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Transmission Line Protection and Fault Location Based on Travelling Wave Measurement

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***Abstract*—Last decade power systems have faced blackouts. Also smart grid concepts are developing to increase overall system performance. The need and the challenge is high accuracy distance to the fault measurement algorithm in transmission line protection. The article describes differential travelling wave protection also as distance to the fault measurement principles. The distance to the fault calculation deviations are investigated, also as classified as the stochastic and systematic. The systematic deviation elimination methods are described.**

***Index Terms*—Electromagnetic transient, power system protection.**

I. INTRODUCTION

The electrical systems global problem of last ten years is electric system *blackout*. Such phenomenon is described as part or all electric system switches off as the consequences of electric network equipment failures or operational staff errors.

Smart Grid ideas are involved to electric power grid to increase the operational and energy supply reliability, control flexibility of the grid, also as to increase the electric energy quality and improve relationship between electric energy producer and consumer. The concept of *Smart Grid* involves wide variety innovative technical decisions. One of the *Smart Grid* concepts task is to increase the electricity network reliability. Electric network reliability could be described as the probability of failure. The failure power network part immediate shut down increase the electric network reliability.

New generation technologies instead of existing ones should be developed and installed for the faster failures identification and clearness to prevent the electrical system from *blackouts*. The faster disconnection of monitored part of system also as faster regulating systems start-up could be initiated as the element of fault clearness conception in the transmission network.

Difficult electric power network models should be involved to investigate principally new generation fast fault identification methods. Such models should describe many phenomenon which had no necessity to be analysed in classical relay protection concept. The electromagnetic transient in network consists of faster or slower current and voltage components. Complete and distinct transient process view could be yielded only with many electrical unit components. Such task could be covered only with fast electromagnetic transient.

The need of use and complement of existing power network special models arise for the investigation of fast fault identification models and algorithms.

II. OVERVIEW OF THE METHODS OF FAST FAULT IDENTIFICATION IN TRANSMISSION NETWORK

Couple of methods are known [1]–[7] for the fast fault identification in transmission network. However, only few of them could be considered as practically applicable for the protection and fault location.

First method applicable for the protection scheme uses an idea of multiple registration of travelling wave propagated from fault [8]. 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. In practice the part of travelling wave refract, dissipate due to line losses. On other hand if the fault is nearby the busses, the reflected from bus bar wave propagate to fault.

The part of wave has reflected and the refracted part of wave propagates towards other busses. Two travelling waves propagated towards busses are registered. The second wave is refracted at the fault, so if the line length is high significant error could be encountered.

Registrations of propagated wave are performed in the both side of line for the second method, as depicted in Fig. 1. The time stamps are fixed at the travelling wave

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arrival moments.

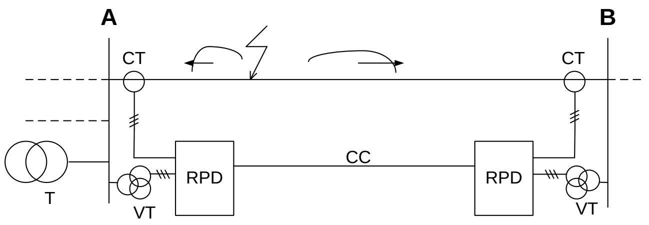

Fig. 1. The placement of devices in the network. CT – conventional current transformer; VT – voltage transformer; RPD – relay protection device; CC – communication channel.

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 [9]. The fast and separated communication channel between relay protection devices could be used for method realization.

Special requirements for the communication channel create inconvenience for the second method implementation. However, GPS synchronization of the timers of relay protection devices could be used. Timer synchronization error for the case of worst atmospheric condition is about $1\ \mu s$. So, the error distance to the fault if we assume that travelling wave propagation speed $v \sim c$: $\Delta l \approx v \cdot \Delta t \approx 2.95 \cdot 10^{8} \cdot 1 \cdot 10^{-6} \approx 295$ m. Due to travelling wave losses in the line, the propagation speed of wave is less than the speed of light. However, the precision of fault location could not be reached more than 250 m. Besides the disadvantages the method has an advantage – the general purpose communication channel between devices could be used to transfer time stamps.

III. DISTANCE TO THE FAULT PLACE CALCULATION AND ERROR EVALUATION

Network structure, connected to the end of line should be evaluated for the creation of fast fault identification models. The fault place voltage source magnitude and rise time variation could be neglected using travelling wave registration at the both line ends.

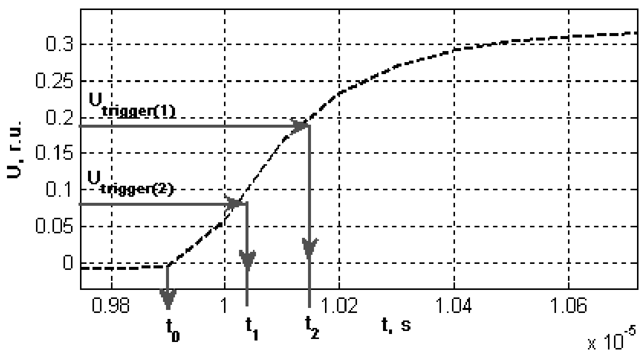

Fig. 2. The travelling wave registration magnitude influence to the distance to the fault calculation error.

Travelling wave registration moment depends on trigger level and could be described as the function $t_x = f\left(U_{\text{trigger}}\right)$. The registration deviation is described as time difference between registered and exact time moments: $\Delta_{t1}\left(U_{\text{trigger}}\right) = t_x - \frac{l}{c} = t_x - t_0$. The deviation $\Delta_{t1}\left(U_{\text{trigger}}\right)$ is not constant for all travelling wave rise time and reach's minimum value at $l = x_{\text{exact}} = t_0 \cdot c$ as depicted in Fig. 2.

Travelling waves are measured at the both line ends as it is depicted in Fig. 1. Then the exact distance to the fault could be expressed

$$x_{\text{exact}} = \frac{l - \Delta t \cdot c}{2}, \tag{1}$$

where $\Delta t = t_{0A} - t_{0B}$ – the exact time moments for each travelling wave travelled to substation A and B; $c = 295\,\text{m}/\mu\text{s}$ - speed of light; l – exact distance between substations A and B.

Exact distance to the fault is calculated using the measured travelling wave time moments t_x for each substation A and B

$$x_{\text{exact}} = \frac{l - \left(t_{xA} - \Delta_{t1A} - t_{xB} + \Delta_{t1B}\right) \cdot c}{2} = \frac{l - \Delta t \cdot c}{2} + \frac{c}{2} \cdot \Delta_t, \tag{2}$$

where t_{xA} – travelling wave arrival time at the substation A; t_{xB} – travelling wave arrival time at the substation B; Δ_{t1A} – travelling wave registration deviation at the substation A; Δ_{t1B} – travelling wave registration deviation at the substation B.

Distance to the fault in (1) is calculated for the normalized measured values:

$$\mathbf{U} = \frac{\mathbf{U}_{\text{measured}}}{\max\left(\mathbf{U}_{\text{measured}}\right)}, \tag{3}$$

$$\mathbf{I} = \frac{\mathbf{I}_{\text{measured}}}{\max\left(\mathbf{I}_{\text{measured}}\right)}. \tag{4}$$

Deviation $\Delta_t = \Delta_{t1A} - \Delta_{t1B}$ acquire the highest values during the fault in the beginning of the line and are negligible for the fault in the middle of the line $0 \le \left|\Delta_t\right| \le \Delta_t\left(U_{\text{trigger}}\right)$.

A. *Substation time delay*

Transmission line connects substation which configuration quite rare match each other. The configuration mismatch leads to different equivalent substation capacitance. The travelling wave front sharpness is reduced by substation capacitance. Different capacitance at the both substation A and B leads to different steepness of the travelling wave, as depicted in Fig. 2.

Travelling wave induced voltage front time delay at the substation could be evaluated using expression

$$\mathbf{T} = \mathbf{C}_{\text{f}} \cdot \mathbf{Z}_{\text{BE}}, \tag{5}$$

where $\mathbf{C}_\mathrm{f}$ – substation phase capacitance; $\mathbf{Z}_\mathrm{BE}$ – transmission lines, connected to the substation equivalent surge impedance.

Calculations for the 110 kV transmission lines with tower type P110-3 are made (Fig. 3). The network consists of substation with capacitance $C = 1\mathrm{nF}$ and three transmission lines with phase-phase channel surge impedance $Z_\mathrm{B} = 343\Omega$. The equivalent transmission lines phase-phase channel surge impedance $Z_\mathrm{BE} = 114\Omega$. The phase to phase voltage additional delay due to substation capacitance is depicted in Fig. 4. The time delay could be found from (5), which yields $T = 1\mathrm{nF}\cdot 114\Omega = 0{,}1143\,\mu\mathrm{s}$.

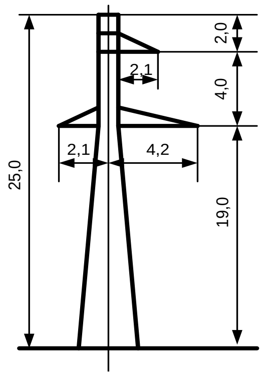

Fig. 3. Tower type P110-3, distances are shown in meters.

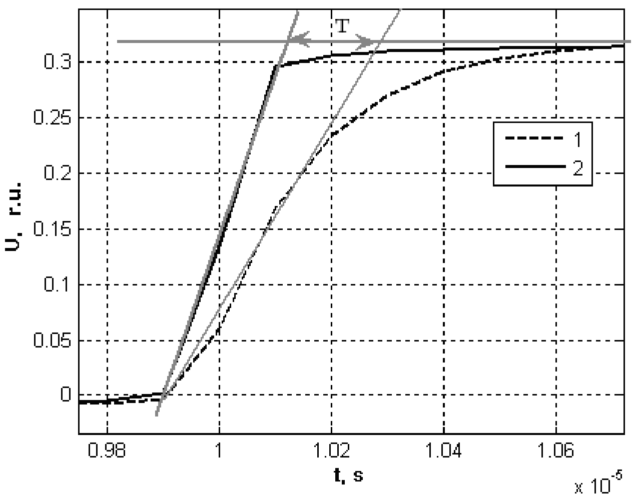

Fig. 4. The phase to phase voltage at the substation: 1 – substation capacitance evaluated and equal to $C = 1$ nF; 2 – substation capacitance not evaluated. Calculation performed for 110 kV transmission line with tower type P110-3. Line length is 3 km.

Travelling wave induced voltage front time delay mainly depend on network topology, line surge impedance and substation capacitance. The first wave induced voltage and current at substation has the relation

$$\mathbf{I}_{(\mathrm{s})} = \mathbf{T}_\mathbf{i}^{-1}\mathbf{C}_\mathrm{f}\,\mathbf{T}_\mathbf{u}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{U}_{(\mathrm{s})}, \qquad (6)$$

where $\mathbf{T}_\mathbf{i}$ and $\mathbf{T}_\mathbf{u}$ denotes current and voltage eigenvectors; $\mathbf{I}_{(\mathrm{s})}$ and $\mathbf{U}_{(\mathrm{s})}$ denotes current and voltage eigenvalues accordingly.

Deviations in (2) could be separated. The substation time delay changes the accuracy of the algorithm by component

$$\Delta_\mathrm{T} = \Delta_\mathrm{TA} - \Delta_\mathrm{TB}, \qquad (7)$$

where Δ_TA – additional travelling wave delay due to substation A capacitance; Δ_TB – additional travelling wave delay due to substation B capacitance.

Travelling waves induce voltages at the substation and currents in the lines then reach the substation. The equation below shows relation between currents, voltages and travelling wave as the voltage

$$\mathbf{U}_{(\mathrm{s})}^{+} = 0{,}5\cdot\mathbf{Z}_{\mathrm{B}(\mathrm{s})}\mathbf{I}_{(\mathrm{s})} + 0{,}5\cdot\mathbf{Z}_{\mathrm{B}(\mathrm{s})}\mathbf{Z}_{\mathrm{BE}(\mathrm{s})}^{-1}\mathbf{U}_{(\mathrm{s})}, \qquad (8)$$

where indices (s) denotes parameters as eigenvalues.

Equation (8) for the travelling wave is valid only for the first time moment then there is no reflected waves. Equation requires information about the lines connected to the substation: number of lines and their surge impedance. So, additional information should be supplied to the protection device.

Distance to the fault measurement results would comprise deviation component Δ_T in case of voltage channels are used for the fault identification. Accordingly, the deviation Δ_T could be neglected using current channel (6). However, the highest precision could be reached if the calculations are not based on currents, or on voltages, but are based on travelling wave. In this case $\Delta_\mathrm{T} = 0$.

B. Deviation due to auxiliary transformer

Auxiliary transformer due to non-ideal transient characteristics changes travelling wave rise time, some frequency components are amplified, some of them suppressed. The additional deviation to the calculated distance to the fault value is added by the auxiliary measurement transformers which influence could be evaluated as

$$\Delta_\mathrm{mg} = \Delta_\mathrm{mgA} - \Delta_\mathrm{mgB}, \qquad (9)$$

where Δ_mgA – additional travelling wave delay due to measurement transformers in substation A; Δ_mgB – additional travelling wave delay due to measurement transformers in substation B.

C. Deviation due to placement of auxiliary transformer

Current and voltage auxiliary transformers are placed far away from registration devices in the high voltage substation. The distance from auxiliary transformer to the relay protection device could seek up to 100 m or $\approx 0{,}33\,\mu\mathrm{s}$ in time domain. So the total method deviation

$$\Delta_\mathrm{p} = \begin{cases} 0, & \mathit{then}\,\Delta_\mathrm{pA} = \Delta_\mathrm{pB}, \\ \Delta_\mathrm{p2}, & \mathit{then}\,\Delta_\mathrm{pA} >> \Delta_\mathrm{pB}, \end{cases} \qquad (10)$$

where Δ_pA – additional travelling wave delay in substation A; Δ_pB – additional travelling wave delay in substation B.

Deviation due to different distance from auxiliary transformers to protection devices could be eliminated during the commissioning of the relay protection devices.

Deviation values (7), (9), (10) are fixed and could be eliminated during the commissioning. The influence mainly depend on distance to the fault: higher distance leads to lower deviation (7), (9), (10) influence to the distance to the fault measurement error.

The deviation Δ_t in (3) and (4) could be written

$$\Delta_t = |\Delta_T| + |\Delta_{mg}| + |\Delta_p|. \quad (11)$$

Deviations (7), (9), (10) could be classified as systemic, because they could be evaluated during the commissioning process. However the real line could have additional parameters deviation, such as: difference in ground resistivity along line length; the different overhead line wire height due to relief, different distance between wire, wire icing, the type of fault. The mentioned deviation could have stochastic character and the algorithm would have stochastic errors.

Differential algorithm as the protection function is absolutely selective and is very fast, because it does not require any special signal processing and calculation. The same differential principle is applied for the fault place calculation, described above.

IV. CONCLUSIONS

Differential travelling wave method is absolutely selective transmission line protection method. The method itself eliminate travelling wave rise at the fault place conditions, i.e. eliminate unknown conditions such as fault impedance during the fault.

Differential travelling wave distance to the fault calculation method deviation is influenced by systematic and stochastic errors. Special filters could be used to eliminate travelling wave substation delay also as measurement transformer shape distortion.

Distance to the fault calculation error dependability on defined trigger level was discussed. The error would be negligible for the protection function. However, it should be evaluated for the distance to the fault measurement.

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