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# Allocation of power losses and energy in the distribution network

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***Abstract.*** The goal is to determine methods for calculating power losses in a three-phase four-wire low voltage distribution network using measurements of a balance smart meter and consumer smart meters, and to establish the factors influencing the power losses and their allocation among individual network wires, loads, and consumers. The study involved examining three methods for determining power losses for current measurement snapshot. The first method suggests calculating losses as the difference between the power supplied to the network and the total power consumed. The second method calculates power losses using the contribution method. The third method, which in addition to measurement information requires knowledge of the topology and parameters of the network components, determines power losses based on the results of the state estimation method. The research proposes an algorithm for transition from a four-wire distribution network modeling to a three-wire one. The algorithm allocates power losses of the neutral wire among the phase wires. The findings indicate that the negative losses in the network with unbalanced phase loads are caused by the presence at the nodes of the least loaded phase of higher voltage than the voltage at the power supply node. The reason for higher losses in phases with minimal load is the uneven allocation of loads in the phases. In addition, the study reveals that the power loss values obtained by the contribution method, i.e. directly from the measurements of smart meters, are closer to the losses determined from the readings of the balance meter and consumer meters, compared to the losses found from the state estimation results. The considered methods for calculation and allocation of power losses are illustrated by an example of a real-world distribution network equipped with smart meters. The paper demonstrates the examples of allocating total power losses between phase wires and a neutral wire, among phase wires only, and between total loads at phase nodes and individual consumers in phases.

***Keywords:*** distribution network, smart meters, power losses, allocation of power losses

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ЭНЕРГЕТИКА

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# Разнесение потерь мощности и энергии в распределительной сети

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***Резюме.*** Цель – определение способов вычисления потерь энергии в трехфазной четырехпроводной распределительной сети низкого напряжения с использованием измерений балансового интеллектуального счетчика и интеллектуальных счетчиков потребителей, и установление факторов, влияющих на потери, а также разнесение потерь между отдельными проводами сети, нагрузками и потребителями. Анализируется три способа расчета потерь для текущего среза измерений. В первом способе потери определяются как разность поступающей в сеть мощности и мощности суммарного потребления, во втором расчет потерь производится методом адресности. В третьем способе, для которого помимо информации об измерениях требуется знание топологии и параметров элементов схемы сети, потери определяются по результатам метода оценивания состояния. Предложен алгоритм перехода от четырехпроводного моделирования распределительной сети к трехпроводному, заключающийся в разнесении потерь мощности в нейтральном проводе между фазными проводами. Показано, что в сети с несбалансированными нагрузками фаз причиной отрицательных потерь является наличие в узлах наименее загруженной фазы более высоких напряжений, чем напряжение в узле питания. Установлено, что причиной более высоких потерь в фазах с минимальной нагрузкой является неравномерность распределения нагрузок в фазах. Кроме того, установлено, что значения потерь, полученных методом адресности, т.е. непосредственно по измерениям интеллектуальных счетчиков, ближе к потерям по показаниям балансового счетчика и счетчиков потребителей по сравнению с потерями, найденными по результатам оценивания состояния режима сети. Рассмотренные методы расчета и разнесения потерь проиллюстрированы на примере реальной распределительной сети, оснащенной интеллектуальными счетчиками, приведены примеры разнесения суммарных потерь мощности между фазными проводами и нейтральным проводом, только между фазными проводами, между суммарными нагрузками в узлах фаз и отдельными потребителями в фазах.

***Ключевые слова:*** распределительная сеть, интеллектуальные счетчики, потери активной мощности, разнесение потерь

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## INTRODUCTION

Large-scale introduction of smart meters in low-voltage secondary distribution networks allows measurement of energy consumed by loads and of voltage magnitudes. Such information is the main means for solving the problems of state monitoring and for assessment of power losses and their reduction that determine the efficiency of an intelligent network.

The paper analyzes possible approaches to determining energy losses from measurements of smart meters and the factors affecting the allocation of losses between phase wires and the neutral wire. We show the possibility of allocating losses between total loads or individual consumers connected to phases of a three-phase four-wire secondary distribution network.

The problem of losses allocation between consumers is not a new one. It emerged in the late 1990s in connection with the development of market relations in the electric power industry when a need for determination of the share of energy sources in power supply of specific loads and for determination of losses occurring in the networks during energy transmission that are to be compensated by players of the electricity market became obvious. An unambiguous solution using matrix [1] and graph [2] algorithms that can also be applied to an opened distribution network was found to the problem of power flows allocation in the transmission network. For a unique allocation of power losses between consumers, the losses were proposed to be determined as a difference between power transmitted to a consumer from the power source and power received by a consumer [3]. The paper demonstrates that this method is also valid for an opened distribution network, however, many papers published recently analyze other possible approaches to the allocation of losses between phases of a distribution network or between phases and a neutral wire [4–8].

The most important characteristics of a three-phase four-wire network that distinguish it from high-voltage networks are: operation of a network as an opened one; imbalance of phase loads that can be single-phase, two-phase, and three-phase ones; the impedance ratio, as a rule, is r/x>1 [9]; equal dependence of voltage on both active and reactive power. To take into account the imbalance of a secondary distribution network, its three-phase four-wire model [10, 11] shown in Fig. 1 is used.

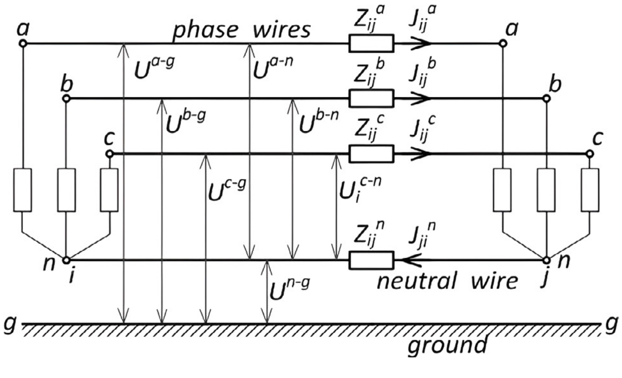


***Fig. 1. The equivalent circuit for a section of a three-phase four-wire network without a ground conductor***
***Рис. 1. Схема замещения секции трехфазной четырехпроводной сети без заземлений нейтрального провода***

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All the considered approaches to calculating the power losses in the distribution network use data on the average hourly measurements in the supply node and in the load nodes of each phase of active and reactive power of loads and voltage magnitudes relative to a neutral wire [9] that are synchronously made by smart meters [13, 14] over a long period of time. That information is stored in the protocols of Automatic System for Commercial Accounting of Power Consumption (ASCUE) [12] analogous to the Advanced Metering Infrastructure (AMI) [14, 15].

## METHODS FOR CALCULATION AND ALLOCATION OF LOSSES IN THE DISTRIBUTION NETWORK

***Use of balance meter measurements.*** Under the availability of a smart three-phase balance meter in the power supply node of a distribution network the difference between energy supplied to each phase and total energy consumed by its loads within an hour is the easiest way to calculate hourly losses, total hourly energy losses in the feeder being equal to total energy losses in three phases. This method of loss calculation does not require data on the parameters of the network equivalent circuit, but requires information about the topology of the distribution network and information about the phases to which the smart meters are connected [15–17]. It also does not allow one to divide losses into technical and commercial ones, losses due to electricity theft or due to non-recorded power consumption, for example, for lighting. However, should all the consumers be equipped with smart meters, and should there be no electricity theft, it is the difference between energy supplied to the phase and total energy supplied to consumers can, in our opinion, be the best criterion for evaluating the approaches to allocation of total losses in the feeder between phases.

***Calculation of losses based on the results of state estimation.*** Use of the results of state estimation that unlike the previous method requires the availability of additional data on the parameters of components of an equivalent circuit of a distribution network is the most common way of loss calculation.

In the simple iteration method used in the paper, an iteration-based calculation of voltage at each *k*-th iteration of state estimation includes three stages [11, 18, 19].

Nodal currents in phase wires and in a neutral wire are determined first based on the measurements of power and voltage [11]. Then voltages $\dot{U}_{i_k}^{f,n} = u_{i_k}^{'f,n} + ju_{i_k}^{''f,n}$ of phase *f* = *a, b, c* wires to ground and of a neutral *n* wire to ground are determined based on the solution of an over determined system of a linear equation for phase wire and a neutral wire [11]. Voltages of phase wires to a neutral wire are finally determined as a vector difference between vectors of nodal voltages of phase wires to ground and nodal voltages of a neutral wire to ground $\dot{U}_{i\,k+1}^{f-n} = \dot{U}_{i\,k}^{f} - \dot{U}_{i\,k}^{n}$ [11].

Use of voltages of phase wires and a neutral wire to ground $\dot{U}_{i_k}^{f,n}$ and of phase wires to a neutral wire $\dot{U}_{i\,k+1}^{f-n}$ allows independent consideration of load flows both in a four-wire network and in a three-wire network; in this case only currents $\dot{I}_{i-j}^{f}$ in phase wires coincide in both representations of the network [11].

Load flows $P_{i-j}^{f,n}$, $P_{j-i}^{f,n}$ at the beginning and at the end of sections $i-j$ of phase wires and of a neutral wire in the four-wire network that are computed using conjugated complexes of currents $I^{*f,n}_{i-j}$ and voltages of phase wires to ground and of a neutral wire to ground [11] are equal to:

$$P_{i-j}^{f,n} = real\left(I^{*f,n}_{i-j}\dot{U}_i^{f,n}\right),$$
$$P_{j-i}^{f,n} = real\left(I^{*f,n}_{i-j}\dot{U}_j^{f,n}\right). \quad (1)$$

Load flows $P_{i-j}^{f-n}$, $P_{j-i}^{f-n}$ at the beginning and the end of sections *I - j* of a feeder are determined using voltages of phase wires to neutral wire [11] and differ from load flows in phase wires $P_{i-j}^{f}, P_{j-i}^{f}$ by the value $I^{*f}_{i-j}\dot{U}_i^{n}$, $I^{*f}_{i-j}\dot{U}_j^{n}$ that is equal to a production of a conjugated complex of current in section $I^{*f,n}_{i-j}$ by voltage of a neutral wire to ground

$$P_{i-j}^{f-n} = real\left(I^{*f}_{i-j}\dot{U}_i^{f-n}\right) = real\left(I^{*f}_{i-j}\dot{U}_i^{f} - I^{*f}_{i-j}\dot{U}_i^{n}\right),$$
$$P_{j-i}^{f-n} = real\left(I^{*f}_{i-j}\dot{U}_j^{f-n}\right) = real\left(I^{*f}_{i-j}\dot{U}_j^{f} - I^{*f}_{i-j}\dot{U}_j^{n}\right). \quad (2)$$

Power losses in the section using expressions (1) are determined as

$$\Delta P_{i-j}^{f,n} = P_{i-j}^{f,n} - P_{j-i}^{f,n} = real\left(I^{*f,n}_{i-j}\left(\dot{U}_i^{f,n} - \dot{U}_j^{f,n}\right)\right), \quad (3)$$

and for expression (2) as

$$\Delta P_{i-j}^{f-n} = P_{i-j}^{f-n} - P_{j-i}^{f-n} = real\left(I^{*T}_{i-j}\left(\dot{U}_i^{f} - \dot{U}_j^{f}\right) - I^{*T}_{i-j}\left(\dot{U}_i^{n} - \dot{U}_j^{n}\right)\right). \quad (4)$$

The value of expression $I^{*f}_{i-j}\left(\dot{U}_i^{n} - \dot{U}_j^{n}\right)$ determines the difference between active power losses in the phases of a three-phase three-wire network and those in the four-wire network [11].

The value of expression determines the difference between active power losses in the phases of a three-wire three-phase network and those in the four-wire network

$$\Delta P^{n}_{i-j} = real\left(-I^{*a}_{i-j}\left(\dot{U}^{n}_{i}-\dot{U}^{n}_{j}\right)-I^{*b}_{i-j}\left(\dot{U}^{n}_{i}-\dot{U}^{n}_{j}\right)-I^{*c}_{i-j}\left(\dot{U}^{n}_{i}-\dot{U}^{n}_{j}\right)\right)= real\left(I^{*n}_{i-j}\left(\dot{U}^{n}_{i}-\dot{U}^{n}_{j}\right)\right), \quad (5)$$

where conjugated current in a neutral wire equals the sum of currents in phase wires with a negative sign [18]

$$I^{*n}_{i-j} = \left(I^{n}_{a\,i-j} - jI^{n}_{p\,i-j}\right) = -\left(I^{*a}_{i-j} + I^{*b}_{i-j} + I^{*c}_{i-j}\right). \quad (6)$$

Thus, expression (6) allows one to allocate losses in a neutral wire between phase wires. Possibility of occurrence of negative values of losses in separate sections of feeders and total losses in separate phases is an important peculiarity of such an allocation of losses in a neutral wire.

## CALCULATION OF LOSSES DIRECTLY BASED ON READINGS OF SMART METERS

Calculation of losses based on the data of average hourly measurements of single-phase and three-phase smart meters installed in the nodes of consumers' connection to a distributed feeder is another possibility of using expression (4) for determination of power losses [12, 20]. It should be noted that voltage magnitudes in the load nodes that are used in this method for losses calculation are voltages to a neutral wire [12].

Total losses of active power in the phase in this method are determined as a sum of losses that is equal to difference between power supplied from the supply node of a distribution network numbered as 1 to every load node $i$, and to load in the $i$-th node

$$\Delta P^{f-n} = \sum_{i=2}^{m}\left(P^{f\ \ trans}_{1-i} - P^{f}_{i}\right) = \sum_{i=2}^{m}\left(\frac{U_1^{\,f-n}}{U^{f-n}_{i}}P^{f}_{i} - P^{f}_{i}\right) = \sum_{i=2}^{m}\left(\frac{U_1^{\,f-n} - U^{f-n}_{i}}{U^{f-n}_{i}}P^{f}_{i}\right), \quad (7)$$

hence, for calculation of losses occurring during transmission of average hourly power (energy per hour) from node 1 of feeder supply to $i$-th load node or to $i$-th consumer, simultaneous measurements in each phase of voltage magnitude to a neutral wire in nodes 1 and $i$, and active power of load in the $i$-th node of the feeder or of the $i$-th consumer are needed. Identification of phases of consumer connection to feeders is a required initial stage of such calculations.

Analysis of expression (7) explains occurrence of negative power losses in the feeder's sections. Imbalance of phase loads in a three-phase distribution network originates currents in a neutral wire. The higher the imbalance of phase currents, the higher will be the current occurring in a neutral wire. Current increase in a neutral wire causes increase of voltage in it and change in the voltages of phase wires to a neutral wire. It is known [11] that this voltage in the least loaded phase, especially in its dangling node, may become higher than voltage in the power supply node when difference between voltages $U_1^{\,f-n} - U^{f-n}_{i}$ and power losses at estimation of its transfer from a supply node to a node with higher voltage will be negative.

Determination of consumer's load contribution into total losses for every phase requires neither the knowledge on topology nor on parameters of an equivalent circuit. It suffices to have a list $m$ of consumers and readings of voltage and load for each consumer. Should several smart meters be installed on the supports of the main feeder, each support can be assigned the number of a load node, and then an average hourly total capacity of load and average hourly voltage magnitude can be computed for each phase.

It is this information on readings in the nodes of each phase that is used for assessing the contribution of losses in the phase into total losses in the feeder. Lower requirements to observability (lower that those to state estimation) are a peculiar feature of such calculation of losses. Actually, computation of active power losses does not require knowledge on reactive loads, whereas under the lack of measurements in some nodes or at individual consumers one can assess only losses related to power transfer to consumers equipped with smart meters.

## ILLUSTRATION OF THE WAYS OF ALLOCATION OF LOSSES IN A LOW-VOLTAGE DISTRIBUTION NETWORK FEEDER

Methods for losses computation and allocation are further exemplified by data taken from ASKUE Protocols of a real feeder of a low voltage distribution network for maximum winter and minimum summer loads. There are 25 private houses with three-phase and single-phase loads that are connected to a feeder, Fig. 2. Average hourly values of active and reactive power and magnitudes of voltages in phases are measured by three-phase and single-phase smart meters installed on nine out of 11 supports of the main feeder. Average hourly values of active and reactive power entering from the feeder supply node and voltage in the supply node are measured by a balancing three-phase meter. Phases of consumer connection to

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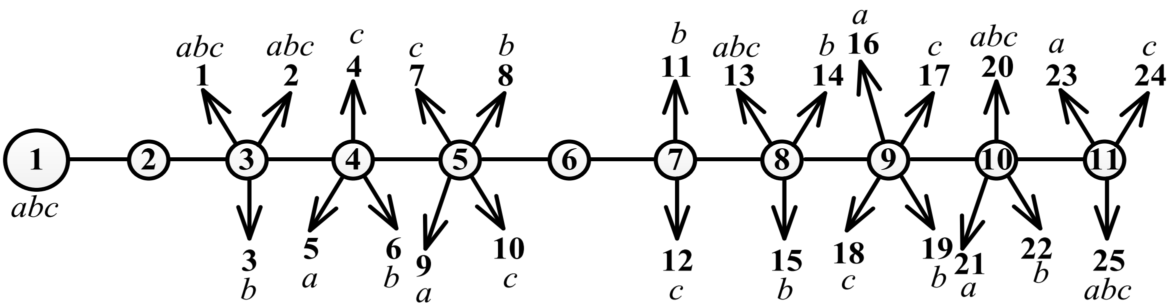

*Fig. 2. A feeder of a distribution network*
*Рис. 2. Фидер распределительной сети*

the feeder were determined at the initial stage of studies. It showed that 10 consumers are connected to phase *a*; 13 consumers are connected to phase *b*, and 12 consumers are connected to phase *c*. Average hourly magnitudes of active and reactive loads and average readings of voltages in nine nodes of phases were calculated for meters; phases *b* and *c* included eight load nodes, and phase *a* included seven load nodes.

Fig. 3 shows current values in phases and in a neutral wire that were obtained based on the results of state estimation for the first section of a feeder in the distribution network that is connected to a power source for 40 hours of maximum loads. Analysis of curves proved the imbalance of phase currents, current of phase *à* being the maximum one that causes high current in a neutral wire that is comparable to currents in phases *à* and *b*.

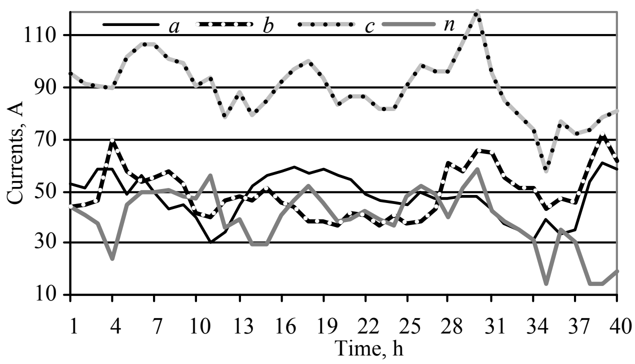


*Fig. 3. Currents in phases and a neutral wire of the first section of the feeder for 40 hourly slices of measurements*
*Рис. 3. Токи в фазах и нейтральном проводе первой секции фидера для 40-часовых срезов измерений*

Ranging the average hourly power losses (hourly energy losses) in phases and in a neutral wire that were obtained based on the results of state estimation, Fig. 4, coincides with ranging the currents of phases the maximum losses for which occur in phase *c*, and losses in phase *a* exceed losses in phase *b*.

Additions to hourly energy losses in phases of

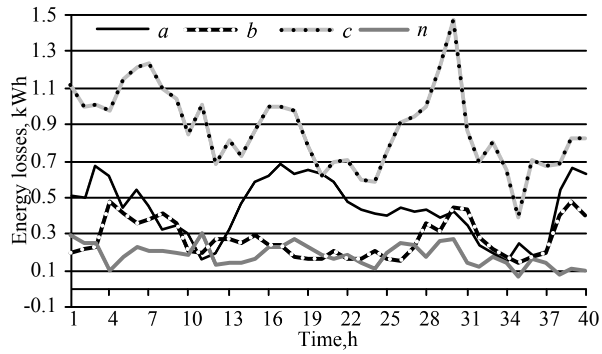


*Fig. 4. Hourly energy losses in phases and a neutral wire of the feeder for 40 hourly slices of measurements*
*Рис. 4. Часовые потери энергии в фазах и нейтральном проводе фидера для 40-часовых срезов измерений*

a low-voltage feeder that are totally equal to energy losses in a neutral wire are shown in Fig. 5, thus, positive additions correspond to a highly loaded phase *c*, whereas negative additions belong mainly to phases *a* and *b*.

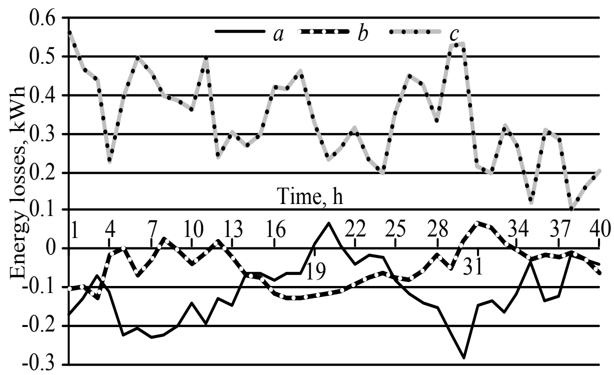


*Fig. 5. Allocation of hourly energy losses in a neutral wire between phase wires when a four-wire network is represented as a three-wire one*
*Рис. 5. Разнесение часовых потерь энергии в нейтральном проводе между фазными проводами при представлении четырехпроводной сети как трехпроводной*

Hourly energy losses in phase wires that were obtained after re-allocation of losses in the neutral wire between them following expression (4) are given in Fig. 6, which shows that the phase with maximum losses coincides with a phase with maximum current.

Closeness of losses in the most loaded phase *c* chosen for comparison to losses determined for this phase using readings of the balance meter proves validity of allocation of losses in the neutral wire between phase wires Fig. 6.

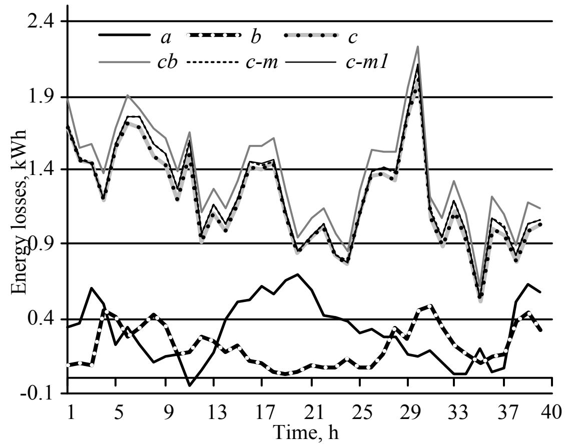


***Fig. 6. Hourly energy losses in phases a, b, c for the case of three-phase representation of feeder for 40 hourly slices of measurements; cb – energy losses in phase determined using readings of a balance meter; c-m and c-m1 – energy losses in phase determined directly based on measurements of smart meters using average loads and voltage magnitudes in the feeder nodes, and loads and voltages of individual consumers***

***Рис. 6. Часовые потери энергии в фазах при трехфазном представлении фидера для 40 часовых срезов измерений, cb – потери энергии в фазе с, найденные с использованием показаний балансного счетчика; c-m и c-m1 – потери энергии в фазе с, найденные непосредственно по измерениям интеллектуальных счетчиков по средним нагрузкам и модулям напряжений в узлах фидеров и по нагрузкам и напряжениям отдельных потребителей***

Fig. 7 shows, for comparison, hourly power losses in phase wires for 40 slices of measurements at minimum-load conditions that have small negative power losses in all phases. Presence of negative power losses is the main property typical of a distribution network that is discussed in many papers [5–8].

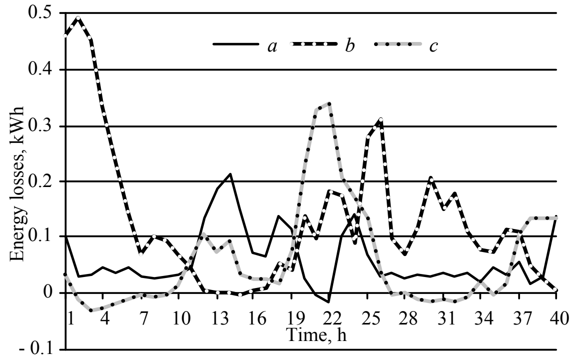


***Fig. 7. Hourly energy losses in phases for the case of three-wire representation of a four-wire network for 40 slices of measurement at the minimum load***

***Рис. 7. Часовые потери энергии в фазах при трехпроводном представлении четырехпроводной сети для 40 срезов измерений режима минимальных нагрузок***

The second peculiar feature of a distribution network is availability of higher losses in the minimum loaded phase (i.e., in the phase with minimum total load) than losses in the phase with higher total load. Losses in the distribution network are due to irregularity of loads in phases when loads at the end of a phase are higher than loads at its beginning. Power losses in the wire with uniformly distributed load are three times lower than power losses at the same load applied at the end of the wire [21]. Presence of maximum total losses in phase *a* with minimum total load is illustrated by graphs in Fig. 8 and Fig. 9.

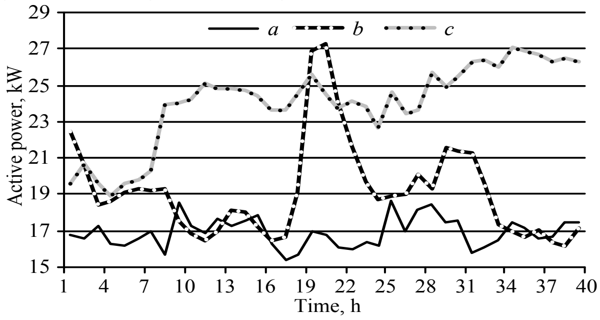


***Fig. 8. Average hourly values of total loads in feeder phases within 40 hours***

***Рис. 8. Среднечасовые значения суммарных нагрузок в фазах фидера в течение 40 ч***

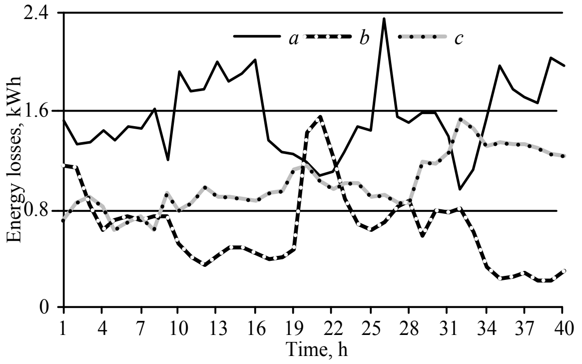


***Fig. 9. Hourly energy losses in the feeder phases within 40 hours***

***Рис. 9. Часовые потери энергии в фазах фидера в течение 40 ч***

Inconsistency of total loads and losses is due to irregularity of total phase loads that for phase *a* are the lowest at the beginning of a feeder Fig. 10, and the highest at the end of a feeder Fig. 11.

For confirming the coincidence of results on allocation of total losses between phases based on the results of state estimation and a balance meter with directly measured losses using expressions (7) for $m$ loaded nodes and for $m1$ consumers, where $m1>m$, the latest losses in the most highly loaded phase in the mode of maximum load were added to graphs Fig. 6.

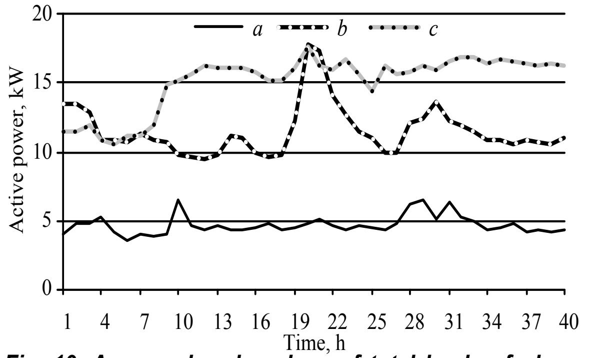


*Fig. 10. Average hourly values of total loads of phases at the beginning of a feeder within 40 hours*
*Рис. 10. Среднечасовые значения суммарных нагрузок фаз в начале фидера в течение 40 ч*

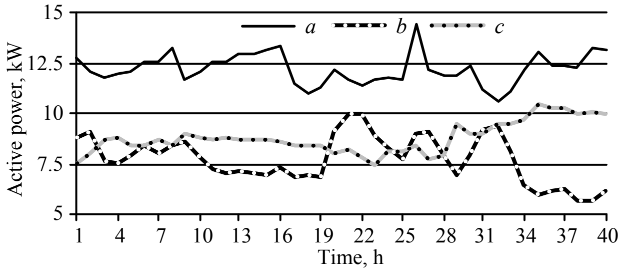


*Fig. 11. Average hourly values of total loads of phases at the end of a feeder within 40 hours*
*Рис. 11. Среднечасовые значения суммарных нагрузок фаз в конце фидера в течение 40 ч*

Analysis of graphs shows that losses by consumer loads are most close to the test estimate of losses measured by a balance meter, then come losses by loads of nodes and, finally, losses determined using the results of state estimation. When comparing losses, the sequence indicated goes with total values of losses for the phase c within 40 hours and are equal to 1.146 kWh, 1.068 kWh, 1.067 kWh, 1.030 kWh.

Possibilities for determining the contribution of individual loads into total losses have been illustrated for the conditions of minimum summer loads in Fig. 12 as a daily curve with accumulation that represents allocation of hourly energy losses in phases a, b, c between loads of the phase nodes and loads of houses connected to the phases, respectively. Hourly energy losses during its transmission from the supply node to every load node were determined based on measurements of loads and voltage magnitudes using expression (7). For example, losses caused by power transfer to load of node 11 of phase c include losses that occurred during power transfer to loads of houses 24 and 25.

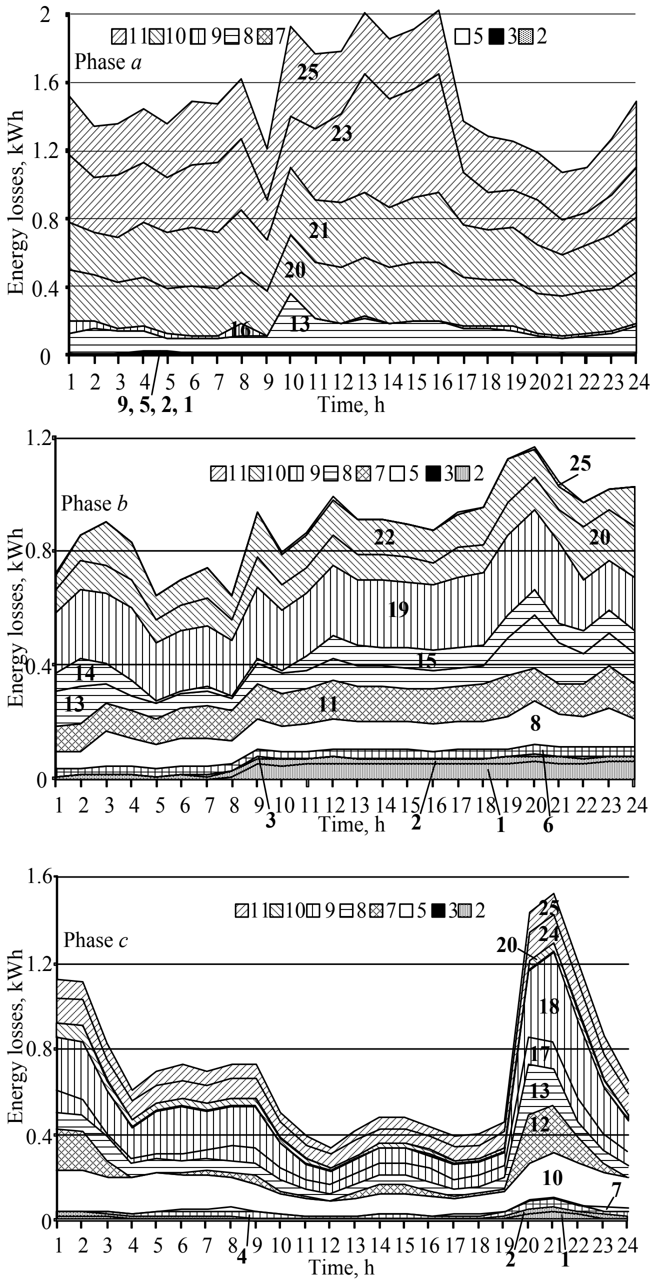


*Fig. 12. Allocation of hourly energy losses in phases a, b, c between loads of the phase nodes and loads of houses connected to the phase, 3–11-phase nodes; 1–25-houses number*

*Рис. 12. Разнесение часовых потерь энергии в фазах a, b, c между нагрузками узлов и нагрузками домов, подключенных к фазе, 3–11 номера узлов; 1–25 номера домов*

## CONCLUSIONS

The research solves the problem of determination of total power losses in a three-phase four-wire distribution network and allocation of those losses between phase wires and a neutral wire, between phase wires only, and between loads or individual consumers connected to phases of a distribution network.

A method for allocation of losses in a neutral wire between phase wires is proposed that allows substitution of four-wire representation of a network by a three-wire one during load flow and power losses computation.

The paper shows that losses computed directly based on readings of smart meters using total loads in the feeder nodes and loads of separate consumers are closer to losses determined using a balance meter than losses determined using the results of state estimation.

A new idea on the conditions for occurrence of negative losses in the feeder phases with imbalanced loads leading to reduction of total power losses in them has been proposed. The cause of occurrence of higher losses in the feeder phase with minimum loads than in the phases with maximum loads that is due irregularly distributed loads has been investigated.

All the results obtained are exemplified by 40 slices of measurements taken from real protocols of a distribution network for different loads.

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