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ANALYTICAL SYNCHRONIZATION OF TWO-END MEASUREMENTS FOR TRANSMISSION LINE PARAMETERS ESTIMATION AND FAULT LOCATION

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Abstract: *This paper presents a new setting-free approach to synchronization of two-end current and voltage unsynchronized measurements. Authors propose new non-iterative algorithm processing three-phase currents and voltages measured under normal steady state load condition of overhead line. Using such synchronization the line parameters can be estimated and then precise fault location can be performed. The presented algorithm has been tested with ATP-EMTP software by generating great number of simulations with various sets of line parameters proving its usefulness for overhead lines up to 200km length.*

Keywords: *Power transmission line, two-end measurements, analytical synchronization, line parameters, estimation.*

1. Introduction

Free marketing and deregulation observed all over the world have imposed an increased demand on the high quality of power-system protection and control devices together with their supplementary equipments. Among different capabilities of these devices, the fault location on power lines for an inspection-repair purpose became a very important function. Fault location is a process aimed at locating the occurred fault with the highest possible accuracy. This allows to send a repair crew to the right place for repairing the damage caused by a fault. Then, the line can be quickly returned to the service [1].

Latest technological achievements in the field of communication create new possibilities for fault location exhibiting better accuracy. Fault location algorithm utilizing two-end measurements has been proposed in [2] and such approach needs proper synchronization so both measurement sets have common time reference. Use of GPS (Global Positioning System) is one solution to assure this. Such fault location principle is shown in Figure 1a. Three-phase voltage $\{v_S\}=\{v_{SA}, v_{SB}, v_{SC}\}$ and current $\{i_S\}=\{i_{SA}, i_{SB}, i_{SC}\}$ from the sending end S, three-phase voltage $\{v_R\}=\{v_{RA}, v_{RB}, v_{RC}\}$ and current $\{i_R\}=\{i_{RA}, i_{RB}, i_{RC}\}$ from the receiving end R supply the measuring units MU_S, MU_R. The A-D converters of these units are controlled by the satellite system: Global Positioning System (GPS). The GPS maintains the so-called coordinated universal time with an accuracy of $\pm 0.5\mu s$. This allows simple and accurate determination of a distance to fault: d [p.u.]. Also some fault location algorithms calculate an involved fault resistance R_F.

However, in cases where GPS signal is unavailable (Figure 1b) it is possible to perform synchronization of two-end measurements using analytical methods such as the ones proposed in [3–5].

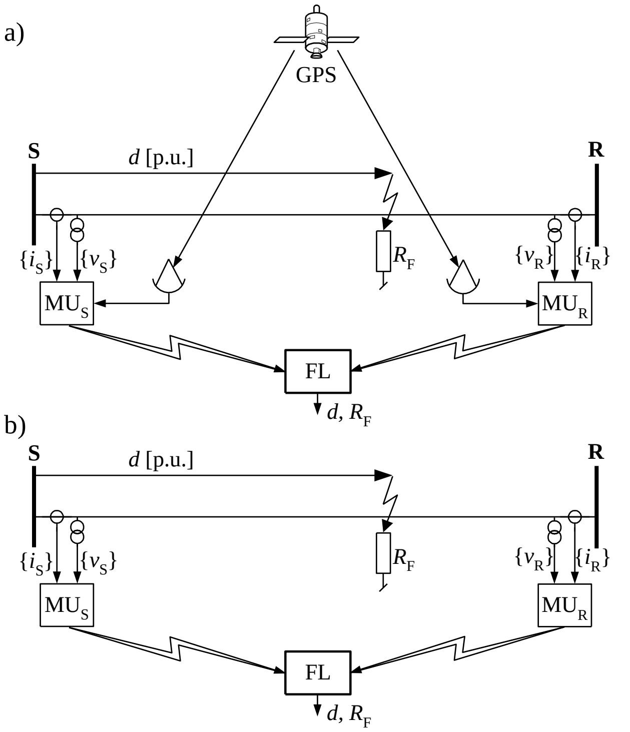

Figure 1. Schematic diagram for two-end fault location with: a) synchronized measurements by using GPS, b) unsynchronized measurements

The cited algorithms [3–5] require knowledge of line parameters. Global tendency in development of new approaches to fault location is to create an approach which is as much setting-free as possible. The algorithm

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proposed in [6] offers fault location procedure without need of knowledge of line parameters, assuming synchronization problem is solved. Obvious next step is to develop a fault location algorithm without requirement of synchronization and line parameters setting. Short lines unsymmetrical faults have been covered by the method presented in [7]. More complex numerical algorithms are presented in [8–11] covering both synchronization angle and fault location determination together.

This paper presents a new smart method for synchronization of two-end measurements based on processing pre-fault current and voltage measurements. It can also be used in other application such as wide area monitoring, protection and control system [12], in cases where use of GPS technology appears to be too expensive, yet use of synchronized two-ends measurement would be beneficial. Its simplicity allows online setting-free synchronization. Moreover, there are many algorithms proposed for line parameter estimation [13–19] which assume precise synchronization of voltage and current phasors covering many different overhead line configurations. Therefore this article can be treated as expansion of the methods cited in this section.

2. Analytical Synchronization and Line Parameters Estimation

The presented algorithm utilizes current and voltage signals from both ends of the line during normal steady state operation. Use of pre-fault positive-sequence currents and voltages (Figure 2 – superscript 'pre') is considered for making the synchronization. For this purpose the measurements from the bus R are assumed as the basis, while all phasors of the current and voltage signals from the end S are multiplied by the synchronization operator: exp(jδ), where δ is the synchronization angle to be determined, without knowing the line parameters.

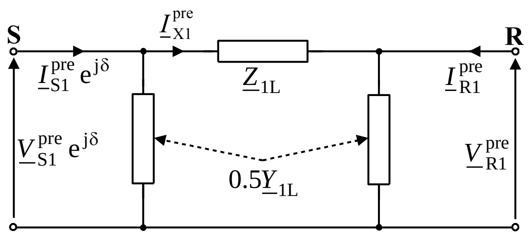

Figure 2. Equivalent circuit diagram of transposed overhead line for pre-fault positive-sequence

All calculations are based on processing the positive-sequence components, thus a transposed line is assumed. An example of calculation of positive-sequence component for the S-bus currents and voltages are performed as follows:

$$\underline{I}_{S1}^{pre} = \tfrac{1}{3}(\underline{I}_{SA}^{pre} + \underline{a}\underline{I}_{SB}^{pre} + \underline{a}^2\underline{I}_{SC}^{pre}) \tag{1}$$

$$\underline{V}_{S1}^{pre} = \tfrac{1}{3}(\underline{V}_{SA}^{pre} + \underline{a}\underline{V}_{SB}^{pre} + \underline{a}^2\underline{V}_{SC}^{pre}) \tag{2}$$

where:

$\underline{a} = \exp(\mathrm{j}2\pi/3)$,

$\underline{I}_{SA}^{pre}$, $\underline{I}_{SB}^{pre}$, $\underline{I}_{SC}^{pre}$ – phasors of currents measured at the S-bus in phases A, B, C,

$\underline{V}_{SA}^{pre}$, $\underline{V}_{SB}^{pre}$, $\underline{V}_{SC}^{pre}$ – phasors of voltages measured at the S-bus in phases A, B, C,

$\underline{V}_{S1}^{pre}$, $\underline{I}_{S1}^{pre}$ – pre-fault positive-sequence component of voltage and current at the S-bus.

According to the equivalent circuit diagram of overhead line during normal steady state condition (Figure 2) one can calculate the auxiliary current $\underline{I}_{X1}^{pre}$ in two ways:

$$\underline{I}_{X1}^{pre} = \underline{I}_{S1}^{pre}e^{j\delta} - \frac{\underline{Y}_{1L}}{2}\underline{V}_{S1}^{pre}e^{j\delta} \tag{3}$$

$$\underline{I}_{X1}^{pre} = -\underline{I}_{R1}^{pre} + \frac{\underline{Y}_{1L}}{2}\underline{V}_{R1}^{pre} \tag{4}$$

Combining (3) and (4) allows to calculate the line admittance $\underline{Y}_{1L}$ similarly as in [15] and [17], but additionally with including the synchronization operator:

$$\frac{\underline{Y}_{1L}}{2} = \frac{\underline{I}_{S1}^{pre}e^{j\delta} + \underline{I}_{R1}^{pre}}{\underline{V}_{S1}^{pre}e^{j\delta} + \underline{V}_{R1}^{pre}} \tag{5}$$

Equation (4) can be transformed to:

$$\left|\underline{V}_{S1}^{pre}e^{j\delta} + \underline{V}_{R1}^{pre}\right|^2 \frac{\underline{Y}_{1L}}{2} = (\underline{I}_{S1}^{pre}e^{j\delta} + \underline{I}_{R1}^{pre})(\underline{V}_{S1}^{pre}e^{j\delta} + \underline{V}_{R1}^{pre})^* \tag{6}$$

where $\underline{X}^*$ is the complex conjugate of $\underline{X}$.

The basis of the introduced method relies on considering that the line admittance is of capacitive nature, i.e. with negligible real part:

$$\mathrm{Re}\{\underline{Y}_{1L}\} = 0 \tag{7}$$

Usage of (7) for (6) leads to obtaining the formula for the synchronization angle, which is independent of the line parameters, as follows:

$$\mathrm{Re}\{(\underline{I}_{S1}^{pre}e^{j\delta} + \underline{I}_{R1}^{pre})(\underline{V}_{S1}^{pre}e^{j\delta} + \underline{V}_{R1}^{pre})^*\} = 0 \tag{8}$$

To solve (8) for the synchronization angle one needs to use the Euler's formula:

$$e^{j\delta} = \cos(\delta) + \mathrm{j}\sin(\delta) \tag{9}$$

Currents and voltages phasors in (8) can be split into real and imaginary parts. With consideration of (9), the (8) can be expressed as:

$$A_1\sin(\delta) + A_2\cos(\delta) + A_3 = 0 \tag{10}$$

where:

$$A_1 = \mathrm{Re}\{\underline{I}_{S1}^{pre}\}\mathrm{Im}\{\underline{V}_{R1}^{pre}\} - \mathrm{Im}\{\underline{I}_{S1}^{pre}\}\mathrm{Re}\{\underline{V}_{R1}^{pre}\}$$
$$- \mathrm{Re}\{\underline{I}_{R1}^{pre}\}\mathrm{Im}\{\underline{V}_{S1}^{pre}\} + \mathrm{Im}\{\underline{I}_{R1}^{pre}\}\mathrm{Re}\{\underline{V}_{S1}^{pre}\}$$
$$A_2 = \mathrm{Re}\{\underline{I}_{S1}^{pre}\}\mathrm{Re}\{\underline{V}_{R1}^{pre}\} + \mathrm{Im}\{\underline{I}_{S1}^{pre}\}\mathrm{Im}\{\underline{V}_{R1}^{pre}\}$$
$$+ \mathrm{Re}\{\underline{I}_{R1}^{pre}\}\mathrm{Re}\{\underline{V}_{S1}^{pre}\} + \mathrm{Im}\{\underline{I}_{R1}^{pre}\}\mathrm{Im}\{\underline{V}_{S1}^{pre}\}$$
$$A_3 = \mathrm{Re}\{\underline{I}_{S1}^{pre}\}\mathrm{Re}\{\underline{V}_{S1}^{pre}\} + \mathrm{Im}\{\underline{I}_{S1}^{pre}\}\mathrm{Im}\{\underline{V}_{S1}^{pre}\}$$
$$+ \mathrm{Re}\{\underline{I}_{R1}^{pre}\}\mathrm{Re}\{\underline{V}_{R1}^{pre}\} + \mathrm{Im}\{\underline{I}_{R1}^{pre}\}\mathrm{Im}\{\underline{V}_{R1}^{pre}\}$$

By proper manipulations on trigonometric functions one may express (10) as a quadratic equation:

$$B_2 \tan^2(\delta/2) + B_1 \tan(\delta/2) + B_0 = 0 \qquad (11)$$

where:
$B_0=A_3+A_2$, $B_1=2A_1$, $B_2=A_3-A_2$.

Solving (10) yields two possible solutions for $\tan(\delta/2)$ and thus two solutions for the unknown synchronization angle δ. To select a proper one, the following criteria can be applied:

$$\text{if } \left|\frac{\underline{I}_{S1}^{pre} e^{j\delta_{(1)}} + \underline{I}_{R1}^{pre}}{\underline{V}_{S1}^{pre} e^{j\delta_{(1)}} + \underline{V}_{R1}^{pre}}\right| \le \left|\frac{\underline{I}_{S1}^{pre} e^{j\delta_{(2)}} + \underline{I}_{R1}^{pre}}{\underline{V}_{S1}^{pre} e^{j\delta_{(2)}} + \underline{V}_{R1}^{pre}}\right| \rightarrow \delta = \delta_{(1)}$$
$$\text{if } \left|\frac{\underline{I}_{S1}^{pre} e^{j\delta_{(1)}} + \underline{I}_{R1}^{pre}}{\underline{V}_{S1}^{pre} e^{j\delta_{(1)}} + \underline{V}_{R1}^{pre}}\right| > \left|\frac{\underline{I}_{S1}^{pre} e^{j\delta_{(2)}} + \underline{I}_{R1}^{pre}}{\underline{V}_{S1}^{pre} e^{j\delta_{(2)}} + \underline{V}_{R1}^{pre}}\right| \rightarrow \delta = \delta_{(2)} \qquad (12)$$

where: $\delta_{(1)}$, $\delta_{(2)}$ are the solutions obtained from (11).

An alternative way for determining the synchronization angle can be obtained by comparing (2) and (3), which gives the formula for the unknown synchronization operator:

$$e^{j\delta} = \frac{-\underline{I}_{R1}^{pre} + 0.5\underline{Y}_{1L}\underline{V}_{R1}^{pre}}{\underline{I}_{S1}^{pre} - 0.5\underline{Y}_{1L}\underline{V}_{S1}^{pre}} \qquad (13)$$

The synchronization operator is a complex number with the unit magnitude:

$$\mathrm{abs}(e^{j\delta}) = 1 \qquad (14)$$

The property (14) allows to formulate the following quadratic equation:

$$\left(\left(\mathrm{abs}(\underline{V}_{S1}^{pre})\right)^2 - \left(\mathrm{abs}(\underline{V}_{R1}^{pre})\right)^2\right)\cdot x^2$$
$$+ 2\left(\mathrm{imag}(\underline{V}_{S1}^{pre}\cdot(\underline{I}_{S1}^{pre})^*) - \mathrm{imag}(\underline{V}_{R1}^{pre}\cdot(\underline{I}_{R1}^{pre})^*\right)\cdot x \qquad (15)$$
$$+ \left(\left(\mathrm{abs}(\underline{I}_{S1}^{pre})\right)^2 - \left(\mathrm{abs}(\underline{I}_{R1}^{pre})\right)^2\right) = 0$$

where:
$x = 0.5\omega_1 C_{1L}$ – half of a total line admittance for the fundamental frequency,
ω_1 – fundamental radial frequency,
C_{1L} – total line shunt capacitance for the positive-sequence.

Solving of the quadratic equation (15) yields two results for the line admittance and thus two results for the sought synchronization angle – according to (13). Selection of the valid result appears as not difficult since it has been checked that only one result is of practical case, i.e. consistent with the real conditions.

Summarizing, the unknown synchronization angle (or the synchronization operator) can be determined in two ways:

- by solving the quadratic trigonometric formula (11) and using the selection (12),
- according to (13) with prior determination of the line shunt admittance (15).

The first way of the synchronization (according to equations (11)–(12)) was taken for further considerations presented in Section 3.

Synchronizing two-end measurements with use of the synchronization angle determined and selected according to (10)–(11) the shunt admittance of a line can be calculated from (3) as follows:

$$\underline{Y}_{1L} = \frac{2(\underline{I}_{S1}^{pre} e^{j\delta} + \underline{I}_{R1}^{pre})}{\underline{V}_{S1}^{pre} e^{j\delta} + \underline{V}_{R1}^{pre}} \qquad (16)$$

To calculate the line impedance for the positive-sequence one may write for the equivalent circuit diagram of overhead line (Figure 2):

$$\underline{V}_{S1}^{pre} e^{j\delta} - \underline{V}_{R1}^{pre} = \underline{Z}_{1L}\underline{I}_{X1}^{pre} \qquad (17)$$

Substitution of (2) and (16) into (15), with proper rearrangements yields:

$$\underline{Z}_{1L} = \frac{(\underline{V}_{S1}^{pre})^2 e^{j\delta} - (\underline{V}_{R1}^{pre})^2 e^{-j\delta}}{\underline{I}_{S1}^{pre}\underline{V}_{R1}^{pre} - \underline{I}_{R1}^{pre}\underline{V}_{S1}^{pre}} \qquad (18)$$

Performing analytical synchronization ((11)–(12)) and then determining the line parameters ((16) and (18)) opens a possibility for precise two-end synchronized fault location, as presented in [1].

3. ATP-EMTP Evaluation of the Algorithms

To test the presented method a distributed parameter model of overhead line (Clarke model) has been utilized. This assures all wave phenomena relevant for long overhead lines are taken into account. To evaluate errors of the developed method itself, ideal current and voltage transformers have been modeled. Since the applied ATP-EMTP software [20] returns perfectly synchronized signals, currents and voltages from the S-bus have been de-synchronized by a specific angle for testing purposes.

Results of the performed tests follow. Line impedance/admittance parameters used in overhead 200km line model are presented in Table 1. Tables 2–6 show results how the synchronization angle calculation results are dependent on de-synchronization angle, as well as line resistance, reactance, capacitance and line length, respectively.

Table 1. Line parameters used in ATP-EMTP simulations

Positive-sequence Resistance	0.0276Ω/km
Positive-sequence Reactance	0.3151Ω/km
Positive-sequence Capacitance	13nF/km
Line Length	200km
Rated Voltage	400kV

Table 2. Line of the parameters from Table 1 – determined synchronization angle (δ) and error for different values of de-synchronization angle

De-synchronization angle	δ	Error
[°]	[°]	[°]
–120	–120.066	0.066
–60	–60.066	0.066
0	–0.066	0.066
60	59.934	0.066
120	119.934	0.066
180	179.934	0.066

The results from Table 2 indicate that the de-synchronization degree does not influence accuracy of determining the synchronization angle. For the considered test line (Table 1) this error is constant and very low (0.066^{o}).

Influence of change of resistance, reactance, capacitance and length of the line on accuracy of determining the synchronization angle is shown in Tables 3–6. A given line parameter was altered around its value from Table 1.

Alteration of line resistance, reactance and capacitance (Tables 3–5) within quite wide range does not deteriorate substantially the accuracy. Accurate analytical synchronization is still possible, i.e. the maximum angle error is around 0.3^{o}.

Table 3. Line of the parameters from Table 1 but with change of the line resistance – determined synchronization angle (δ) and error for different values of positive-sequence line resistance

Positive-Sequence Resistance	δ	Error
[Ω/km]	[°]	[°]
0.01	19.952	0.048
0.02	19.940	0.060
0.0276	19.934	0.066
0.05	19.923	0.077
0.10	19.911	0.089
0.20	19.896	0.104
0.50	19.833	0.167

Table 4. Line of the parameters from Table 1 but with change of the line reactance – determined synchronization angle (δ) and error for different values of positive-sequence line reactance

Positive-Sequence Reactance	δ	Error
[Ω/km]	[°]	[°]
0.10	19.972	0.027
0.20	19.956	0.043
0.3151	19.934	0.066
0.50	19.887	0.112
1.00	19.707	0.292

Table 5. Line of the parameters from Table 1 but with change of the line capacitance – determined synchronization angle (δ) and error for different values of positive-sequence shunt capacitance

Positive-Sequence Shunt Capacitance	δ	Error
[nF/km]	[°]	[°]
5	19.987	0.013
10	19.958	0.042
13	19.934	0.066
20	19.855	0.145
30	19.692	0.308

Table 6. Line of the parameters from Table 1 but with change of the line length – determined synchronization angle (δ) and error for different line length

Line Length	δ	Error
[km]	[°]	[°]
20	19.999	0.001
40	19.998	0.002
60	19.997	0.003
80	19.994	0.006
100	19.990	0.010
150	19.972	0.028
200	19.934	0.066
250	19.865	0.135
300	19.751	0.249

Taking the considered test line of the parameters defined in Table 1 and making it shorter: (20–150)km and also longer: 250 and 300km, respectively, it was obtained that accuracy of the synchronization for such lines is also very good (Table 6). In particular, for lines up to 100km the achieved synchronization accuracy (maximum error: 0.010^{o}) is comparable with the accuracy of the GPS satellite system. For a 300km line the error does not exceed 0.25^{o}, which corresponds to (1/72) of the sampling period under the typical sampling frequency of 1000Hz, thus the angle error is a small fraction of the sampling interval.

Table 7 presents the test results for typical tower configurations of overhead lines in Poland.

Table 7. Overhead 200km lines of typical tower geometries – determined synchronization angle (δ) and error

Tower Type	R_1 [Ω/km]	X_1 [Ω/km]	C_1 [nF/km]	δ [°]	Error [°]
B2	0.12	0.41	8.83	19.943	0.057
O24	0.12	0.40	8.96	19.943	0.057
H52	0.06	0.42	8.70	19.948	0.052
M52	0.06	0.39	9.40	19.945	0.055
Y52	0.03	0.32	11.00	19.949	0.051
Z52	0.03	0.32	11.19	19.947	0.053

4. Conclusions

To the best of the author's knowledge, there are no non-iterative solutions in the literature, which offer analytical synchronization of measurements acquired at different line ends asynchronously, without utilizing line parameters. Innovative contribution of this paper relies on showing that the set of calculations:

- analytical synchronization,
- line parameters estimation,
- fault location,

can be split into three separate steps to be performed in simple non-iterative calculations. First two parts which are based on processing the pre-fault measurements are addressed in this paper. Non-iterative nature of these calculations are suitable for simple implementation in modern digital line protection terminals.

The developed synchronization algorithm has been thoroughly tested with ATP-EMTP software. The results obtained for the considered test line and also for the 200km lines of typical tower geometries with assuming a line transposition prove high accuracy of the presented algorithm. It was achieved that the achieved accuracy of the analytical synchronization is comparable with the GPS synchronization. This error can be even reduced by introducing its compensation with use of the distributed parameter line model.

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