The Tool supported Detection of Faulted Section and Fault Locator in HVDC lines

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***Abstract*: This work is aimed at traveling wave principles considering three subsections of the HVDC transmission. This configuration appears when power is transmitted by different environments requiring mixed configuration of cable and overhead line. In point of traveling wave principle some aspect of reflection and transmission should be supported including reflection, transmission coefficient as well as attenuation or phase change processes. Presented idea describes application of traveling wave distribution generator as supported tools for real traveling pulses recognition.**

***Keywords*: fault location[1], HVDC line, traveling waves**

I. Introduction

The theory of determining fault location (FL) by the use of traveling wave (TW) was reported as early as 1931. It recognized that a fault generates a very high frequency traveling wave pulse on the faulted line. In general detection of this pulse and echo of the pulse, with appropriate timing accuracy, allows determination of the distance to the fault [3].

The fault location based on traveling wave principles is unaffected by fault resistance and provides a consistent level of accuracy many times better than conventional ‘impedance’ type fault locators known from AC transmission lines [4].

Two general FL methods based on TW are on either end or single end measurements of TW. In figure 1 and below related equations describes rules how the accurate location is determined [5,6].

Double end method

$$\begin{cases} X_M = \frac{1}{2}\left[v(T_{M1} - T_{N1}) + L\right] \\ X_N = \frac{1}{2}\left[v(T_{N1} - T_{M1}) + L\right] \end{cases} \quad (1)$$

Single end method

$$X_M = \frac{1}{2} v \Delta T \; , \; \Delta T = \left(T_{M2} - T_{M1}\right) \quad (2)$$

Where :

X_M - distance from F to station M

X_N - distance from F to station N

L – Total line length

v –propagation velocity of the TW in line

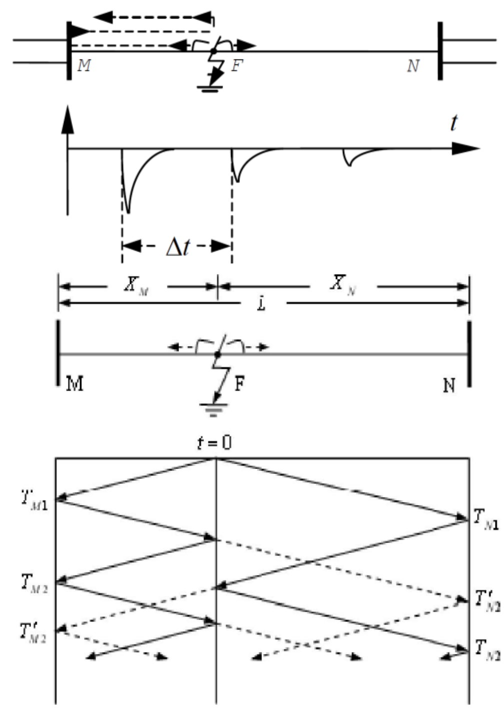

Fig. 1 Bewley lattice diagram from [6]

II. Principles of Traveling Wave in Segmented Transmission Line

When long power transmission lines are considered some aspects of distributed nature of the environment should be introduced [1,2]. Voltage and current in the transmission line can be expressed for particular instant of time t and particular position *x* along the length of the line *l*. In order to express suitable relations for voltage *u(x,t)* and current *i(x,t)* a small section of the transmission line, of length *Δx* , should be considered much precisely. It is assumed that finite element of the line *Δx* can be treated as a lumped element with quasi-stationary parameters *RΔx*, *LΔx*, *CΔx*, *GΔx*. It allows representing this lumped equivalent circuit as two-terminal-pair.

In case of bipolar transmission, resistance of the line is longitudinal resistance of the conductor. It is consider the same for supply and return conductor. Inductance mainly represents longitudinal inductance of the both conductors. Only in special cases this inductance is also supported by the inductance

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between conductors and the ground. Capacitance of the line includes capacitance between supply and return conductors as well as capacitance between conductors and the ground. It is placed as crosswise element at the equivalent circuit. Conductance represents leakage effect between conductors and between conductors and the ground.

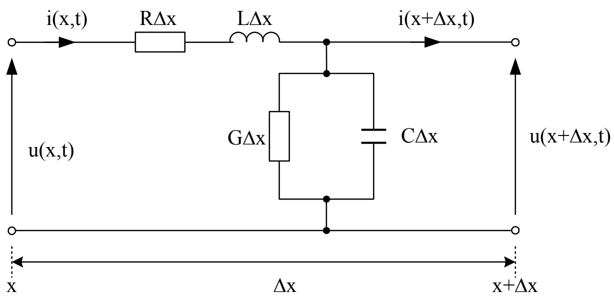

Fig. 2. Lumped equivalent of a small section Δx of the transmission line

Kirchhoff laws related to lumped equivalent of *Δx* are expressed:

$$\begin{aligned} u(x,t) &= R\cdot\Delta x\cdot i(x,t) + L\cdot\Delta x\cdot\frac{\partial i(x,t)}{\partial t} + u(x+\Delta x,t) \\ i(x,t) &= G\cdot\Delta x\cdot u(x+\Delta x,t) + C\cdot\Delta x\cdot\frac{\partial u(x+\Delta x,t)}{\partial t} + i(x+\Delta x,t) \end{aligned} \tag{3}$$

Eliminating *Δx*, second derivative of the equations with respect to x and respect to t are expressed as:

$$\begin{aligned} \frac{\partial^2 u}{\partial x^2} &= R\cdot G\cdot u + (R\cdot C + L\cdot G)\cdot\frac{\partial u}{\partial t} + L\cdot C\cdot\frac{\partial^2 u}{\partial t^2} \\ \frac{\partial^2 i}{\partial x^2} &= R\cdot G\cdot i + (R\cdot C + L\cdot G)\cdot\frac{\partial i}{\partial t} + L\cdot C\cdot\frac{\partial^2 i}{\partial t^2} \end{aligned} \tag{4}$$

Considering a transmission line having *R,L,C,G* and signal at the sending end with given frequency ω then the magnitude and phase of this signal, as it reaches at any section distance x from the sending end, change referring to propagation constant *γ*. Propagation considers attenuation *α* and phase shift *β*:

$$e^{-\gamma x} = e^{-\alpha x}\cdot e^{-j\beta x} \tag{5}$$

The level of propagation constant *γ* is correlated with electrical parameters of the line and investigated frequency of the transmitted signal *ω*, so that:

$$\begin{aligned} &\gamma = \alpha + j\beta = \sqrt{\underline{Z}\cdot\underline{Y}} = \sqrt{(R+j\omega L)\cdot(G+j\omega C)}; \\ &\alpha = \sqrt{\frac{1}{2}\left(ZY + RG - \omega^2 LC\right)}; \beta = \sqrt{\frac{1}{2}\left(ZY - RG - \omega^2 LC\right)} \end{aligned} \tag{6}$$

Next parameter of the line which is directly associated with the electrical parameter of the line is the surge impedance (characteristic impedance) Z_f.

$$\underline{Z}_f = \sqrt{\frac{\underline{Z}}{\underline{Y}}} = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \tag{7}$$

Proposed tool for generation of the pulses is based on traveling wave equations for $R\approx 0$, $G\approx 0$

$$\begin{aligned} \frac{\partial^2 u}{\partial t^2} &= \frac{1}{L\cdot C}\frac{\partial^2 u}{\partial x^2} = v^2\,\frac{\partial^2 u}{\partial x^2} \\ \frac{\partial^2 i}{\partial t^2} &= \frac{1}{L\cdot C}\frac{\partial^2 i}{\partial x^2} = v^2\,\frac{\partial^2 i}{\partial x^2} \end{aligned} \tag{8}$$

Solution of discussed equations leads to general expression of voltage and current at given instant of time *t* and at given points of the line x , where *α* represent attenuation. Phase change *β* is neglected in this consideration:

$$\begin{aligned} u(x,t) &= \left[m(x-vt) + n(x+vt)\right]e^{-\alpha t} \\ i(x,t) &= \frac{1}{z_f}\left[m(x-vt) - n(x+vt)\right]e^{-\alpha t} \end{aligned} \tag{9}$$

In case when the attenuation does not depend of frequency and has minimum value $e^{-\alpha vt} = e^{\alpha(x-vt)}e^{-\alpha x} = e^{-\alpha(x+vt)}e^{\alpha x}$, then:

$$\begin{aligned} u(x,t) &= M\,(x-vt)\cdot e^{-\alpha x} + N\,(x+vt)\cdot e^{\alpha x} \\ i(x,t) &= \frac{1}{z_f}\left[M\,(x-vt)\cdot e^{-\alpha x} - N\,(x+vt)\cdot e^{\alpha x}\right] \end{aligned} \tag{10}$$

Referring to above formulas we can reveal that voltage is the sum of two traveling wave. The u_M represents forward traveling wave of voltage traveling in positive +*x* direction of length. It is also called incident wave. The u_N represents backward traveling wave of voltage traveling in negative -*x* direction of length. It is also called reflected wave. Sum of these two traveling wave follows by Kirchhoff law:

$$\begin{aligned} &u(x,t) = u_M\,(x,t) + u_N\,(x,t); \\ &u_M\,(x,t) = M\,(x-vt)\cdot e^{-\alpha x};\quad u_N\,(x,t) = N\,(x+vt)\cdot e^{\alpha x} \end{aligned} \tag{11}$$

In case of current there is visible negative sign in the solution. Current can be expressed as difference of two traveling wave. The i_M represents forward traveling wave of current traveling in positive +*x* direction of length. It is also called incident wave. The i_N represents backward traveling wave of current traveling in negative -*x* direction of length. It is also called reflected wave. These currents fulfill the Kirchhoff law:

$$\begin{aligned} &i(x,t) = i_M\,(x,t) - i_N\,(x,t); \\ &i_M\,(x,t) = \frac{1}{z_f}M\,(x-vt)\cdot e^{-\alpha x};\quad i_N\,(x,t) = \frac{1}{z_f}N\,(x+vt)\cdot e^{\alpha x} \end{aligned} \tag{12}$$

The surge current *i(x,t)* traveling along the line is always accompanied by a surge voltage *u(x,t)*. For the reverse wave, it can be similarly shown that the surge current *i(x,t)* is associated with a surge voltage with negative sign. Generally, voltage and current wave are being reflected at the source and the load. A combination of this wave determines the total voltage and current at the source and load, ends of the line.

A. Reflection of traveling wave at termination

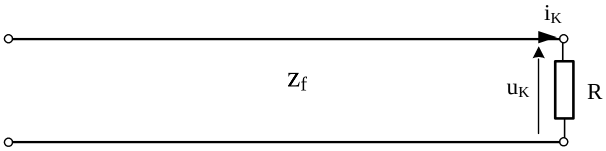

Fig. 3. Visualization of the reflection at termination

Transmitted wave of voltage $u_k(x,t)$ at the end of the line with resistance R is the fraction of incident voltage wave (surge) $u_M(x,t)$ in the correspondence to the transmission factor r_{KU}. Transmitted wave of current $i_K(x,t)$ at the end of the line with resistance R is the fraction of incident current wave (surge) $i_M(x,t)$ in the correspondence to the transmission factor r_{KI}.

$$r_{KU} = \frac{u_K(x,t)}{u_M(x,t)} = \frac{2 \cdot R}{R + z_{f1}}; \quad r_{KI} = \frac{i_K(x,t)}{i_M(x,t)} = \frac{2 \cdot z_{f1}}{R + z_{f1}} \quad (13)$$

Similar comments can be expressed in point of the reflection. Reflected wave of voltage $u_N(x,t)$ at the end of the line with resistance R is the fraction of incident voltage wave (surge) $u_M(x,t)$ in the correspondence to the reflection factor r_{NU}. Reflected wave of current $i_N(x,t)$ at the end of the line with resistance R is the fraction of incident current wave (surge) $i_M(x,t)$ in the correspondence to the reflection factor r_{KI}.

$$r_{NU} = \frac{u_N(x,t)}{u_M(x,t)} = \frac{R - z_{f1}}{R + z_{f1}}; \quad r_{NI} = \frac{i_N(x,t)}{i_M(x,t)} = \frac{R - z_{f1}}{R + z_{f1}} \quad (14)$$

B. Reflection of traveling wave at junction

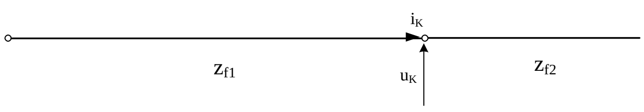

Fig. 4. Visualization of the reflection at junction point

Presented in the previous subsection discussion can be expanded in case of consideration of traveling wave at junction point where traveling wave on the transmission line with surge impedance Z_{f1} reaches the point with differ surge impedance Z_{f2}.

Finally, after derivation we obtain particular transmission and reflection factors at junction point for voltage and current respectively:

$$r_{KU} = \frac{u_K(x,t)}{u_M(x,t)} = \frac{2 \cdot z_{f2}}{z_{f2} + z_{f1}}; \quad r_{KI} = \frac{i_K(x,t)}{i_M(x,t)} = \frac{2 \cdot z_{f1}}{z_{f2} + z_{f1}} \quad (15)$$
$$r_{NU} = \frac{u_N(x,t)}{u_M(x,t)} = \frac{z_{f2} - z_{f1}}{z_{f2} + z_{f1}}; \quad r_{NI} = \frac{i_N(x,t)}{i_M(x,t)} = \frac{z_{f2} - z_{f1}}{z_{f2} + z_{f1}}$$

C. Reflection of traveling wave at junction with shunt resistance

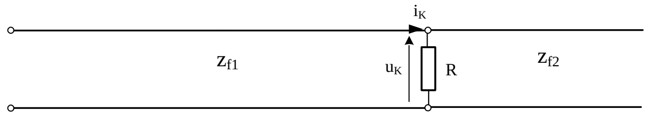

Fig. 5. Visualization of the reflection at junction with shunt resistance

This consideration describes model of fault at junction point with fault resistance. The reflection of the traveling wave distributed along surge impedance Z_{f1} is realized as reflection with parallel connection of resistance R and surge impedance of second segment of the transmission.

$$r_{KU} = \frac{2 \cdot \frac{R \cdot z_{f2}}{R + z_{f2}}}{\frac{R \cdot z_{f2}}{R + z_{f2}} + z_{f1}}; \quad r_{KI} = \frac{2 \cdot z_{f1}}{\frac{R \cdot z_{f2}}{R + z_{f2}} + z_{f1}} \quad (16)$$
$$r_{NU} = \frac{\frac{R \cdot z_{f2}}{R + z_{f2}} - z_{f1}}{\frac{R \cdot z_{f2}}{R + z_{f2}} + z_{f1}}; \quad r_{NI} = \frac{\frac{R \cdot z_{f2}}{R + z_{f2}} - z_{f1}}{\frac{R \cdot z_{f2}}{R + z_{f2}} + z_{f1}}$$

Especially if surge impedance $Z_{f1}=Z_{f2}$ disused case represents model of fault in line with fault resistance R:

$$r_{KU} = \frac{2 \cdot R}{2 \cdot R + z_{f1}}; \quad r_{KI} = 1 + \frac{z_{f1}}{2 \cdot R + z_{f1}} \quad (17)$$
$$r_{NU} = \frac{-z_{f1}}{2R + z_{f1}}; \quad r_{NI} = \frac{-z_{f1}}{2R + z_{f1}}$$

III. SELECTION OF TW PULSES FOR FAULT LOCATION

At any instant of time the wave at all points of the line can be identified or at any point of the line the time of arrival of each wave can be seen. In order to construct reflection lattice it is necessary to determine the reflection and transmission (refraction) coefficient at each junction. These factors are characteristic for particular junction point or fault resistance.

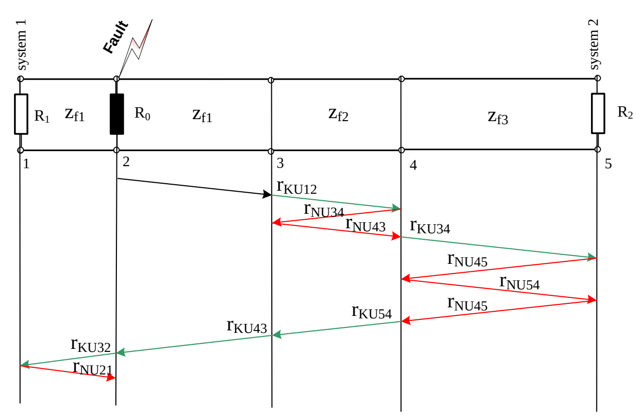

Fig. 6. Visualization of the three segmented configuration with R_0 as fault resistance and the manner of the coefficient r calculation and notation

Every backward wave becomes a new forward wave in the way to previous junction point. Every transmitted wave becomes a new forward wave in their way to next junction point.

Process of the reflection and transmission uses reflection and transmission factors which are characteristic for particular junction point or fault resistance or terminal. The calculation of the successive reflection is oftentimes a long and involved process, particularly when reflections may occur from a whole series of neighboring junctions. The manner of coefficient *r* calculation for three segmented configuration is presented in Fig. 6.

Fault location based on single end method is the most challenging method. Determination of the proper TW pulses required for proper selection of faulted section and accurate fault location is dependent on the line topology. Fig. 7 represents pulses distribution when overhead line (OHL) topology is considered. Single-end principle application requires selection of the proper pulses with respect to their polarity. Configuration which use two environment OHL and cable introduces problem of different velocity and reflection in junction point. Fig. 8 depicts pulses distribution.

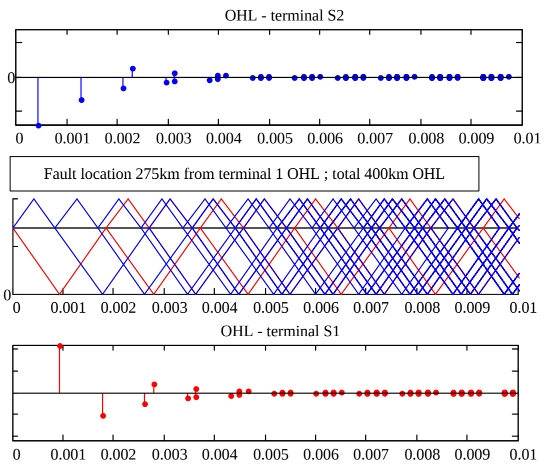

Fig. 7. Visualization of the pulses distribution for fault second half of pure OHL (400km OHL) – fault distance 275km

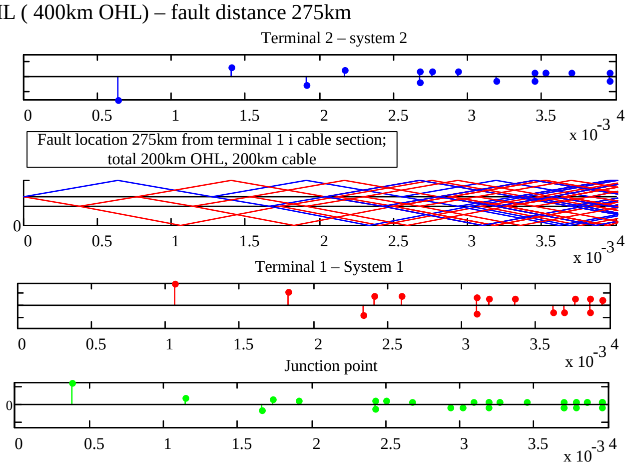

Fig. 8. Visualization of the pulses distribution for fault in second section of OHL-Cable configuration (200km OHL, 200km cable) when fault distance is localized in second section 275km

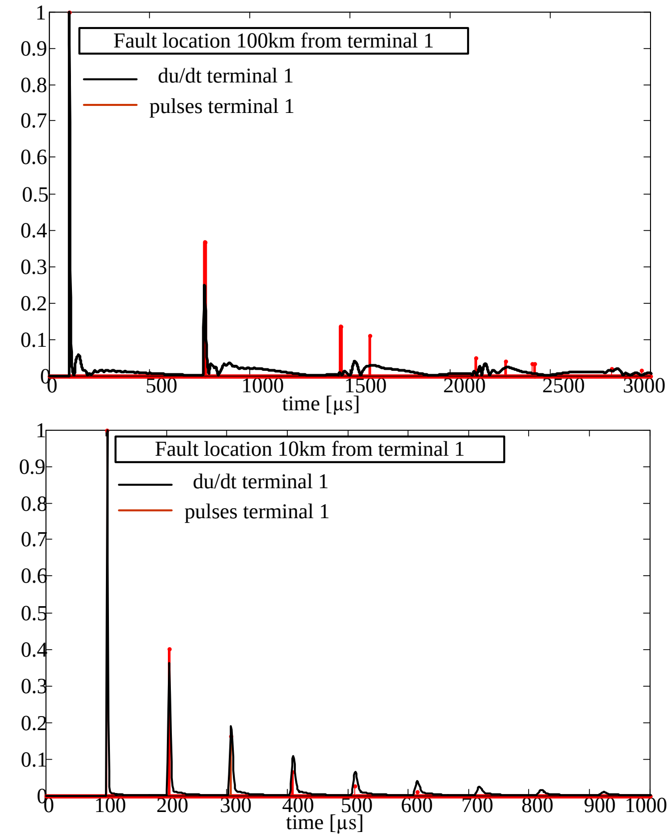

Fig. 9. Visualization of the pulses distribution generated by proposed tool in comparison to derivative of the voltage at the node of terminal 1 of the three segmented configuration Cable-OHL-Cable.

Practical application of the tool can be performed using time arrival and absolute value of the pulses polarity. In this case the attenuation can be introduce on fixed level. This simplification is acceptable when magnitude and sign of the impulses are not considered as active element of minimizing the error function. Fig. 9 presents comparison of reference set of traveling pulses obtained by the tool and derivative of voltage during the fault when PSCAD simulation of three segmented line in configuration Cable-overhead line-cable was realized. Generate by the presented tool set of impulses covers the real impulses. Additionally, Fig. 10, with connection to Table I, represent the mechanism of described tool when every property of impulses are considered including: magnitude, sign and time position of the impulses. This approach is typical for one-ended fault location procedure. Generation of the impulses is activated for three segmented environment is considered cable-OHL-cable. Table I express details of the impulses including its position and magnitude. Having parameters of the transmission configuration it is possible to generate distribution of the pulses in particular nodes with respect to polarization, magnitude and time of the arrival. This set can be used for objective function based on minimum error in relation to derivative of voltage or current.

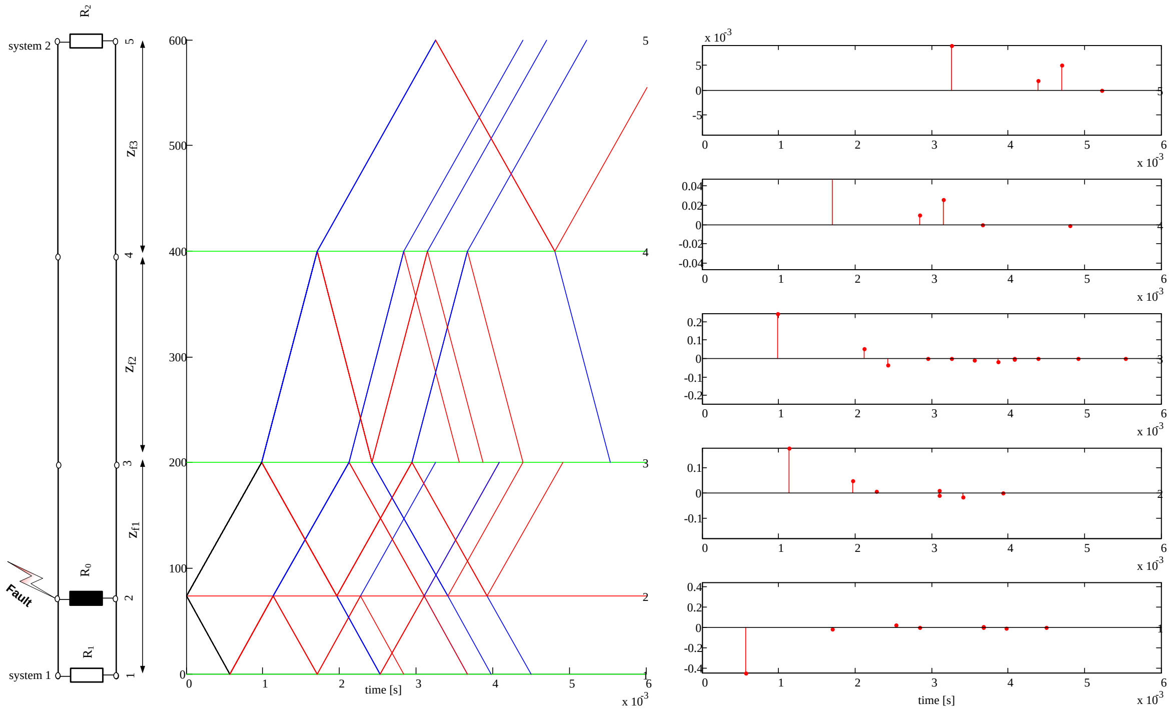

Fig. 10. Visualization of the example of pulses generation for three segmented configuration with R_0 as fault resistance at 73km among the configuration cable(200km)-overhead line (200km)- cable (200km) with limitation to 6 passages.

TABLE I
FRAGMENT OF FIG.6 SHOWING ARRIVAL TIME AND MAGNITUDE OF PULSES WITH LIMITATION TO 6 PASSAGES

Node 1		Node 2		Node 3		Node 4		Node 5	
Time	Magnitude	Time	Magnitude	Time	Magnitude	Time	Magnitude	Time	Magnitude
0.0006	-0.4436	0.0011	0.1801	0.0010	0.2456	0.0017	0.0466	0.0033	0.0091
0.0017	-0.0147	0.0020	0.0481	0.0021	0.0524	0.0028	0.0099	0.0044	0.0019
0.0025	0.0253	0.0023	0.0060	0.0029	-0.0022	0.0037	-0.0004	0.0052	-0.0001
0.0028	-0.0005	0.0031	0.0103	0.0024	-0.0349	0.0032	0.0261	0.0047	0.0051
0.0037	0.0054	0.0031	-0.0103	0.0033	0.0017	0.0048	-0.0009	0.0064	-0.0001

IV. CONCLUSIONS

Presented tool for supported fault location in HVDC lines applies every aspects of traveling wave conditions including reflection and transmission coefficient. The idea of tool application is to generate a number of traveling pulses distribution and its numerical comparison or fitting to measured derivative of voltage. The objective function can lead to detection of the fault on the basis of best fitting of the pulses distribution and derivative of voltage in considered nodes. Thus, even single ended principle of fault detection can be considered even in three segmented configuration.

Application of presented tool gives possibility to generate reference sets of traveling wave pulses with respect to magnitude, sign and time shift. Reference set can be compare with measured set of traveling wave and minimum error function indicates fault location. Accuracy depends on precision of reference set generation that requires every details data of the transmission configuration including surge impedances of the segments and both end systems resistance. In practical application of the tool the time instant of arrival wave is suggested to use directly for fault location with assumption of steady state velocities of the particular segments and constant attenuation.

V. REFERENCES

[1] Chan-Ki Kim et al, *HVDC transmission. Power Conversion Application in Power Systems*, Wiley (Asia) Pte Ltd, 2009, p. 251.

[2] C. R. Paul, *Transmission Lines in Digital and Analog Electronic Systems. Signal Integrity and Crosstalk*, Willey, 2010.

[3] L. Yongli, Z. Yi and M. Zhiyu, *Fault Location Method Based on The Periodicity of the Transient Voltage Traveling Wave*, IEEE Proceedings. PowerCon. International Conference on Power System Technology, Vol. 3, Tianjin China, Nov. 2004, pp. 389-392.

[4] Crossley P.A., Gale P.F, Aurangzeb M. *Fault location using high frequency travelling wave measured at a single location on a transmission line*. Developments in Power System Protection, Amsterdam, Holland, 9-12 April 2001, 403-406.

[5] E. O. Schweitzer, M. Ando, R.A. Baker, *Development and field-data evaluation of single-end fault locator for two-terminal HVDC transmission lines - Part 1: data collection system and field data*, IEEE Transactions on Power Apparatus and Systems , vol. PAS-104, No. 12, December 1985, pp. 3524- 3530.

[6] E. O. Schweitzer, M. Ando, R.A. Baker, *Development and field-data evaluation of single-end fault locator for two-terminal HVDC transmission lines* - Part 2: Algorithm and evaluation, IEEE Transactions on Power Apparatus and Systems , vol. PAS-104, No. 12, December 1985, pp. 3531- 3537.