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Algorithmic foundations of automated monitoring of commercial and technical power losses in distribution networks

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Abstract. It is known that significant power losses in power distribution networks (PDNs) caused by unauthorized power withdrawals (UPWs) lead to a decrease in their technical and economic performance. There are no digital technologies designed for separate assessment and monitoring of technical and commercial power losses in modern automatic system for commercial metering of power consumption (ASCMPC), which are currently widely used for automation and computerization of processes in distribution networks. The article proposes a new algorithm for solving the above problem on the basis of data obtained from electricity meters included in the ASCMPC structure. In order to ensure the solvability of the identification problem, the concept of a virtual network model characterizing the desired state of the PDN in the absence of UPW is introduced. On its basis, algebraic equations are obtained, the solution of which allows to identify technical and commercial power losses in three-phase networks. The obtained results are oriented on further improvement of modern ASCMPC and increase of their efficiency and reliability. **Key words:** distribution network, power losses, identification and monitoring algorithm.

Introduction

Automation of information processes in power distribution networks (PDNs) is currently carried out on the basis of implementation of automatic system for commercial metering of power consumption (ASCMPC) [1], which are elements of Smart Grid [2] technology. As it is known, ASCMPC hardware-software complexes belong to the class of information-measuring systems, the main function of which is commercial accounting of electric power in PDNs. The analysis of the functional structure of existing ASCMPCs shows that they do not solve the tasks of separate identification and operational monitoring of technical and commercial power losses in the network [3], as well as do not perform optimization tasks [4-7], which reduces their efficiency and technical and economic performance of distribution companies. In particular, this is due to the fact that to date, adequate and constructive methods for solving the above problems have not been sufficiently developed, taking into account such factors as the presence of unauthorized power withdrawals (UPW) in the network [8 -10], and the asymmetry of PDN operation modes [11-14]. The problem also lies in the fact that most PDNs belong to the class of large dynamic systems, which have a complex structure and function under conditions of incomplete information about their states and parameters. In [15, 16] some approaches to identification of power losses in 0.4 kV distribution networks are proposed. The article considers algorithmic problems related to the development of these approaches.

Task definition

We consider a four-conductor 0.4 kV PDN, the conditional design scheme of which is shown in Fig. 1, where k, ν - index variables, representing phase numbers, respectively A, B, C $(k = \overline{1,3})$ and the network's electrical circuits $(\nu = \overline{1,n})$; $\widetilde{E_k}$ – instantaneous electromotive force of power supply source for $k-$ phase; $\tilde{I}'_{k\nu}$, $\widetilde{U}'_{k\nu}$, $\dot{Z}_{k\nu}$ – sinusoidal instantaneous current, voltage and complex load resistance of the customer with coordinate (k, ν) correspondingly; $\tilde{\imath}'_{k\nu}, \dot{z}_{k\nu}$ – sinusoidal instantaneous current and complex resistance of ν - inter-customer site of k phase; $\tilde{J}'_{\nu}$, $\dot{z}_{\nu}$ – instantaneous current and complex resistance of ν – site of neutral conductor; $\tilde{I}'_{k}$, $\widetilde{U}'_{k}$ – instantaneous currents and voltages at the inputs of the corresponding phases.

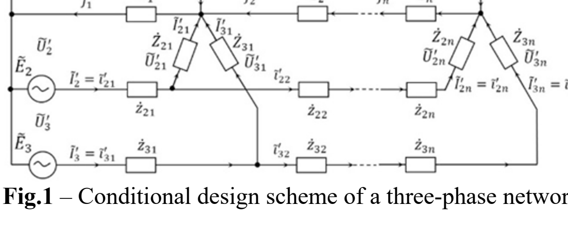

Fig.1 – Conditional design scheme of a three-phase network.

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Let us assume that the following conditions are fulfilled:

1. The distribution network operates in asymmetrical mode;

2. There are unauthorized power withdrawals (UPW) in the network;

3. Cross-sections of phase and neutral conductors are assumed to be the same, i.e. $\dot z_{k\nu} = \dot z_\nu$;

4. At discrete time moment $\underline{t = t_\xi}$ synchronous measurements of the effective values of currents I'_k, $I'_{k\nu}$ and voltages U'_k, $U'_{k\nu}$ at the inputs of phases and loads of the network, respectively, as well as power factors $c_k = \cos\varphi'_k$ and $c_{k\nu} = \cos\varphi'_{k\nu}$ between them are performed using the ASCMPC electricity meters. The received information is recorded in the ASCMPC database and vectors of input phase currents $I' = [I'_1, I'_2, I'_3]$ are formed on their basis. According to the above data, the active P_κ, $P_{\nu\kappa}$ and reactive Q_κ, $Q_{\kappa\nu}$ powers consumed by the phases and customers of the network, respectively, are determined using known formulas.

At the moment $(t = t_\xi)$ of synchronous measurements of electricity meter readings included in the ASCMPC, the distribution network may be in operative (normal, desired) (C^o) or disturbed (C') state. There are no uncontrolled power losses in the network in the first case (state C^o). There are uncontrolled power losses in at least one of its phases in the disturbed state of the network (C'). In this case, the following balance ratios for capacities are valid:

$$\dot S_\kappa(\xi) = \dot S^a_\kappa(\xi) + \dot S^T_\kappa(\xi) + \Delta\dot S_\kappa(\xi), \quad \kappa = \overline{1,3}, \quad (1)$$

where $\dot S_\kappa(\xi)$ – total capacity, consumed by κ phase at the time moment $t = t_\xi$; $\dot S^a_\kappa(\xi)$ – total complex power consumed by customers of κ phase; $\dot S^T_\kappa(\xi)$ – technical power losses in κ phase; $\Delta\dot S_\kappa$- uncontrolled power losses in κ phase of the network, caused by the presence of UPWs in the PDN.

Thus powers $\dot S_\kappa(\xi)$ and $\dot S^a_\kappa(\xi)$ are known values, as in the existing ASCMPC it is possible to calculate their values according to the data of active and reactive powers received from the balance meter and customer meters using known formulas:

$$\dot S_\kappa(\xi) = P_\kappa(\xi) + jQ_\kappa(\xi), \quad (2)$$

$$\dot S^a_\kappa(\xi) = \sum_{\nu=1}^{n} \dot S_{\kappa\nu}, \quad k = \overline{1,3}, \quad (3)$$

where $\dot S_{k\nu} = P_{k\nu} + jQ_{k\nu}$; $j = \sqrt{-1}$ – imaginary value.

It shall be noted that technical power losses $\dot S^T_k(\xi)$ and commercial losses $\Delta\dot S_\kappa(\xi)$ in standard ASCMPC are not defined separately. Only the total $\dot S^\Sigma_k(\xi)$ power losses are estimated in existing ASCMPCs based on measurement data, i.e.

$$\dot S^\Sigma_k(\xi) = \dot S^T_k(\xi) + \Delta\dot S_\kappa(\xi) = \dot S_k(\xi) - \dot S^a_k(\xi), k = \overline{1,3}.$$

The task is to identify commercial $\Delta\dot S_\kappa(\xi)$ and technical $\dot S^T_k(\xi)$ power losses in real time based on measurement data obtained from ASCMPC electricity meters.

The solution of the generated identification problem includes the following main stages:

1. Building a virtual network (VN) model.
2. Identification of the current condition of the real network.
3. Formation of the general scheme of identification of power losses in PDN.
4. Estimation of input desired phase currents of the virtual network.
5. Estimation of currents of unauthorized customers.
6. Construction of the algorithm for identification of power losses in the network.

Building a virtual network (VN) model

It can be noted that the identification problem under consideration belongs to the class of those problems in which the initial data and conditions for its solution are not fully specified, i.e. the problem should be solved under conditions of insufficient information about the state of the real network. This uncertainty is due to the lack of data on unauthorized consumers, such as their coordinates and load parameters. Under these conditions, in order to solve the identification problem formulated above, we further introduce the concept of virtual network (VN) model, which describes the desired state of the real PDN under certain conditions. The analysis shows that for this purpose it is reasonable to introduce two types of virtual networks (Fig. 2):

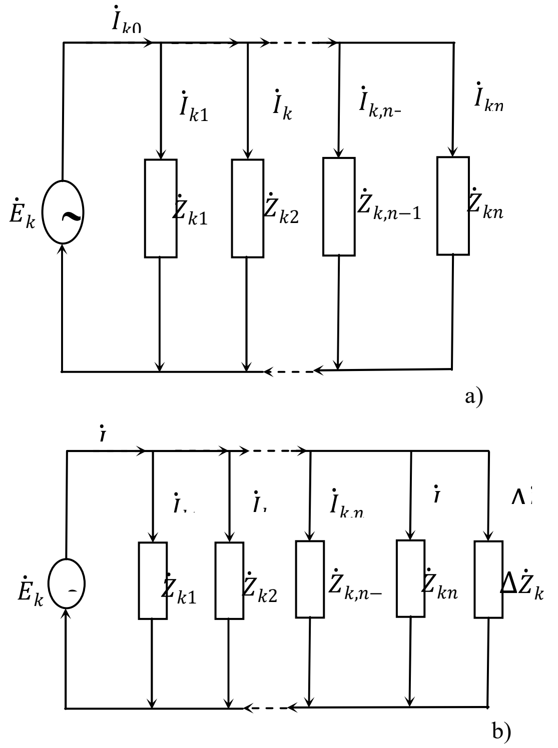
1. Virtual network of the first type (BC_1), which is characterized by the fact that there are no uncontrolled power losses $\Delta\dot S_k$, and the inter-customer resistances $\dot z_{k\nu}$ have zero values (Fig. 2a):

$$\Delta\dot S_\kappa=0, \quad k = \overline{1,3}, \quad \dot z_\nu=0, \quad \nu = \overline{1,n}. \quad (4)$$

2. Second virtual network (VN_2) - there are UPWs, i.e., the following conditions are fulfilled (Fig. 2b):

$$\Delta\dot S_k \neq 0, k = \overline{1,3}, \quad (5)$$

As well as ratios (4). Here $\dot E_k$ – complex electromotive force of network supply source; $\dot I_{k\nu}$, $\dot Z_{k\nu}$ – complex current and resistance of the virtual customer load, having the coordinate (k, ν); $\dot I_{k0}$, $\dot I_k$- complex current at the inputs of k –phase BC_1 and BC_2 respectively; $\Delta\dot I_k$, $\Delta\dot Z_k$ – complex current and resistance of load of unauthorized customer connected to the corresponding phase of the PDN. Next, without loss of generality of the task and for the sake of brevity, let us consider the k phase of the virtual network to which *n* customers are connected.



a)

b)

Fig. 2 – Virtual networks diagrams.

Input phase currents $\dot I_{k0}$ BC$_1$ characterize the normal operation mode of the considered real distribution network in the absence of uncontrolled currents $\Delta \dot I_k$. Therefore, hereafter we will call them the desired phase currents. A comparative analysis of the structures of the original PDN (Fig. 1) and virtual networks (Fig. 2) under conditions (4) and (5) shows that the following ratios for the complex currents $\dot I_k$, $\dot I_{k0}$ and $\Delta \dot I_k$ are valid:

$$\dot I_{k0} = \sum_{\nu=1}^{n} \dot I'_{\kappa\nu}, \quad k = \overline{1,3}, \tag{6}$$

$$\dot I_k = \dot I_{k0} + \Delta \dot I_k, \ k = \overline{1,3}, \tag{7}$$

where $\dot I_k = \dot I'_k$.

Current values $\dot I_{k\nu}$ and voltage values $\dot U_{k\nu}$, describing the state of the virtual networks differ from their corresponding values characterizing the state of the initial - real PDN (Fig.1.), i.e $\dot I_{k\nu} \neq \dot I'_{k\nu}$, $\dot U_{k\nu} \neq \dot U'_{k\nu}$. At the same time, the values of resistances $\dot Z_{k\nu}$ of the loads of customers of real and virtual networks have the same values. Further, we will represent the above network variables in the following complex form [17]:

$$\dot I_{k\nu} = I_{k\nu}\, e^{j(\beta_k + \alpha_{k\nu})}, \tag{8}$$

$$\dot Z_{k\nu} = Z_{k\nu}\, e^{j\varphi_{k\nu}}, \ k = \overline{1,3}\,, \nu = \overline{1,n},$$

where $I_{k\nu}, Z_{k\nu}$ - modules of the corresponding complex values; $\varphi_{k\nu}$ - resistance argument $\dot Z_{k\nu}$; $\propto_{k\nu}$ - deviations of phase shifts from their basic values β_k, defined by formulas $\beta_k = \frac{2(k-1)\pi}{3}$.

Complex resistances $\dot Z_{k\nu}$ of loads of network customers are known values which are calculated on the basis of readings (data) of customer electricity meters according to the formulas:

$$Z_{k\nu} = \frac{U'_{k\nu}}{I'_{k\nu}}, \ \varphi_{k\nu} = arccos(\mathrm{c}_{k\nu}), \tag{9}$$

Relevant conductivities$\dot Y_{k\nu}$ of loads of network customers:

$$\dot Y_{k\nu} = \frac{1}{\dot Z_{k\nu}} = Y_{k\nu} e^{-j\varphi_{k\nu}}, k = \overline{1,3}\,, \nu = \overline{1,n}, \tag{10}$$

where $Y_{k\nu}$= $\frac{1}{Z_{k\nu}}$. At the same time, the powers $\dot S_{k\nu}$, consumed by the network customers and included in expressions (3) are determined by the formulas:

$$\dot S_{k\nu} = (I'_{k\nu})^2 \dot Z_{k\nu}, k = \overline{1,3}\,, \nu = \overline{1,n}. \tag{11}$$

Identification of the current state of the real network

Under the conditions of the task under consideration, the current values of phase currents $I'_k = I'_k(t_0)$ at the input of the initial real distribution network (Fig. 1) at time $t = t_0$ are measured by the balance three-phase meter, which are contained in the ASCMPC database in the form of vector $I' = [I'_1, I'_2, I'_3]$. The complex currents of unauthorized consumers $\Delta \dot I_k$ can be represented as:

$$\Delta \dot I_k = \Delta I_k\, e^{j(\beta_k + \Delta\alpha_k)}, \ k = \overline{1,3}, \tag{12}$$

where ΔI_k, $\Delta\alpha_k$ – modules and phases of complex currents $\Delta \dot I_k$ respectively. Estimates of the effective values of ΔI_k will be identified later.

The analysis shows that it is reasonable to use the following conditions to identify the current state of the PDN:

$$\Delta I_k \leq \Delta I, \ k = \overline{1,3}, \tag{13}$$

where ΔI – maximum permissible error of current measurement in ASCMPC.

Obviously, if at least one of the ratios (13) is not fulfilled, there are UPW in the network, and their fulfillment means that the PDN operates in the normal mode. Thus, ratios (13) can be used as a criterion condition for identifying the current state of the PDN.

Formation of a general scheme for identification of capacity losses

We will consider the virtual network diagrams shown in Fig. 2. Let us denote by $\dot S'_k$ the powers consumed by the loads of the k-phase of BC2. The analysis shows that there are following balance ratios between the powers $\dot S'_k, \dot S^a_k$ and $\triangle \dot S_k$:

$$\dot S^a_k + \triangle \dot S_k = \dot S'_k, \ k = \overline{1,3}, \tag{14}$$

Where the total power $\dot S^a_k$ consumed by the loads of the k-phase is determined by formula (3). Each of these components, when conditions (4) and (5) are fulfilled, is determined by the following functional dependencies:

$$\dot S^a_k = {I_{k0}}^2 \dot Z_{k0}, \ \dot S'_k = {I_k}^2 \dot Z_k, \tag{15}$$

$$\triangle \dot S_k = {\triangle I_k}^2 \triangle \dot Z_k, \ k = \overline{1,3},$$

where $\dot Z_{k0}, \dot Z_k$,- total resistances of virtual phases shown on Fig 2a and Fig. 2b respectively; $\triangle \dot Z_k - load\ resistance$ of unauthorized consumer connected to the phase of number k. Estimates of unknown values included in ratios (15) will be defined later.

As can be seen from Figure 2, the corresponding conductivities are determined by the following formulas:

$$\dot{Y}_{k0} = \sum_{v=1}^{n} \dot{Y}_{kv}, \dot{Y}_k = \dot{Y}_{k0} + \Delta\dot{Y}_k, \qquad (16)$$
$$\dot{Y}_{k\nu} = \frac{1}{\dot{Z}_{k\nu}}, \qquad \Delta\dot{Y}_k = \frac{1}{\Delta\dot{Z}_{k,}}.$$

Now, taking into account (15) and (16), ratios (14) can be represented in the form:

$$I_{k0}^2\dot{Z}_{k0} + \frac{\triangle I_k^2}{\triangle \dot{Y}_k} = \frac{I_k^2}{\dot{Y}_{k0} \dot{+}\triangle \dot{Y}_k}, \qquad k = \overline{1,3}.$$

After simple transformations the last equations will be written in the form:

$$a_k(\triangle \dot{Y}_k)^2 + b_k\Delta\dot{Y}_k + c_k = 0,\ k = \overline{1,3}, \qquad (17)$$

Where coefficients a_k, b_k, c_k are determined by the formulas:

$$a_k = \dot{S}_k^a,$$
$$b_k = \dot{S}_k^a\dot{Y}_k^0 + \triangle I_k{}^2 - I_k{}^2,$$
$$c_k = \Delta I_k{}^2\dot{Y}_k^0.$$

To solve the quadratic equations (17), we can use the well-known Veta formula:

$$\Delta\dot{Y}_k = \frac{-b_k \pm \sqrt{b_k{}^2 - 4a_kc_k}}{2a_k}, \qquad k = \overline{1,3}. \qquad (18)$$

As a result, the required load resistances $\triangle\dot{Z}_k$ of unauthorized consumers will be determined:

$$\Delta\dot{Z}_k = \frac{1}{\Delta\dot{Y}_k},\ k = \overline{1,3}. \qquad (19)$$

Then the required values of power losses $\Delta\dot{S}_k$ caused by unauthorized withdrawals in the phases of the real network, taking into account (8), are calculated by the formulas:

$$\Delta\dot{S}_k = \frac{\Delta I_k{}^2}{\Delta\dot{Y}_k},\ k = \overline{1,3}, \qquad (20)$$

where the effective values of currents of unauthorized consumers $\Delta\, I_k$ will be defined further.

Now, based on the balance ratios (1), we determine the values of technical losses $\dot{S}_k^T$ of capacities in the phases of the real network:

$$\dot{S}_\kappa^T(\xi) = \dot{S}_\kappa(\xi) \dot{-} S_\kappa^a(\xi) - \Delta\dot{S}_k, k = \overline{1,3}, \qquad (21)$$

Where $\dot{S}_\kappa(\xi) -$ complex capacity, consumed by k phase of the real network at the time moment $t = t_\xi$, which is calculated from the data of the balance three-phase electricity meter according to formulas (2).

Let us assume that data collection from the ASCMPC meters is performed at discrete moments of time $t = t_{\xi,}$ $t = t_{\xi+1}$, $t = t_{\xi+2}$, …, $t = t_{\xi+m}$. Then the use of the above computational procedure on the basis of these data makes it possible to perform automated operational control and monitoring of power losses in PDN in real time.

Estimation of input desired phase currents of the virtual network

To calculate the effective values of the input desired currents I_{k0} BC$_1$, we write the first ratios of the system (15) in the form:

$$\dot{S}_k^a = \frac{I_{k0}{}^2}{\dot{Y}_{k0}}, \qquad k = \overline{1,3}. \qquad (22)$$

Now let us represent the complex quantities $\dot{S}_k^a$ and $\dot{Y}_{k0}$ in exponential form:

$$\dot{S}_k^a = S_k^a e^{j\varphi_k^a}, \qquad (23)$$
$$\dot{Y}_{k0} = Y_{k0}\, e^{-j\varphi_k^a}, k = \overline{1,3}\,,$$

where $S_k^a, Y_{k0}, \varphi_k^a$ – modules and phases of complex values $\dot{S}_k^a$ and $\dot{Y}_{k0}$ respectively.

Ratios (22) taking into account (23) have the form:

$$S_k^a e^{j\varphi_k^a} = \frac{I_{k0}{}^2}{Y_{k0}} e^{j\varphi_k^a}, k = \overline{1,3}. \qquad (24)$$

Based on equations (24), we obtain the numerical values of the desired input desired phase currents I_{k0} of the virtual network, since S_k^a and Y_{k0} are known values:

$$I_{k0} = \sqrt{S_k^a Y_k^a} = \sqrt{\frac{S_k^a}{Z_k^a}}, k = \overline{1,3}. \qquad (25)$$

Estimation of currents of unauthorized consumers

For this purpose, based on ratios (7), let us write expressions for the complex currents $\Delta\dot{I}_k$of unauthorized consumers:

$$\Delta\dot{I}_k = \dot{I}_k - \dot{I}_{k0}, k = \overline{1,3}. \qquad (26)$$

Preliminarily these currents are represented in exponential form

$$\dot{I}_k = I_k e^{j(\beta_k+\alpha_k)},$$
$$\dot{I}_{k0} = I_{k0} e^{j(\beta_k+\alpha_k^0)},$$

where $I_k, I_{k0}, \alpha_k, \alpha_k^0$ – effective values and phase shifts of related complex currents.

It can be shown that the parameters of the indicated currents satisfy the following equations:

$$\Delta I_k{}^2 - I_k{}^2 - I_{k0}{}^2 + 2I_kI_{k0}\cos\theta_k = 0\,,$$
$$I_k{}^2 - I_{k0}{}^2 - \Delta I_k{}^2 - 2\Delta I_kI_{k0}\cos\eta_k = 0, \qquad (27)$$
$$\Delta I_{k0}{}^2 - \Delta I_k{}^2 - I_k{}^2 + 2\Delta I_kI_k\cos(\lambda_k) = 0,$$

where $\eta_k, \theta_k, \lambda_k -$ phase shift differences defined by the formulas:

$$\eta_k = \alpha_k^0 - \Delta\alpha_k, \lambda_k = \alpha_k - \Delta\alpha_k, \theta_k = \lambda_k - \eta_k, k = \overline{1,3}.$$

The aggregate of ratios (27) is a system of algebraic equations that includes three equations with three unknown values ΔI_k, η_k and λ_k. The analysis of ratios (27) has shown that the required currents ΔI_k are determined on the basis of the solution of the following equations:

$$\Delta I_k^4 + e_k\Delta I_k^2 + r_k^2$$
$$+ q_k\sqrt{\Delta I_k^8 + m_k\Delta I_k^6 + d_k\Delta I_k^4 + s_k\Delta I_k^2 + r_k^4} = 0,$$
$$k = \overline{1,3}, \qquad (28)$$

Where their coefficients are known values, which are determined by the formulas:

$$e_k = -2f_k, f_k = I_k^2 + I_{k0}^2,$$
$$r_k = I_k^2 - I_{k0}^2, m_k = -4f_k,$$
$$d_k = 16I_k^2I_{k0}^2 + 6r_k^2, s_k = -4f_kr_k^2.$$

The choice of the sign function q_{kv} is carried out as follows:

$$q_{k1} = \begin{cases} +1, if\ sign(\Delta I_k^4 + e_k \Delta I_k^2 + r_k^2) < 0, \\ -1, if\ sign(\Delta I_k^4 + e_k \Delta I_k^2 + r_k^2) > 0. \end{cases}$$

The solution of the algebraic equation (28) for a given k does not present special difficulties on the basis of numerical methods [18-20], since its approximate solution ΔI_{k0} can be obtained on the basis of ratio (26), i.e., $\Delta I_{k0} = I_k - I_{k0}$.

General algorithm for identification of power losses in the network

Based on the obtained results, the following enlarged algorithm for identification and monitoring of power losses in the distribution network can be formulated.

1. Cyclic polling of the balance three-phase and ASCMPC customer electricity meters at a discrete moment of time$t = t_\xi$.
2. Recording of the received information into the ASCMPC database and formation of vectors $I' = [I_1', I_2', I_3']$.
3. Calculation of complex resistances $\dot{Z}_{kv}$ and conductances $\dot{Y}_{kv}$, as well as powers $\dot{S}_{kv}$, consumed by the network customers according to formulas (9) - (11), respectively.
4. Estimation of total powers $\dot{S}_k^a$ and resistances $\dot{Z}_k^a$ using formulas (3) and (24), respectively.
5. Determination of input desired phase currents I_{k0}, $k = \overline{1,3}$, by formulas (25).
6. Identification of uncontrolled current values $\Delta I_k, k = \overline{1,3}$ by solving algebraic equations (28).
7. Verification of the current state of the PDN by checking the conditions (13).
8. If ratios (13) are fulfilled, there are no UPWs in the network. Pass to item 1. Otherwise, proceed to item 9.
9. Determination of conductances $\Delta \dot{Y}_k$ by solving equations (17).
10. Estimation of commercial $\triangle \dot{S}_k$ and technical $\dot{S}_k^T$ $(k = \overline{1,3})$ power losses in the PDN by formulas (20) and (21), respectively, at time $t = t_\xi$.
11. Go to point 1 and repeat the computational procedure for consecutive time instants $t = t_{\xi+m}$, where $= 1, 2, 3, \ldots$.

Conclusions

The practice of operation of modern ASCMPC used for control and metering of electric power in 0.4 kV distribution networks shows that they essentially lack digital technologies allowing to effectively solve the tasks of operational identification and monitoring of power losses with separate identification and estimation of such components as technical and commercial losses. A new computational algorithm for solving this problem based on the concept of a virtual model of a distribution network describing its desired state in the absence of external random factors, which, in particular, include unauthorized power withdrawals, is proposed. This utilizes measurement data received via communication channels from electricity meters installed in the transformer substation and at network customers. Systems of algebraic equations that describe functional relationships between variables and parameters of a virtual model of a three-phase network are obtained. Methods for solving these equations and a generalized algorithm for identifying and monitoring technical and commercial power losses in the distribution network are proposed. The obtained results are oriented for the development of algorithmic and special software for the subsystem of operational monitoring of power losses in PDN as part of ASCMPC.

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