New approaches and digital technology automation tasks processes of control and accounting of electricity in distribution networks

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Abstract. This paper studies 0.4 kV power distribution networks (PDN) and automated systems for electricity monitoring and metering (ASEMM) As is known, one of the main tasks of ASEMMs is the digitalization of PDNs, aimed at further improving the efficiency and reliability of their operation. It is advisable that new models, methods, and intelligent technologies used for automation and informatization of distribution networks should also be focused on minimizing their power losses, which are currently fairly high thus significantly compromising the technical and economic performance of automation systems employed and PDNs. Modern (conventional) ASEMMs, implemented at the facilities of utilities, do not have the appropriate technical, algorithmic, and software tools designed to reduce power losses in the PDN. This is due to the fact that conventional ASEMMs mainly solve the problem of remote data collection from the system meters and their digital processing for the purpose of revenue metering of electricity. In this regard, the paper proposes methodological, algorithmic, and digital technologies designed to solve a set of new functional tasks in the conventional ASEMMs, aimed at reducing power losses in DPNs by optimizing their operating conditions.

Introduction

In the context of the energy crisis, the most important task is the problem of saving electricity through the introduction of new scientific methods and digital technologies at power sector facilities. Analysis of the results of operation of modern automated 0.4 kV power distribution networks (PDN) shows that they lose more than 11-12% of electricity in the form of technical and commercial losses of the total amount coming to the inputs of facilities of distribution utilities. By comparison, electricity losses in developed countries average 6-7%. It follows that there is significant potential for their reduction based on the use of new modern technologies that can back further improvement of the system of monitoring and metering of electricity in PDNs.

As is known, at present, in order to automate and digitalize information processes in PDNs, new technologies in the form of automated systems for electricity monitoring and metering (ASEMM) [1, 2], which can be considered as elements of Smart Grid technology [3, 4], are actively and widely adopted. The practice of their use has shown that they fail to ensure adequately the desired level of electricity losses, since these automated systems are mainly designed for electricity revenue metering. Analysis shows that to significantly reduce electricity losses in the PDN it is necessary to additionally solve a set of problems related to the optimization of operating conditions of facilities [5-8], diagnostics of critical states of distribution grids [9-11], including the identification of places of unauthorized consumption (theft) of electricity [12-14], and the monitoring of electricity losses [15, 16] in real time. This set of tasks in the existing (conventional) ASEMMs is currently not adressed. The purpose of this study is to formulate proposals to improve conventional ASEMMs, which include in their composition new additional information subsystems, focused on significantly reducing technical and commercial losses of electricity.

Structure and tasks of conventional ASEMMs

As is known, electricity losses in low-voltage distribution networks are caused by such main factors as: current and voltage asymmetry [5, 17]; unauthorized electricity consumption (theft) in DPNs [14, 18]; non-linear properties of loads of network consumers [17, 19]; exceeding the critical levels of wear of wires of backbone network lines. These factors cause the networks to deviate from their rated operating conditions. Unbalanced PDNs is a consequence of unbalanced loads and their unequal distribution over the phases of the three-phase network, which is one of the main factors that lead to increased

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losses of active power in networks and transformer substations. According to published research, in lines with distributed load with a relative deviation of phase currents from their average value in the range of 0.3 - 0.5 technical losses increase on average by 35%. The results of experimental studies to determine electricity losses in power supply systems of single-family dwelling units show that technical losses from the unbalance in transmission lines and transformer substations account for more than 6% of the total amount of electricity consumed in DPNs [20]. In this case, the quality of power deteriorates, and the probability of failure of household appliances and industrial plants increases. A number of technologies [5, 21-23], which have not found wide practical application due to the complexity of their technical implementation, have been proposed to solve the problem of balancing adjustment of distribution networks. In particular, balancing adjustment devices with special transformers are practically not used in 0.4 kV networks, as they are the sources of technical electricity losses in networks, and they are complex engineering systems and have a rather high cost. As part of the process of combating the above undesirable factors, the most promising is the use of the potential capabilities of integrated hardware and software systems of ASEMM, developed on the basis of AIM, MDM, and APM technologies [24-26]. Such information systems have been developed by a number of companies abroad, such as JSC "Systems and Technologies" Group, JSC “Electrotechnical factories “Energomera”, Research and Production Corporation “Lianozovo Electromechanical Plant” (JSC LEMZ R&P Corp.), Research and Production Corporation "MIR" (Russia), ADD Grup (Moldova), Yitran (Israel), Hexing Electrical Co.Ltd. (PRC), SigmaTelas (Lithuania) [27-30].

The generalized structure of conventional ASEMMs is shown in Fig.1,

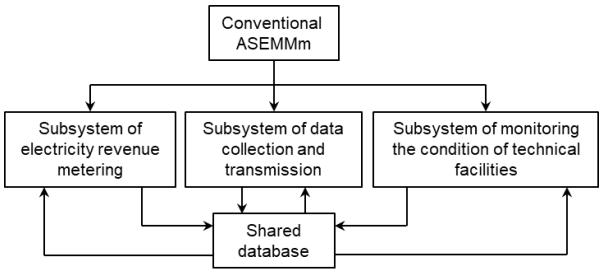

Fig.1 - Generalized structure of subsystems of conventional ASEMMs

which includes the following information subsystems:

• revenue metering of electricity consumed by DPN consumers;

• automated collection of data from the system's electricity meters and transfer of the necessary data to the upper control level;

monitoring the condition of electricity meters and other technical facilities.

To store regulatory, reference, process, measurement, and other data in the ASEMM there is a shared database set up. Through this database the necessary information is exchanged between these functional subsystems, whose main functions are:

• remotely collecting energy consumption data with a specified sampling rate (hour, week, month, etc.);

• automated metering of electricity consumed by network consumers and the provision of multi-tariff options at the same time;

• continuous monitoring of the use of energy;

• controlling power and remotely disconnecting/reconnecting network consumers;

• getting up-to-date information about meter failures and malfunctions in the system;

• calculating energy balance of the distribution network;

• setting up a shared database and preparing reports and other information materials;

• exchanging information with the upper control level.

Analysis of the functional structure of modern ASEMMs shows that the main function of these information systems is revenue metering of electricity in distribution networks. Their main advantages are:

1)automation of processes of measurement data collection, without the participation of inspectors (supervisors) in charge of power supply and electricity metering;

2)elimination of the human factor in the collection of data on energy consumption, which enables ending corrupt practices;

3)automatic disconnection of the consumer in case of late payment and exceeding the set limit on electric power consumption.

At the same time, analysis of the results of the use of conventional ASEMMs shows that the existing composition of functional subsystems is not focused on minimizing the technical and commercial losses of electricity in the PDN. In this regard, there is a need to develop new methods and digital technologies focused on improving the conventional ASEMMs used in distribution networks. One possible way in this direction is to develop a modernized information and control system on the platform (basis) of conventional ASEMMs, designed to address optimization, diagnostic, and monitoring tasks in the PDN.

Structure and tasks of the modernized ASEMM

Our analysis shows that as part of conventional ASEMMs, it is advisable to address the following functional tasks:

• automatic control of technical losses of electricity, ensuring optimization of distribution network operating conditions;

• detection and identification of the coordinates of unauthorized electricity consumption (thefts);

• diagnostics of the condition of the wires of the sections of the network backbone line that connect different consumers;

• on-line monitoring of technical and commercial electricity losses in the PDN.

Our analysis shows that addressing these tasks as part of the ASEMM system can significantly reduce technical and commercial losses of electricity, as well as improve power quality and reliability of power supply to consumers. In this regard, there is a need to develop new scientific methods and digital technologies focused on the modernization of conventional ASEMMs used in distribution networks. One of the possible ways in this direction is to create new additional information subsystems as part of conventional ASEMMs, aimed at addressing the above optimization, diagnostic, and monitoring tasks. The structure of the proposed modernized ASEMM is shown in Fig. 2.

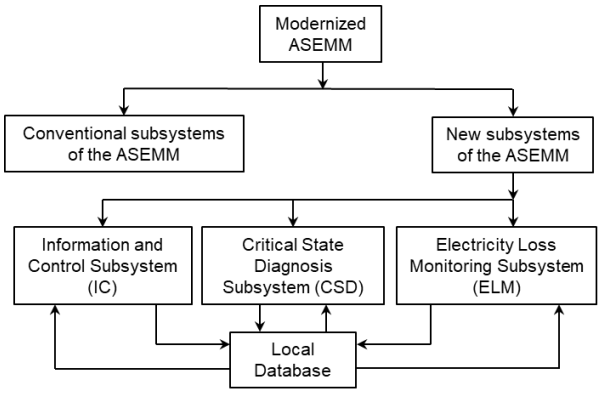

Fig.2 - Structure of additional subsystems of the ASEM

It includes conventional information subsystems of the ASEMM (Fig. 1), as well as new subsystems: IC, CSD, and ELM, designed to address the above additional functional tasks. In this case, to build an IC subsystem we use the following objective function as the performance metric of the system:

$$E=J \quad (1)$$

where J is the value of the effective current in the zero wire of the initial section of the network.

Minimization of the performance metric (1) is equivalent to the optimization of the operating conditions of the unbalanced PDN, in which the balancing adjustment of the initial section of the network and the minimum imbalance of the values of total power consumed by each of the network phases is provided. This can significantly reduce technical losses in the transformer power sources of the PDN as well as improve their reliable operation. In order to minimize the objective function E, we introduce the criterion function F(p), which defines the measure of deviation of the desired state of the distribution network in terms of power p at its input from the actual state defined by the vector p=[p_1, p_2,_p_3], where p_k is the modulus of the power consumed by the k-th network phase. As a result, the problem of optimization of the distribution network operating conditions is reduced to solving the following extreme-value problem:

$$\min_{p \in P} F(p) = F(p^*), \quad (2)$$

where P - discrete admissible subset; $p*$ - optimal desired vector. An algorithm for solving the extreme-value problem (2) is proposed in [8].

From a technical perspective, the IC subsystem is implemented by means of a digital controller (DC) [8,31], the structure of which is shown in Fig. 3.

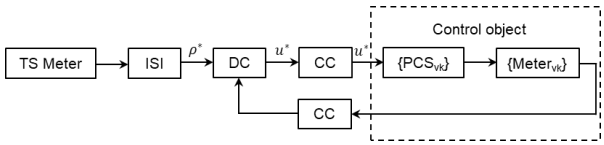

Fig. 3 - Functional structure of the IC subsystem

It is assumed that a group of loads of network consumers, to which electricity Meters$_{vk}$ are connected, together with the actuators of the system, is a control object. The key functional unit of the system is the digital controller (DC) based on a microcontroller unit. The DC unit generates control actions $u*$ applied to the object based on a special algorithm (control rule). The program governing the operation of the DC is formed by the initial state identifier (ISI) of the automatic system in the form of the setting action ρ*. The control signal $u*$ is a digital command code, which is formed as the vector u*=[Φ_1,Φ_2,β], where Φ_1,Φ_2 - numbers (names) of pairs of phases in which it is necessary to switch network consumers from a more loaded phase (Φ_1) to a less loaded one (Φ_2); β- vector composed of the coordinates (addresses) of consumers of the phase Φ_1 who are to be switched. This control signal $u*$ is transmitted to the actuators of the system through the communication channel (CC). Such actuators are phase current switches ($PCS_{v\kappa}$), designed to carry out the required switching of loads of network consumers from one phase to another [7, 8]. The phase current switch ($PCS_{v\kappa}$) is implemented on the basis of a separate microcontroller unit. In conventional ASEMMs, various data transmission technologies (PLC, GSM, etc.) are used as CCs.

The procedure for synthesizing an algorithm for the functioning (control) of the digital controller includes the following main steps:

1. Formation of the initial data of the control task.
2. Situational analysis of the object.
3. Control algorithm synthesis.

Input data for the task are formed by reading the information recorded in the data concentrator of the ASEMM, and by writing it to the local database of the system. As such information one uses, in particular, the active and reactive powers consumed by the phases and consumers of the network. The situational analysis is carried out to determine the structure of phase switching, i.e., to identify the names of the phases (Φ_1,Φ_2,), in which it is necessary to carry out the switching operations of the corresponding loads of the network consumers. The synthesis of the control rule u* is carried out on the basis of the found vector. Methods, algorithms, and technologies for the construction of the IC subsystem are proposed in [7, 8].

The main functions of the Electricity Loss Monitoring (ELM) subsystem are the identification and continuous monitoring of technical and commercial

electricity losses in the DN. When there is unauthorized consumption (thefts) of electricity in the network, the balance of complex powers is determined by the following relationships:

$\dot{S}_k(\xi) = \dot{S}_k^a(\xi) + \dot{S}_k^T(\xi) + \dot{S}_k^x(\xi)$, k=$\overline{1,3}$,

where k- index variable denoting the number of the corresponding phase (A, B, C), k=$\overline{1,3}$; $\dot{S}_k$- complex power consumed by the k-th phase at a discrete moment of time t =t_ξ; $\dot{S}_k$ - total complex power consumed by all consumers of the k-th phase; $\dot{S}_k^T$ - technical power losses in the k-th phase; $\dot{S}_k^x$- uncontrolled power losses in the k-th phase of the network. In this case, the powers $\dot{S}_k(\xi)$ and are $\dot{S}_k^a(\xi)$ known values. It should be noted that in the existing ASEMMs, technical $\dot{S}_k^T$ and commercial $\dot{S}_k^x$ losses are not determined, and only the values of total power consumed $\dot{S}_k$ by the network phases and electric power consumer $\dot{S}_k^a$ are evaluated. The main task of the ELM subsystem is to identify the values $\dot{S}_k^T$ and $\dot{S}_k^x$ and $\dot{S}_k^x$ to conduct continuous monitoring of uncontrolled power losses in the distribution network on their basis. At the same time, to effectively address the tasks of the ELM subsystem, virtual DPN models are introduced for consideration, describing the desired states of real-world networks in the absence of unauthorized consumers there. Methods and algorithms for solving the problems of the subsystem in question are proposed in [12, 13].

In the "Critical State Diagnosis of the Network" subsystem two problems are solved:

- detection and identification of unauthorized power consumption (thefts) in the PDN;
- diagnosis of the condition of wires of sections of the backbone line connecting different consumers by their wear and tear level.

The solution to these problems is based on the identification of the PDN model using numerical methods [32, 33] and the estimation of complex resistances of inter-consumer sections of the three-phase network [11]. At the same time, it is possible to assess the level of wear and tear of the backbone line wires. Mathematical conditions for determining the critical states of the DPN are obtained. The results of solving the problems can be used to take appropriate organizational and engineering measures to eliminate the specified critical states of the PDN, which makes it possible to reduce electricity losses caused by unauthorized consumption of electricity and critical levels of wear and tear of wires of sections of the backbone line. Methods and technologies for building the CSD subsystem are outlined in [15, 16].

Data exchange between IC, ELM, and CSD subsystems can be performed through the local database of the information system. Input data for addressing new functional tasks come from the ASEMM data concentrator. In turn, the concentrator receives data by polling the electricity meters installed at the network consumers and in the transformer substation.

Conclusion

Despite the active and widespread adoption of integrated hardware and software systems of ASEMMs in distribution networks, technical and commercial losses of electricity remain quite high. We made several proposals on improving traditional systems of automation and digitalization of networks. They are based on the development of new functional subsystems as part of conventional ASEMMs. Such subsystems are designed to address the following major functional tasks: automatic control of electricity losses, which ensures a reduction of technical losses in distribution networks (including losses in the transformer power sources); detection and identification of places of unauthorized consumption (theft) of electricity, real-time identification and monitoring of technical and commercial electric power losses in the network; diagnosis of the condition of wires of inter-consumer sections of the backbone line by their wear and tear level.

The creation and use of software of new functional subsystems allows the modernization of the conventional ASEMM into an information and control system. This makes it possible to improve significantly its efficiency and economic performance of distribution utilities, as well as the reliability of the transformer power supply sources of networks.

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