Limitations of Traveling Wave Fault Location

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Limitations of Traveling Wave Fault Location

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***Abstract*—The estimation accuracy of traveling waves (TWs) arrival times, caused by a short circuit on the power line, to the installation location of the fault locator and, therefore, the ability to determine the fault location (FL), is largely determined by the level of the front of the TWs themselves: the lower TW level, the more difficult it is to recognize it. In this connection, it is obvious that it is necessary to calculate the power system regimes to determine the TW fronts values to estimate the TW fault location feasibility in a particular electrical network. When installing the TW fault locator, usually are compare the characteristic impedance beyond the bus with the characteristic impedance of the transmission line: if the first is less than the second preference is given to measuring current. Vice versa - preference is given to measuring the voltage. However, the existing methods do not take into account the influence on the TW value of the power system elements located between the short circuit and the locator and, like the characteristic impedance beyond the bus, which can significantly reduce the TW value. This approach can lead to the installation of the locator in the network, where it will be completely useless due to the insufficient for measurement TWs values. The purpose of this article is to determine the limitations of TWFL methods based on an analysis of TW front values for different network configuration and voltage classes.**

Keywords— power line, traveling wave fault location, short circuit

I. INTRODUCTION

The estimation accuracy of the traveling waves (TWs) arrival times and, consequently, the possibility of implementing any TW fault location (FL) methods is largely determined by the front value of TWs themselves: the lower the TW level is the more difficult to recognize it against the background of the power system frequency signal and the noise of the power system. In this connection, it is obvious that it is necessary to calculate the power system regimes to determine the TW fronts values to estimate the TWFL feasibility in a particular electrical network.

When installing the TW fault locator, usually are compare the characteristic impedance beyond the bus with the characteristic impedance of the transmission line: if the first is less than the second, then at the installation place of the locator, the current TWs increase, and the voltages decrease. In this connection, preference is given to measuring current. And vice versa - if the characteristic impedance beyond the bus is greater than the characteristic impedance of the transmission line, then preference is given to measuring the voltage [1], [2].

However, the existing methods do not take into account the influence on the TW value of the power system elements located between the short circuit (SC) and the locator and, like the characteristic impedance beyond the bus, which can significantly reduce the TW value. This approach can lead to the installation of the locator in the network, where it will be completely useless due to the insufficient for measurement TWs values.

The purpose of this article is to determine the limitations of TWFL methods based on an analysis of TW front values for different network configuration and voltage classes.

II. TRAVELING WAVE ANALYSIS

SC is accompanied by the appearance of TWs propagating in both directions from its place. In this case, the TWs in the phases contain independent from each other modal components [3], [6]:

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = T \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix}, \qquad (1)$$

where u_γ – voltage TWs in phases, $\gamma = \overline{A, B, C}$; $u_\alpha; u_\beta$ – voltage TWs in α and β modes (line-modal components); u_0 – voltage TW in zero mode (zero-modal component), T – transformation matrix.

Modal components of current TWs and voltage TWs are related by the known equation [3]:

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \begin{bmatrix} z_{c,\alpha} & 0 & 0 \\ 0 & z_{c,\beta} & 0 \\ 0 & 0 & z_{c,0} \end{bmatrix}^{-1} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix}, \qquad (2)$$

where i_α, i_β – current TWs in α and β modes (line-modal components); i_0 – current TW in zero mode (zero-modal component); $z_{c,\alpha} = z_{c,\beta} = z_c - z_c^{'}$ – transmission line characteristic impedance of α and β modes; $z_{c,0} = z_c + 2z_c^{'}$ – transmission line characteristic impedance of zero mode; z_c, $z_c^{'}$ – own and mutual characteristic impedances of the transmission line.

Due to the different losses in the modes, these modal components have different velocity and attenuation. Therefore, moving away from SC, they gradually diverge from each other and decrease.

Traditionally, the value on which locators operate are the line-modal components (TWs in α or β modes), since they

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are less attenuated than the zero-modal component, therefore, they are easier to measure [4], [5]. Therefore, it is obvious that it is necessary to characterize the fundamental possibility of using TW locator in electrical networks of different configurations based on the analysis of the maximum TW front value of the line-modal components at the locator installation place, guided by a simple rule: it is impossible to use TW locator in the network if the maximum TW front value is below the locator threshold.

To determine the maximum TW front value of line-modal components, we assume that the considered transmission line:

- has no losses, that is, the modal components do not attenuate;

- perfectly transposed [3]. In this case, the transformation matrix is defined as:

$$T = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ 1 & 1 & 1 \end{bmatrix}.$$

It is obvious that the estimation of the maximum front value of the voltage TW and current TW line-modal components at the installation place of the locator should begin with determining the same values at the SC place.

A. Formation of TWs in phases in the place of SC

As can be seen from (1) and (2), to determine the front of voltage TW and the current TW in α and β modes, it is first necessary to estimate the voltage TW fronts value in the phases.

On the fault phases voltage TWs propagate in both directions with a rectangular front of magnitude

$$u_f = -k_u u_{pr}, \tag{3}$$

where u_{pr} – pre-fault voltage; k_u – pre-fault voltage and voltage traveling wave coupling factor.

For phase-to-ground SC (Fig. 1,a) [7]:

$$k_u^{K1} = \frac{1}{1 + \frac{2R_f}{z_c}}, \tag{4}$$

$$u_{pr}^{K1} = u_n; \tag{5}$$

and for a phase-to-phase SC (Fig. 1,b):

$$k_u^{K2} = \frac{1}{2(1 + \frac{R_f}{z_c})}, \tag{6}$$

moreover, the TWs in the fault phases are opposite in sign and equal

$$u_{pr}^{K2} = u_{n,\gamma} - u_{n,\gamma+1}, \tag{7}$$

where u_n – pre-fault phase voltage; R_f – SC resistance.

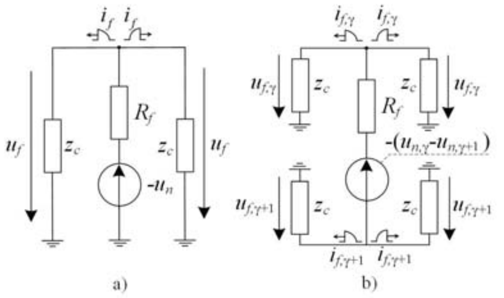


Fig. 1. Equivalent circuit for calculating the TWs fronts values in phases: a) for a phase-to-ground SC; b) for phase-to-phase SC

With a phase-to-ground SC, voltage TWs in unfault phases arise due to electromagnetic coupling between the wires and have the same polarity as the voltage TW in the fault phase [8]:

$$u_{nf} = u_f k_{pc}, \tag{8}$$

where $k_{pc} = \frac{z_c^{'}}{z_c}$ – coupling factor (for OHL $k_{pc} < 0{,}3$ [8][8]).

With a phase-to-phase SC, the fault phases create in the unfault phase voltage TWs of the same magnitude, but different polarity (7), (8). In this connection, the resulting voltage TW in the unfault phase is zero.

Other types of SC arise from phase-to-ground and phase-to-phase SCs [9] and are not considered in this article.

B. TWs modal components in the SC place

Using the magnitudes of TWs in phases (3)-(8), it is possible to determine the TWs in modes (1) during phase-to-ground SC

$$\begin{bmatrix} u_{f,\alpha}^{K1} \\ u_{f,\beta}^{K1} \\ u_{f,0}^{K1} \end{bmatrix} = \begin{bmatrix} -\frac{2(1-k_{pc})}{3} k_u^{K1} u_{pr}^{K1} \\ 0 \\ -\frac{(1+2k_{pc})}{3} k_u^{K1} u_{pr}^{K1} \end{bmatrix}, \tag{9}$$

and phase-to-phase SC

$$\begin{bmatrix} u_{f,\alpha}^{K2} \\ u_{f,\beta}^{K2} \\ u_{f,0}^{K2} \end{bmatrix} = \begin{bmatrix} 0 \\ -\frac{2}{\sqrt{3}} k_u^{K2} u_{pr}^{K2} \\ 0 \end{bmatrix}. \tag{10}$$

Using (2) is defined the current TWs in the modes in SC place:

$$\begin{bmatrix} i_{f,\alpha}^{K1} \\ i_{f,\beta}^{K1} \\ i_{f,0}^{K1} \end{bmatrix} = \begin{bmatrix} -\frac{2}{3z_c} k_u^{K1} u_{pr}^{K1} \\ 0 \\ -\frac{1}{3z_c} k_u^{K1} u_{pr}^{K1} \end{bmatrix}, \tag{11}$$

and phase-to-phase SC

$$\begin{bmatrix} i_{f,\alpha}^{K2} \\ i_{f,\beta}^{K2} \\ i_{f,0}^{K2} \end{bmatrix} = \begin{bmatrix} 0 \\ -\dfrac{2}{\sqrt{3}(1-k_{pc})z_c} k_u^{K2} u_{pr}^{K2} \\ 0 \end{bmatrix}. \quad (12)$$

From (9)-(12) it follows that the voltage and current TW of the β mode during phase-to-phase SC are greater than the voltage and current TW of the α mode during phase-to-ground SC

$$\frac{u_{f,\beta}^{K2}}{u_{f,\alpha}^{K1}} = \frac{i_{f,\beta}^{K2}}{i_{f,\alpha}^{K1}} = \frac{3(z_c + 2R_f)}{2(z_c + R_f)(1-k_{pc})} > 1. \quad (13)$$

In this connection, further analysis will be carried out for the case of a phase-to-phase SC.

C. TWs propagation through the network

1) TWs propagation along the overhead line

Because losses are not taken into account, the voltage TW $u_{i,\beta}$ and the current TW $i_{i,\beta}$, incident on the installation place of the locator, will be equal to the voltage TW $u_{f,\beta}$ and the current TW $i_{f,\beta}$ at the SC place.

2) Propagation of TWs along overhead lines with tap

The front value of the current TW $i_{i,\beta}$ and the voltage TW $u_{i,\beta}$, incident on the installation place of the locator during an SC behind the q-th tap (all taps have a characteristic impedance of β mode $z_{tap,\beta}$):

$$i_{i,\beta} = \frac{1}{\left(1 + \dfrac{z_{c,\beta}}{2z_{tap,\beta}}\right)^q} i_{f,\beta}; \quad (14)$$

$$u_{i,\beta} = \frac{1}{\left(1 + \dfrac{z_{c,\beta}}{2z_{tap,\beta}}\right)^q} u_{f,\beta}. \quad (15)$$

D. TWs at the installation place

The locator will measure the sum of the incident $u_{i,\beta}$ and reflected $u_{r,\beta}$ voltage TWs, as well as the sum of the incident $i_{i,\beta}$ and reflected $i_{r,\beta}$ current TWs [3], [10]:

$$\begin{cases} u_{TW,\beta} = u_{i,\beta} + u_{r,\beta}; \\ i_{TW,\beta} = i_{i,\beta} + i_{r,\beta}. \end{cases} \quad (16)$$

Reflected current and voltage TWs can be expressed in terms of incident TWs:

$$\begin{cases} u_{r,\beta} = k_r u_{i,\beta}; \\ i_{r,\beta} = -k_r i_{i,\beta}. \end{cases} \quad (17)$$

where $-1 \le k_r \le 1$ – TW reflection coefficient:

$$k_r = \frac{z_{e,\beta} - z_{c,\beta}}{z_{e,\beta} + z_{c,\beta}}, \quad (18)$$

where $z_{e,\beta}$ – β mode equivalent characteristic impedance of adjacent network elements, located beyond the bus.

Then the voltage TW $u_{TW,\beta}$ and the current TW $i_{TW,\beta}$ at the installation place of the locator:

$$\begin{cases} u_{TW,\beta} = (1 + k_r) u_{i,\beta}; \\ i_{TW,\beta} = (1 - k_r) i_{i,\beta}. \end{cases} \quad (19)$$

III. LIMITATIONS OF LOCATOR APPLICATION

Estimate the influence of the configuration and power system parameters on the maximum front value of the voltage $u_{TW,\beta}^{\max}$ and the current TW $i_{TW,\beta}^{\max}$ at the locator installation place.

The condition for the maximum of the voltage TW front value and the current TW front value in the β *mode at the SC place*

The maximum voltage TW front value (10) and current TW front value (12) in the β mode during a two-phase SC is achieved under the following conditions:

$$\begin{cases} R_f = 0, k_u^{K2} = 1; \\ u_{pr}^{K2} = \sqrt{2} U_{\max}; \\ k_{pc} = k_{pc}^{\max} = 0{,}3; \\ z_c = z_c^{\min}, \end{cases} \quad (20)$$

where $U_{\max}$ – maximum operating line-to-line voltage of the electrical network [11].

The condition for the maximum of the voltage TW front value and the current TW front value in the β *mode at the locator installation place.*

From (18) and (19), it follows that the front of the voltage TW $u_{TW,\beta}$ and the current TW $i_{TW,\beta}$ will reach the maximum value at [12]:

$$\begin{cases} k_r = 1, \text{ i.e. } z_{e,\beta} \gg z_{c,\beta} \ (\textit{for voltage}); \\ k_r = -1, \text{ i.e. } z_{e,\beta} \ll z_{c,\beta} \ (\textit{for current}). \end{cases} \quad (21)$$

A. Overhead power line

With a phase-to-phase SC on overhead lines, the voltage TW front $u_{TW,\beta}$ and the current TW front $i_{TW,\beta}$ (19) taking into account (6), (7), (10) and (12) at the installation place of the locator estimate the maximum values under conditions (20) and (21):

$$u_{TW,\beta}^{\max} = 2\sqrt{\frac{2}{3}}U_{\max} = 1,633U_{\max}, \qquad (22)$$

$$i_{TW,\beta}^{\max} = 2\sqrt{\frac{2}{3}}\frac{U_{\max}}{(1-k_{pc})z_c^{\min}} = 2,332\frac{U_{\max}}{z_c^{\min}}, \qquad (23)$$

where $z_c^{\min}$ – minimum characteristic impedance of overhead power line [13].

Calculations show that with an SC on overhead lines, the maximum of the current TW front value $i_{TW,\beta}^{\max}$ (23) in 6-35 kV networks is low (Table 1). Therefore, it seems inappropriate to use all TWFL current methods in 6-35 kV networks.

A completely different situation with a voltage TW $u_{TW,\beta}^{\max}$ (22), which has high front value. Therefore, in 6-35 kV networks it is more advantageous to use TWFL voltage methods. However, it is known that it is difficult to measure the voltage TW due to the narrow frequency bandwidth of electromagnetic VTs [4], [14]. Therefore, alternative options for measuring the voltage TW should be considered [15], [16].

TABLE I. MAXIMUM CURRENT AND VOLTAGE TW FRONT VALUE IN β MODE DURING PHASE-TO-PHASE SC

U_n, kV	$U_{\max}$, kV	$z_c^{\min}$, Ohm	$u_{TW,\beta}^{\max}$, p.u.	$i_{TW,\beta}^{\max}$, p.u.
6	6,9	473	3,253	0,171
10	11,5	473	3,253	0,140
35	40,5	475	3,274	0,266
110	126	385	3,241	1,017
220	252	360	3,241	1,633
330	363	255	3,111	1,660
500	525	245	2,97	2,500
750	787	245	2,969	1,836

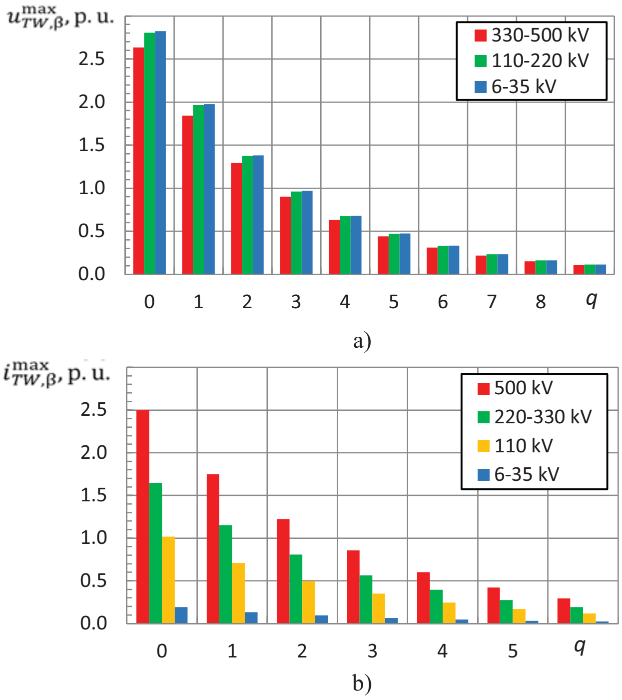
B. *Overhead power line with taps*

The front value of the incident current TW and voltage TW of β mode (14), (15) will be greatest when the β mode power line characteristic impedance is minimum $z_{c,\beta} = z_{c,\beta}^{\min}$, and the β mode characteristic impedance of the tap is maximum $z_{tap,\beta} = z_{tap,\beta}^{\max}$ [13]. Calculations show that for all voltage classes, the maximum front value of the current TW and voltage TW incident on the locator installation place (14), (15):

$$i_{i,\beta} = 0,7^q i_{f,\beta};\ u_{i,\beta} \approx 0,7^q u_{f,\beta}.$$

Under the condition (20) and (21) according to (19), taking into account (14)-(15), it is possible to determine the maximum current TW front value and voltage TW front value in β mode at the locator installation place for any number of taps on the transmission line (Fig. 2).

The more taps on the power line between the place of the SC and the place where the locator is installed leads to the lower measured maximum value of the current TW and voltage TW in β mode. Using the proposed method with known measurement noise, it is possible to determine the maximum number of taps on the overhead line, at which the locator will be able to fix the arrival time of the current TW front and voltage TW of β mode (the TW front value must be higher than the noise).



a)

b)

Fig. 2. Maximum TW front value of β mode in the place where the locator is installed for SC behind the $q-th$ tap a) voltage TW, b) current TW

IV. CONCLUSION

The TW front value directly affects the accuracy of TW arrival times estimation, and, consequently, the possibility of realizing TWFL. Therefore, the analysis of regimes is paramount when considering the feasibility of using a locator in one or another electrical network.

Studies have shown that in 6-35 kV networks, due to the insufficient maximum TW value, the use of current TWFL is almost impossible. A completely different situation with a voltage TW, which has high front value. Therefore, in 6-35 kV electrical networks, the use of a voltage TWFL seems to be more advantageous.

Also, difficulties with the use of locator arise when there are taps on the power line - the more taps on the power line between the place of the SC and the place where the locator is installed leads to the lower measured maximum value of the current TW and voltage TW.

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