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# STATE ESTIMATION METHOD DEVELOPMENT FOR SCADA AND SYNCHRONIZED PHASOR MEASUREMENTS INTEGRATION WITHIN POWER SYSTEM

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***Abstract:*** *In modern power systems, a special kind of measurement systems was actively implemented for the last 20 years. These measurement systems have a high-precision synchronized time stamp, which makes it possible to obtain, in addition to the effective value of line current and bus voltage, the electrical phase angles. In previous years, a large number of methods for steady state obtaining based on telemetry (state estimation) have been formed. These measurements are based on consideration of only modules of these quantities, as well as active and reactive components of injection power of nodes and flows in the branches. Most of these methods were based on the weighted least squares method, or other methods based on the maximum likelihood method, for which one requires determination of weighting factors of measurements, traditionally chosen on the basis of relative errors of these measurements. However, there is a problem of taking into account the electrical angles measurements, for which the relative error is fundamentally indeterminable. Also there is a problem associated with integration of phasor measurements with traditional measurement tools into a single measuring system due to a significant differences in accuracy and update frequency. This paper proposes an approach for combining phasor measurements with traditional SCADA measurements as a part of state estimation procedure, taking into account the described problems.*

***Keywords***: *static state estimation, synchronized phasor measurements, maximum likelihood method, choice of weighting factors, linear state estimation.*

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## Introduction

Classical methods of state estimation (SE) are based on measurements of effective currents and voltages of nodes, measurements of active and reactive components of capacities of nodes and branches. Due to the nonlinearity of relationship between current, voltage, and power, the SE task turns out to be nonlinear, which introduces considerable difficulties in its practical implementation. The methods for solving this problem turn out to be iterative, non-robust, insufficiently reliable, and potentially long to calculate. As a conclusion, the issues of transition from iterative to direct solution of ES problem became relevant. The main way of such a transition is to get rid of power measurements. The development and implementation of synchronized phasor measurement (SPM) tools allowed one to use only measurements of complex currents and voltages in SE tasks, which ensured the emergence of integrated linear state estimation (LES) methods [1–3].

The most popular SE methods use weighting factors measurement, which are selected based on the measurement instrument errors. All measurements included in the classic SE have data on relative error. However, for measurements of phase angles of currents and voltages which appeared in the SPM system, it is impossible to record the relative error due to their nature. This issue is particularly relevant for the problem of the specified complex linear SE. Consequently, the important issue is combined usage of phase angles measurements and other classical methods.

There are power systems [1–3] in which complete observability is provided entirely by SPM. In such networks, the idea of using the complex currents and voltages received from measuring devices for LSE solving is implemented. For the Russian energy systems, which are characterized by branching and large length, at present there is no possibility to implement the LSE idea, due to the lack of sufficient number of PMU devices to ensure observability. Moreover, the very possibility of LSE is not yet justified.

Currently, SPM are not ubiquitous, due to their high prices in the past, as well as inertia of transition to new technologies. Accordingly, it is necessary to consider issues of smooth transition to the joint use of SPM and SCADA, which requires development of hybrid SE methods. The present work is devoted to these questions. In addition, this article discusses the issues on SE development so that when a local network segment observed by PMU appears, it becomes possible to use LSE the most effectively.

**Maximum likelihood method in SE task**

Despite recent publications on non-quadratic methods [4], and evolution of computational procedures [5], the weighted least squares method is the most used method in practice for SE. It consists in minimizing the weighted sum of squares of deviations of estimated related quantities from measurements, which can be written in the form [6–7]:

$$\Phi_2(X) = \sum_{i=1}^{M} \alpha_i \cdot (y_i(X) - y_i^{\text{ТИ}})^2 \to \min \\ \{h_j(X) = 0, \quad j = 1...K, \tag{1}$$

where $X$ is vector of basic state parameters, of dimension $N$, through which all other parameters can be expressed, $M$ is the number of measurements used in SE task, $y_i^{\text{TM}}$ is telemetry parameter, $y_i(X)$ is analytical expression of the parameter being measured through independent variables $\boldsymbol{X}$, $\alpha_i$ is weighting factor, $\{h_j(x) = 0, \quad j = 1...K$ is limitations showing information that is known to be accurate. Observability requires measurement redundancy, or $M > N$, when the system is nondegenerate $\{y_i(X) = y_i^{\text{ТИ}}, \quad i = 1...M$. As applied to the power system, $X$, most often, refers to the vector of modules and phase angles of voltages; $y_i^{\text{TM}}$ refers to measurements of nodal and linear values of current modules, active and reactive power components, nodal voltage modules; $y_i(X)$ is analytical expression of the parameter being measured only through modules and phases of voltages, $\{h_j(x) = 0, \quad j = 1...K$ is substation limitations with zero power takeoff, limitations on power factors.

The effectiveness of SE procedure directly depends on the choice of coefficients $\alpha_i$. Each time the coefficients $\alpha_i$ are selected on the basis of operating experience (empirically), by an expert, based on recommendations for their choice (heuristically) [1, 8]. Nowadays, these recommendations suggest setting $\alpha_i$ values inversely proportional to the square of relative measurement error $\theta_i$, , which is indicated in the passport of the measuring device. Until recently, these methods of choosing weight coefficients effectively coped with the task, presumably due to the accumulated operating experience of the corresponding software systems. Moreover, to date, the errors of all instruments for measuring the characteristics of a power system are metrologically normalized by the relative error. The recently introduced SPM devices, making it possible to measure phase electric angle of complex values, which cannot be normalized by relative error, have revealed a new problem when taking into account these angles in SE.

In order to substantiate the approach to the choice of weighting factors for measuring dissimilar parameters, we consider the least squares method from the standpoint of the maximum likelihood method. We consider power system for which SE task is performed. We assume that *M* telemetry is performed in a power system as in the previous task. Since all these measurements have errors, we suppose that for all these errors, probability densities $\rho_i(\Delta y_i)$ are given, where *i* is measurement number from 1 to *M*, $\Delta y_i$ is a random error value, which is usually taken as continuous. Then it turns out that

$$y_i = y_i^{\text{TM}} + \Delta y_i, \tag{2}$$

where $y_i$ is the estimated value of the characteristic being measured. From (1) it follows that

$$\Delta y_i = y_i - y_i^{\text{TM}}. \tag{3}$$

We suppose that all measurements are carried out independently of each other, that is, measurement errors are independent random variables. Then, to determine the probability density of the entire measurement system $\rho_p(\Delta Y)$, the probability density of vector of such values ΔY are multiplied [9], and, therefore,

$$\rho_p(\Delta Y) = \prod_{i=1}^{M} \rho_i(\Delta y_i). \tag{4}$$

This function is most often taken as the likelihood function in the maximum likelihood method [9].

Also, we suppose that it is reliably known that parameters $y_i$ are interconnected by a system of equations:

$$\left\{ f_j(X,Y) = 0, \quad j = 1...L, \right. \tag{5}$$

where $f_j(X,Y)$ is interconnection functions, which are determined by information about specific physical phenomena and objects, *L* is the number of interconnection equations. Therefore, the optimization problem for the maximum likelihood method can be written as:

$$\begin{gathered} \Phi(Y) = \prod_{i=1}^{M} \rho_i(y_i - y_i^{\text{TM}}) \to \max \\ \left\{ f_j(X,Y) = 0, \quad j = 1...L. \right. \end{gathered} \tag{6}$$

The solution of this optimization problem is estimation of *X* parameters.

If we assume that all random variables $\Delta x_i$ are normally distributed, in other words, we can write:

$$\rho_i(\Delta y_i) = \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma_i} \cdot \exp\left( -\frac{\Delta y_i^{\,2}}{2 \cdot \pi \cdot \sigma_i^{\,2}} \right), \tag{7}$$

Where $\sigma_i$: is dispersion of random variable $\Delta y_i$, then, given that the exponential function and multiplication by a positive constant do not affect the order relation, and knowing that at exponent multiplication its degrees are added, we can rewrite expression (5) in the form of the least squares method

$$\Phi(Y)=\sum_{i=1}^{M}\frac{1}{\sigma_i^2}\cdot(y_i-y_i^{\text{TM}})^2\rightarrow\min \\ \left\{ f_j(X,Y)=0, \quad j=1...L. \right. \tag{8}$$

The transition from maximization (5) to minimization (7) was accomplished by changing the sign in the exponent. Problem (8) is itself a weighted least squares problem. To finally transform expression (8) into expression (1), it is additionally required to assume that there is an equivalent transformation

$$\left\{ f_j(X,Y)=0, \quad j=1...L \right. \Rightarrow \begin{cases} y_j(X)=y_j, & j=1...M, \\ h_j(X)=0, & j=1...K. \end{cases} \tag{9}$$

From expressions (1)–(8) it can be seen that the method of least squares (1) is a special case of the maximum likelihood method. Consequently, the weighting factors $\alpha_i$ are completely equivalent to the reciprocal of the square of dispersion $1/\sigma_i^2$.

Further we list the assumptions made during transition from the maximum likelihood method to the method of least squares:

1. The probability density of all errors is predeterminedly known, unchanged in time and is a normal distribution.
2. The system of constraints in the form of equalities in optimization problem should be performed under any conditions and there should be no doubt about its correctness.
3. The dispersions must be constant and known in advance.
4. There should be no, or should be known in advance the magnitude of systematic measurement error $\sigma_i$.

All these assumptions are used in the least squares method (1) described at the beginning of the section, although they were implicitly accepted there.

**The choice of weights for the method of weighted least squares for SE task**

As already noted, for all measurements the instrument passport normalizes the relative error $\theta_i$. Traditionally, in the least squares method (1), it is recommended [1, 8] to choose weighting factors as

$$\alpha_i=\frac{1}{(\theta_i\cdot m_i)^2}, \tag{10}$$

where $m_i$ is the scaling coefficient of measurement, which is selected based on the physical nature of the measured value. For example, for voltage modules, current modules and power components, this coefficient will differ because they are dissimilar. Strictly speaking, the main problem of the described method is that it is fully applicable only under the condition that $\theta_i$ is not relative, but absolute error, but usually it is applied to relative errors. This problem was not previously manifested, due to the fact that all measurements were normalized to relative error. However, the relatively recent appearance of SPM has led to the possibility of measuring characteristics that can in principle be normalized only by absolute error, namely, the phase angles of electrical quantities. The application of the old approach (9) to new measurement systems leads to the fact that the accumulated experience, on the basis of which the scaling coefficients $m_i$ were chosen, is inapplicable and, as a conclusion, this can lead to an unpredictable mode distortion as a result of its SE. Worse, for the current SE paradigm it is impossible even to normalize this mode distortion, since the measure of mode deviation from the standard turns out to be uncertain.

In this paper, it is proposed to replace the traditional method of choosing weight coefficients. The purpose is to take into account the heterogeneity of parameters, which, first of all, manifests itself in combined usage of modules and phase angles of electrical quantities. The essence of the proposed method is that all measurements should be divided into $M_\Theta$ measurements with normalized absolute error $\Theta_i, \quad i=1...M_\Theta$, and $M_\theta$ measurements with normalized relative error $\theta_i, \quad i=1+M_\Theta...M$. For measurements with normalized absolute error, it is proposed to calculate the weighting factor as

$$\alpha_i = \frac{1}{\Theta_i^2}, \tag{11}$$

and for measurements with normalized relative error it is proposed to calculate the weighting factor as

$$\alpha_i = \frac{1}{(\theta_i \cdot y_i^{\text{TM}})^2}. \tag{12}$$

Accordingly, the objective function and the constraint system will take the form:

$$\begin{gathered} \Phi(Y) = \sum_{i=1}^{M} \alpha_i \cdot (y_i - y_\text{i}^{\text{TM}})^2 \to \min \\ \left\{ f_j(X,Y) = 0, \quad j = 1...L, \right. \end{gathered} \tag{13}$$

where $\alpha_i$ is weighting factor corresponding to (11) for measurements with normalized absolute error and to (12) for measurements with normalized relative error.

Further we show how the transition was made from expression (8), where $1/\sigma_i^2$ are used as weights, to weights written in expressions (11)–(12). For this we take the first group of assumptions: normalized absolute errors correspond to the confidence interval of the measured value. This can be mathematically written as

$$\Theta_i = S_i \cdot \tau_i \approx \sigma_i \cdot \tau'_i, \tag{14}$$

where $S_i$ is sample standard deviation corresponding to the series of measurements assumed to be performed for instrument calibration, $\tau_i$ is the Student's coefficient corresponding to the performed series of measurements and the required reliability of measurements (for example 99%) $\tau'_i$ is the Student's coefficient corresponding to infinite number of measurements and the same reliability as for $\tau_i$. The equality sign in (14) shows that measuring devices are assumed to be verified by a series of tests on a more accurate device, and an approximate equality sign indicates that an infinite number of tests were made during such verification [10]. Taking into account that the largest error [10] is indicated in the instrument passports, these assumptions seem to be acceptable for further reasoning.

The second group of assumptions is: the normalized relative error can be calculated as

$$\theta_i = \frac{S_i \cdot \tau_i}{y_i^e} \approx \frac{\sigma_i \cdot \tau'_i}{y_i^e} \approx \frac{\sigma_i \cdot \tau'_i}{y_i^{\text{TM}}}, \tag{15}$$

where $y_i^e$ is etalon value of the parameter being measured, $y_i^{\text{TM}}$ is actual measurement value with an error. The first equality sign of expression (15) means the assumption that the measuring devices are assumed to be verified by a series of tests using a more accurate instrument normalized by reference values. The following sign of approximate equality shows the assumption that an infinite number of tests were performed during calibration. The second sign of approximate equality shows the assumption made in this paper that the reference value is approximately equal to telemetry.

**Coordinate conversion to perform linear SE**

When considering SE with SPM, it became possible to formulate the LSE task. In foreign publications [1–3] the following approach to LSE is considered. PMUs are assumed to provide real and imaginary values for currents and voltages. We assume that in the branch of power system connecting the nodes *s* and *t*, the node *s* has a PMU, which measures complex values of voltage of node *s* and current of $s-t$ branch. In this case, for this PMU, one can write a fragment of the objective function and the system of constraints (13):

$$\phi_{PMU}(Y)=\alpha_{U\Re}\cdot(y_{U\Re}-y_{U\Re}^{\text{TM}})^2+\alpha_{U\Im}\cdot(y_{U\Im}-y_{U\Im}^{\text{TM}})^2+\alpha_{I\Re}\cdot(y_{I\Re}-y_{I\Re}^{\text{TM}})^2+\alpha_{I\Im}\cdot(y_{I\Im}-y_{I\Im}^{\text{TM}})^2$$

$$\begin{cases}-g_{ss}\cdot U_s'+b_{ss}\cdot U_s''+g_{st}\cdot U_t'-b_{st}\cdot U_t''=I_{st}',\\ -b_{ss}\cdot U_s'-g_{ss}\cdot U_s''+b_{st}\cdot U_t'+g_{st}\cdot U_t''=I_{st}'',\\ y_{U\Re}-U_s'=0,\quad y_{U\Im}-U_s''=0,\\ y_{I\Re}-I_{st}'=0,\quad y_{I\Im}-I_{st}''=0,\end{cases} \tag{16}$$

where $U_s'$ and $U_s''$ are real and imaginary part of the node *s* voltage; $U_t'$ and $U_t''$ are real and imaginary part of the node *t* voltage; $I_{st}'$ and $I_{st}''$ are real and imaginary part of current, entering the node $s$ from the branch $s-t$; $g_{ss}$ and $b_{ss}$ are real and imaginary part of intrinsic conductance of $s-t$ branch in the node *s*; $g_{st}$ and $b_{st}$ are real and imaginary part of intrinsic conductance of $s-t$ branch in the node $t$; $\alpha_{U\Re}$, $\alpha_{U\Im}$, $\alpha_{I\Re}$ and $\alpha_{I\Im}$ are measurements weights of real and imaginary parts of current and voltage, respectively.

A serious advantage of this approach is the ability to reformulate system (16) in terms of classical formulation of the problem of the method of least squares (1). If in the considered power system there is complete observability using only PMU, then this approach leads to solving systems of linear equations, which makes the SE task itself to be solved quickly, robustly and without using iterative methods.

However, an equally serious drawback of this approach is the uncertainty of measurements weights. From the point of view of the above approach of the maximum likelihood method (13), this way of formulating the objective function and the constraint system turns out to be incorrect, since SPM does not indicate the errors of the real and imaginary components of the vector dimensions, but one specifies relative errors of its modules and absolute errors of its angles.

We write the fragment of the objective function and the system of constraints (16) for the case when the measurements are modules and angles of complex parameters

$$\phi_{PMU}(Y)=\alpha_V\cdot(y_V-y_V^{\text{TM}})^2+\alpha_\delta\cdot(y_\delta-y_\delta^{\text{TM}})^2+\alpha_I\cdot(y_I-y_I^{\text{TM}})^2+\alpha_\psi\cdot(y_\psi-y_\psi^{\text{TM}})^2$$

$$\begin{cases}-g_{ss}\cdot V_s\cdot\cos(\delta_s)+b_{ss}\cdot V_s\cdot\sin(\delta_s)+g_{st}\cdot V_t\cdot\cos(\delta_t)-b_{st}\cdot V_t\cdot\sin(\delta_t)=I_{st}\cdot\cos(\psi_{st}),\\ -b_{ss}\cdot V_s\cdot\cos(\delta_s)-g_{ss}\cdot V_s\cdot\sin(\delta_s)+b_{st}\cdot V_t\cdot\cos(\delta_t)+g_{st}\cdot V_t\cdot\sin(\delta_t)=I_{st}\cdot\sin(\psi_{st}),\\ y_V-V_s=0,\quad y_\delta-\delta_s=0,\\ y_I-I_{st}=0,\quad y_\psi-\psi_{st}=0,\end{cases} \tag{17}$$

where $V_s$ and $\delta_s$ are module and angle of voltage of node $s$; $V_t$ and $\delta_t$ are module and angle of voltage of node $t$; $I_{st}$ and $\psi_{st}$ are module and angle of current, entering node $s$ from branch $s-t$; $\alpha_V$, $\alpha_\delta$, $\alpha_I$ and $\alpha_\psi$ are weights for voltage module, voltage angle, current module and current angle as a complex value.

The approach (17) described in [1], despite the correctness of formulation, has an important disadvantage compared to the approach (16), it assumes an iterative solution of a system of nonlinear equations, regardless of what type of measurement (SCADA or SPM) is used.

In order to combine the linearity of approach (16) and statistical correctness of approach (17), the formulation of the problem presented in (18) is proposed. It is important to note that in formulation (18) an assumption is made that is not crude, namely: it is assumed that the deviation of measurements of modules and angles of the complex values from their reference values turned out to be small values. This made it possible to rotate the coordinate system of the real and imaginary components of the complex parameters so that the actual components $u'_s$ and $i'_{st}$ correspond to the module measurements, and the imaginary components $u''_s$ and $i''_{st}$ correspond to the angle measurements multiplied by the module measurements

$$\phi_{PMU}(Y) = \alpha_V \cdot (y_V - y_V^{\text{TM}})^2 + \alpha_\delta \cdot (y_\delta - y_\delta^{\text{TM}})^2 + \alpha_I \cdot (y_I - y_I^{\text{TM}})^2 + \alpha_\psi \cdot (y_\psi - y_\psi^{\text{TM}})^2$$

$$\begin{cases} -g_{ss} \cdot U'_s + b_{ss} \cdot U''_s + g_{st} \cdot U'_t - b_{st} \cdot U''_t = I'_{st}, \\ -b_{ss} \cdot U'_s - g_{ss} \cdot U''_s + b_{st} \cdot U'_t + g_{st} \cdot U''_t = I''_{st}, \\ y_V - u'_s = 0, \quad y_\delta - \dfrac{1}{y_V^{\text{TM}}} \cdot u''_s = 0, \\ u'_s = U'_s \cdot \cos(y_\delta^{\text{TM}}) - U''_s \cdot \sin(y_\delta^{\text{TM}}), \\ u''_s = U'_s \cdot \sin(y_\delta^{\text{TM}}) + U''_s \cdot \cos(y_\delta^{\text{TM}}), \\ y_I - i'_{st} = 0, \quad y_\psi - \dfrac{1}{y_I^{\text{TM}}} \cdot i''_{st} = 0, \\ i'_{st} = I'_{st} \cdot \cos(y_\psi^{\text{TM}}) - I''_{st} \cdot \sin(y_\psi^{\text{TM}}), \\ i''_{st} = I'_{st} \cdot \sin(y_\psi^{\text{TM}}) + I''_{st} \cdot \cos(y_\psi^{\text{TM}}). \end{cases} \tag{18}$$

Formulation (18), in conjunction with the maximum likelihood approach, allows one to perform the state evaluation, upon condition that the network is observable from the SPM point of view, as follows:

$$diag(Y^{\text{TM}})^{-1} \cdot A \cdot X = D, \tag{19}$$

where $Y^{\text{TM}}$ is telemetry vector, $A$ is information matrix, $X$ is state parameters vector, $D$ is vector, the elements of which are equal to one.

The essence of the method indicated in (19) consists in the complex estimation of state, where the complex values of measurements themselves are given as weights in equations. This gives grounds to call it as "a linear method of state estimation weighted by measurements" (Measurements Weighted Linear State Estimation), which we will abbreviate as "MWLSE".

In [11], the SE method is shown, in which it is assumed that each measurement group has its own estimation procedure: linear for SPM measurements and non-linear for SCADA. The first one to be performed is linear SE on more accurate SPM measurements. This will be the first level of SE. The second performed is non-linear SE with fixing the results of the first SE level as constants. The test calculations performed for this method showed that a two-level SE leads to a significant increase in the computational speed, with a high accuracy of the obtained flow distribution.

The proposed MWLSE method allows one to more accurately perform the linear SE required for a two-level SE. Thanks to the choice of weighting factors specified in (19), the linear SE performed for the data from SPM becomes more accurate, which is critical for performing the second level of non-linear SE according to SCADA.

**Computational experiment**

We consider electrical network shown in Figure 1, where the etalon current distribution mode is shown in section a), etalon mode with indication of flow distribution is shown in b), and c) is an example of measurements with errors. It is assumed that PMUs are installed in nodes 1 and 3, which measure voltages at these nodes and currents in lines 1-2 and 2-3 from the PMU side.

For this network and for this composition of measurements, we will perform a linear SE using two methods. The first method involves formulation of the objective function according to the approach (16). Due to the fact that the choice of weighting factors used in (16) is not presented in the literature, in this example the coefficients were chosen in the same manner as described in [1], where this method is called “Linear State Estimation” (LSE). The result of such an SE is shown in Figure 2, where the resulting current distribution a) and flow distribution b) are labeled with a superscript “LSE”. The box shows the result of comparison of the calculated mode using SE with the reference mode in accordance with the criterion

$$S=\sum_{i=1}^{L}\left(\left(\left|\dot{S}_{i\text{н}}^{LSE}-\dot{S}_{i\text{н}}^{\text{e}}\right|\right)^{2}+\left(\left|\dot{S}_{i\text{к}}^{LSE}-\dot{S}_{i\text{к}}^{\text{e}}\right|\right)^{2}\right), \tag{20}$$

where $L$ is amount of lines, and subscripts “s” and “f” correspond to start and finish of the line.

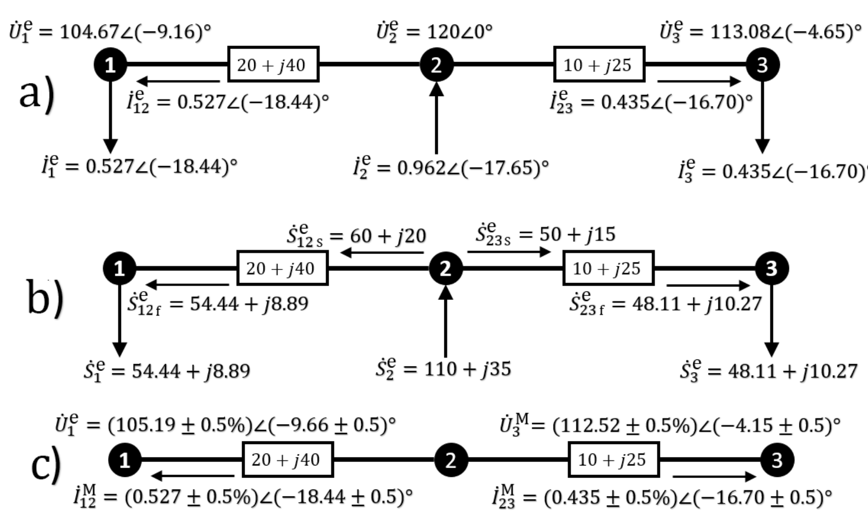


Fig. 1. An example of an electrical network of 110 kV for matching SE

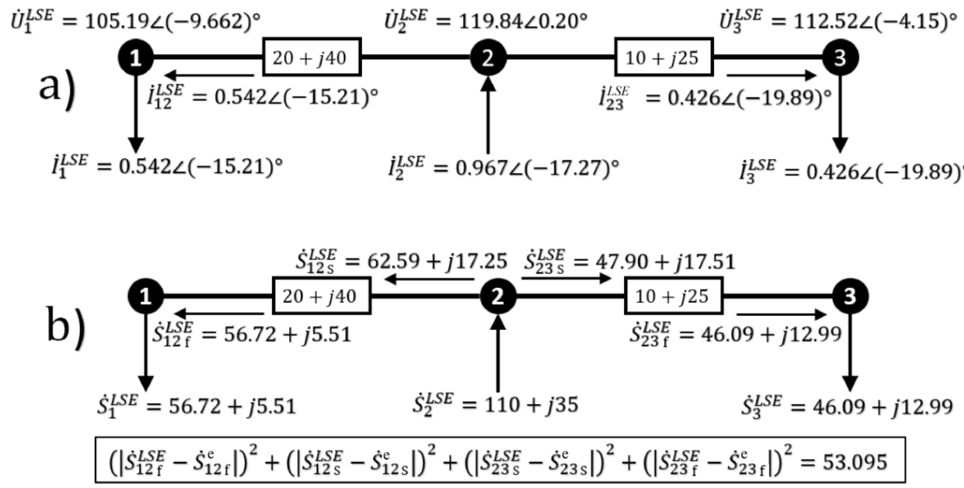


Fig. 2. The SE result for measurements shown in Figure 1, *c*) according to the first method

The specified criterion (20) shows the deviation measure of the estimated mode from etalon for lines power, which to the greater extent shows error in mode calculation when choosing control actions related to the change in flow distribution. As a result of calculation by the first method, the value of this criterion turned out to be 53.095.

As a second method, the proposed MWLSE method (19) was considered, which was tested on the same circuit and for the same measurements for the purpose of comparison with the first method. The calculation result is shown in Figure 3, where, also, the current distribution a) and flow distribution b), are marked with a superscript "LSE". For this method, the value of the criterion (20) turned out to be 0.826, which is almost two orders of magnitude less than that for the first method. As it can be seen from comparison of two final results from two SE methods, one can confidently judge the much higher accuracy of the MWLSE method.

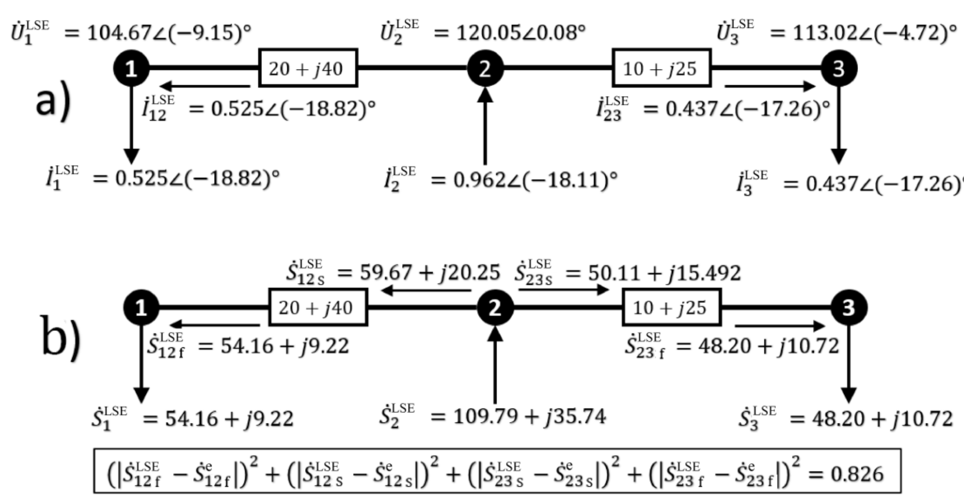


Fig. 3. SE result for measurements depicted in Figure 1 using the MWLSE method

For persuasiveness, the method has been tested on a number of IEEE test problems, namely, for IEEE-14, IEEE-RTS96, IEEE-30, IEEE-57, IEEE-118 networks. The test results showed a higher accuracy of MWLSE, and the following was revealed. Firstly, it turned out that the accuracy of the proposed method in comparison with the LSE method is the higher, the higher the voltage class of the network under consideration is. Secondly, it was noticed that the comparative accuracy of the proposed method decreased with the weighting of mode, but still, it remained higher than for other methods.

**Conclusions**

As it is known, in EES for the state estimation by SCADA telemetry, the least-squares weighted method finds the greatest application. The SPM systems that have emerged in recent years have made it possible to move to an accelerated linear state estimate LSE. However, this method does not guarantee high accuracy of the final result.

The proposed state estimation method, called MWLSE, is intended for networks that are monitored using PMUs in the WAMS information support system. It is as robust and computationally fast as the linear state estimation method LSE used in foreign power systems, but it turned out to be much more accurate for all the cases considered.

**References**

1. Haughton DA, Heydt GT. A Linear State Estimation Formulation for Smart Distribution Systems. *IEEE Transactions on Power Systems; May 2013*. 28(2):1187-1195. http://dx.doi.org/10.1109/ TPWRS.2012.2212921.

2. Zhang L, Bose A, Jampala A., et al. Design, Testing, and Implementation of a Linear State Estimator in a Real Power System. *IEEE Transactions on Smart Grid*; *July 2017*. 8(4):1782-1789. DOI: 10.1109/TSG.2015.2508283.

3. Ghiocel SG., Stefopoulos G, Chow JH., et al. Phasor-Measurement-Based State Estimation for Synchrophasor Data Quality Improvement and Power Transfer Interface Monitoring. *IEEE Transactions on Power Systems*; March 2014; 29, (2):881-888. DOI: 10.1109/TPWRS.2013.2284098.

4. Khokhlov MV. Robastnoe ocenivanie sostoyaniya elektroenergeticheskih sistem na osnove nekvadratichnyh kriteriev [dissertation]. Yekaterinburg; 2010. Available at: http://elar.urfu.ru/handle/ 10995/19860. Accessed: 25 Feb 2019. (In Russ).

5. Maksimenko DM, Mashalov EV, Neuimin VG. Ocenivanie sostoyaniya na baze optimizacionnogo algoritma v PK RastrWin3. *Izvestiya NTC Edinoj energeticheskoj sistemy*. 2013; 2(69):36-44. (In Russ).

6. Gamm AZ. *Statisticheskie metody ocenivaniya sostoyaniya elektroenergeticheskih system*. Moscow: Nauka, 1976. (In Russ).

7. Schweppe FC, Wildes J. Power system static state estimation. Part 1: exact model. *IEEE Transactions On Power Systems*. 1970; 1:120-125.

8. Prikhno VL, Chernenko PA. *Operativnyj raschet rezhima energosistemy po dannym teleizmerenij*. Irkutsk: SEI SB AS USSR, 1982. (In Russ).

**Литература**

1. Haughton D.A., Heydt G.T. A Linear State Estimation Formulation for Smart Distribution Systems // IEEE Transactions on Power Systems; May 2013. Vol. 28, iss. 2. pp. 1187-1195.

2. Zhang L., Bose A., Jampala A., et al. Design, Testing, and Implementation of a Linear State Estimator in a Real Power System // IEEE Transactions on Smart Grid; July 2017. Vol. 8, iss. 4. pp. 1782-1789.

3. Ghiocel S.G. et al. Phasor-Measurement-Based State Estimation for Synchrophasor Data Quality Improvement and Power Transfer Interface Monitoring // IEEE Transactions on Power Systems; March 2014. Vol. 29, iss. 2. pp. 881-888.

4. Хохлов М.В. Робастное оценивание состояния электроэнергетических систем на основе неквадратичных критериев: Дис. ... канд. техн. наук. Екатеринбург; 2010. Доступно по: http://elar.urfu.ru/handle/10995/19860. Ссылка активна на 25 февраля 2019.

5. Максименко Д.М., Машалов Е.В., Неуймин В.Г. Оценивание состояния на базе оптимизационного алгоритма в ПК RastrWin3 // Известия НТЦ Единой энергетической системы. 2013. №2(69). С. 36-44.

6. Гамм А.З. Статистические методы оценивания состояния электроэнергетических систем. М.: Наука, 1976. 220 с.

7. Schweppe F.C., Wildes J. Power system static state estimation. Part 1: exact model // IEEE Transactions On Power Systems. 1970. №1. pp. 120-125.

8. Прихно В.Л., Черненко П.А. Оперативный расчет режима энергосистемы по данным телеизмерений. Иркутск: СЭИ СО АН СССР, 1982. С.70-75.

9. Nikulin MS.; Vinogradov IM., ch. editors. Likelihood Relations Criterion. *Mathematical Encyclopedia*. Moscow: Soviet Encyclopedia, 1984; 4: 151-1216. (In Russ).

10. GOST R 8.000-2015. Gosudarstvennaya sistema obespecheniya edinstva izmerenij (GSI).

11. Bartolomey P.I., Semenenko S.I. Power Systems State Estimation Acceleration on the Basis of the Synchronized Phasor Measurements in the Power System Steady State Control Tasks. *International Youth Scientific and Technical Conference Relay Protection and Automation (RPA)*; *27-28 Sep 2018; Moscow, Russia*. Moscow; 2018. pp. 1-10.

9. Никулин М.С. Отношения правдоподобия критерий // Математическая энциклопедия / Виноградов И. М. (гл. ред.). М.: Советская энциклопедия, 1984. Т. 4. С.151-1216.

10. ГОСТ Р 8.000-2015. Государственная система обеспечения единства измерений (ГСИ). Основные положения.

11. Bartolomey P.I., Semenenko S.I. Power Systems State Estimation Acceleration on the Basis of the Synchronized Phasor Measurements in the Power System Steady State Control Tasks // International Youth Scientific and Technical Conference Relay Protection and Automation (RPA); 27-28 September 2018; Moscow, Russia. Moscow, 2018. pp. 1-10.

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