Development Issues of Systems for Automation and Digitalization of Power Distribution Networks

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***Abstract* — This paper studies 0.4 kV power distribution networks (PDNs) and automated systems for electricity monitoring and metering (ASEMM). As is known, a main task of ASEMMs is to digitalize PDNs, which is aimed at 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 and significantly compromise 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 to reduce power losses in the PDN. This is due to the fact that conventional ASEMMs mainly collect remote data from the system meters and ensure their digital processing for the purpose of revenue metering of electricity. In this regard, the paper proposes methodological, algorithmic, and digital technologies to accomplish a set of new functional tasks in the conventional ASEMMs, aimed at reducing power losses in PDNs by optimizing their operating conditions.**

***Index Terms*: Distribution network, power losses, automation issues.**

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I. Introduction

In the context of the energy crisis, the most important task is to save electricity through the introduction of new scientific methods and digital technologies at power sector facilities. Analysis of the operation of modern automated 0.4 kV power distribution networks (PDNs) shows that they lose more than 11–12% of electricity in the form of technical and commercial losses of the total amount supplied to the facilities of distribution utilities. By comparison, electricity losses in developed countries average 6–7%. Thus, there is significant potential for their reduction based on the new modern technologies that can back further improvement of the electricity monitoring and metering system in PDNs. As is known, the current automation and digitalization of information processes in PDNs involves active and wide adoption of 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]. The practice of their use has shown that they fail to adequately ensure the desired level of electricity losses, since these automated systems are mainly designed for electricity revenue metering. Analysis indicates that to significantly reduce electricity losses in the PDN it is necessary to additionally perform 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. The existing (conventional) ASEMMs do not address this set of tasks. This study aims to formulate proposals to improve conventional ASEMMs by incorporating new additional information subsystems in them, with the view to significantly reducing technical and commercial losses of electricity.

II. 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 unbalance [5, 17]; unauthorized electricity consumption (theft) in PDNs [14, 18]; non-linear properties of loads of network consumers [17, 19]; exceeded critical levels of wear of wires of backbone network lines. These factors cause the networks to deviate from their rated operating conditions. Unbalanced PDNs are 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 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 conducted to determine electricity losses in power supply systems of single-family dwelling units show that technical losses due to the unbalance in transmission lines and transformer substations account for more than 6% of the total amount of electricity consumed in PDNs [20]. In this case, the quality of power deteriorates, and the probability of failure of household appliances and industrial plants increases. Some technologies [5, 21–23] proposed to solve the problem of voltage and current balancing in the distribution networks did not find wide practical application due to the complexity of their technical implementation. In particular, balancers 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 rather expensive and complex engineering systems. The most promising way of combating the above undesirable factors is to use 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 such companies 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. It includes the information subsystems for:

- revenue metering of electricity consumed by PDN consumers;
- automated data collection 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.

There is a shared database designed to store regulatory, reference, process, measurement, and other data in the ASEMM. Through this database the necessary information is exchanged between the indicated subsystems, whose main functions are:

- to remotely collect energy consumption data with a specified sampling rate (hour, week, month, etc.);
- to provide automated metering of electricity consumed by network consumers and multi-tariff options at the same time;
- to continuously monitor the use of energy;
- to control power and remotely disconnect/reconnect network consumers;
- to get up-to-date information about meter failures and malfunctions in the system;
- to calculate energy balance in the distribution network;
- to set up a shared database and prepare reports and other information materials;
- to exchange information with the upper control level.

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

1. automation of processes of measurement data collection, without involving inspectors (supervisors)

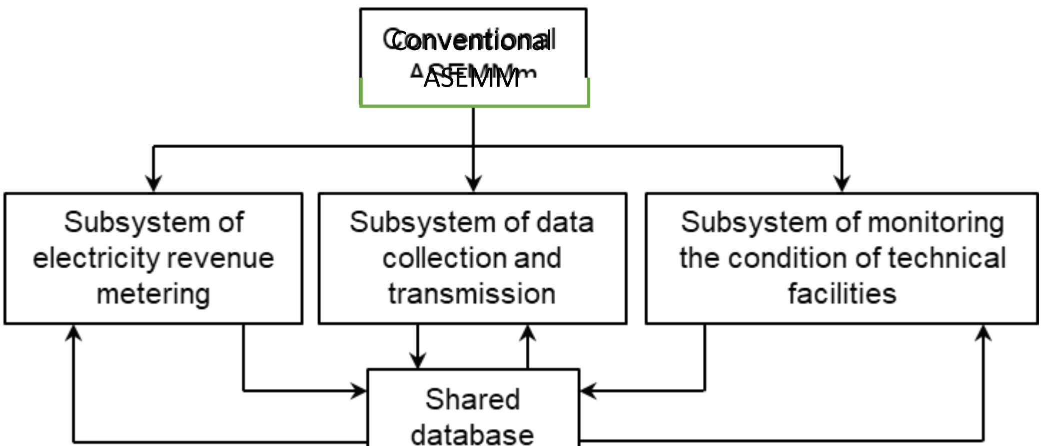

Fig. 1. Generalized structure of subsystems of conventional ASEMMs.

in charge of power supply and electricity metering;
2. elimination of the human factor in the collection of data on energy consumption, which ends corrupt practices;
3. automatic disconnection of the consumer in the case of late payment and exceeded limit on electric power consumption.

At the same time, analysis of the use of conventional ASEMMs shows that the existing set of functional subsystems does not focus 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 targeted at 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.

III. Structure and Tasks of the Modernized ASEMM

Our analysis shows that the conventional ASEMMs should address the following functional tasks:

- automatic control of technical losses of electricity to ensure optimization of distribution network operating conditions;
- detection and identification of the coordinates of unauthorized electricity consumption (thefts);
- diagnosis of the condition of the wires in 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 performing these tasks within the ASEMM can significantly reduce technical and commercial losses of electricity, and 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, to carry out the above optimization, diagnostic, and monitoring tasks. The structure of the proposed modernized ASEMM is shown in Fig. 2.

It includes conventional information subsystems of the ASEMM (Fig. 1) and new subsystems (IC, CSD, and ELM) designed to perform 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:

$$E = J, \tag{1}$$

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, which involves balancing the initial section of the network and provides the minimum imbalance of the values of total power consumed by each of the network phases. This can significantly reduce technical losses in the transformer power sources of the PDN and 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 absolute value of the power consumed by the k-th network phase.

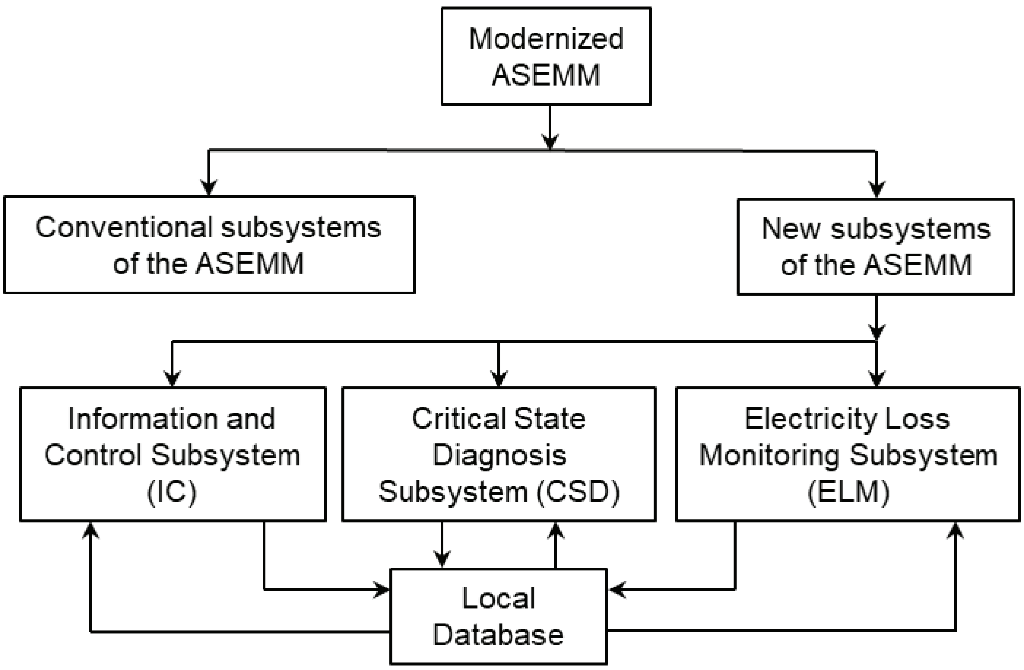

Fig. 2. Structure of additional subsystems of the ASEMM.

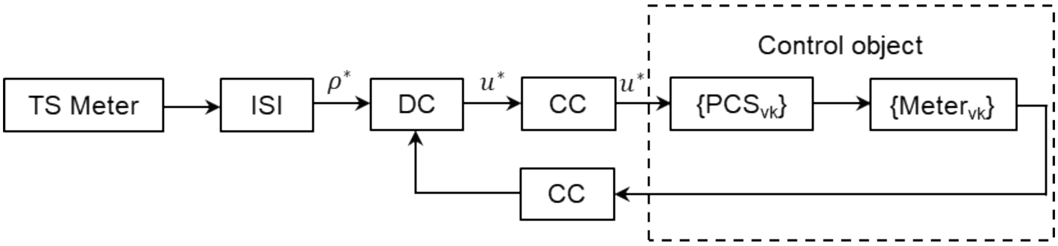

Fig. 3. Functional structure of the IC subsystem.

As a result, the 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 is a discrete admissible subset; p^* is an 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.

It is assumed that a group of loads of network consumers, to which electricity meters $C\text{ч}_{vk}$ 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 $u^* = [\Phi_1, \Phi_2, \beta]$, where Φ_1, Φ_2 are 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 is a vector composed of the coordinates (addresses) of phase Φ_1 consumers 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) designed to carry out the required switching of loads of network consumers from one phase to another [7, 8]. The phase current switch (PCS) 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 of 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 is provided by reading the information recorded in the data concentrator (DC) of the ASEMM, and by writing it to the local database of the system. Such information, in particular, includes 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 (Φ1, Φ2), in which it is necessary to perform the switching operations of the corresponding loads of the network consumers. The synthesis of the control rule u* is based on the found vector $p^* = [p_1^*, p_2^*, p_3^*]$. 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 power distribution network. When there is unauthorized consumption (thefts) of electricity in the network, the balance of phasor powers is determined by the following relationships:

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

where k is an index variable denoting the number of the corresponding phase (A, B, C), $k = \overline{1,3}$; $\dot{S}_k$ is the phasor power consumed by the k-th phase at a discrete moment of time $t = t_\xi$; $\dot{S}_k^a$ is total phasor power consumed by all consumers of the k-th phase; $\dot{S}_k^T$ is technical power losses in the k-th phase; $\dot{S}_k^x$ is uncontrolled power losses (UPL) in the k-th phase of the network. In this case, the powers $\dot{S}_k(\xi)$ and $\dot{S}_k^a(\xi)$ are known values. It should be noted that the existing ASEMMs do not determine technical $\dot{S}_k^T$ and commercial $\dot{S}_k^x$ losses, but only evaluate the values of total power $\dot{S}_k$ consumed by the network phases and electric power consumers $\dot{S}_k^a$. The main objective of the ELM subsystem is to identify the values $\dot{S}_k^T$ and $\dot{S}_k^x$ and 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, models of virtual PDN are introduced for consideration, which describe 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].

The “Critical State Diagnosis of the Network” subsystem solves two problems:

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

These problems are solved by identifying the PDN model with the numerical methods [32, 33] and the estimation of complex resistances of inter-consumer sections of the three-phase network [11]. At the same time, the level of wear and tear of the main power line wires can be assessed. Mathematical conditions for determining the critical states of the PDN are obtained. The solutions to 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 in the sections of the main power line. Methods and technologies for building the CSD subsystem are outlined in [15, 16].

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

IV. 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. The paper presents several proposals to improve traditional systems of the network automation and digitalization. They are based on the development of new functional subsystems as part of conventional ASEMMs. Such subsystems are designed to carry out the following major functional tasks: automatic control of electricity losses, which ensures a reduction in 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 in the inter-consumer sections of the main power line by their wear and tear level.

The creation and use of software of the new functional subsystems allow upgrading the conventional ASEMM into an information-and-control system. This can significantly improve the efficiency of ASEMM, the economic performance of distribution utilities, and the reliability of the transformer power supply sources of networks.

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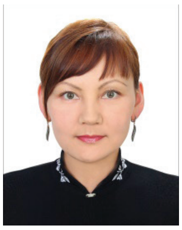

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