THE WAVE PROPAGATION ANALYSIS PRODUCED BY PARTIAL DISCHARGES IN HIGH VOLTAGE CABLE IN DIRECT AND RETURN TIME

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***Abstract* – This paper presents the mathematical model of current and voltage signal reestablishment in direct and return time measured in high voltage cable at the some moment of time. Also, it takes in considerations all cable construction particularities. Some signal propagation particularities in cable in direct and return time depending of faults presents or its missing (un-quality connection of two or more cables through muff, current leakage to ground, breaks of cable etc.) are presented.**

Keywords: *mathematical model, partial discharges, high voltage cable, wave propagation, cable defects.*

1. INTRODUCTION

The high voltage cables constitute one of main power system components. Its defaults can have grave consequences. This problem becomes still more acute during implementation in practices of so called “smart grids”, where the power systems are interconnected. From these reasons in last time grows the number of researches in this direction which have a purpose to introduce preventive maintenance. That will permits the anticipation of grave fault appearance, and respective the taking of proper measures.

Currently, is known that about the current technical state of the high voltage equipments can judged on the basis of the voltage pulses parameters analysis produced by the partial discharges. These pulses have a short duration (the order ns), but its parameters measurement is not a problem today. The main problem constitutes a processing of measured data and elaboration of veridical conclusions about technical current state of the analyzed equipment. This is owed the fact, that the high voltage cable for the high-frequency pulses are represented as a circuit with distributed parameters. Each fault or points of cables connection through muffs constitute for these pulses heterogeneities, which conduct to its reflection and dispersion. Because, the measurement of these pulses parameters is possible, as rule, to the cable ends, we really will measure absolutely different parameters against initial pulses parameters. And in this case is very difficult to formulate a correct conclusion about the current technical state of high voltage cable.

This problem becomes still more acute in the case when exists many faults. In distinguish, is very hard to notice a dangerous defects, if before it against the point of measurement is found out a minor defect. Due to the process of reflection and attenuation, this dangerous fault has a minor influence in form of measured signal.

In the aim of settlement of the propagate peculiarities of short time waves in cable, in suggested work a mathematical model, based on the numerical computation method, what permits the reestablishment in return time of measured signal at some moment of time is proposed. In such mode we tried of stable the exact place of partial discharge appearance and determination of it real parameters.

2. RESEARCH OF WAVES PROPAGATIONS IN DIRECT AND RETURN TIME

The research of the propagation process of current and voltage waves in the high voltage cable is done with help of mathematical model. This is a mathematical model based on a numerical computation method so called method of characteristics (the Godunov method).

According as is known from literature the waves propagations in cable is described with help of the cable equations (1):

$$\begin{aligned} -\frac{\partial u}{\partial x} &= L\frac{di}{dt} + Ri; \\ -\frac{\partial i}{\partial t} &= C\frac{du}{dt} + Gu. \end{aligned} \tag{1}$$

On the basis of these equations with help of the characteristics method were achieved the mathematical model, which proper describes the physical structure of high voltage cable [1]:

a) Current and voltage in seminodes:

$$i^{n-1/2} = \left(L_{n-1/2} + \frac{\tau}{2} R_{n-1/2} \right)^{-1} \left(\frac{\tau}{h_n} (u^{n-1} - u^n) + (L_{n-1/2} - \frac{\tau}{2} R_{n-1/2}) i_{n-1/2} \right),$$
$$u^{n-1/2} = \left(C_{n-1/2} + \frac{\tau}{2} G_{n-1/2} \right)^{-1} \left(\frac{\tau}{h_n} (i^{n-1} - i^n) + (C_{n-1/2} - \frac{\tau}{2} G_{n-1/2}) u_{n-1/2} \right). \quad (2)$$

b) Current and voltage in nodes:

$$u^n = \left(v_{n-1/2} C_{n-1/2} + v_{n+1/2} C_{n+1/2} \right)^{-1} (i_{n-1/2} - i_{n+1/2} + v_{n-1/2} C_{n-1/2} u_{n-1/2} + v_{n+1/2} C_{n+1/2} u_{n+1/2});$$
$$i^n = i_{n-1/2} + v_{n-1/2} C_{n-1/2} (u_{n-1/2} - u^n). \quad (3)$$

c) Current and voltage in marginal points:

$$\alpha_0 i_0 + \beta_0 u_0 = f_0;$$
$$i_0 - v_{1/2} C_{1/2} u_0 = i_{1/2} - v_{1/2} C_{1/2} u_{1/2};$$
$$\alpha_l i_N + \beta_l u_N = f_l;$$
$$i_N + v_{N-1/2} C_{N-1/2} u_N = i_{N-1/2} + v_{N-1/2} C_{N-1/2} u_{N-1/2}. \quad (4)$$

d) Determination of Z vector, which contain unknown values:

$$Z = B^{-1} Y \quad (5)$$

where

$$B = \begin{vmatrix} 1 & 0 & +vC & 0 \\ 0 & 1 & 0 & -vC \\ 1 & -1 & 0 & 0 \\ 0 & 0 & +1 & -1 \end{vmatrix}; \quad \begin{aligned} &Y = (Y_1, Y_2, Y_3, Y_4)^T \\ &Y_1 = \left(i^- + vCu^- \right)_{n-1/2} \\ &Y_2 = \left(i^+ - vCu^+ \right)_{n+1/2} \\ &Y_3 = Y_4 = 0 \end{aligned}$$

On the basis of this mathematical model was done a lot of simulations in function of faults present or no, its parameters etc. Forwards we will present only some results to can understand the difficulty of some conclusions elaboration on the basis of these results concerning the current technical state of testate cable.

As circuit for study we considered the scheme presented in fig. 1. This scheme give the possibility to model the serial connecting-up four portions of cable with help of three muffs (M1, M2, M3); modeling of current leakages to earth in three arbitrary points of cable, which are presented through RLC circuits with concentrated parameters; in the beginning of cable have modeled a generator of signal with internal adjustable resistor and parallel RLC circuit, and at an end of cable have connected also a RLC circuit.

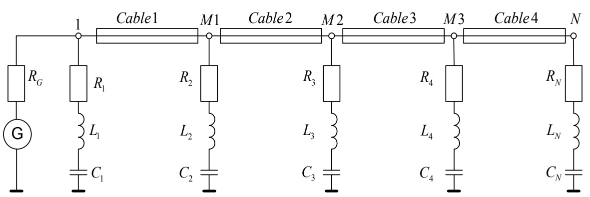

Figure 1. The scheme of cable line modeling consisting from four portions of cables.

On fig. 2 is presented the measured voltage to the end of the cable line (in the point *N*) for the case when the line is without loss and next conditions: the cable line is divided in 300 points; in the beginning of cable line and in the points *N3= 30, N4= 90* and *N5= 150* on a duration of 10 computation steps we apply an unitary stair signal; the end of the cable line is in idle regime, and beginning of line after 10 computation steps also are setup in idle regime; in the point *N3* have current leakage $R_2 = 2Z_0$, in the point *N4* have current leakage $R_3 = 3Z_0$ and in the point *N5* have current leakage $R_4 = 3Z_0$, where Z_0 is the characteristic resistance of the cable line. The muffs quality was considered ideally.

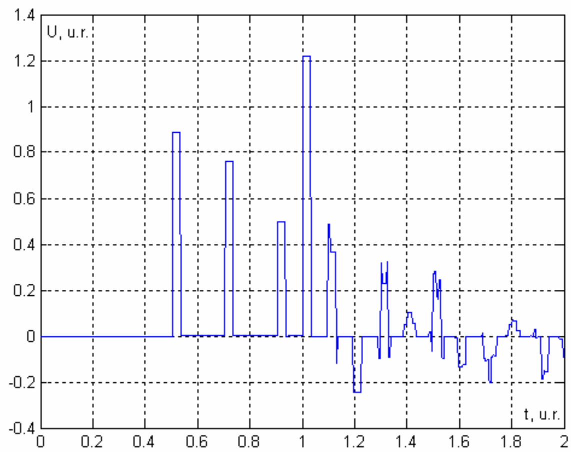

Figure 2. The voltage at the end of cable line for two wave runs on cable length for next conditions: $R_1 = \infty, C_1 = \infty$, $L_1 = 0$; $R_2 = 2$, $C_2 = \infty, L_2 = 0$; $R_3 = 3, C_3 = \infty, L_3 = 0$ $R_4 = 4$, $C_4 = \infty, L_4 = 0$; $R_N = \infty, C_N = \infty, L_N = 0$.

From fig. 2 is obvious that all faults are placed in first half of the cable line, but that gravity of each isn't clearly.

In order to can do a more correct analysis of each fault severity is useful to recover this signal in return time. For this purpose is necessary to modify the mathematical model of computation in direct time.

Therefore, first, we replace computation step in time τ with $-\tau$, then in all matrices what describe the marginal points we replace the variable vC with $-vC$. Forwards in computation relations (3) and (4) we replace also variable vC with $-vC$. And last in the computation relations of the functions Y_1 and Y_2 we replace also variable vC with $-vC$.

On fig. 3 is presented result of the reestablishment in return time of the signal from fig. 2.

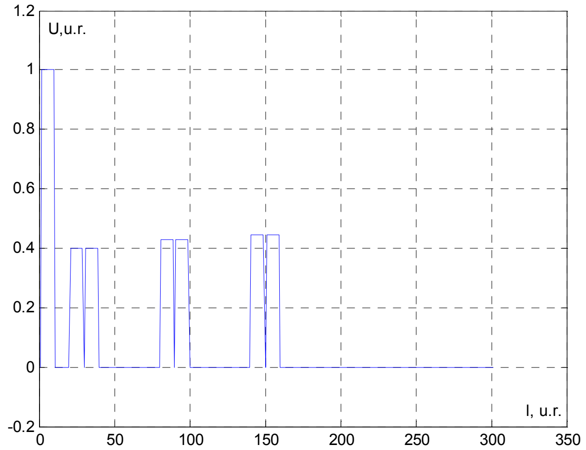

Figure 3. The voltage along the cable line restored in return time for condition from fig.2.

From fig. 3 is already much clear, that in cable line exists three places in which appear the partial discharges (in the point 30, 90 and 150), and most grave fault is placed in the point 30. In such mode is easier to do analysis of studied cable current technical state. At realization of this procedure its need to take in account that the cable ends must have connected the loads more or less than 10% from cable characteristic resistance. Otherwise it is impossible to recover the initial signal.

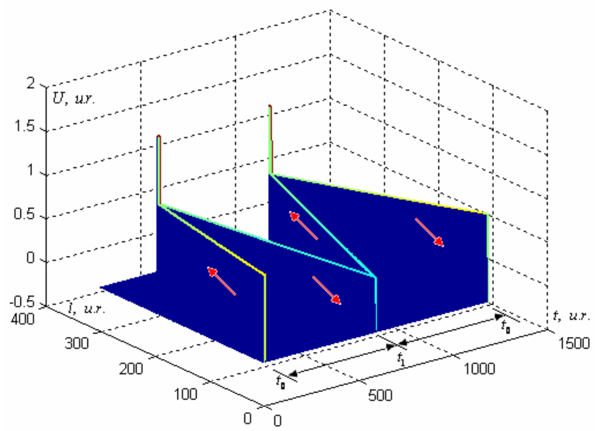

Figure 4. The voltage variation in cable line for losses $R = 0.5u.r.$ in direct time $t_0 \rightarrow t_1$ and in return time $t_1 \rightarrow t_0$.

Let's analyze how influences the cable losses, what characterizes the real line. For the simplification of the calculations we will consider present in cable line only a signal from generator. In fig. 4 is shown the measured voltage to the end of the line for applying of unitary voltage stairs during 10 computation steps at its beginning. The losses in cable line constitutes $R = 0.5u.r.$

From fig. 4 is obvious that in the moment of time t_1 we measure a signal decreased against one applied depending on losses in cable. In the case when in cable line don't exists the heterogeneities then don't exists reflections too and it is simple to calculating the initially value of applied pulse according [2]. The thing is complicated many in the case when exists leakages of current or un-quality connections of muffs. To admit, that in the point *N3=50* have connected a resistance to earth $R_2 < Z_0 = 0.7Z_0$, and in the point *N4=180* have connected a resistance to earth $R_3 > Z_0 = 1.7Z_0$. Losses in cable consider $R = 0.5Z_0$. The result of simulation is presented on fig.5.

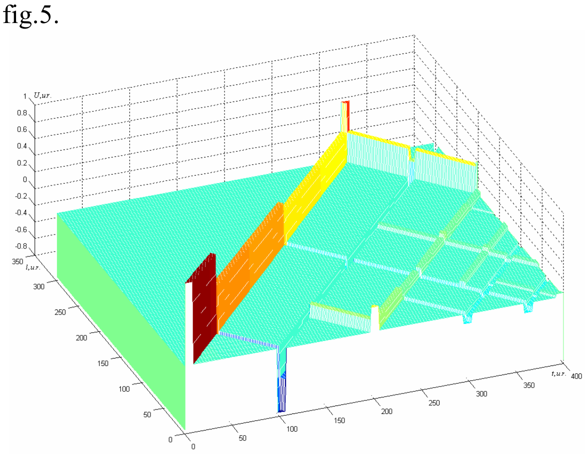

Figure 5. The voltage variation along the cable line for applying of unitary voltage stairs during $t = 10\tau$ at it beginning and $R_2 = 0.7Z_0$ in point 50, $R_3 = 1.7Z_0$ in point 180.

So kind of presentation permits the visualization of the wave propagation mode to the touch of fault point. It's clear seen, that a current leakage to earth conduct to the reflection of a wave part with opposite sign, indifferently if this value is more or little than the characteristic resistance of the line. This thing enables to us judge about fault type analyzing the measured signal to the end of the line. According as we seen from fig. 6 a un-quality muff connection caused the wave reflection from this point with the same sign.

From fig. 6 we see, that with how much un-quality is muff connection, with as much is more the value of the reflected wave, as well as the exact place of muff location is clear seen.

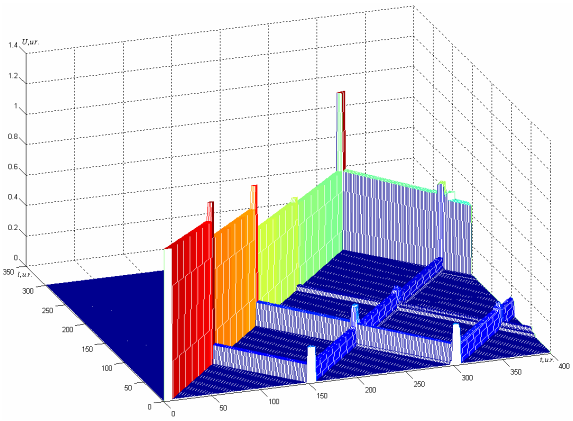

Figure 6. The voltage variation along the cable line for $M_1 = 0.3Z_0$ in point 75, $M_2 = 0.5Z_0$ in point 150, $M_3 = 0.1Z_0$ in point 220.

Usually, a defect like current leakage to earth can be described as a *RC* circuit. In fig. 7 is presented the voltage curve measured at cable line beginning obtained as the result of unitary voltage stairs application at in beginning, which contain 3 identical defects - $R_2 = 1, C_2 = 0.01$ located in the point 60, $R_3 = 1, C_3 = 0.01$ located in the point 140 and $R_4 = 1, C_4 = 0.01$ located in the point 220. All cable line is formed from 300 points, and all the values are presented in relative units.

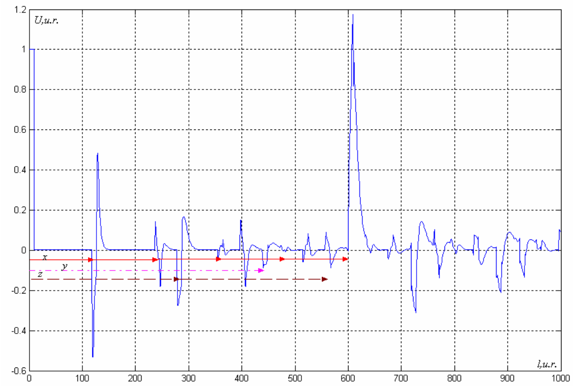

Figure 7. The voltage at the line input for: $R = 0.1$, $R_2 = R_3 = R_4 = 1$, $C_2 = C_3 = C_4 = 0.01$ placed in 60, 140 and 220 points of cable.

According as is seen from fig. 7 is very difficult to determinate the number and the place of defect appearance. In the case when is only one defect the time among the reflected pulses is practical same. In fig. 7 aren't such a thing and this enables to us affirm that exists more the one defect. Usually, in order to find place of defects we can exclude pulses which are repeated with same periodicity. The number of pulses series which have same periodicity will be the number of defects in cable line.

In fig. 7 emphasized 3 series of pulses repeat. First series marked with red arrows(x – solid arrow) has a length of 120 points, what means that first defect is located in the point 60, because the wave goes through the double distance – up to defect and backward. The second type of arrows has a brown color (z – dash arrows) and they have duration of 280 points. This means that second defect is located in the point 140 of the cable line. The third type of arrows is magna (y dash-dot arrows) and they have duration of 440 points, what means that the third defect is located in the point 220.

But the defects graveness is more difficult to established, with all that defects are identically. We can proceed in follow mode. We will be determining the reflection coefficient from each defects of incident wave. And doing comparison between these coefficients, you see that defects have same graveness. In such mode we can do a correct analysis about the graveness of detecting defects.

3. CONCLUSIONS

1. Using the mathematical model of signal reestablishment in return time measured along cable line at some moment of time we can formulate more veridical conclusions concerning the place of defects appearance and its graveness. In order to can using this method it's necessary to connecting at the ends of the cable line loads which have values little or big with at least 10% against characteristic resistance of cable.
2. On the basis of measured results of voltage at the beginning of cable (or at it end) during period of time we can determine the number of defects if will select the number of pulses series which have the same periodicity. The graveness of each defect can be established by comparison of reflection coefficient of each incident wave with the reflected wave from every defect

4. ACKNOWLEDGMENTS

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