Hardware and Software System for Investigating and Testing Novel Methods and Technologies for Automating Processes in Electrical Distribution Networks

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***Abstract* — At present, automating and digitalizing processes in electrical distribution networks (EDN) involve a widespread use of software and hardware systems of automated electricity control and metering systems (AECMS). They are mainly designed for commercial electricity metering tasks. At the same time, these automated systems do not perform optimization of operating conditions of distribution networks, operational monitoring of technical and commercial losses of electricity, nor do they diagnose network conditions, including locating unauthorized electricity withdrawals (UEW). To date, the National Academy of Sciences of the Kyrgyz Republic and some scientific centers in other countries have developed the scientific framework and technologies for addressing these issues in real time. In order to test and assess the effectiveness of these new results, it is advisable to establish an automated experimental system (AES), which is essentially a physical model of AECMS. This is due to the fact that the use of automated information systems currently used in distribution networks for this purpose is practically impossible. This paper discusses the general structure, functional objectives, and main directions of research using AES. The system includes a physical model of the distribution network and the main functional components of modern AECMS, such as a data concentrator, a computer server, single-phase and three-phase electricity meters and a telecommunications module for transmitting and receiving data. The specialized software of the experimental system relies on novel methods and technologies designed to accomplish the aforementioned functional objectives, which are currently absent in modern AECMS. The AES is planned to be used not only for conducting scientific research and experiments, but also for the educational process in technical universities that offer training programs in electric power engineering.**

***Index Terms* — Distribution electric network; control and monitoring of electric power losses; automated experimental system; functional structure.**

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I. Introduction

Currently, AECMS software and hardware systems are actively implemented in electrical distribution networks (EDN) [1–3], which are developed using Smart Grid technology [4, 5]. These systems belong to the class of data and measurement systems, which are designed to automate commercial electricity metering through remote data collection from electricity meters installed at consumer locations. At the same time, conventional AECMSs fail to accomplish various important functional tasks. Achieving these functionalities can significantly enhance the performance of automated systems, boost the economic indicators of distribution companies, and improve the quality of electricity. These tasks involve optimizing EDN operating conditions by balancing a three-phase network [6–10], conducting real-time monitoring of electricity losses [11–13], and identifying the locations of unauthorized electricity withdrawals (UEW) [14–17]. The accomplishment of these functional tasks is directly related to reducing electricity losses in networks, which are currently very high. To minimize both technical and commercial losses of electricity in EDNs, the National Academy of Sciences of the Kyrgyz Republic is conducting theoretical and applied research aimed at improving traditional AECMSs, which are currently increasingly implemented in distribution networks. These studies have yielded innovative methods and digital technologies [7, 10, 13, 15, 18–20] developed to enhance traditional AECMSs. It is worth noting that investigating and testing the performance of these technologies necessitate a set of data from real facilities operating within AECMS. However, obtaining such data with given characteristics presents significant organizational and technical challenges in practice. Therefore, an automated experimental system (AES) was developed to explore and develop new engineering and software solutions in the field of automation and digitalization of processes within distribution networks. This system is a simplified physical model of AECMS.

II. Functional Structure of the Automated Experimental System

Traditional AECMSs belong to the class of data and measurement systems that mainly accomplish the following tasks:

- Commercial metering of electricity consumed by EDN consumers;
- Automated data collection from the system electricity meters and transmission of the necessary data to the upper control level;
- Monitoring of states of electricity meters and other technical devices.

Since these automated systems do not optimize operating conditions and do not minimize electricity losses in EDNs, to enhance the performance of traditional AECMSs, we propose introducing additional information subsystems designed to:

- Optimize the operating conditions of electrical distribution networks based on balancing of phase loads.
- Detect and monitor technical and commercial power losses in real time.
- Identify and locate places of unauthorized electricity withdrawals (thefts) (UEW).
- Identify the electrical state of the EDN in real time.

The structure of AES is shown in Fig. 1. It includes new functional information subsystems that are absent in traditional AECMSs. These are the subsystems of network operation optimization (NOO), electricity loss monitoring (ELM), unauthorized electricity withdrawal location (UEWL), and the network electrical state identification (NESI).

The Network Operation Optimization (NOO) subsystem is technically implemented through a digital controller (DC) [7, 10]. The DC block, based on a special algorithm (control law), generates control actions u^* to the object. In

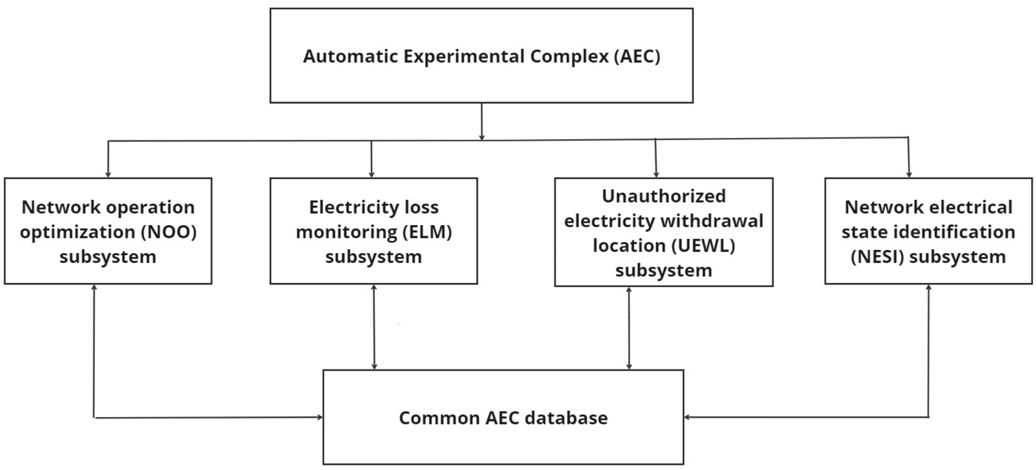

Fig.1. Functional structure of the AES

this case, the control signal u^* is a command digital code, which has the form of vector $u^* = [\Phi_1, \Phi_2, \beta]$, where Φ_1, Φ_2 are numbers (names) of a phase pair within 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 consumers to be switched. This control signal u^* is transmitted via a communication channel (CC) to the executive elements of the system, which are represented by phase current switches (PCSs) designed to switch loads of network consumers from one phase to another [7, 10]. The phase current switch is based on a separate microcontroller.

Methods, algorithms, and technologies for constructing the NOO subsystem are proposed in [7, 10].

The main functions of the Electricity Loss Monitoring (ELM) subsystem are the identification and continuous monitoring of technical and commercial electricity losses in EDN. In the case of unauthorized electricity withdrawals (thefts) from the network, the balance of complex power 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 indicating the number of the corresponding phase (A, B, C), $k = \overline{1,3}$, $\dot{S}_k$ is complex power consumed by the k-th phase at a discrete point in time $t = t_\xi$; $\dot{S}_k^a$ is the total complex 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 loss (UEWL) in the k-th network phase. The powers $\dot{S}_k(\xi)$ and $\dot{S}_k^a(\xi)$ are known quantities. It is important to note that the existing AECMSs do not determine technical $\dot{S}_k^T$ and commercial $\dot{S}_k^x$ losses, but only assess the total power $\dot{S}_k$ consumed by network phases and electricity consumers $\dot{S}_k^a$. The main task of the ELM subsystem is to identify quantities $\dot{S}_k^T$ and $\dot{S}_k^x$ and on their basis carry out continuous monitoring of uncontrolled electricity losses in the distribution network. In order to effectively accomplish the tasks of the ELM subsystem, models of virtual EDNs are introduced into consideration, describing the desired states of real networks in the absence of unauthorized consumers in them. Methods and algorithms for the tasks of the subsystem in question are proposed in [13, 19].

The UEWL subsystem detects and locates the places of unauthorized electricity withdrawals within the EDN [15].

The NESI subsystem is designed to identify parameters and variables of the network state that are inaccessible for measurement [13, 18, 19]. These parameters include complex resistances of the inter-consumer sections of the network, voltage and current vectors at given points of the EDN, as well as the internal resistance of the transformer power supply of the network.

The common AES database includes regulatory, reference, and operational data necessary for the system operation. These data include the structure and parameters of the EDN physical model, measurement data obtained from electricity meters, and results of AES information

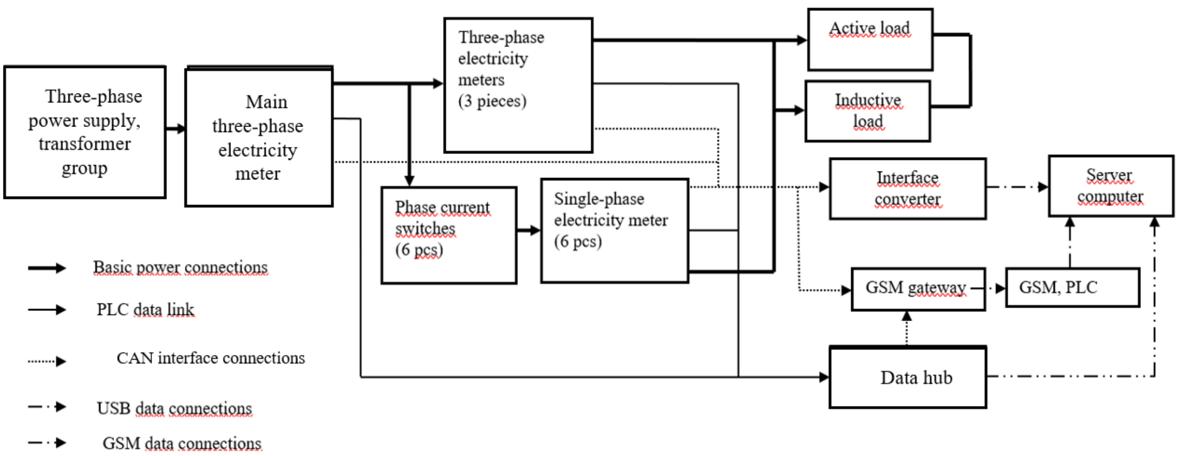

Fig. 2. Block diagram of AES

subsystems' operation.

The basic values recorded from each electricity meter at a given time $t = t_0$ and stored in the common database are: effective values of currents I_{kv} and voltages U_{kv} at EDN loads; capacity factors $c_{kv} = \cos\varphi_{kv}$, where $k = 1,3$, $v = \overline{1, n_k}$. Here k is the phase number (A, B, C), n_k is the number of consumers connected to phase number k.

The structure of the functional components of the AES is shown in Fig. 2. It is worth noting that the developed AES is essentially a mini model of the AECMS software and hardware complex, since it includes almost all its main functional components and a simplified physical model of the distribution network.

III. The AES Technical Means

The main functional components of AES are:

- Physical model of the distribution network.
- Transformer power supply.
- Server computer.
- Data hub (DH).
- Single-phase and three-phase electricity meters.
- Phase current switch (PCS).
- Communication channel.

The server computer implements the algorithmic and specialized software of the AES functional subsystems (NOO, ELM, UEWL, NESI), which was developed in the C software environment. The central block of the NOO subsystem is a digital controller (DC), which generates an algorithm for controlling facilities represented by consumer electricity meters. The synthesis of the control algorithm is carried out on the basis of the principles and methods of automatic control [21–23]. The initial data necessary for the latter to function and included in the structure of the common database comes from the hub database. The data hub is part of conventional AECMS and performs the following main functions:

- Cyclic collection of data on the energy consumption of consumers and network parameters at specified nodes in an automatic or automated mode.
- Pre-processing of data coming from electricity meters.
- Transfer of necessary data on energy consumption and the status of metering devices.
- Data exchange between data hub and the common system database.
- The phase current switch (PCT) performs the following functions:
  - Implementation of control actions by controlling the state of consumer meters that can be switched from one phase to another by the command signal from the digital controller.
- Generation of control signals about the state of consumer meters.

The technology for receiving data from AECMS electricity meters, developed by SigmaTelas based on GSM, is used as a communication channel (CC), while the PLC technology, as well as a radio channel, can be employed to transmit control command signals to the control object (electricity meters).

Electricity meters provide the following functions [2, 3]:

- Measuring electrical parameters (currents, voltages, active and reactive powers, and others) that characterize the state of network loads.
- Monitoring the status of functional units.
- Receiving and transmitting control and monitoring signals, as well as measurement data.

The AES can simulate various operating conditions of the distribution network, for example, balanced and unbalanced conditions of the network; broken power line; connection of unauthorized consumers to the network.

IV. Main Directions of Research Based on AES

The main idea behind the AES development is to conduct experimental research and develop innovative methods and digital technologies aimed at enhancing the traditional AECMS. In this regard, the joint operation of the developed AES information subsystems (NOO, ELM, UEWL, NESI) and the physical model of the EDN of a given structure is simulated.

The measurements of the parameters of the physical network model and the operational parameters of the AES subsystems at appropriate times are recorded in a common database. Next, the obtained calculation and measurement data are compared and analyzed. This analysis examines the effectiveness of the proposed information subsystems when used within the traditional AECMS. A generalized scheme of experimental studies based on AES is shown in Fig. 3.

The AES information subsystems provide physical quantities that characterize the current state of the EDN and the performance indices of the system. The quantities identified are as follows:

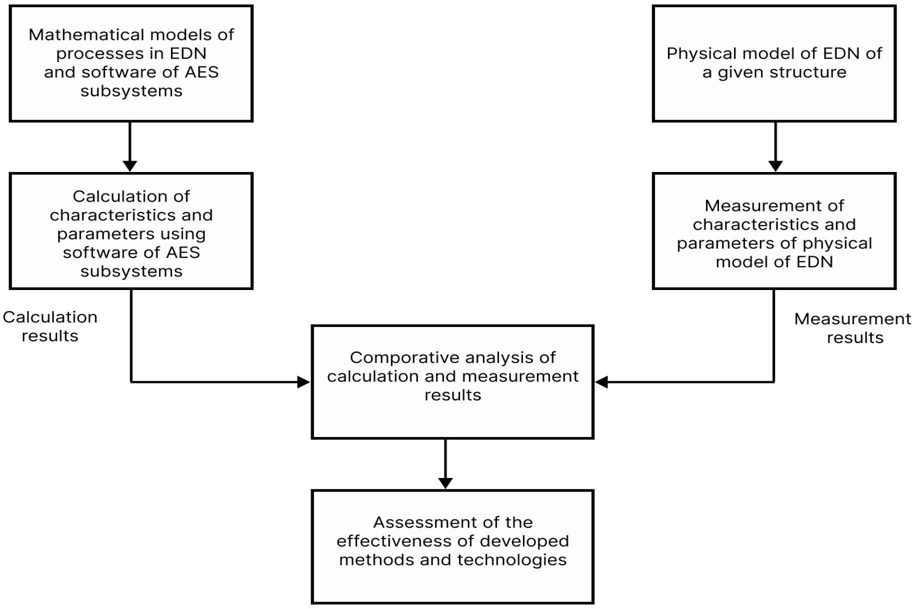

Fig. 3. Generalized scheme of experimental studies based on AES

- Technical power losses in the network;
- Commercial power losses in electrical distribution network;
- Effective values of currents and voltages that are not available for measurement;
- Complex resistances of inter-consumer sections of the distribution network, which are not controlled as part of traditional AECMS;
- Power consumed by the network phases in the presence of uncontrolled current leaks in the network;
- Neutral wire currents in inter-consumer sections of the network.

By simultaneously using measuring instruments, we can obtain data on the magnitudes of the above variables and performance indices of the system at appropriate points in time.

Through the AES operation, we can determine the following parameters:

- Characteristics of the assessment accuracy for the identified variables (voltage, current, power, and others) and three-phase network parameters that are not available for measurement;
- Performance indices of the AES subsystems, which can be represented by the shares of technical and commercial electricity losses in the total volume of electricity supplied to the input of the distribution network.

Thus, based on a comparison of data gathered simultaneously by the AES information subsystems and using various measuring instruments, one can evaluate the performance of the developed methods and digital technologies designed to enhance the traditional AECMS.

V. Conclusion

Improving traditional AECMS is the most important pathway in the automation and informatization of processes in EDNs. One of the tasks is to develop innovative functional subsystems within EDN that leverage scientifically grounded approaches and digital technologies to minimize electricity losses in the network in real time. An automated experimental system (AES) has been established to explore and test these new developments. This system integrates all the main components of AESMS and has developed functional subsystems, which implement new methods and algorithms designed to optimize the operating conditions of distribution networks and monitor technical and commercial electricity losses. The results of experimental studies allow the assessment of the performance of the information subsystems developed within the AES and the evaluation of the potential for their practical use as part of traditional AECMSs. The AES can also be employed in the educational process to train undergraduates and graduate students specializing in automation and digitalization of management and control processes within electrical networks.

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