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Transmission Line Fault Distance Measurement based on Time Difference between Travelling Wave Reflection and Refraction

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Introduction

Relay protection and automation principles have not been changed for a log time. Only nonessential methods changes some times had appeared. For example innovative filters such as *sin*, *cos*, *band* or *Fuzzy logic* was implemented.

Some typical solutions of conventional relay protection have tried to use for atypical applications. For example AR function or zero sequence differential algorithm have used for high impedance grounded or insulated networks faulted feeder detection.

Another innovative suggestion is to use neural network for identification of fault type, using steady - state current and voltage components [4]. The third and fifth frequency components are calculated using DFT from measured voltage and current signals. Fault types are classified using neural network algorithm. The learning processes are performed using models of various network modes. The practical disadvantage of such model is due to availability of different substation and lines configuration. The variation of available configuration makes great amount of calculation needed for learning of neural network.

Generally electromagnetic processes registration methods for relay protection could be divided in to the five groups. The first method uses an idea of registration of travelling wave propagated from fault. The travelling waves reflect from substation busses due to significant difference of wave impedance. The line impedance is much higher than bus bar. Reflected travelling wave from bus bar propagate towards fault and reflect as well, due to difference of wave impedance. Propagated towards bus bar travelling wave repeatedly are recorded. After that the distance from the buses to the fault could be calculated. The distance would be proportional to difference between time stamps of nearby registrations.

The registrations of propagated wave are performed in the both side of line for the second method. The time stamps are fixed at the travelling wave arrival moments. Then the distance to the fault would be proportional to difference of time value. The error of the method depends on precision of relay internal timer synchronization and known line length. The fast and separated communication channel between relay protection devices is required for method realization.

The idea of injection of outsource signal to transmission line is used for the third method. The generation of outsource signal is synchronized with registration of received travelling wave. Then the time difference is calculated between generated signals and reflected from fault. This method has disadvantage which is pronounced then the fault is short i.e. the fault duration is less then travelling wave propagation time from fault to busses and back. Furthermore, another disadvantage could be seen due to the line wave channel heterogeneous.

Instead of case two, the separated and fast communication channel is not needed for fourth method. The propagated travelling waves are measured in both sides of line. GPS synchronize the timers of relay protection devices. Timer synchronization error for the case of worst atmospheric condition is about 1 μs. So, the error distance to the fault if we assume that travelling wave propagation speed $v \sim c$: $\Delta l = v \cdot \Delta t = 3e8 \cdot 1e-6 = 300m$. Due to travelling wave losses in the line, the propagation speed of wave is less then the speed of light. Nonetheless, the precision of fault location could not be reached more than $250m$. Despite the disadvantages the method has advantage. The general purpose communication channel between devices could be used to transfer time stamps.

The fifth method is similar to third. Automatic reclose AR function is used instead of outsource signal to define the fault position. Nonetheless, it seems that this method hardly conform protection system requirements. Some of travelling wave registration methods mentioned above are materialized.

Some of mentioned methods are materialized for distance to fault measurements. The advantages and disadvantages of fault location and relay protection methods are described in [1].

The multiple travelling wave reflection investigation method is described and presented in this article. The time difference between travelling wave refraction and reflection is calculated for all propagated waves. The described method is similar, but at the same time different to mentioned above fault distance calculation method.

Travelling wave in the one line network

Generally, the line could be characterized with matrices: impedance $\underline{Z}$, conductance $\underline{Y}$, surge impedance $\underline{Z}_L$, propagation coefficient $\underline{\gamma}$.

For the refracted travelling wave $\underline{W}$ valid equation:

$$\underline{U} + \underline{I} \cdot \underline{Z}_L = \underline{W} \cdot e^{-\gamma x}. \quad (1)$$

For the reflected wave $\underline{V}$:

$$\underline{U} - \underline{I} \cdot \underline{Z}_L = \underline{V} \cdot e^{-\gamma x}. \quad (2)$$

Reflection coefficient:

$$\underline{\beta}(k) = \{\underline{U}(k) + \underline{I}(k) \cdot \underline{Z}_L\}^{-1} \cdot \{\underline{U}(k) - \underline{I}(k) \cdot \underline{Z}_L\}. \quad (3)$$

The index k has the meaning of harmonic, also as current and voltage have complex value. For the simplicity purpose, the underline and index is not used in the article.

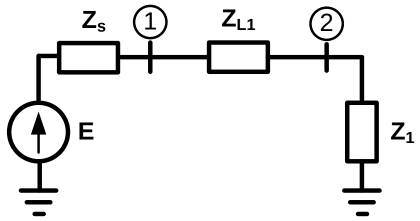

Fig. 1. Simple network equivalent diagram

The voltage in the node 2 at the time moment $0 \le t < 7 \cdot \tau$ for the one line network scheme, depicted in Fig. 1 could be described as:

$$u_2(t) = u_{2(1)}(t-\tau) + u_{2(2)}(t-3\tau) + u_{2(3)}(t-5\tau) + \ldots, \quad (4)$$

here $u_{2(1)}(t-\tau) = \alpha \cdot \alpha_2 \cdot e(t-\tau)$; τ – the wave travelling time along line; $u_{2(2)}(t-3\cdot\tau) = \alpha \cdot \alpha_2 \cdot \beta \cdot \beta_2 \cdot e(t-3\tau)$; $u_{2(3)}(t-5\cdot\tau) = \alpha \cdot \alpha_2 \cdot (\beta \cdot \beta_2)^2 \cdot e(t-3\tau)$.

The current in the load could be described respectively.

Travelling wave multiple reflection in the network

Assume, that transmission network, depicted in Fig. 2 consists of fault source with impedance $\underline{Z}_s$, four line with surge impedance $\underline{Z}_{L1}$, $\underline{Z}_{L2}$, $\underline{Z}_{L3}$, $\underline{Z}_{L4}$, propagation coefficient $\underline{\gamma}_1$, $\underline{\gamma}_2$, $\underline{\gamma}_3$, $\underline{\gamma}_4$ and load impedance $\underline{Z}_2$, $\underline{Z}_3$, $\underline{Z}_4$.

The refraction and reflection wave equations, referenced to investigation line 1, for the travelling wave propagated from node 1 to node 2, could be written:

$$W_{12} = W_1 \cdot e^{-\gamma_1 x_1}, \quad (5)$$

$$V_{12} = \frac{Z_{L2} - Z_{L1}}{Z_{L2} + Z_{L1}} \cdot W_1 \cdot e^{-\gamma_1 x_1}, \quad (6)$$

here W_1 – refracted wave at node 1; W_{12} – propagated wave from node 1 to 2; V_{12} – propagated wave from node 1 to 2, reflected wave.

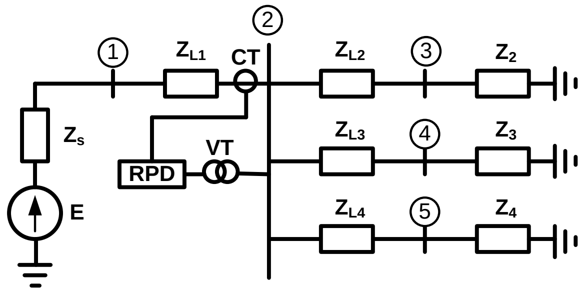

Fig. 2. Multiline network equivalent diagram

Whereas travelling wave spread through line 2 to node 3, reflect and generate current and voltage change in the node 2. The refraction and reflection wave equations, for the waves propagated from node 3 to 2, referenced to investigation line 1, could be written:

$$W_{32} = (Z_{L1} - Z_{L1}) \cdot \frac{W_3 \cdot e^{-\gamma_2 x_2}}{Z_{L1} + Z_{L2}} = 0, \quad (7)$$

$$V_{32} = (Z_{L1} + Z_{L1}) \cdot \frac{W_3 \cdot e^{-\gamma_2 x_2}}{Z_{L1} + Z_{L2}} = 2 \cdot Z_{L1} \cdot \frac{W_3 \cdot e^{-\gamma_2 x_2}}{Z_{L1} + Z_{L2}}, \quad (8)$$

here W_3 – refracted wave in node 3; W_{32} – propagated wave from node 3 to 2; V_{32} – propagated wave from node 3 to 2, reflected wave.

Similar equations could be written for lines 3 and 4. The equation (7) base equation is (1), however minus is described as travelling wave opposite direction to relay protection device. Sign is changed in equation (8) accordingly.

Fault distance measurement algorithm

Electric power transmission network consists of 3 phase system. For that reason 3 phase currents and voltages are measured. Fault distance algorithm calculates all three phase separately. An algorithm, presented in the article is for one phase and common for other phases.

Transmission network transient model is used for fault to distance measurement algorithm investigation. The D'Alamber equations or characterized mesh (1-4) are used describe network model in wide frequency range. Current and voltage signals conversion from frequency to time domain is performed using equations described in [3].

Electromagnetic transient processes character depends on network parameters and structure. Transient process time constant varies depending on refraction, reflection coefficients, on propagation coefficient, also on ground structure.

Current flow and voltage changes are influenced by propagated to node travelling wave. The multiple wave reflection could be seen in wide time range. However each later on wave reflection takes over larger network part, or on other words, additional current and voltage distribution, influenced by network parameters (4). Travelling wave analysis in moving narrow window $\Delta t = t_2 - t_1$ is used to avoid network structure and analyse only investigation object. Limited duration window Fourier transform produce limited band frequency signal $\Delta f = f_2 - f_1$.

Assume that DFT with in narrow window is applied for simple network structure, depicted in Fig. 1. Equation (4) yields node voltage $u_2(t) = u_{2(1)}(t-\tau)$ for time moment $0 \le t < 3\cdot\tau$. Reflected wave forms node voltage $u_2(t) = u_{2(1)}(t-\tau) + u_{2(2)}(t-3\tau)$ at the time moment $3\cdot\tau \le t < 5\cdot\tau$. The DFT, applied for time moment $3\cdot\tau \le t < 5\cdot\tau$ produce:

$$U_2(k) = U_{2(1)}(k) + U_{2(2)}(k), \tag{9}$$

here $3\cdot\tau \le t < 5\cdot\tau$; $k = 0,1,2,3...$

The margin of $U_{2(1)}(k)$:

$$\lim_{x\to L} U_{2(1)}(k) = \alpha\cdot\alpha_2\cdot E\cdot R(k) = \alpha\cdot\alpha_2\cdot E, \tag{10}$$

here $R(k) = \exp(-\gamma\cdot x) = \exp\left(-x\cdot j\cdot w\cdot\sqrt{1+\xi}/v\right)$; $k = 0,1,2,3...$.

Equation (9) could be rewritten after evaluation of (10):

$$U_2(k) = \alpha\cdot\alpha_2\cdot E + U_{2(2)}(k);\ 3\cdot\tau \le t < 5\cdot\tau, \tag{11}$$

here $k = 0,1,2,3...$

After remove of steady–state component the equation (11) produce:

$$U_2(k) = U_{2(2)}(k);\ 3\cdot\tau \le t < 5\cdot\tau;\ k = 1,2,3... \tag{12}$$

The voltage of node *2* for time interval $5\cdot\tau \le t < 7\cdot\tau$:

$$U_2(k) = U_{2(3)}(k);\ 5\cdot\tau \le t < 7\cdot\tau;\ k = 1,2,3... \tag{13}$$

The rectangular window with width $\Delta t \le L/v$ is used for measured current and voltage values. The adaptive filtering technique [2] is used to remove noise component from the signal. The DFT is performed for filter output: $U(k) = F\{u(n)\}$ and $I(k) = F\{i(n)\}$.

Further on calculation is performed for moving rectangle window with complex voltage and current value. The refracted and reflected waves (1-2) is calculated regarding investigation line (5-8). The equations $\underline{W}$ and $\underline{V}$ are equal zero, then the travelling wave front do not exist as it could be described from (10-13). At the wave front $\underline{W} \ne 0$ and $\underline{V} \ne 0$. The different travelling wave values for different time moment yields wave front in time domain and allow avoid differentiation operation. Summarizing mentioned above, from the faulty line or network structure propagated travelling wave is registered in the moving window.

The equations (5) and (6) are valid for refracted and reflected wave, propagated from faulty line. The equations (7) and (8) are valid for wave propagated from network to faulty line. So, the refracted wave do not act as the trigger, on opposite the reflected wave is registered. The timer is started at time moment t_1, then reflected wave is registered (8), and stopped at the time moment t_2, then refracted wave is registered (5).

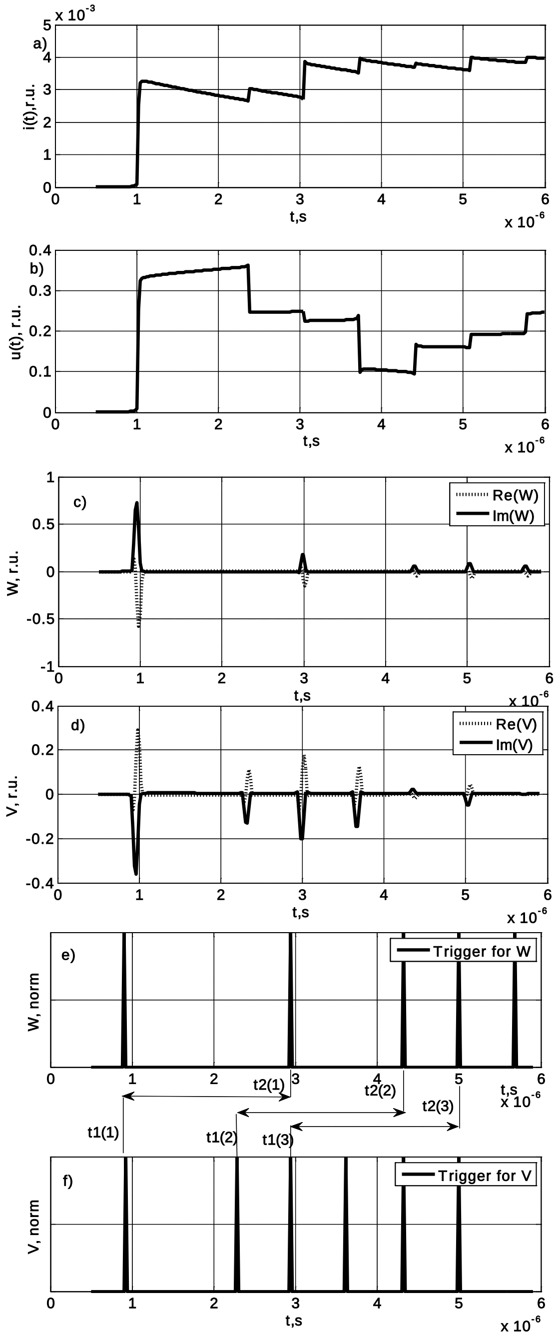

Fig. 3. Distance to fault measurement principal: a) current in the line 1 at node 2; b) voltage in the node 2; c) refracted wave real and imaginary parts; d) reflected wave real and imaginary parts; e) and f) the algorithm triggered refracted and reflected waves

The distance to the fault for each calculation step *i* could be described using expression $x_{(i)} = \left(t_{2(i)} - t_{1(i)}\right)\cdot v/2$, there v – travelling wave speed in the medium.

The calculation is performed for the network structure depicted in Fig. 2. The algorithm behaviour is depicted in Fig. 3.

Table 1. Calculation summary

No	Z_s, Ω	$x_{(1)}, m$	$\Delta_{(1)}, \%$	$x_{(2)}, m$	$\Delta_{(2)}, \%$	$x_{(3)}, m$	$\Delta_{(3)}, \%$
$l_1 = 300(m)$, $l_2 = 200(m)$, $l_3 = 300(m)$, $l_4 = 400(m)$, $Z_{L1} = Z_{L2} = Z_{L3} = Z_{L4} = 300(\Omega)$, $Z_2 = Z_3 = Z_4 = 10(\Omega)$.							
1	50	303	1.0	306	2.0	309	3.0
2	400	306	2.0	309	2.0	309	2.0
3	600	306	2.0	309	2.0	309	2.0

The ideal x_{ideal} and calculated $x_{(i)}$ distance to fault values describes algorithm performance error $\Delta_{(i)}$:

$$\Delta_{(i)} = 100 \cdot \frac{x_{ideal} - x_{(i)}}{x_{ideal}}. \qquad (14)$$

Calculation summary and algorithm error values are presented in Table 1.

Acknowledgment

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Conclusions

1. The usage of Fourier transform combining with moving window allows neglect travelling wave previous reflection due to fact that it belongs to steady state component.
2. Reflection coefficient could be used as trigger to set the time calculation.
3. Refraction coefficient regarding to investigation line always yields zero for the travelling waves propagated toward investigation line.
4. The refraction coefficient acquire non zero value for the waves propagated from investigated line.
5. The refraction coefficient could be used as trigger to stop time calculation. So the distance to the fault could be calculated as the time difference between refracted and reflected waves, multiplied by half wave speed value.
6. High accuracy approximately *(1-3)%* is reached for the measured distance equal *300* meters.

References

1. **Šiožinys V.** Investigation of Possibilities of New Relay Protection Principles Application for Electric Power Transmission Lines // The 18th International Conference „Electromagnetic Disturbances EMD‘2008“. – Vilnius Gediminas Technical University. – 2008. – Vol. 2. – P. 33–36.
2. **Markevičius L. A., Šiožinys V.** Filtering Technique for Transient Process Practical Measurement Applications // The 19th International Conference „Electromagnetic Disturbances EMD‘2009“.
3. **Markevičius L. A., Šiožinys V.** Signal Conversion from Frequency to Time Domain Peculiarities for Transient Process Identification // The 18th International Conference „Electromagnetic Disturbances EMD‘2008”. – Vilnius Gediminas Technical University. – 2008. – P. 199–202.
4. **Eissa M. M., Sowilam G. M.** A New Protection Detection Technique for High Impedance Fault Using Neural Network // IEEE Trans. – 2006. – Vol. E-06. – P. 146–151.

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V. Šiožinys. Transmission Line Fault Distance Measurement based on Time Difference between Travelling Wave Reflection and Refraction // Electronics and Electrical Engineering. – Kaunas: Technologija, 2010. – No. 2(98). – P. 25–28.

The relay protection principles based on travelling wave are observed. Transmission line fault distance measurement algorithm based on time difference between travelling wave reflection and refraction is proposed. An algorithm, its mathematical prove, modelling results and errors are presented in article. The simple scheme calculation example is presented to describe fault location algorithm behaviour. Transmission line model with 4 lines which length is from 200 to 400 meters is used to represent algorithm. The distance to fault location calculated error is in range of 1–3%. Ill. 3, bibl. 4 (in English; summaries in English, Russian and Lithuanian).

В. Шёжинис. Измерения расстояния места повреждения в передаточиых сетях на основе разницы во времени между отраженной и преломленной бегущей волны // Электроника и электротехника. – Каунас: Технология, 2010. – № 2(98). – С. 25–28.

Анализируются релейные принципы защиты на основе бегущей волны. Предлагается алгоритм измерения расстояния к месту аварии в передаточиых сетях, основанный на разницу во времени между отраженной и преломленной бегущей волны. Алгоритм, математические доказательства, представлены результаты моделирования и ошибок. Простой пример и схема приводится для описания поведения алгоритма в расчете места повреждения. Модель передаточных сетей с 4 линиями, длиной от 200 до 400 метров используется для представления алгоритма. Расчетные ошибки расстояния до места повреждения находится в диапазоне 1–3%. Ил. 3, библ. 4 (на английском языке, рефераты на английском, русском и литовском яз.).

V. Šiožinys. Gedimo vietos nustatymas perdavimo tinklo linijose, remiantis kritusios ir atsispindėjusios bangos laiko skirtumu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 2(98). – P. 25–28.

Apžvelgti relinės apsaugos principai, paremti elektromagnetinių bangų registracija. Sudarytas ir pasiūlytas perdavimo tinklo linijų gedimo vietos nustatymo algoritmas, pagrįstas laiko skirtumo tarp atsispindėjusios ir kritusios bangų skaičiavimu. Aprašomas algoritmas, matematinis pagrindimas, pateikiami modeliavimo rezultatai ir paklaidos. Pateiktas nesudėtingos schemos skaičiavimo pavyzdys, parodantis gedimo vietos nustatymo algoritmo savybes. Elektros perdavimo tinklo modelio, kurį sudaro keturios linijos nuo 200 iki 400 m, naujojo algoritmo, apskaičiuoto atstumo iki gedimo vietos, paklaida siekė 1–3%. Il. 3, bibl. 4 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).