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NEW METHOD OF DATA TRANSMISSION DELAY ESTIMATION FOR FEEDER DIFFERENTIAL PROTECTION

This paper is concerned with the problem of accurate aligning of digital data for purpose of feeder differential current protection. The method proposed makes use of knowledge of line susceptance for estimating the communication channel propagation time. The performance of the method is investigated under variable operational conditions of the 400 kV overhead transmission line. The outcomes show high efficiency of the approach allowing for essential improvement of sensitivity of a percentage differential protection.

1. INTRODUCTION

The requirement of the optimal operation of the systems is common in all fields of engineering. It relates mainly to the efficiency expressed in the real profits. Since the system is expected to give maximal profits under minimal yet necessary investments all its components tends to work in or above their nominal conditions. Such circumstances relates to contemporary power systems, as well. Limited investments resulting from different reasons cause that power systems are operated close to their stability margins.

To maintain safe state of a power system, limited but indispensable investments are required to allow for high speed fault clearing. A number of protection concepts are involved in relaying of power systems, yet the most effective are conceptions related to as unit protection. Such approach results in individual protection of sections of a power system. One of the most frequently used unit protection systems is differential current relaying. Its principle is to sense the difference between the incoming and out-

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going terminal currents of the protected section. The method is used for protection of power transformers, generators, generator-transformer units, motors, busbars and feeders.

The last enumerated element of the power system is distinctive from others by its longitudinal size. The essential difference in application of the method to feeder protection is that because of long distances between terminals the extra media for information interchange is required. Such a protective relaying is known as a digital/numerical current differential protection.

1.2. SENSITIVITY DETERIORATION FACTORS

The fundamental conditions required for maximal sensitivity of digital current differential protections are as follows:

- linear transformation of current transformers (CTs) in full range of prospective fault currents (composite error of 0%),
- no in zone leakage currents due to e.g. capacitance of the transmission line or installed compensating inductors,
- perfect transposition of the line (the symmetry of the line is unfeasible in faulty conditions),
- ideal synchronization of sampling at both terminals,
- no time delay of data transmission from the opposite relay.

The last effect is the most essential for stability of feeder differential protection. Considering ideal conditions except the last enumerated, one can assess delay in time domain or angular error for the transmission line of length *l* under assumed digital signal transmission propagation time. In practice, the velocity of transmission is in the range of 70% to 100% of the light velocity, for a strand wire and a light fiber based systems, respectively. Additionally, propagation time in electronic components should be concerned. Practically in 50 Hz power system, for a short line of 50 km length delay can reach 1.7 ms (i.e. 2) and for a long line of 500 km it is an angular lag of 40°. Now, one can compute apparent differential current for normal conditions and for external faults. Apparent differential current is a function of the through current according to fundamental formula:

$$I'_d = \sqrt{(I_S)^2 + (I_R)^2 - 2 I_S I_R \cos\varphi} \qquad (1)$$

where I_S, I_R are currents in sending and receiving terminal and φ is the angular lag. If both current are assumed to be equal $\underline{I}_S = -\underline{I}_R = \underline{I}_{SR}$, eq. (1) changes into the formula

$$I'_d = \sqrt{2} I_{SR} \sqrt{1 - \cos\varphi} \tag{2}$$

For restraint current I_r defined as mean magnitude of incoming and outgoing currents it is possible to assess minimal necessary slope of the characteristic in the percentage differential plane:

$$\frac{I'_d}{I_r} = k_{1\_\min} = \sqrt{2} \sqrt{1 - \cos\varphi} \tag{3}$$

If in addition capacitance charging current of the line, usually of 1A per kilometer for 400kV overhead lines is concerned, then the operating characteristic is biased by off-set $I_{d\_\min}$.

$$I_{d\_\min} = I_C * l \tag{4}$$

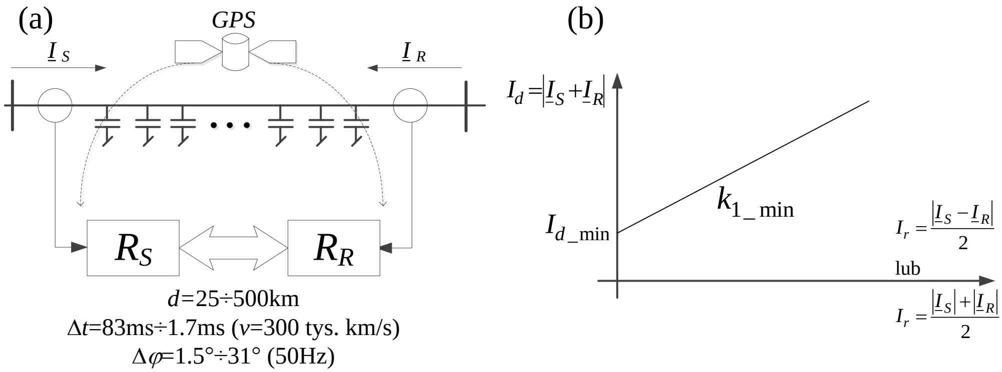

Fig. 1. Operational scheme of differential-current protection of feeder (a) and percentage differential characteristic (b).

For the worse conditions of line differential protection operation as far as uncompensated data transmission delay and capacitance charging currents are concerned the operational characteristic set according to eqs. (3) and (4) is depicted in Fig. 1(b). The differential element trips CBs when the magnitude of the differential current is greater than the sum of pre-set pick-up current $I_{d\_\min}$ and $k_{1\_\min}$ percentage of restraint current.

1.3. TRANSMISSION CHANNEL DELAY - REMEDIES

So far a few approaches to the current data aligning have been proposed. The simplest one is to assume a constant delay evaluated before commencement of protection system. Such approach despite simplicity is effective, yet only for dedicated communications channels.

When the transmission path can change due to e.g. failure of the primary transmission system configuration or multiplexed channel are used then more sophisticated methods of data alignment are required. One of the most effective solutions is "ping-pong" algorithm [1]. Transmitted data are stamped locally with time tags which allow for estimation of actual delay in both directions even in case of channel propagation time asymmetry.

The most precise method of delay compensation and sampling synchronization is based on GPS [2, 3]. However, reliance on the system independent of the protection system owner is not optimal solution.

2. CHANNEL TIME-DELAY COMPENSATION METHOD

2.1. APPARENT PHASE SHIFT ESTIMATION

The conception of the method is based on the knowledge of the total positive susceptance of the line B_1. The locally measured current is not delayed whereas the current received from the opposite terminal is lagged by φ with respect to expected remote counterpart of the local current, so that $\underline{\tilde{I}}_R = \underline{I}_R \exp(-j\varphi)$.

Resulting apparent differential current is the vectorial sum of charging current and geometrical difference between expected (remotely sampled current) and locally received one:

$$\underline{\tilde{\Delta}} = \underline{I}_S + \underline{\tilde{I}}_R = \underline{I}_{CS} + \underline{I}_{CR} \exp(-j\varphi) + \underline{I}_{LOAD} (1.0 - \exp(-j\varphi)) \tag{5}$$

where $\underline{I}_{CL(R)}$ are capacitive currents incoming into the line and $\underline{I}_{LOAD}$ is load current theoretically invisible in differential current measured by inversely connected CTs as depicted in Fig. 2.

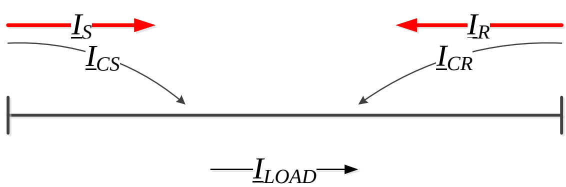

Fig. 2. Currents in analyzed line.

Let us remove from both sides of eq. (5) capacitive current estimated on the basis of locally measured phase voltage related to the geometrical center of the line:

$$\begin{aligned}\underline{\tilde{\Delta}} - j\underline{V}_{1/2L}B_1 &\approx \underline{I}_{CS} + \underline{I}_{CR}\exp(-\varphi) + \underline{I}_{LOAD}(1.0 - \exp(-j\varphi)) - \underline{I}_{CS} - \underline{I}_{CR} = \\ &= (\underline{I}_{LOAD} - \underline{I}_{CR})(1 - \exp(-j\varphi))\end{aligned} \tag{6}$$

where

$$\underline{V}_{1/2L} = \underline{V}_L - 0.5Z_1\underline{I}_S \tag{7}$$

Moreover we know that

$$\underline{\tilde{I}}_R = (\underline{I}_{CR} - \underline{I}_{LOAD})\exp(-j\varphi). \tag{8}$$

Substitution of (8) into (6) yields

$$\underline{\tilde{\Delta}} - j\underline{V}_{1/2L}B_1 = (\exp(-j\varphi) - 1)\frac{\underline{\tilde{I}}_R}{\exp(-j\varphi)} \tag{9}$$

One can estimate the lagging angle of the received current from (9) as:

$$\varphi = -angle\left(-\frac{\underline{\tilde{I}}_R}{\underline{\tilde{\Delta}} - j\underline{V}_{1/2L}B_1 - \underline{\tilde{I}}_R}\right). \tag{10}$$

Substituting $\underline{\tilde{\Delta}} = \underline{I}_S + \underline{\tilde{I}}_R$ into (10) one gets the final formula of the lagging phase of the received current resulting from the channel time delay as

$$\varphi = -angle\left(\frac{\underline{\tilde{I}}_R}{j\underline{V}_{1/2L}B_1 - \underline{I}_S}\right) = angle\left(\frac{j\underline{V}_{1/2L}B_1 - \underline{I}_S}{\underline{\tilde{I}}_R}\right) \tag{11}$$

2.2. LAGGING PHASE COMPENSATION

At least two approaches to the compensation for the lagging phase of received current phasor are possible. The correction can be carried out in an angular and time domains. The former method can be related to received phasor which should be advanced by angle resulting from eq. (11).The corrected differential current would be as follows:

$$\underline{\hat{\Delta}}_1 = \underline{I}_S + \underline{\hat{I}}_R = \underline{I}_S + \underline{\tilde{I}}_R \exp(j\varphi) \tag{12}$$

The angular correction can be related to locally measured current as well. In this case the local current phase must be delayed by angle (11) resulting in compensated differential current as follows:

$$\underline{\hat{\Delta}}_2 = \underline{\hat{I}}_S + \underline{\tilde{I}}_R = \underline{I}_S \exp(-j\varphi) + \underline{\tilde{I}}_R \,. \tag{13}$$

In the third method the compensation is made in time domain, i.e. samples of local current are saved in the FIFO register and utilized with time delay resulting from the estimated channel delay and assumed sampling frequency according to following formula:

$$\hat{\Delta}_3(n) = \hat{I}_S(n) + \tilde{I}_R(n) = I_S(n-k) + \tilde{I}_R(n) \quad \text{where} \quad k = round\left(\frac{\varphi}{2\pi}\frac{f_s}{50}\right). \tag{14}$$

The two former methods compensate for the apparent phase shift, yet they do not align samples of signal. As result, compared phasors may temporally relates to pre- and fault conditions. The impact of this effect has to be examined for concerned protective algorithm. The latter method is free of data misaligning problem, yet delay of ALARM or tripping signal issue will be inevitable.

2.3. SYSTEM MODELED

The investigations of the algorithm have been carried out on the basis of relaying signals obtained from computer simulations of the power system with double circuit 400kV overhead transmission line. The system was supplied from high (left hand side)

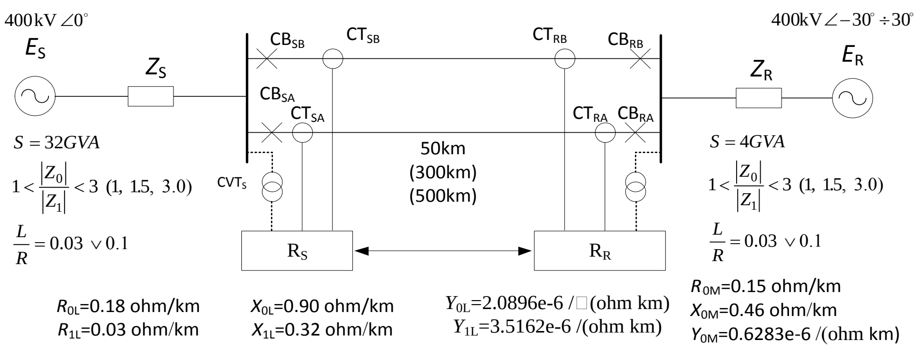

Fig. 3. The basic diagram of the test system

and low (right hand side) power capacity equivalent power systems as depicted in Fig. 3. The loads were variable and ranged from 0MW to the nominal value of the line.

Relaying signals have been synchronously sampled with 6.4 kHz rate and transmitted with apparent lagging phase shift in the ranges 2°÷12°, 30°÷40°, 40°÷50° for 50 km, 300 km and 500 km line lengths respectively. The shifts chosen for every load case remained constant, i.e. no variability of communications channel time delay was modelled.

3. THE ALGORITHM PERFORMANCE

3.1. PERFORMANCE OF THE ALGORITHM FOR CORRECT CHOICE OF B_1

First of all, the investigations covered relation of compensation errors for given line length to the restraint current resulting from the load of the line. The restraint current was computed as difference between phasors of sending and receiving (delayed) terminal phase currents. Figs. 4(a), 5(a) and 6(a) show location of the operating quantity on the percentage differential plane in pre-fault conditions for no channel delay correction. One can notice the increase of slope of the edge of restraining region as well as the increase of pick up differential current to be set in potential differential relay as the line length increases. The figures allow for estimation of theoretical maximal sensitivity of the differential algorithm. Making assumption of constant voltage along the line the simple computations for maximal loads give resistances of 385 Ω, 210 Ω, 220 Ω possible to be detected for lines of 50 km, 300 km and 500 km lengths, respectively.

Figs. 4(b), 5(b) and 6(b) depict efficiency of the proposed correction method. As can be seen the load of the line has essential impact on accuracy of compensation. In

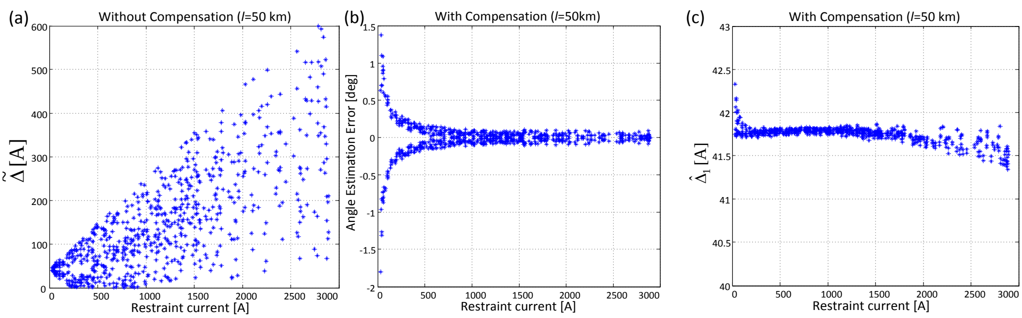

Fig. 4. Differential current in pre-fault conditions on the line of 50 km length with delay transmission angle from the range of 2°÷12° before (a) and after compensation (c). Errors of delay angle estimation (b).

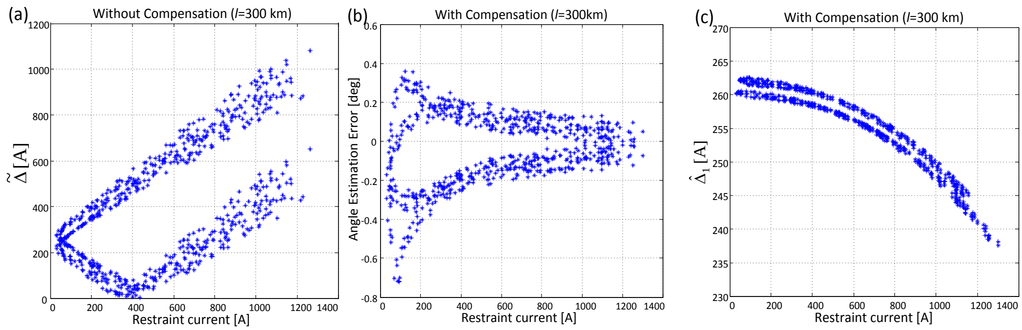

Fig. 5. Differential current seen in pre-fault conditions on the line of 300 km length with delay transmission angle from the range of 30°÷40° before (a) and after compensation (c).
Errors of delay angle estimation versus the load (b).

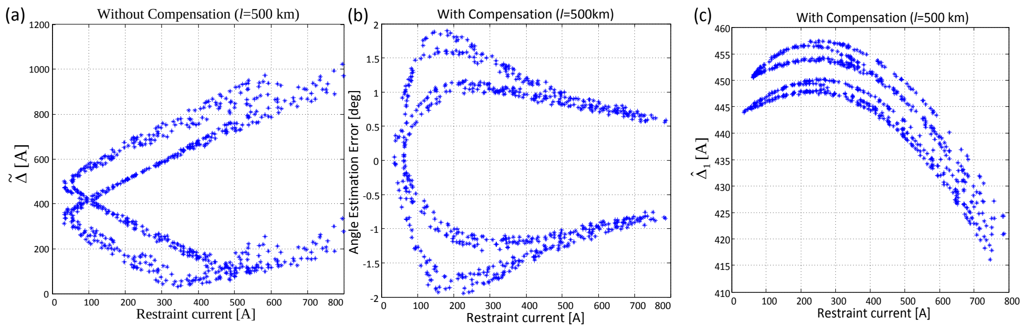

Fig. 6. Differential current seen in pre-fault conditions on the line of 500 km length with delay transmission angle from the range of 40°÷50° before (a) and after compensation (c).
Errors of delay angle estimation versus the load (b).

fact the effect is not cause by the load as such, yet relatively high CT errors for currents much less than the nominal current and an inaccuracy of the mean line voltage computation with use of eq. (7). However, the absolute errors of compensation are less than 2°. It gives maximal relative errors of 16% (50 km) , 2% (300 km) and 4% (500 km). One can notice that accuracy improvement appears with increasing restraint current (increasing load) what is very valuable feature of the method. Therefore, the magnitude of the vectorial sum of the line charging current and apparent differential current after compensation is almost constant and takes values of 43 A, 260 A, 460 A for line lengths of 50 km, 300 km, 500 km, respectively. These in turn results in improved sensitivity for faults via resistances of up to 5 kΩ, 890 Ω and 500 Ω.

Figs. 4(c), 5(c), 6(c) show the differential current seen in pre fault conditions after compensation of the transmission delay. It is readily noted that apparent differential current decreases with the increase of the load current.

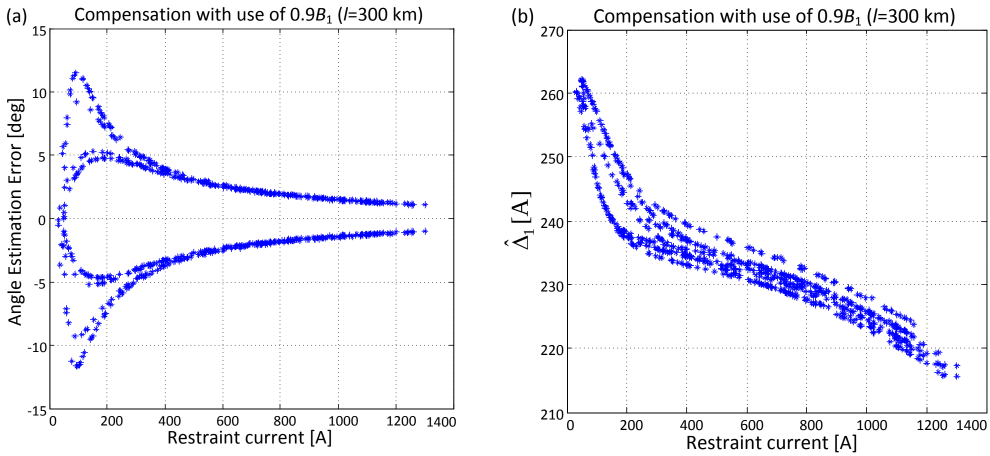

Fig. 7. Delay angle estimation errors versus the load (a) and differential current in pre-fault conditions (b) on the line of 300 km length with delay transmission angle from the range of 30°÷40° for 0.9B_1 used in computations

3.2. PERFORMANCE OF THE ALGORITHM FOR INCORRECT CHOICE OF B_1

As line parameters can be known imprecisely the question arises as to method robustness to some discrepancy between the actual line positive sequence susceptance and value of B_1 used in the algorithm. Therefore, additional investigations have been carried out for under- and overestimated susceptance of 300 km length line.

Fig. 7 depicts outcomes for susceptance underestimated by 10% with respect to the actual value. It is well visible that despite essentially worsened angle estimation the differential current is still below 270 A and decreases for higher through currents. For overestimated susceptance used in the algorithm the maximum of differential current in pre-fault conditions is below 290 A (Fig. 8).

4. CHANGE OF PATH DELAY OR FAULT IN THE SYSTEM

The estimated angle shift is to be saved and used for correction of the incoming remote phase current phasors. However, the question arises as to the necessary action to be undertaken after actuation of the relay. The reason for such a case may be either actual internal fault or essential change of the path delay. The proposal of flow chart for action to be undertaken after relay actuation is shown in Fig. 9.

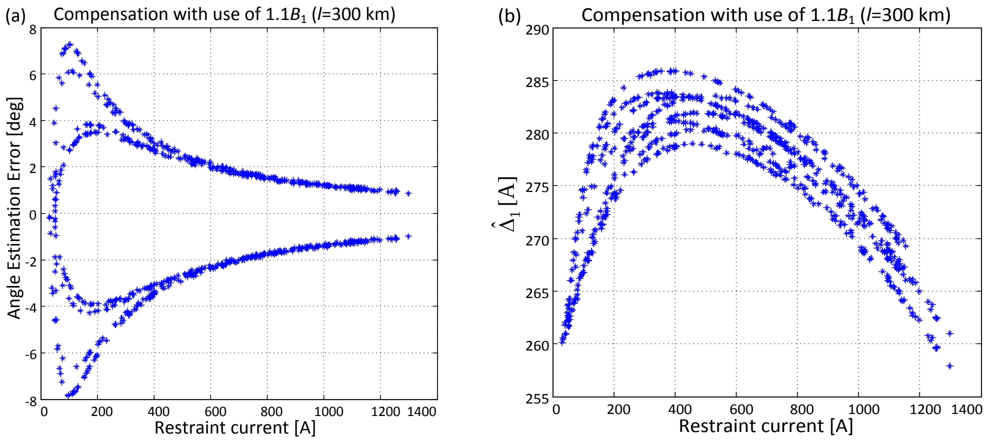

Fig. 8. Delay angle estimation errors versus the load (a) and differential current in pre-fault conditions (b) on the line of 300 km length with delay transmission angle from the range of 30°÷40° for $1.1B_1$ used in computations

4.1. REAL CHANGE OF PATH DELAY

It is assumed that the saved estimate will be updated cyclically. In case of relatively slow and slight changes of the path delay the differential element should not become actuated. However, in case of essential change of actual delay the differential relay will be probably actuated. In such scenario tripping may be restrained by verification of magnitudes of currents from both line terminals. The negligible change of magnitudes should indicate the failure to operate. In aforementioned cases the corrective angle should be updated.

4.2. FAULTS

In case of external fault and valid pre-estimate of corrective angle the differential element will not be actuated. In case of internal fault the relay is expected to be actuated and the short circuit in the line will be additionally confirmed by essential change of current magnitudes at both terminals.

4.3. SIMULTANEOUS PATH DELAY CHANGE AND FAULT CONDITIONS

Simultaneous internal or external fault conditions and change of the path delay is unlikely scenario. However, for such situations there is no solution and it probably

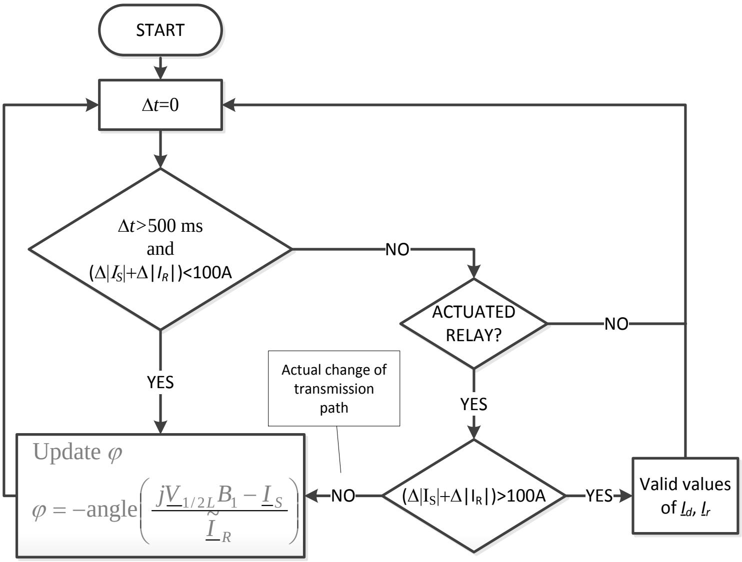

Fig. 9. The flowchart of the corrective angle updating algorithm

will result in issue of ALARM. The less discrepancy between the corrective angle estimates for all free phases may be the additional criterion for the acceptance of up-dating.

5. CONCLUSIONS

The presented algorithm allows for essential increase of feeder differential protection sensitivity. It has been shown that compensation of communications channel time delay under no charging line current compensation provides detection of faults via resistances up to 5 kΩ, 890 Ω and 500 Ω on lines of 50 km, 300 km, 500 km lengths, respectively. Moreover, 10% error in setting of line susceptance results in 30% error of communications path time delay estimation. However, actual performance of the compensating algorithm should be tested with the prospective protection algorithm, i.e. percentage differential algorithm, α-plane method etc.

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NOWA METODA KOMPENSACJI EFEKTU OPÓŹNIENIA TRANSMISJI DANYCH DLA POTRZEB PRĄDOWO-RÓŻNICOWYCH ZABEZPIECZEŃ LINII PRZESYŁOWYCH

W artykule zaprezentowano nowa metodę synchronizacji danych przesyłanych kanałem teleinformatycznym dla potrzeb przekaźników różnicowoprądowych napowietrznych linii elektroenergetycznych. Szacowanie opóźnienia przesyłu danych dokonywane jest na podstawie znajomości susceptancji linii oraz lokalnego pomiaru napięcia, lokalnego prądu fazowego i przesłanego prądu z przeciwległego końca linii w warunkach przedzwarciowych. Dokładność metody została sprawdzona dla różnych stanów pracy dwutorowej napowietrznej linii 400 kV. Wyniki badań potwierdzają dużą dokładność szacowania i tym samym korekcji kątowej między prądami z obu końców linii. Opracowana metoda kompensacji pozwala na zasadniczą poprawę czułości zabezpieczenia różnicowego linii przesyłowych.