Determination of Phase Loads in the Primary Distribution Network Using Smart Meters

Irina I. Golub *, Evgeny V. Boloev, and Yana I. Kuzkina

Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The paper presents an option for determination of phase loads in the primary distribution network using the results of state estimation of the secondary distribution network that are obtained by smart meter measurements installed at the load and generator nodes. The problem of state estimation in the secondary distribution network based on measurements of the active and reactive nodal powers and voltage magnitudes rather than by the Newton method traditionally used for this purpose is solved by a method of simple iterations. Efficiency of using the proposed approach for determination of phase loads of the primary distribution network for each hour of daily curve of nodal powers is illustrated by the example of a 32-node test network..**

***Index Terms* — distribution network, renewable generation, smart meter, state estimation, voltage control.**

I. Introduction

The major share of power losses and power transmission costs as well as power supply reliability costs are known to fall on distribution networks. This fact requires special attention to the distribution networks reliability and ways to enhance their efficiency.

Primary and secondary distribution networks are traditionally operated as opened ones, power flows in their feeders being directed from the primary distribution substation to the load nodes. A low-voltage secondary distribution network is modeled as a three-phase network with a zero wire; it can have single-, two- and three-phase loads, which leads to unbalance of currents and voltages both in the secondary and primary distribution networks.

A major trend in upgrading the traditional passive network is transition to an active intelligent network that integrates renewable energy sources, power storage units and active loads. Power flow directions in the active networks are changed during the day; load nodes may become generator ones, and voltage deviations may exceed permissible levels. First, we should understand that network behavior radically changes and then make a decision on its enhancement, improvement of its reliability and efficiency of its operation. The main way to ensure the flexible transition from a traditional passive network to an intelligent active one can be accurate and reliable state estimation (SE).

The state estimation methods are widely used in high and ultra-high voltage networks that are used for power transmission from power stations to distribution networks. Invention of synchronized phasor measurements played a major role in increasing the state estiamtion reliability. State estimation based on Phasor Measurement Units allows measurements of power transmitted to the primary medium-voltage distribution network, whereas loads of primary and secondary distribution networks cannot be measured.

Power meters in traditional distribution networks are as a rule installed on the medium-voltage side of primary substations only, while there is no data on the state of secondary distribution substations. There are methods that use such measurements for approximate estimation of load flows and power losses in the distribution network [1] but such measurements are rather scarce for state estimation even in the traditional networks, to say nothing about the active ones.

The average hourly loads determined based on measurements of power consumed and recorded in the reports of an Automatic System for Commercial Accounting of Power Consumption (ASCAPC) can be used for load flow calculation in the initial stage of transition to an active distribution network. The smaller the time interval between

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* Corresponding author.
E-mail: golub@isem.irk.ru

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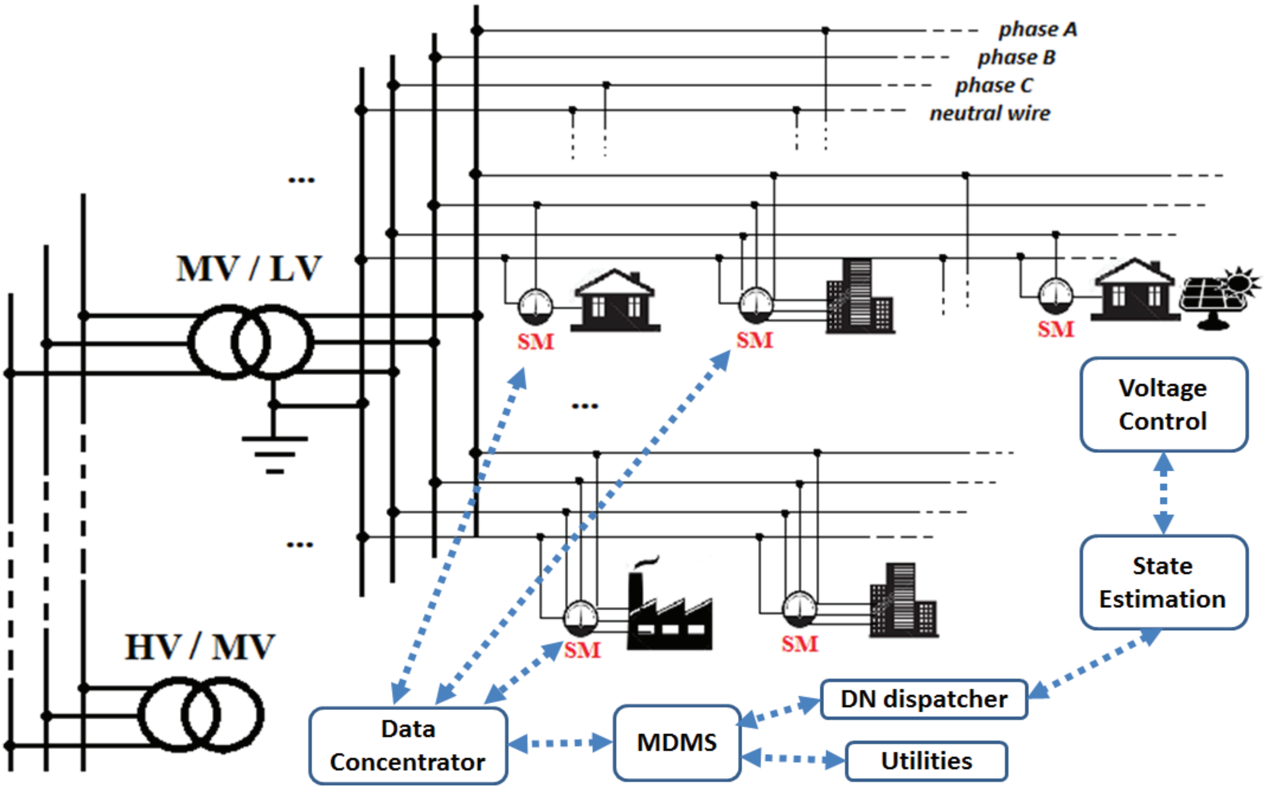

Fig. 1. Hierarchy of Advanced Metering Infrastructure for acquisition, transfer and processing of the Smart Meter recordings

measurements (subject to coincidence of time intervals for load determination), the higher the accuracy of load flow calculations using the ASCAPC data. It is also important to exclude errors in the data on connection of low-voltage feeders to transformer substations and in the data on the network topology that are obtained from special-purpose geographic systems. Information on connection of loads to feeder phases is of major importance and, as a rule, it requires special research. Load flow calculation based on average hourly loads can increase the accuracy of determining the nodal voltages and losses, but this accuracy is insufficient for state estiamtion.

The paper is arranged as follows.

Section II discusses the principles of building a system for collecting and processing measurements from smart meters, and the problem of clarifying information on the placement of meters in the phases of the distribution network.

Section III proposes an approach to significantly simplify the procedure for state estimation of the secondary distribution network. The approach is associated with solving a nonlinear system of measurement equations by simple iteration method.

Section IV analyzes the problem of placing smart meters to ensure the observability of all state variables in the distribution network or the observability of only voltage magnitudes.

Section V illustrates the effectiveness of the proposed approach for the state estimation and identification of phase loads and nodal voltages of the primary distribution network using a test network as an example.

II. Smart Meters and Modern Metering Infrastructure

The most complete and reliable data on the state of secondary distribution network can be obtained by the state estimation methods that use smart meters installed at load and/or generator nodes.

Meters of ELSTER Company [2] with 0.2S, 0.5S, 1 precision at 15-minute discreteness of metering are examples of smart meters. Similar meters are installed in the distribution networks of Europe. Ministry of Energy of Russia has developed a draft law stimulating the introduction of smart digital meters for power metering. Some Russian cities (Kaliningrad, Yaroslavl, and Tula) implement pilot projects on the use of smart meters [3, 4].

Advanced Metering Infrastructure (AMI) [5, 6] that unites an active distribution network, a communication network and a modern metering system is responsible for data transfer from a smart meter to the data acquisition and processing system, and back. Along with the consumed power, some smart meters can measure active and reactive power, active and reactive currents and voltage magnitudes at the nodes where they are installed [7].

Smart meter measurements processed by state estimation algorithms can be used for analysis of voltage and current admissibility, for calculation of power losses, and for assessment of the distribution network reliability.

Moreover, estimates of load flows in the secondary distribution network that at each phase come from the primary distribution network can be used for calculation of a three-phase load flow and/or state estimation of the primary distribution network.

A list of activities that need data on loads and load flows in the primary distribution network is rather extended. It includes power losses, reactive power control, optimization of capacitor banks allocation, network reconfiguration, load forecast, network enhancement, relay protection, and automation.

Fig. 1 presents an AMI hierarchy for the smart meter data collection and transfer to data concentrators at substations. The data are transmitted to Meter Data Management System (MDMS) for further processing of recordings on power consumed by utilities. The smart meter data are used by a distribution network dispatcher or by the state estimation algorithms.

Different media and communication means are used for the AMI arrangement [8]. Power Line Communication (PLC) technology became popular in both Europe and Russia. It ensures high-speed data transfer via power lines [9], has limited transfer capability and long response time to incoming smart meter messages.

ZigBee [10] and cloud technologies [11] are the most popular wireless technologies. In Kazakhstan and Belorussia, the cellular communication is used for communication between smart meters [4]. Wireless communication is less costly but distance and correctness of signals transmitted are limited, speed of data transfer is low, and ability to detect obstacles and bypass them is low. Moreover, wireless technologies can create noises for other devices. PLC is, as a rule, used for recordings transfer into data storage units located at primary distribution substations; communication between meters of one feeder is performed via wireless channels.

Before commencing the state estimation of the secondary distribution network as well as for meters used in the Automatic System for Commercial Accounting of Power Consumption (ASCAPC), we need data on the phase to which loads are connected and where smart meters are installed. A measurement experiment proposed in [12] is an efficient approach to phase identification in the distribution network. It consists in assessing mutual correlation of voltage profiles at two nodes of the network within a short period of time. The first one is a power supply node in the distribution network or the nearest node at every phase of which the voltage magnitudes are measured at certain time moments. The second node is represented by successive nodes with smart meters for voltage magnitude measurements taken simultaneously with the measurements in the phases of the first node. The phase of smart meter connection is determined based on the maximum values of cross-correlation coefficients.

The question if it possible to synchronize smart meter measurements has no answer. The authors of the first publications [13] are convinced that their synchronization is possible. Nevertheless, despite the existence of methods for synchronization of smart meter measurements, the authors of [14] recommend considering currently used smart meter measurements as non-synchronized ones and an interval of their transmission is advised to be taken equal to 15, 30 or 60 minutes. The authors of [15] propose compensating for the lack of smart meters synchronization at state estimation by increasing their error [15].

III. State estimation of the secondary distribution network

Let us analyze the possibility of using the smart meter measurements that include active $Z_P^{a,b,c}$ and reactive $Z_Q^{a,b,c}$ nodal capacities and voltage magnitudes $Z_U^{a,b,c}$ at phases *a, b, c* for state estimation of the secondary distribution network and the possibility of using the measurements of zero values of active and reactive nodal capacities (injections) at the transit nodes as additional ones. A secondary distribution network is modeled as a three-phase network disregarding cross-resistances between phase wires and shunt susceptance.

State variables phasor elements are real $u_i^{'a,b,c}$ and imaginary $u_i^{''a,b,c}$ components of phase voltage $u^{a,b,c} = u_i^{'a,b,c} + ju_i^{''a,b,c}$ at nodes $i = 1,..., n$ of the calculation model. Their real components that are equal to the measured voltage magnitudes are used as measured voltages. Admissibility of such substitution is determined by proximity of imaginary components of voltage in the secondary distribution network to zero, at the same time the imaginary voltage component at power supply node in the distribution network is fixed at a zero value.

A method of simple iterations is proposed to solve the non-linear system of measurement equations instead of the commonly used Newton iteration method based on linearization of measurement equations by their decomposition into Taylor series.

SE procedure in this method includes two steps repeated in an iterative manner. Values of nodal currents, here referred to as 'pseudo measurements' are determined at the first step of the first iteration using the measured values of active and reactive nodal powers and measurements of voltage magnitudes at node *i*, namely:

$$z_{Jai}^{a,b,c} - jz_{Jpi}^{a,b,c} = \left(z_{iP}^{a,b,c} - jz_{iQ}^{a,b,c}\right) \Big/ z_{U'i}^{a,b,c} \qquad (1)$$

State variables are determined at the second step using pseudo measurements of currents with a real component of voltages, and their values are inserted in denominator of equation (2) at subsequent iterations:

$$z_{Jai}^{a,b,c} - jz_{Jpi}^{a,b,c} = \left(z_{iP}^{a,b,c} - jz_{iQ}^{a,b,c}\right) \Big/ \left(u_i'^{\,a,b,c} + j\,u_i''^{\,a,b,c}\right) \qquad (2)$$

Iterations are terminated when maximum difference between state variables obtained at neighboring iterations does not exceed the calculation accuracy specified in advance. Linear equations of measurements that correspond to the phase values of active and reactive components of currents and a real voltage component measured at node i can be represented as:

$$\begin{pmatrix} g_i^{a,b,c} & b_i^{a,b,c} \\ -b_i^{a,b,c} & g_i^{a,b,c} \\ I^{a,b,c} & 0^{a,b,c} \end{pmatrix} \begin{pmatrix} u_i'^{a,b,c} \\ u_i''^{a,b,c} \end{pmatrix} = \begin{pmatrix} z_{Ja\,i}^{a,b,c} \\ z_{Jp\,i}^{a,b,c} \\ z_{U'i}^{a,b,c} \end{pmatrix} \quad (3)$$

where $g_i^{a,b,c}$ and $b_i^{a,b,c}$ are nodal conductance and susceptance matrices; $I^{a,b,c}$ and $0^{a,b,c}$ are identity and zero matrices, respectively.

System (3) in the general form can be written as:

$$H_z^{a,b,c} \cdot u^{a,b,c} = z_z^{a,b,c} \quad (4)$$

Similarly, equations of measurements of zero nodal currents at the transit node i will have the form:

$$H_0^{a,b,c} \cdot u^{a,b,c} = 0 \quad (5)$$

Let us represent the aggregation of equations (3) and (5) as:

$$H \cdot u = \begin{pmatrix} H_z^{a,b,c} \\ H_0^{a,b,c} \end{pmatrix} \cdot u^{a,b,c} = \begin{pmatrix} z_z^{a,b,c} \\ 0 \end{pmatrix} = \overline{z} \quad (6)$$

System (6) has a unique solution if the number of equations in it equals the number of variables (a basic system of measurements), and a rank of matrix H referred to as observability matrix [16, 17] equals the number of state variables. For smoothing the effect of errors in some measurements on the estimation of state variables, the measurement equations are multiplied by weight coefficients $R^{-1/2}$

$$R^{-1/2} H \cdot u = R^{-1/2} \overline{z} \quad (7)$$

where R is dispersion of measurement errors.

Such weighing has no effect on the solution to the basic measurement system. The necessary condition of the weighing efficiency is measurements redundancy that ensures the absence of critical measurements whose loss leads to the loss of observability. With redundant measurements, the matrix $R^{-1/2}H$ becomes re-defined as the number of rows in it exceeds the number of columns. There is no classic solution to the re-defined systems (7) but we can obtain a solution vector u that would allow minimization of the distance between vectors of the right-hand and left-hand sides of (7) by using the criterion of the squared differences sum minimization:

$$J(u) = (\overline{z} - Hu)^T R^{-1} (\overline{z} - Hu) \quad (8)$$

This method is called a method of weighted least squares and minimization problem solution can be obtained from a normal system of equations with a square matrix:

$$\left(H^T R^{-1} H\right) u = H^T R^{-1} \overline{z} \quad (9)$$

Estimates of the state variables obtained by solving (9)

$$u = \left(H^T R^{-1} H\right)^{-1} H^T R^{-1} \quad (10)$$

are used for calculation of estimates of both measured variables (nodal current and voltage magnitudes in our case) and unmeasured variables (load flows).

The matrix in equation (9) written for three phases is very big, which creates additional computational difficulties as compared to calculations of one phase at balanced loads. Experience of calculating the load flows in the low-voltage four-wire distribution network with unbalanced phase loads [1] shows that in the case of zero mutual inductances between phase, neutral and earth, calculation of load flow for each phase can be carried out independently. Currents and voltages in the zero wire and in the ground can be determined in the second stage of calculations. This approach can also be used for state estimation of each phase individually. Another advantage of the iteration method over the Newton method is that it is unnecessary to re-calculate the matrix in expression (9) in the course of iterations.

IV. Selection of the number and localities for measurements in the secondary distribution network

Ensuring the topology observability of the active model of a distribution network phase that includes a power supply node and *N-1* load nodes under the absence of transit nodes in it, requires at least one measurement of real voltage component and *N-1* measurements of active power. Out of *2·(N-1)* smart meter measurements taken at the load or generator nodes, *N-2* measurements are redundant. Similarly, for reactive model observability it suffices to fix the imaginary voltage component and measure *N-1* reactive power. Thus, there are no redundant measurements in the reactive model.

For the cases where it is impossible to install smart meters at all the nodes with loads and/or generations to ensure observability of nodal voltage magnitudes only, which is of special importance for the networks with renewable generation, the authors of [18] proposes using the algorithm [19] of selecting the minimum number of single-channel PMU to select the minimum number of smart meters. Additional constraints were introduced into this algorithm that prohibit installation of meters at the transit nodes and installation of more than one smart meter at any node. To provide the reactive model observability it was proposed to specify the zero values of measurements of transverse voltage components. It is worth noting that transit nodes neighboring two branches and leaf nodes without nodal power at them are not included into the phase equivalent circuit when selecting the mix of measurements.

In [20], the authors demonstrate that at minimum set of measurements as well as at location of meters at all the load and/or generator nodes, estimates of voltage

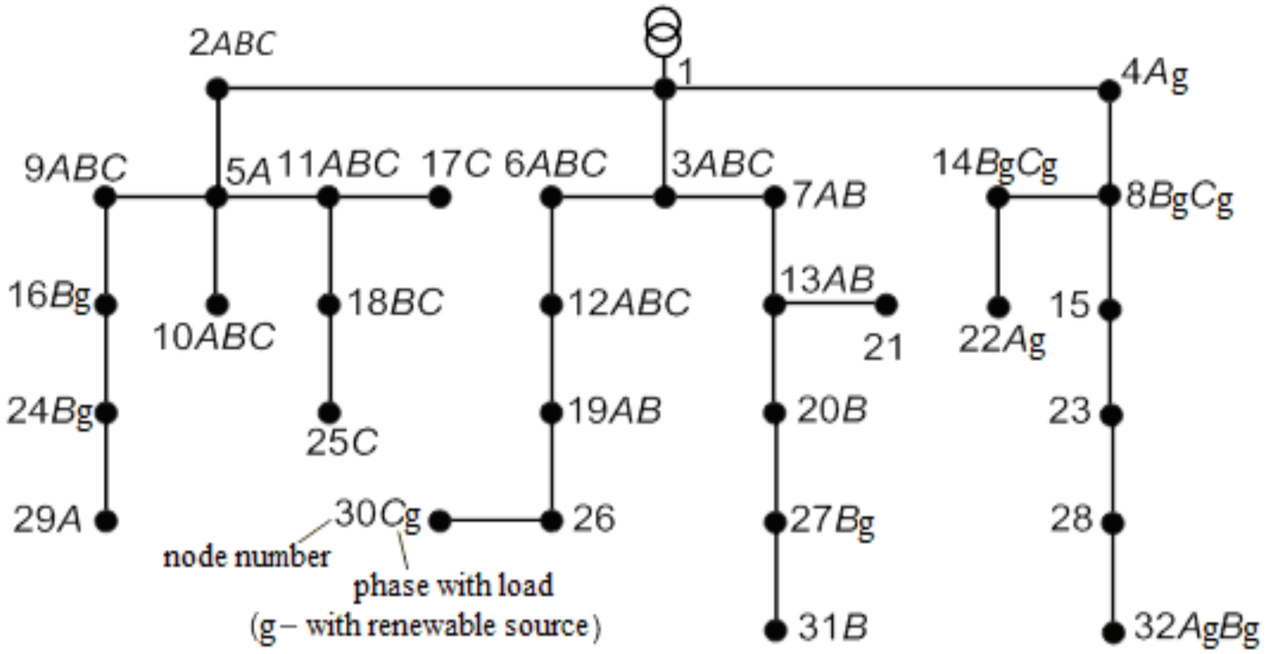

Fig. 2. Scheme of the secondary distribution network

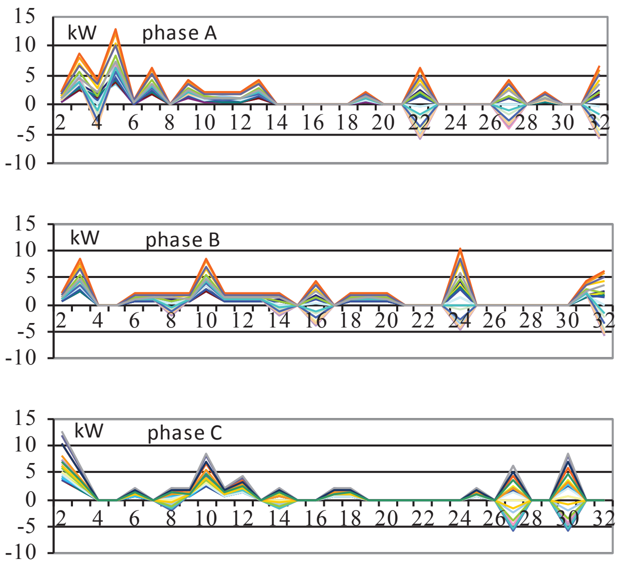

Fig. 3. Active nodal powers in phases A, B, C

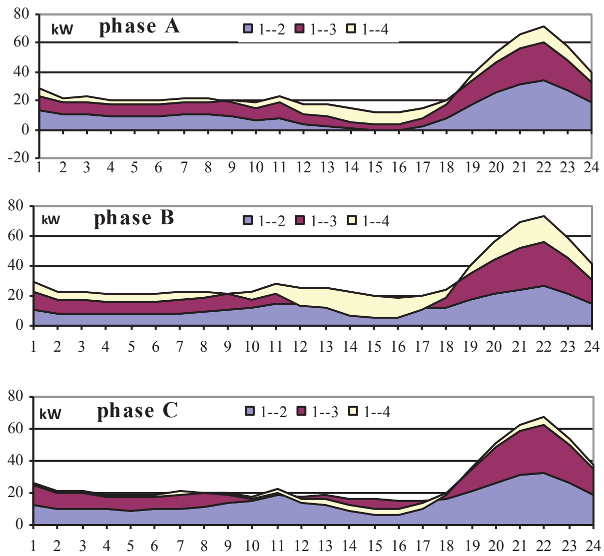

Fig. 4. Measurement of load flows over time in feeder sections 1-2, 1-3, 1-4 the sum of which equals load in the primary distribution network for phases A, B, C

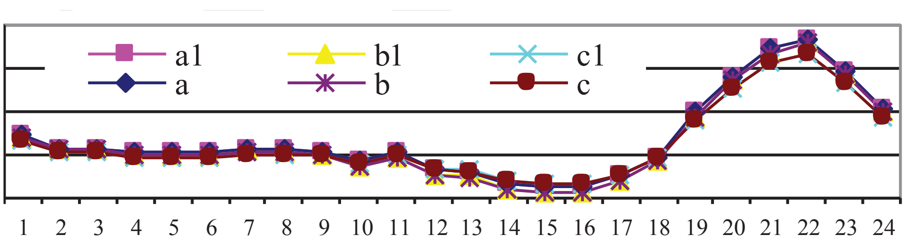

Fig. 5. Test values a1, b1, c1 and estimates of loads in the primary distribution network a, b, c in phases A, B, C (kWh)

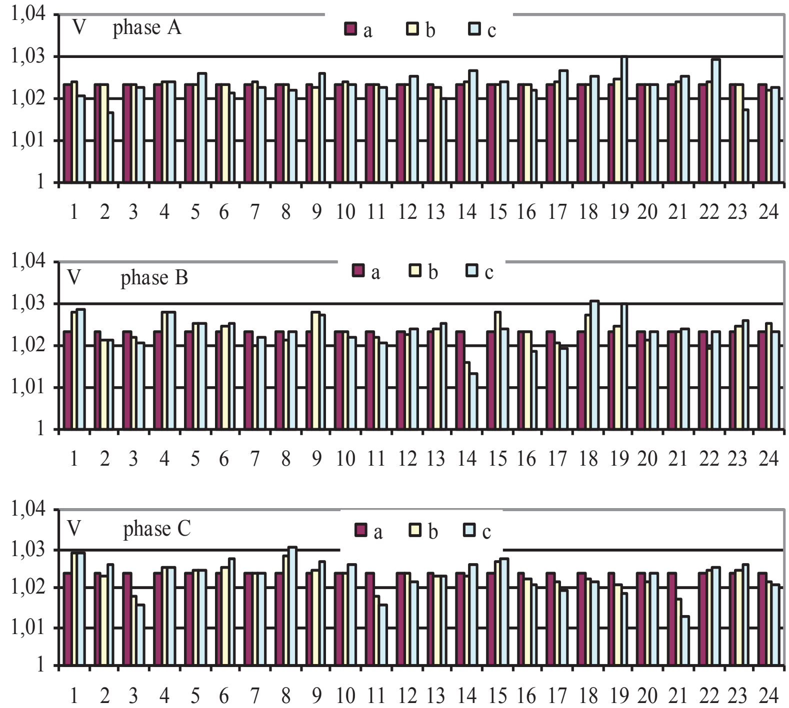

Fig. 6. The change in the relative values of phase voltage magnitudes at the first network node, test values (a); estimates of phase voltage magnitudes obtained from measurements at all load and generator nodes (b), and from the minimum set of measurements (c)

magnitude obtained during state estimation can be used to monitor voltage levels at the nodes of the secondary distribution network. Equating the 'measurements' of imaginary voltage components to zero results in significant errors in the assessment of both reactive and active current (power) components in branches and current (power) injections. Therefore, the authors of [20] concluded that the observability of all the state variables of the distribution network by measurements from smart meters that include measurements of nodal currents (powers) and voltage magnitudes is ensured provided smart meters are installed at all the load nodes.

V. Determination of phase loads in the primary distribution network

Let us illustrate an option of using the estimates of load flows in each phase of a test secondary distribution network that includes 32 nodes (Fig.2) for determination of phase loads in the primary distribution network. Data on hourly values of nodal capacities of each phase in the three-phase network were taken from [21].

Fig. 3 shows the values of active nodal powers in phases A, B, C for each hour of a daily curve. In phase A, there are 15 transit nodes, 12 load nodes, and four (4) generator nodes. The number of transit, load and generator nodes for phase B is equal to 13, 13 and 5, respectively, and those for phase C are 17, 10 and 4, respectively.

Data on loads and generation formed the basis for calculation of load flow at each phase of a test network. The values typical of low-voltage distribution network were taken for resistance and reactance of phase wires. Results of load flow calculations, referred to as test ones, were used for preparing the measurements of nodal power and voltage magnitudes that were to include measurement errors.

For modeling the measurement errors, the errors whose root mean square deviations were taken equal to 0.66W and 0.4V were introduced into the test values of nodal powers and voltage magnitudes.

For phases A, B, and C, Fig. 4 demonstrates the diagrams reflecting the change in time of both separate values of load flows in sections 1-2, 1-3, 1-4 of feeders that were obtained based on the state variables estimates, and their total values that can be considered as a change in the total phase load of the primary distribution network over time.

Graph in Fig. 5 illustrates test values and estimates of phase loads in the primary distribution network.

Fig. 6 shows the time variation of the test relative phase values of the voltage magnitudes at the first network node, estimates of phase values of the voltage magnitudes obtained from measurements at all load and generator nodes and for the minimum set of measurements: phase A - measurements at nodes 2, 6, 7, 10, 11, 19, 22, 27, 29, 32; phase B - measurements at nodes 2, 6, 10, 13, 14, 18, 19, 24, 31, 32; phase C - measurements at nodes 2, 10, 12, 14, 17, 25, 27, 30.

As the graphs in Fig. 6 show, although the estimates of the phase voltages obtained from the minimum set of measurements are less accurate than the estimates obtained from measurements at all load and generator nodes, they can be used to monitor the voltage at all the nodes of secondary distribution network, as noted earlier.

VI. Conclusion

We have demonstrated an option for determination of phase loads in the primary distribution network by using the results of estimation of load flows in the feeders of the secondary distribution network that were obtained by smart meters. Loads and voltages at all the nodes of the primary distribution network can be estimated in a similar manner and can be further used for calculation of three-phase state estimation. Additional measurements, if any, should also be included in the measurement set. Similarly to the linear state estimation procedure, the use of a simple iteration method for non-linear state estimation of distribution network makes the estimation procedure rather simple and time efficient.

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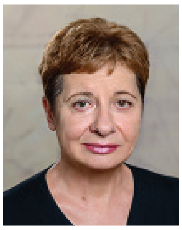

Golub I.I. Professor, Dr.Sc. in Engineering. She is a Leading Researcher at MESI SB RAS. She graduated from Moscow Power Institute as electrical engineer. Her scientific interests are connected with power system state analysis.

Boloev E.V. Ph.D. in Engineering. He has been a senior researcher at MESI SB RAS, since 2015. He graduated from Angarsk Technological Institute as electrical engineer. His research interests are problems of analysis and development of probabilistic power flow.

Kuzkina Y.I. Second category engineer of Relay Protection and Automation Department, LLC "Engineering Center "Irkutskenergo". She graduated from Irkutsk National Research Technical University as electrical engineer. She has been a postgraduate student at MESI SB RAS, Irkutsk, since 2015.