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One-side spectral method for line fault location in HVDC line

E.A. IVANOVA[1] N.G. LOZINOVA[1] N.S. YAROKH[1] O.V. SUSLOVA[2]

[1] JSC NIIPT
RUSSIA

[2] JSC STC UPS

SUMMARY

The relevance of the discussing issue is caused by the need of accurate and quick determination of the fault location in HVDC transmission lines. The issue becomes more important in the case of the HVDC line consisted of segments with different line parameters. This case could appear when the line route goes through the water barrier and the standard solution is to add the cable parts of the line with the overhead parts. The aim of this study is to develop an one-side LFL method in HVDC line, including segments with different line parameters (for example, overhead and cable segments) and terminal devices, such as smoothing reactors and harmonic filters. The developed method is based on the spectral algorithm and requires frequency analysis of the faulted pole voltage curve during the transient process. In the event of short-circuit of the HVDC line the faulted pole voltage starts dropping dramatically through the short-circuit point. Since the amplitudes of the frequencies in the spectrum of the faulted pole voltage curve varies according to the energy impact of every transient process component it is considered that dominant frequency corresponds to the faulted part of the HVDC line. The process of HVDC line discharging through the short-circuit point represents the decaying oscillation of deformed sine wave or the sum of deformed oscillations. To obtain the dominant frequency in the transient voltage spectrum it is suggested to use the Integral Short Time Fourier Transform.

In the paper the expression binding HVDC line parameters, fault distance, dominant frequency of the transient voltage and converter equivalent circuit parameters are proposed. The developed algorithm was proved on the HVDC line model presented in EMTP-ATP program and included one cable and one overhead segment, transient resistance at the short-circuit point, terminal devices, taking into account the earth frequency response, operation of protective relaying and automation systems. The prototype of the digital model of DC line was the Dc line between LAES-2 and Vyborg substations in Saint-Petersburg suburbs, Russia, being under design.

It is shown that in case of only two segments in the HVDC part the developed algorithm used at the faulted segment side is more accurate. The error of the suggested algorithm applied at the unfaulted line segment side is no more than 1% of the faulted segment length. The error of the suggested algorithm applied at the faulted line segment side is no more than 0,5% of the faulted segment length.

KEYWORDS

Electrical power transmission line, HVDC transmission line, line fault location, short circuit, spectrum algorithm, transient resistance, travelling wave method.

eleshka.ivanova@gmail.com

INTRODUCTION

Electric energy is the basis in providing the vital activity of modern society. Reliable operation of the energy system is a necessary condition for the economic development of any state or country.

High-voltage transmission lines are one of the most vulnerable elements of the power system. During the operation of the power lines, regular and periodic line inspections, preventive measurements and tests, and other regulatory measures are carried out to ensure their smooth and correct operation. Experience has proven that this is not enough for the reliable operation of power lines and power systems in general.

The most frequent and severe type of line damage is short circuit. Emergency outages are the cause of additional costs, leading to interruptions in power supply of consumers. There are no existed operating solutions of the problem of fault location in HVDC lines in Russian electric power system. At the same time, the United Power System (UPS) of Russia has a number of operational features that determine the relevance and timeliness of the development of HVDC technologies for the domestic power industry. Such features could be, among others:

- remoteness of generation facilities from consumers of electrical energy;
- high levels of short-circuit currents in metropolitan cities and the need of their limitation;
- power supply of oil platforms and other consumers connected with overcoming water barriers;
- the problem of connecting renewable energy sources to the UPS and to local power systems;
- the problem of modernization and development of the UPS with the subsequent joining the united power system of the East and a number of isolated power systems;
- export of electric power to neighboring countries.

The introduction of electrical energy transmission technologies by using high voltage direct current (HVDC) will immediately require the use of methods and technical means of the fault location, in particular, on long DC lines.

PROBLEM STATEMENT

In the world practice, the most widely used fault location methods are the ones based on the theory of traveling waves and implying an analysis of the propagation of an electromagnetic wave along power transmission line (wave methods) [1, 2, 3]. However, such methods do not always allow accurate calculation of the distance to the fault. Thus, for example, if a close fault occurs, the difference in the arrival time of the direct and reflected waves - the key parameter for the wave method - will be barely distinguished.

At the case when the HVDC transmission crosses the water barrier the dc cable sections are often supplemented by overhead lines (for example, 240 km Skagerrak HVDC transmission between Denmark and Norway, HVDC Baltic Cable between Germany and Sweden, 250 km link Fenno-Skan between Finland and Sweden, 233 km). The only fault location method known today for fault location in integrated cable and overhead DC line, is expensive and requires the installation of additional equipment at each converter substation at the DC link side (differentiating transformers that allow to have an accurate record of the electromagnetic wave front coming from the fault point).

For the purpose of solution to the problem of fault location in HVDC lines, which consist of several sections with different linear parameters, the fault location algorithm based on the spectral approach is proposed in this paper. This approach is based on the estimation of the frequency spectrum of the line transient voltage and subsequent calculation of the fault distance taking into account the natural oscillation frequency f_0 of the oscillating circuit of the faulted line.

SPECTRUM LFL ALGORITHM BASED ON FOURIER TRANSFORM

Figure 1 shows the waveform of the transient pole-to-ground voltage in the case of a short circuit in the DC cable section of the line, obtained on a digital model of a cable-overhead line 108 km long (41 km is a cable section, 67 km is an air section, the prototype of this line was the one between LAES-2 and Vyborg substations in Saint-Petersburg suburbs, Russia, being under design). In normal operation mode there is a bipolar HVDC line with a pole voltage of 300 kV. At the time t = 3 s, a cable fault occurred on the cable section. The pole voltage began to drop rapidly.

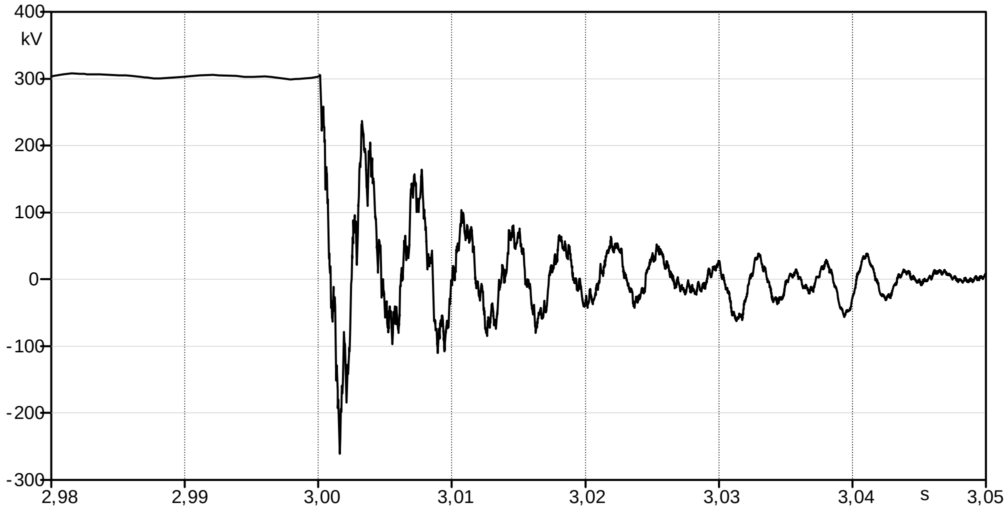

Fig. 1 Waveform of transient pole-to-ground voltage under a short circuit mode in the model of HVDC line

The analysis of the waveform shown in Figure 1 and the waveforms obtained on digital models and on actually operating objects [4, 5, 6, 7] indicates the presence in the decaying transient process of an essentially predominant frequency component f_0 that varies in frequency depending on the distance to the fault site or, in other words, depending on the length of the faulted part of HVDC line. This nature of the process allows making the assumption that the frequency dominating in the spectrum of the line transient voltage is determined mainly by the parameters of the short-circuited line segment in the circuit "faulted pole-ground".

Thus, for a known oscillation frequency and known line parameters, it is possible to determine the length of the faulted line part, i. e. faulted distance.

The need to solve the problem of developing a LFL device for HVDC line consisted of both cable and overhead sections arose with the participation in the HVDC transmission project between the nuclear power plant LAES-2 and the Vyborg substation near the city of St. Petersburg, Russia. The cable section of this power transmission line, according to the project, runs along the bottom of the Gulf of Finland and is further supplemented by an overhead section. The construction of direct current transmission between these substations is conditioned by the need to unload the city from transit flows of power and will ensure an increase in the reliability of the power system in the northern part of St. Petersburg. The operation of the LAES-2 – Vyborg substation HVDC transmission of will prove to be effective from the point of view of energy saving and will provide significant savings on energy losses.

To improve the reliability of the cable-overhead line of this power transmission, it is necessary to install a device for determining the line fault location (LFL unit) in case of short circuits, which are not currently available in domestic practice, and similar devices offered by foreign companies are expensive and require the installation of special measuring instruments at converter substations. The equivalent scheme of HVDC system is shown in Figure 2, where 1 – converter station, 2 – smoothing reactor, 3 – harmonic filter, 4 - voltage divisor, 5 – current transformer, L_1, C_1, L_2, C_2 – components of the high harmonic filter, R_{Tr} – transient resistance at the fault point. In considered case of the dc line smoothing reactor is installed in the middle point of the double-frequency filter. The LFL devices shown in Figure 2 are based on the proposed spectrum LFL algorithm and operate unrelated.

The solution of 2 inverters at Vyborg station allows controlling the power flow so the following operating modes can exist:

1. Transmission of full power of 1000 MW from LAES-2 to the power system of Finland.

2. Full power transmission from LAES-2 to the North-West Integrated power system (IPS).

3. Transmission of full power from LAES-2 with its uniform distribution between the power system of Finland and the North-West IPS.

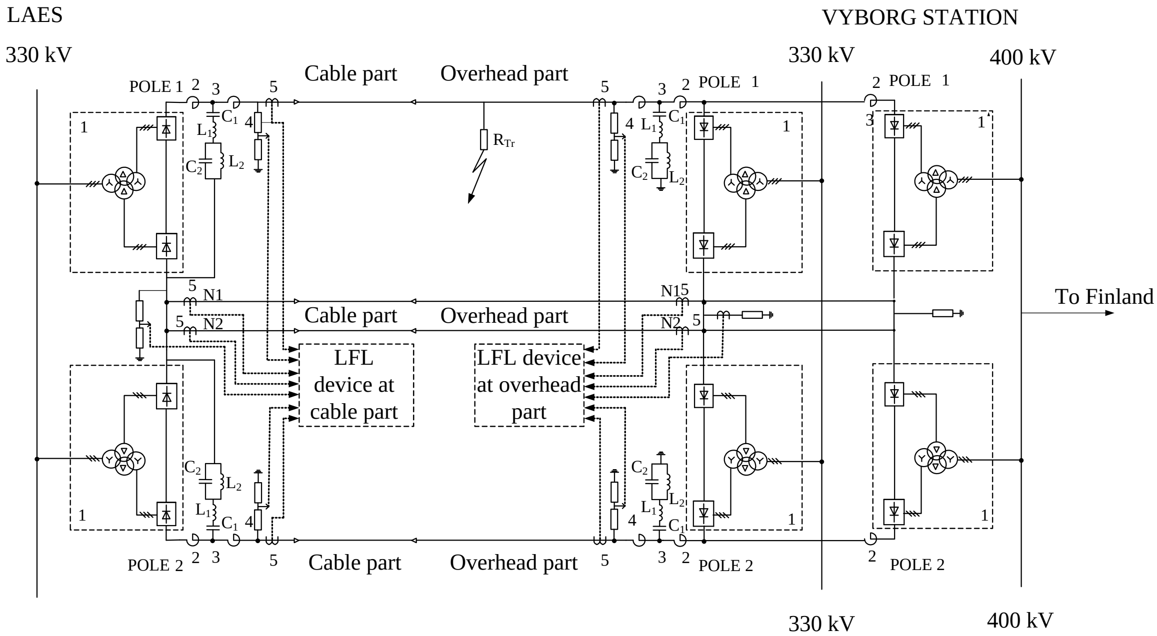

Fig. 2 Equivalent scheme of LAES-2 – Vyborg HVDC system

The appearance in the frequency spectrum of the transient pole-to-ground voltage of the dominant frequency corresponds to the occurrence of a voltage resonance of this frequency in the oscillatory circuit of the faulted section of the line. When the resonance condition in the circuit is fulfilled, the equivalent resistance of the circuit is infinitely large. This corresponds to the zero value of the conductivity of the circuit, the expression for which includes, among others, the frequency of the transient process in a faulted line segment, the line parameters, and the fault distance. Having determined the expression for the conductivity of the closed section of the line and equating the numerator of the resulting expression to zero, it is possible to find from this equation the length l_X of the faulted section of the DC line.

According to the developed one-side LFL algorithm the quadric equation relative to the fault distance in case when the information about the fault is gathered from the LFL side, located at the faulted part of HVDC line (in the Figure 2 - from the LFL device at cable side when the fault occurs in cable part and from the LFL device at overhead side when the fault occurs in overhead part) is as follows:

$$\frac{2}{\pi}\dot{p}_0 C_0 \dot{D}\cdot\left(R_0+\frac{2}{\pi}\dot{p}_0 L_0\right)\cdot l_X^2+\left[\frac{2}{\pi}\dot{p}_0\cdot\left(\dot{Y}_{F-C}L_0+R_{Tr}C_0\dot{D}\right)+\dot{Y}_{F-C}R_0\right]\cdot l_X+\dot{Y}_{F-C}R_{Tr}+\dot{D}=0 \quad (1)$$

where $\dot{D}=1+\dot{p}_0 L_r \dot{Y}_{F-C}$ $\dot{Y}_{F-C}=\dot{Y}_{Filter}+\dot{Y}_{Conv}$ $\dot{Y}_{Conv}=\frac{1}{\dot{p}_0 L''_{Conv}}$,

L_{conv} is converter inductance, L_{r} – is inductance of the smoothing reactor, Z_{filter} – is the harmonic filter impedance, R_0, L_0, C_0 – line parameters per 1 km, l_X – line fault location distance,

$\dot{Y}_{Filter}=\frac{\dot{p}_0 C_1\cdot\left(\dot{p}_0{}^2 L_2 C_2+1\right)}{\dot{p}_0{}^2 L_2 C_1+\left(\dot{p}_0{}^2 L_1 C_1+1\right)\cdot\left(\dot{p}_0{}^2 L_2 C_2+1\right)}$ $p_0=-\alpha_0+j2\pi f_0$ - operator,

f_0 – the predominant frequency component obtained from the frequency spectrum of the transient pole-to-ground voltage,

α_0 - parameter which determines the attenuation of the oscillation process of the short-circuit line discharge process.

In case when the LFL unit is installed only at the unfaulted line segment it is important to correctly present the unfaulted segment (-s), located between LFL unit and faulted segment of the dc line. To present the unfaulted segment it is suggested to model its equivalent circuit as it is shown on the Figure 3.

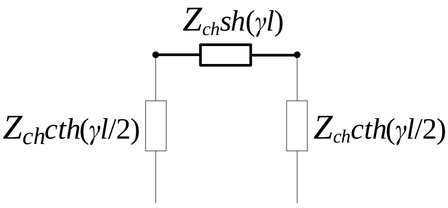

Fig.3 Equivalent circuit of the HVDC line unfaulted segment

On the Figure 3 Zch is a characteristic impedance of the unfaulted segment of the dc line, l – the total length of the unfaulted line segment, γ - coefficient of wave propagation in the unfaulted segment of the line.

$$Z_C=\sqrt{\frac{L_{0\,un}}{C_{0\,un}}};\quad \gamma=j\omega\sqrt{L_{0\,un}C_{0\,un}} \quad (2)$$

where

$L_{0\text{ un}}$, $C_{0\text{ un}}$ – unfaulted line segment parameters per 1 km;

ω – angular frequency.

According to the developed one-side LFL algorithm the quadric equation relative to the fault distance in case when the information about the fault is gathered from the LFL side, located at the unfaulted part of HVDC line (from the LFL device at cable side when the fault occurs in overhead part and from the LFL device at overhead side when the fault occurs in cable part) is as follows:

$$\frac{2}{\pi}\dot{p}_0 C_0 \dot{Z}_1 \cdot \left[\left(R_0 + \frac{2}{\pi}\dot{p}_0 L_0\right)\cdot\left(\dot{Z}_2 \dot{Y}_{F-C} + \dot{D}\dot{F}\right)\right]\cdot l_X^2 + \left[\left(R_0 + \frac{2}{\pi}\dot{p}_0 L_0\right)\cdot\left(\dot{Z}_1 \dot{Y}_{F-C}\dot{F} + \dot{D}\dot{E}\right) + \frac{2}{\pi}\dot{p}_0 C_0 \dot{Z}_1 R_{Tr}\cdot\left(\dot{Z}_1 \dot{Z}_2 \dot{Y}_{F-C} + \dot{D}\dot{F}\right)\right]\cdot l_X +$$

$$+\dot{F}\cdot\left(\dot{Z}_1 \dot{Y}_{F-C} R_{Tr} + \dot{D}\dot{Z}_1\right) + \dot{Y}_{F-C} + \dot{D} R_{Tr}\dot{E} = 0 \quad (3),$$

where $\dot{Z}_1 = \dot{Z}_{ch} cth(\gamma l/2)$, $\dot{Z}_2 = \dot{Z}_{ch} sh(\gamma l)$, $\dot{E} = 2\dot{Z}_1 + \dot{Z}_2$ $\dot{F} = \dot{Z}_1 + \dot{Z}_2$

Solution of the equation (1) gives the fault distance in case when the information about the transient pole-to-ground voltage is gathered from the side of the faulted line (cable or overhead) segment. Solution of the equation (3) gives the fault distance in case when the information about the transient pole-to-ground voltage is gathered from the side of the unfaulted (cable or overhead) line segment.

To test the developed LFL algorithm the model of DC line was represented in the program for calculating the electromagnetic transients (EMTP-ATP) by using Pi-cell model. Each Pi-cell of the cable part of DC line is represented in Figure 4.

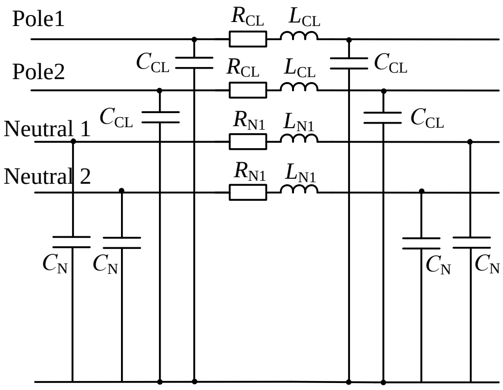

Fig.4 Equivalent scheme of the cable line Pi-cell

In the model of the cable line Pi-cell in Figure 4 the self capacitances of the pole and neutral wires (C_{CL}, C_N) to the ground, inductance and active resistances of the pole and neutral wires (L_{CL}, R_{CL}, L_{N1}, R_{N1}) are taken into account. One Pi-cell of the cable part of DC line is represented in Figure 4. The parameters of the cable line Pi-cell are presented in the

Table 1. Table 1. Parameters of the equivalent cable line Pi-cell

Pi-cell length, km	**Pole wire parameters: *R*, Ohm; *L*, mHn**	**Neutral wire parameters: *R*, Ohm; *L*, mHn**	**Capasitances *C*, µF**
$l_{CL\ Pi\text{-}cell}$=1	R_{CL}=0,019 L_{CL}=0,502	R_{N1}=0,0068 L_{N1}=0,274	C_{CL}=0,301 C_N=0,517

In the model of the overhead line Pi-cell in Figure 5 the self capacitances of the pole and neutral wires ($C_{0\ P}$, $C_{0\ N}$) to the ground, mutual capacitances between both pole wires, both neutral wires and pole and neutral wires ($C_{m\ P}$, $C_{m\ N}$, and $C_{m\ PN}$ respectively), inductance and active resistances of the pole and neutral wires (L_{OL}, R_{OL}, L_{N2}, R_{N2}) are taken into account.

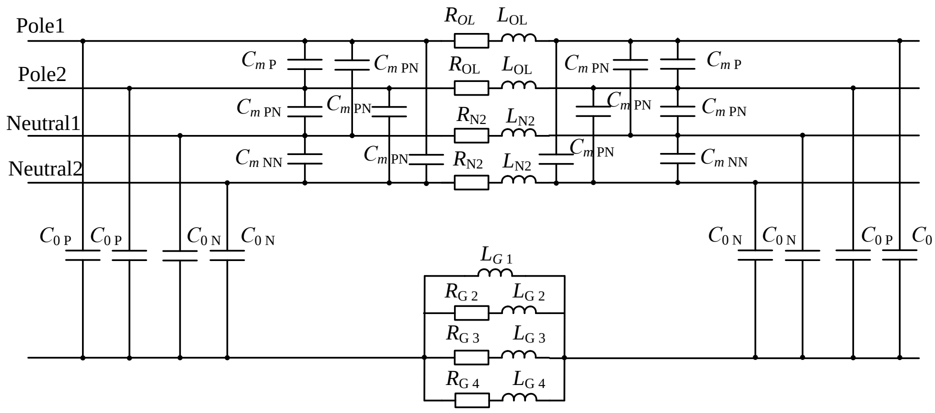

Fig.5 Equivalent scheme of the cable line Pi-cell

Parameters of the overhead line Pi-cell are presented in the Table 2.

Table 2 Parameters of the equivalent cable line Pi-cell

Pi-cell length, km	**Pole wire parameters: *R*, Ohm; *L*, mHn**	**Neutral wire parameters: *R*, Ohm; *L*, mHn**	**Capasitances *C*, μF**
$l_{\text{OL Pi-cell}}$=2,48	R_{OL}=0,026 L_{OL}=1,048	R_{N2}=0,021 L_{N2}=0,952	C_{CL}=0,301 C_{N}=0,517

The parameters of the equivalent ground wire are presented in the overhead line Pi-cell as well. The equivalent ground wire model in considered case consists of parallel R-L-circuits as it is shown in Figure 5. The parameters of the equivalent ground wire circuit are presented in the Table 3.

Table 3 Parameters of the equivalent ground wire R-L-circuits

Cell number, n	**R_n, Ohm/km**	**L_n, mHn/km**	***f*, Hz**
1	0	2,0	0
2	0,118	1,046	100
3	7,08	1,064	10000
4	35,4	0,263	20000

In developed digital Pi-cell model of the DC line consisted of cable and overhead parts experiments of different short-circuit cases were carried out. The results of proposed LFL algorithm obtained from both faulted and unfaulted line part sides in case of short-circuit in either overhead or cable part line were compared and are presented in Table 4.

Table 4 Results of testing proposed one-side LFL algorithm in digital model of HVDC line

Faulted segment	**Result at the faulted side**			**Result at the unfaulted side**		
	Real fault distance, km	**Fault distance obtained from the proposed LFL algorithm, km**	**δ, %**	**Real fault distance, km**	**Fault distance obtained from the proposed LFL algorithm, km**	**δ, %**
Overhead	9,93	10,12	0,46	57,07	57,4	0,78
Overhead	24,82	24,7	0,29	42,18	41,8	0,95
Overhead	34,72	34,4	0,45	32,28	31,5	1,16
Overhead	44,64	44,87	0,34	22,36	23,05	1,03
Overhead	62	62,3	0,44	5	5,6	0,89
Cable	6	5,93	0,17	35	35,5	1,22
Cable	17	17,2	0,49	24	23,85	0,37
Cable	25	24,8	0,48	16	15,63	0,9
Cable	33	33,74	0,63	8	7,6	0,98

Analysis of the error, presented in the Table 4 shows that the accuracy of the proposed algorithm for the case of LFL unit installation at the faulted segment side is about 2 times less than the one of the proposed algorithm for the case of LFL unit installation at the unfaulted segment side. So in the case of only two different segments in HVDC line it is more accurate to use the LFL algorithm for the case of gathering information from the faulted line part side.

CONCLUSIONS

1. To solve the LFL issue in the HVDC line, consisted of both overhead and cable segments carrying out a detailed analysis of the frequency components of the informative signal is proposed. As an informative signal the transient voltage at the one side of DC line is considered.
2. Calculation of the fault distance is considered in the view of the high harmonic filter on the DC side, installed in the midpoint of the soothing reactor. For this purpose, total equivalent conductivity of the short-circuit line model is determined.
3. The error of the proposed LFL spectrum method in considered cases of short-circuit does not exceed 1,22% of the length of a short-circuited segment of the line.
4. In DC lines consisted of only two different segments, as it was shown in the paper, it is recommended to use the LFL spectrum algorithm analyzing the information about the transient pole-to-ground voltage at the faulted segment side. In this case the error of LFL algorithm does not exceed 0,63% of the length of a short-circuited segment of the line.

BIBLIOGRAPHY

[1] Abur A., Magnago F.H. Use of time delays between modal components in wavelet based fault location // International Journal of Electrical Power & Energy Systems. – 2000. – No 22 (6). – P. 397–403.

[2] Chen P., Xu B., Li Jing A Traveling Wave Based Fault Locating System for HVDC Transmission Lines // International Conference on Power System Technology, Chongqing, 22-26 October, 2006: Abstr. - Chongqing, 2006 – P. 1 – 4.

[3] Nanayakkara O.M.K.K. , Rajapakse A.D., Wachal R. Traveling-wave-based line fault location in star-connected multiterminal HVDC systems // IEEE Power & Energy Society General Meeting, Vancouver, BC, 21-25 July, 2013: Abstr. - Vancouver, BC, 2013 – P.1.

[4] Gertsik K.A., Mazurov M.I., Minkin C.I., Shlayfshteyn A.Kh. Spektralnyy metod opredeleniya mesta povrezhdeniya na linii postoyannogo toka [Spectrum line fault location method in the HVDC transmission line]. Avtomatizirovannye sistemy upravleniya tekhnologicheskimi protsessami krupnykh podstantsii, elektroperedach I vstavok postoyannogo toka, 1991, pp. 27 – 34.

[5] Gertsik K.A. i dr. Ispytaniya pribora dlya obnaruzheniya mesta korotkogo zamykaniya na linii elektroperedachi postoyannogo toka Volgograd – Donbass [The tests of the device to detect line fault location point in the Volgograd – Donbass HVDC transmission line] Elektricheskie stantsii, no. 12, 1992, pp. 45 – 53.

[6] Gertsik K.A Eksperimental’noe ispytanie perenapryazhenyi v linii elektroperedachi Volgograd-Donbass pri odnopolyusnom korotkom zamykanii [Overvoltages experimental tests in Volgograd-Donbass HVDC line under the one-pole short circuit mode]. Issledovaniya i razrabotki moschnyh electroperedach postoyannogo toka, 1983, pp.37-44.

[7] Shukr M., Thomas D. W. P., Zanchetta P. VSC-HVDC transmission line faults location using active line impedance estimation. 2nd IEEE ENERGYON Conference&Exhibition, Florence, 2012, pp. 244 – 248.