example of data matrix for the first stage of fault location detection.

i	$l_i = i \cdot \Delta l$ m	$I_i^{(3)}$ kA	$I_i^{(2)}$ kA	$I_i^{(1)}$ kA
1	$l_1 = \Delta l$	$I_1^{(3)}$	$I_1^{(2)}$	$I_1^{(1)}$
2	$l_2 = 2\Delta l$	$I_2^{(3)}$	$I_2^{(2)}$	$I_2^{(1)}$
…	…	…	…	…
i-1	$l_{i-1} = (i-1) \cdot \Delta l$	$I_{i-1}^{(3)}$	$I_{i-1}^{(2)}$	$I_{i-1}^{(1)}$
i	$l_i = i \cdot \Delta l$	$I_i^{(3)}$	$I_i^{(2)}$	$I_i^{(1)}$
i+1	$l_{i+1} = (i+1) \cdot \Delta l$	$I_{i+1}^{(3)}$	$I_{i+1}^{(2)}$	$I_{i+1}^{(1)}$
…	…	…	…	…
n	$l_n = n \cdot \Delta l$	$I_n^{(3)}$	$I_n^{(2)}$	$I_n^{(1)}$

where i – number of calculated point of a possible short circuit on the interval Δ*l*;

l_i – distance from the beginning of line to the fault location; n – the total number of points to be calculated; Δ*l* –sampling step (in meters);

Let it be established that the short circuit is a three-phase one. Determine an interval that meets the following inequality:

$$I_{sc(i+1)}^{(3)} < I_{sc}^{(3)*} < I_{sc(i-1)}^{(3)}, \quad (1)$$

where $I_{sc(i+1)}^{(3)}$, $I_{sc(i-1)}^{(3)}$ – calculated values of short-circuit current at calculated points $(i+1)$ and $(i-1)$, respectively;

$I_{sc}^{(3)*}$ – value of short-circuit current obtained from measurement.

We suppose that $I_{sc}^{(3)*} \approx I_{sci}^{(3)}$ and determine an interval from $(i-1)$ to $(i+1)$, i.e. $l = l_i$, within which the short circuit occurred. To define more exactly the point of a short circuit the sampling step is decreased on the found interval and the exact coordinates of short circuit location are determined. For the limited number of intervals $\Delta(\Delta l)$ the calculation Table is filled (Table 2).

And finally the short circuit point is determined:

$$I^{(3)}_{sc(j+1)} < I^{(3)*}_{sc} < I^{(3)}_{sc(j-1)} \quad (2)$$

Hence, $I^{(3)*}_{sc} \approx I^{(3)}_{sc\,j}$ and the precise coordinates of the short circuit location are determined $l = l_i + \Delta l_{ij}$, where Δl_{ij} is an interval from point $(j-1)$ to $(j+1)$.

Table 2: An example of data matrix for the second stage of fault location detection.

j	$\Delta l_{ij} = j\Delta(\Delta l)$ cm	$I^{(3)}_{ij}$ kA
1	$\Delta l_{i1} = \Delta(\Delta l)$	$I^{(3)}_{i1}$
2	$\Delta l_{i2} = 2\Delta(\Delta l)$	$I^{(3)}_{i2}$
…	…	…
j-1	$\Delta l_{i(j-1)} = (j-1)\Delta(\Delta l)$	$I^{(3)}_{i(j-1)}$
j	$\Delta l_{ij} = j\Delta(\Delta l)$	$I^{(3)}_{ij}$
j+1	$\Delta l_{i(j+1)} = (j+1)\Delta(\Delta l)$	$I^{(3)}_{i(j+1)}$
…	…	…
m	$\Delta l_{im} = m\Delta(\Delta l)$	$I^{(3)}_{im}$

where j – number of the possible short circuit point on the subinterval of $\Delta(\Delta l)$; m – total number of points for subinterval calculation; $\Delta(\Delta l)$ – sampling step (in centimeters); $I^{(3)*}_{sc}$ – measured value of short-circuit current;

The obtained Tables underlie formation of the structural scheme of the considered network fragment to determine coordinates of the short circuit point on-line (Fig. 2) based on measurements of currents, voltages and frequency.

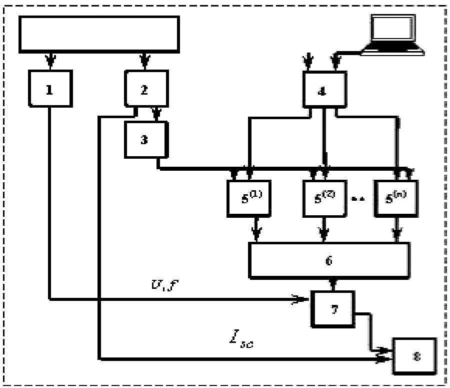

Figure 2: Structural scheme of on-line determination of the short circuit point on the transmission line.

Block 1 is intended for measuring the current effective values of linear voltages at the connection point of transmission line and the current network frequency of the fundamental harmonic. These data come from primary transducers and are adjusted continuously. Their values obtained directly before the short circuit are stored. Block 2 serves for measurement of initial effective values of short-circuit currents during the first period after the short circuit. Currents of all three phases are measured. Block 3 aims to determine the short circuit type: one-, two- or three-phase. Block 4 is a logic device to determine network configuration that is changed by circuit breakers. Hence, the state of network configuration at the given moment can be determined by the state of circuit breakers. Information on their state arrives to Block 4 through telemechanic channels. The network configuration can also be specified directly by dispatcher. Block 5 represents a matrix of the rated currents of transmission line for the concrete configuration. Block 6 is a logic device of the first stage of determining the section, on which the short circuit happened. Block 7 is a logic device of the second stage of determining the short circuit point and includes a matrix of the rated currents for the second stage of determining the short circuit point. Block 8 precisely determines coordinates of the short circuit point.

The method supposes a precise measurement of currents and voltages. Current and voltage transformers with the iron core do not provide specified accuracy. Particularly it concerns current transformers, since at short-circuit currents to be measured their magnetic conductors operate almost in saturation mode, which leads to unforeseeable errors. It is of no consequences for relay protection, however, it is inadmissible for solving this measuring problem. The linear dependence can be provided by using Rogowski coil instead of current transformers. In essence the former is a current-to-voltage transducer. This is convenient for further conversion of information from the analog form into the digital one. High accuracy of current measurement is due to absence of the magnetic core in it. Since there is no ferromagnetic coil in Rogowski coil, the output signal (voltage) will linearly depend on the input value (current).

The magnetic field strength (h) excited by the measured current and the measured current (i) are known to be related by Ampere's circuital law:

$$\oint_L h\,dl = i \quad (3)$$

where L — integration loop that practically coincides with the midline of the measuring (ring) winding.

Multiplying both sides of equality (3) by $\mu_0 S$ we obtain:

$$\oint_L \mu_0 hSdl = \mu_0 Si \quad (4)$$

Application of the known relations

$$b = \mu_0 h; \quad (5)$$

$$bS = \mu_0 hS; \quad (6)$$

$$\oint_L dl = L \quad (7)$$

where b, Φ – magnetic induction and magnetic flux through the winding, respectively,

Differentiate both sides of equation (6) and after some transformations the following relation is obtained

$$\frac{db}{dt} = \frac{\mu_0 S}{L}\frac{di}{dt} = e(t) \quad (7)$$

where $e(t)$— instantaneous value of the emf of a winding turn of Rogowski coil.

In general, vectors h and dl are parallel to each other at all points of integration loop L and then

$$E(t) = eW \quad (8)$$

here $E(t)$ — instantaneous value of the emf of the whole measuring winding of Rogowski coil containing W turns.

Assuming the initial phase of measured current to be zero and after differentiation the following expression is obtained

$$E(t) = C\omega I_m \sin(\omega t - 90^0) \quad (9)$$

where $C = \left(\frac{\mu_0 SW\omega}{L}\right)$— design factor of the transducer.

A phase shifter is used to alter the emf phase by +90 degrees and obtain voltage u_1, proportional to load current

$$u_1 = CI_m \sin \omega t \quad (10)$$

For this purpose $E\{t)$ is divided by ω and a positive phase shift by 90° is performed.

In order to determine voltage proportional to the measured load voltage it is necessary first to obtain current proportional to load voltage with the help of resistive transducer. The obtained current comes to Rogowski coil, at whose outlet the voltage will be proportional to load voltage

$$u_2 = U_m \sin(\omega t + \varphi) \quad (11)$$

It should be noted in addition that division of $E(t)$ by ω eliminates one more error source, i.e. dependence of the result on feed current frequency.

Thus, as distinct from the known methods application of information technologies and Rogowski coil makes it possible to determine precise coordinates of the short circuit location on-line with the required accuracy.

3 CONCLUSIONS

1. The authors offer the method for on-line determination of a fault point on the transmission line. It is based on preliminary theoretical calculation of short-circuit currents at different line cross-sections and determination of initial effective values of short-circuit currents. Here the use is made of the matrices of theoretical calculations of short-circuit currents. The measured values of short-circuit currents are compared with the calculated ones. The accuracy of determining coordinates of the short circuit point can be improved at two stages: approximate and precise.
2. Rogowski coil is suggested for use as primary transducers to improve the accuracy of measurements of the current values of short-circuit currents.

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