

Розподільні електричні мережі не достатньо оснащені засобами моніторингу режимних параметрів. Найбільш розвинену інфраструктуру мають системи комерційного обліку електроенергії. Однак інформація про спожиту електроенергію зберігається у агрегованому вигляді. Це не дає змоги визначати складові балансових витрат електроенергії та аналізувати їх структуру без застосування спрощень.

Запропоновано використовувати типові графіки навантаження для підвищення адекватності результатів оцінювання динаміки режимів розподільних електричних мереж. Для узгодження виміряних параметрів режиму та псевдовимірювань, розрахованих за типовими графіками навантаження, запропоновано використовувати алгоритм на основі методу найменших квадратів. Оцінювання точності проводилось шляхом порівняння графіків електроспоживання абсолютно спостережної мережі з результатами імітаційних розрахунків.

Встановлено, що застосування типових графіків навантаження дає змогу відновлювати графіки електроспоживання з прийнятною точністю за повної відсутності вимірювань. Перетворення агрегованої інформації систем комерційного обліку електроенергії в часові залежності сприяє підвищенню точності результатів моделювання характерних режимів мереж. Як наслідок, підвищується точність визначення технічних втрат та інших складових у структурі балансу електроенергії.

Уточнення складових втрат електроенергії у структурі балансу дозволить виявляти проблемні елементи розподільних мереж та формувати якісніші заходи щодо підвищення їх енергоефективності. Крім того, використання типових графіків навантаження та формування псевдовимірювань, дає змогу зменшити витрати на реалізацію систем моніторингу параметрів розподільних мереж

Ключові слова: розподільна електрична мережа, відновлення параметрів, адекватність, типовий графік навантаження, оцінювання стану

UDC 621.316

DOI: 10.15587/1729-4061.2019.184095

ESTIMATION OF THE DYNAMICS OF POWER GRID OPERATING PARAMETERS BASED ON STANDARD LOAD CURVES

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Received date 20.09.2019

Accepted date 11.11.2019

Published date 23.12.2019

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1. Introduction

Effective implementation of financial settlements requires accurate and reliable information about power consumption. Worldwide experience in the use of smart metering systems involves the installation of smart metering devices by manufacturers and consumers, automation of survey systems, data processing and provision of information about energy production, transmission, distribution and consumption.

In power grids, the main source of measurements is automated systems for commercial accounting of power consumption (ASCAPC). ASCAPC are intended to provide reliable and timely information on power consumption accounting on the basis of which financial settlements between market entities can be made. Today, however, the use of commercial accounting systems in power grids is limited by significant financial costs. The available information does not allow ensuring the observability of operating parameters of power grids and, as a consequence, determining the com-

ponents of power losses in the structure of power balance with sufficient accuracy.

The most effective measure to ensure the observability of power grids is the integration of smart metering devices into ASCAPC with the ability to store and transmit data based on smart metering technology. Such systems allow solving a complex of important tasks. For example, remote reading of metering devices, automated recording at certain intervals, identification of loss centers, as well as instant remote load limitation and termination of power supply to non-payers.

The use of information collected by smart metering systems increases the observability of the power grid by using measured load curves. The presence of synchronized information about the measured operating parameters of the grid allows determining power consumption by standard algebraic methods [1]. However, quite often, due to failure of hardware or information support, this data may not be available for the whole or part of the day. During measurements, as well as information transmission, there are electromagnetic interference, desynchronization or tar-

geted attacks on the information network by third parties in the form of manual or “viral” interference in the information system [2, 3]. This leads to the loss of individual information packets. Thus, a necessary condition for the functioning of the power consumption monitoring information system is the ability to recover lost information.

2. Literary review and problem statement

Today, several approaches are used to verify and restore data on electric loads in ASCAPC and smart metering systems. The paper [4] proposes to use Big Data Technology to control power consumption in power grids. This approach requires considerable investment and large amounts of data for simulation-based decision-making. This makes it impossible to apply such technologies in the initial stages of information system development.

Unlike [4], [5] proposes to fill the information system by simplified calculations of the power grids on the basis of available non-lost data. This method uses the assumption of normalizing power losses. This makes it impossible to use it to clarify the structure of power balance.

The paper [6] proposes to use regression analysis to recover lost data. The disadvantage of this approach is the need for careful synchronization of the regression model parameters. Thus, in the case of parameter resynchronization, the estimation of parameters, regression and perturbation variance becomes biased, which decreases estimation efficiency.

[7] proposes the application of statistical methods for processing lost data based on the removal of all observations with incomplete feature vectors. This approach, similar to [6], requires significant amounts of data. In addition, the results show that lost information can be restored to within 15 %, which is insufficient to create a refined structure of power balance.

In order to improve the accuracy and effectiveness of these approaches, they are combined to provide additional benefits. For example, [8] proposes to use cluster analysis and artificial neural networks to recover only part of the load curve of a particular consumer based on statistical information. Application of neural networks a priori is based on retrospective data, and standard load curves are reproduced by cluster analysis. This approach requires statistical information on the restored load curve, but does not take into account the relationship between operating parameters of the power grid.

Application of state estimation methods [9] allows restoring lost information for each specific mode of the electrical network provided its observability. This approach does not involve the use of functional dependencies of operating parameters and requires a comprehensive approach with other methods of lost data recovery.

[10] proposes to use the characteristic modes method and create a base of load curves of characteristic days. These days relate to public holidays, some weekdays between holidays, days of social events, and usually days characterized by atypical demand. The disadvantage of such methods is obtaining an estimate of total network losses. Therefore, it is difficult to identify specific indicators to clarify the structure of power balance.

[11] proposes to use standard load curves to restore time-aggregated information on power consumption ac-

counting. This approach does not provide sufficient accuracy of results, since standard curves are formed with a large probability distribution scale.

So, the main common requirement of these approaches is the availability of non-lost data. That is, measurements of part of the network in volumes sufficient to recover information or large amounts of retrospective data to recover lost information and detect measurement outliers are needed.

To date, equipping power grids with ASCAPC facilities is quite expensive. Therefore, in most cases, power consumption accounting is carried out using a traditional system. The reporting period in such systems is a calendar month, and collection of indicators is carried out with the participation of the commercial power consumption accounting service of power grids or consumers. This method of collecting and processing commercial measurements is a source of errors and distortions of commercial data. In addition, the aggregation of information makes it difficult to adequately assess the structure of power balance and to identify inefficient subsystems and elements of power grids. This makes it fundamentally impossible to apply the above approaches to accurately investigate changes in the operating parameters of power grids.

The analysis shows that regardless of the equipment of power grids with metering means, it is advisable to use computational methods to increase the observability of networks. Methods for evaluating network modes [9] and standard load curves [10, 11] allow reproducing half-hour network modes with acceptable accuracy.

Thus, the results of commercial power consumption accounting aggregated over the reporting period can be used to control power losses and voltage levels in power grids.

3. The aim and objectives of the study

The aim of the study is to prove the possibility of estimating changes in the operating parameters of power grids using aggregated data of automated systems for commercial accounting of power consumption and standard load curves of consumers.

To achieve the aim, the following objectives were set:

- to analyze the possibilities of using ASCAPC information to increase PG observability under incomplete initial information;
- to develop a method of estimating the operating parameters of power grids using aggregated information of automated systems for commercial accounting of power consumption;
- to check the efficiency of the developed method and adequacy of the results of estimating the operating dynamics of power grids using a full-scale experiment.

4. Analysis of the possibility of using available ASCAPC information to increase the observability of electric networks

According to the concept of building automated systems for commercial accounting of power consumption in conditions of power market [12], ASCAPC for household activities and services is a hierarchical system. It provides automated accounting of power consumption based on data received directly from meters and/or measuring converters.

The main purpose of ASCAPC is solving the issues of financial relations on the basis of accurate and promptly received information, improving the efficiency and rational use of fuel and energy resources and energy saving. According to [12], the ASCAPC database shall contain:

- the value of total power consumption;
- the value of total power consumption for each tariff zone;
- the value of average power according to the specified integration period;
- the value of the maximum power of the integration period during the day, month;
- the value of the maximum power of the integration period for each tariff zone during the day, month;
- the value of power consumption for current and past accounting periods – day, month;
- load curve according to the specified integration period;
- values of power consumption for each tariff zone for current and past accounting periods – day, month;
- information about events related to emergency situations, etc.

Thus, the availability of complete information in the ASCAPC database for the entire power grid can ensure its observability for solving technical, including operational, tasks.

However, to date, most power companies have ASCAPC only for a perimeter (at points of commercial accounting of flows from/to adjacent power grids) and legal consumers. Also, for balancing electric power in regional electric networks, industrial metering means are provided at the main sites of feeders of 110–35 kV substations. Thus, for feeders of power grids, observability is only ensured in the case of power supply to legal consumers.

An additional source of information on power consumption are billing systems of power supply organizations. They store point of sale consumption information for the accounting period.

As the information support of financial settlements of power grids is based on accounting data obtained from different sources with different reliability, the commercial component of power losses increases.

In order to create proper information support and increase the reliability of power consumption accounting information, [11] proposes to use standard load curves (SLC) averaged over time and totality of power receivers. For each SLC there is a list of consumer codes according to the categories of economic activities (CEA), which allows determining the corresponding SLC for a particular consumer. The use of categories of economic activities in the billing system allows comparing information on power consumption during the period of integration with its SLC.

Standard curves are presented in the form of hourly characteristics of mathematical expectation and standard deviation of active and reactive loads, as well as characteristics of the correlation coefficient of active and reactive loads (Fig. 1).

The mathematical expectation of load is normalized relative to the maximum value and is given as a percentage. Thus, the SLC allows decomposing the value of total power consumption for the accounting period to the form of hourly curve of probable load, supplementing information support for solving technical problems.

Table A.1.1
Load curve of consumers of the following categories of economic activity
«01.45» «14.11» «10.42» «32.11» «30.40» «10.31» «30.92» «03.12» «22» «11.05» «24.42»
Month - January Form factor - 1.07

P	39	48	42	55	31	54	49	58	88	59	72	83	71
σ^+	17	17	16	15	13	14	14	17	26	31	31	33	24
Q	12	18	11	19	10	20	19	23	26	20	23	24	16
σ^-	7	7	6	6	4	5	6	11	13	20	19	19	10
K	1	1	1	1	1	1	1	1	1	1	1	1	1

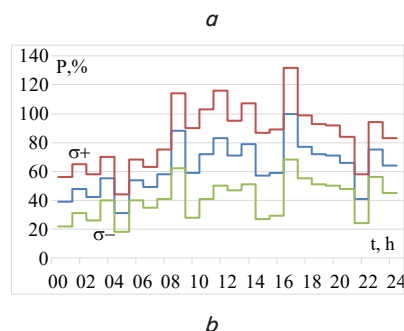


Fig. 1. Presentation of information in the book of standard load curves: *a* – table form; *b* – interpreted graphic form

Traditionally, SLC have been used in power calculations for designing electrical grids, compiling power balances and evaluating power losses associated with transportation and distribution by power grids. The load curves obtained in this way are dependencies of averaged values with given standard deviations. Therefore, their direct use in calculations together with deterministic parameters and measurement results with a given accuracy is incorrect and may decrease the adequacy of results. For data adaptation, additional harmonization measures must be applied that use the properties of power grids, are based on power calculations and minimize errors of reproduction of operating parameters and integrated indicators.

5. Method of estimating the operating parameters of power grids using time-aggregated power consumption accounting data

The problem of using time-aggregated information of automated systems for commercial accounting of power consumption can be considered as the problem of minimizing errors of measurement of PG operating parameters in the theory of state estimation (SE) of the electric network [16]. Several approaches are developed to analyze the reliability of measurement data. The classical SE problem [13–17] for power engineering uses steady-state equations based on the basic laws of electrical engineering – Ohm’s and Kirchhoff’s laws. The variables of these equations are the values of active and reactive power, current and voltage, as well as the parameters of the PG equivalent circuit. The latter are considered conditional-constant. Currents, voltages, active and reactive power flows are considered telemeasurements with a given probability [13].

The electrical network mode characterized by these parameters corresponds to a certain time period and is constantly changing. As a result, there is the need to periodically adjust unsynchronized and faulty telemeasurements that, in combination with probable operating parameters,

the measured values correspond to the conditions of power balance in the PG.

The features of the system of technical monitoring of modern power grids, in particular, the lack of means of synchronized telemetry of operating parameters, do not allow using the methods of state estimation in such networks.

Today, the hardware of the information support of power grids consists mainly of metering devices installed at the inputs of transformer substations and main sections of feeders, which does not provide the necessary observability even for standard modes. Considering the totality of measured parameters in power grids, their accuracy and synchronization capabilities, it is expedient to apply approaches based on the least squares method for SE. Such approaches use the network state equation in the form of current balance as a function of node voltages in polar and rectangular coordinates.

The least squares state estimation method is based on the linearization of the relationship between the measurements and the state variables of the electrical grid. The nonlinear relations between the state vector and the measured electrical variables can be represented as follows [17]:

$$z = h(x) + v, \tag{1}$$

where z is the vector of synchronously measured parameters of electric networks; x is the vector of PG state variables; $h(x)$ is the vector function that relates measurements to state variables based on balance equations for PG; v is the vector of deviations between the measured and calculated operating parameters.

To form the state vector x , an infinite number of combinations of variable values can be used, but the practical value of such a combination is to minimize the absolute values of the vector v . Based on this, the objective function of the problem of determining the PG state vector in the general form:

$$J(x) = \sum_{i=1}^m \frac{[z_i - h_i(x)]^2}{\sigma_i^2} = [z - h(x)]^T W [z - h(x)] \rightarrow \min, \tag{2}$$

where σ is the standard deviation of each measurement;

$$W = \text{diag}[\sigma_1^2, \sigma_2^2, \dots, \sigma_m^2]^{-1}$$

is the inverse diagonal matrix of the expected (estimated) standard deviations of individual measurements.

Usually, the module U_i and phase angle φ_i of voltage at independent network nodes are taken as the state variables x_i . The measured parameters of PG are voltage modules at individual nodes U_i^B , active P_i^B and reactive Q_i^B power in load and generation units equipped with ASCAPC facilities, active P_j^B and reactive Q_j^B power flowing in transmission lines equipped with telemetry facilities.

The peculiarity of power grids is the insufficiency of the observation vector z . That is, the PG state cannot be identified using purely measured parameters, since the problem (2) has no solutions. Supplementing the vector z with information from standard load curves (pseudomeasures) for PG units will allow using the resources of existing metering and monitoring tools to ensure network observability without additional financial costs.

As expected standard deviations of pseudometry W_i for unobservable nodes, it is proposed to use the values given in the atlas of standard load curves for the consumer according to the CEA code [11].

The possibility of state estimation of the power grids using SLC and ASCAPC database is proved by the example of real urban 10 kV PG.

6. Verification of results of estimating the operating dynamics of power grids for determining power losses

To verify the results of estimating the operating dynamics of the partially observable grid on the basis of SLC, a fragment of 10 kV urban networks of Vinnytsia is used – the F-165 feeder of Zahidna 110/10 kV substation. The feeder contains 5 consumer substations (Fig. 2) with 10/0.4 kV transformers of different capacities. The substations feed industrial (17 %) and household (83 %) consumers. Using electronic meters (Table 1), synchronized recording of power input and output parameters with a half-hour interval within 22 days was provided for the feeder. In this way, full network observability was provided to determine balance losses of power. In addition, data were obtained to estimate the dynamics of load distribution between substations for 1056 consecutive half-hour periods. An example of the measurement results is shown in Fig. 3.

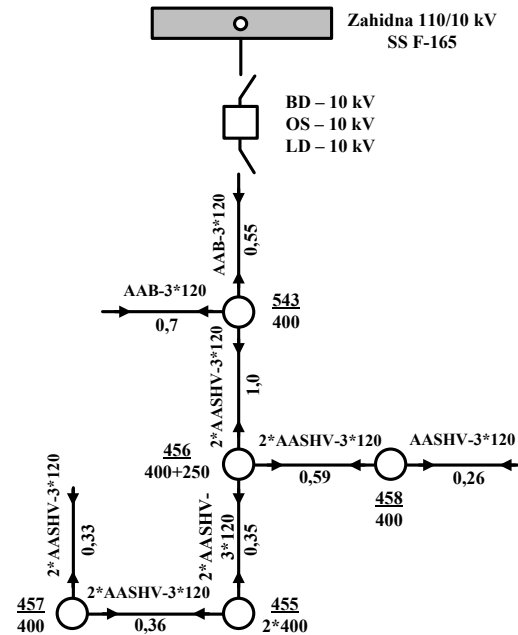


Fig. 2. Fragment of 10 kV observation power grid

Table 1

Smart meter models

TP “Zahidna”	“Elvin” No. 8506
TP-455 (T-1)	“Argo” No. 409036
TP-455 (T-2)	“Argo” No. 409022
TP-456 (T-1)	“Argo” No. 404725
TP-456 (T-2)	“Argo” No. 404785
TP-457	“Argo” No. 404700
TP-458	“Argo” No. 402874
TP-543	“Argo” No. 409061

From Fig. 3, *b* it can be seen that the sample included both working days: the first, second, third, eighth and ninth days, and holidays: from the fourth to the seventh, the tenth and eleventh days. The list of feeder consumers contains legal and household subscribers. The latter makes it possible to summarize the results of the analysis of the main and test samples.

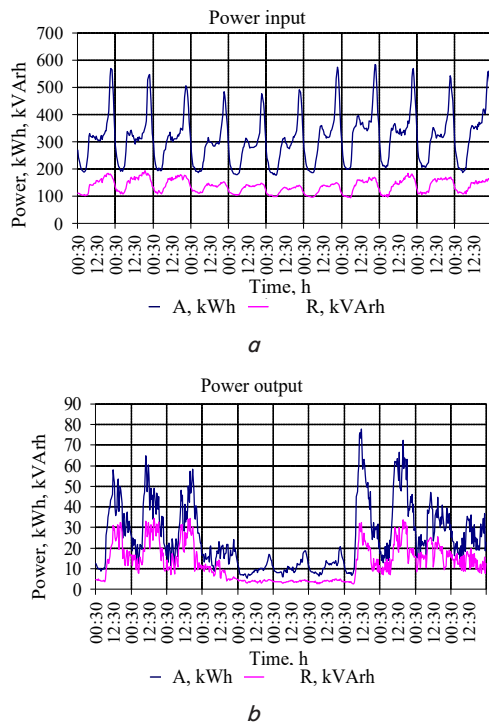


Fig. 3. Example of measured values for eleven days: *a* – power input from the main feeder section; *b* – power output by TP-543

The state estimation of the electrical grid, provided sufficient full observability, was performed on the basis of weighted least squares (WLS) [17] in the MathCad 15 software environment (Mathsoft, USA). Thus, it is proved that, in the presence of complete information on power supply and consumption, the estimated capacity of PG substations practically coincides with the measured values (Fig. 4, *a*). The maximum relative error was calculated by comparing the vector of measured load capacities \mathbf{z} , averaged over a half-hour interval, with their calculated values $\mathbf{h}(\mathbf{x})$:

$$\delta_{\max} = \frac{z_i - h_i(x)}{z_i} \cdot 100 \quad (3)$$

and amounted to less than 0.01 % (Fig. 4, *a*).

For experimental verification of the possibility of using SLC to generate pseudomeasures, the measured load capacities of TP-458, TP-543, TP-455 and TP-456 units were replaced with reproduced according to standard curves and total power consumption during the experiment period (information from ASCAPC). After estimating the PG state and determining $\mathbf{h}(\mathbf{x})$, relative errors of estimating the operating parameters with half-hour averaging were calculated (Fig. 4, *b-d*).

Fig. 4, *b, c* shows the diagrams of changes in the relative error of estimating average load capacities of PG substations

for the case of using pseudomeasures in the unit with the highest power consumption (TP-458) and in the unit with the lowest power consumption (TP-543), respectively. For each of 48 measurements of the daily curve, the relative error of load capacity reproduction does not exceed 0.01 %. That is, using SLC followed by state estimation, information on changes in power consumption in PG units was recovered with high accuracy.

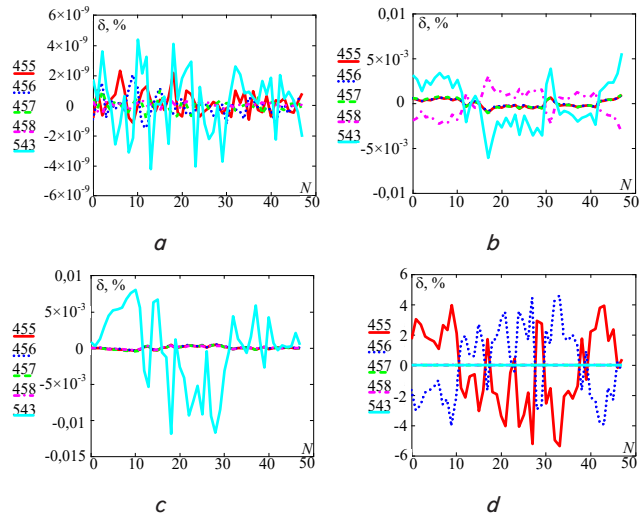


Fig. 4. Maximum relative errors of modeling the PG operating dynamics: *a* – for absolutely observable network; *b* – in the absence of measurements in the TP-458 unit; *c* – in the absence of measurements in the TP-543 unit; *d* – in the absence of measurements in the TP-455 and TP-456 units

Fig. 4, *d* shows the diagrams of changes in the relative error of estimating the average load capacities of substations in the absence of measurement data for the TP-455 and TP-456 units. These units have the largest number of connected lines, so the presence of telemasures for them significantly affects the flow of power in the PG. Analysis of the results showed that the use of load pseudomeasures for the specified units led to an increase in the relative error of estimating the operating parameters by up to 5 % (Fig. 4, *d*).

Thus, according to the results of the experiment, it is found that data on the changes in power consumption in PG can be restored with acceptable accuracy by using standard load curves and ASCAPC information. The obtained results also give grounds for the task of optimizing the structure of the smart metering information system in order to minimize the number of metering devices and provide a given accuracy of reproduction of PG parameters.

7. Discussion of the results of using standard load curves for estimating the dynamics of operating parameters of electric networks

The problem of ensuring the energy efficiency of power grids is related to the need to monitor their parameters. Spatial branching, dynamics of configuration and PG parameters determine the complexity of monitoring systems. Their implementation requires investment, which is often not cost-effective.

The results of the studies show that individual tasks of monitoring PG parameters and planning measures to reduce power consumption can be solved on the basis of pseudometry. Thus, using the aggregated ASCAPC information and standard load curves, it is possible to estimate the average load capacity of an arbitrary PG unit. Recovery accuracy (Fig. 4) is acceptable for use in the calculation of PG operating parameters and power consumption, as well as in optimization procedures for planning power saving measures.

Unlike others, the developed method of estimating the PG operating parameters does not require retrospective data for load recovery. Conversion of power consumption from ASCAPC to the functional form of load curves is performed according to standard load curves [11].

The results of the full-scale experiment confirm the need to consider the relationships between PG units to ensure proper accuracy of load assessment. The absence of measurements for double-ended substations (TP-455 and TP-456) leads to an increase in load estimation error (Fig. 4, *d*). Increasing the number of measurement points gives more accurate results (Fig. 4, *b*, *c*).

The main limitation of the proposed method is the need to provide information on the types of economic activity of subscribers in terms of individual power substations according to CEA. For each substation, weighting factors that characterize the share of subscribers' power consumption by individual types of activities with respect to the total power consumption must be determined. In addition, this information should be updated, which increases the burden on the relevant services of power grid companies.

Further research may raise the problem of developing a method of generating standard aggregate load curves for substations of power grids that provide power to different

types of subscribers, as well as receiving power from dispersed power sources with commensurate capacity.

8. Conclusions

1. Analysis of using ASCAPC data to increase the observability of power grids revealed the need to convert time-aggregated information on power consumption to a functional form of load curve. To solve this problem, it is suggested to use standard load curves according to the types of economic activity of consumers.

2. The method of estimating power grid regimes using time-aggregated ASCAPC information is proposed. The method is based on the formation of pseudomeasures of average capacities using standard load curves. Further minimization of deviations between pseudomeasures and actual power measurements in other units of PG is performed by the weighted least squares method. It is shown that the developed method can be used to recover lost information, reject measurements and synchronize aggregated readings of power meters.

3. The adequacy of the results of estimating of the PG operating parameters is confirmed by comparing the data of computer simulation and field experiment for the real PG. The simulation results show that the application of standard load curves and state estimation methods allows restoring the power consumption curves, averaged over a half-hour interval, with a probability not lower than 95 % in the absence of measurements of part of power substations. The effect of PG equipment with power meters on the adequacy of the results of estimating the operating parameters and power losses needs additional research.

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Всі види релейного захисту основані на порівнянні значень певних ознак при нормальних та аварійних режимах роботи системи. Запропоновано нову ознаку визначення аварійного режиму системи тягового електропостачання постійного струму, а саме, швидкість спадання наруги фідера тягової підстанції. Як відомо, при короткому замиканні в тяговій мережі її напруга знижується. Найбільш різке, практично лінійне, її зменшення спостерігається, по-перше, в перший момент часу аварійного перехідного процесу, і, по-друге, в місці короткого замикання і в точках поблизу нього. Тому крутизна фронту такого зменшення фідерної напруги може бути ознакою короткого замикання. Дана ознака дозволяє визначати вид короткого замикання за дальністю від джерела живлення. Крім того, запропоновані схемні рішення реалізації системи захисту, основані на цій ознаці. Розглядається три варіанти побудови таких систем захисту. Перший варіант з використанням RC фільтра. Другий варіант з використанням імпульсного трансформатора. Третій варіант полягає у використанні мостової схеми. Кожна схема має свої переваги та недоліки, але сучасна електроніка та цифрова техніка дозволяють реалізувати будь яку з них. Це у перспективі сприятиме побудові селективного за дальністю захисту від КЗ. Для цього необхідно використовувати стільки комплектів захисту, скільки точок вздовж тягової лінії необхідно контролювати. Така система також легко реалізується програмними засобами з використанням мікропроцесорної техніки.

Практичні результати, отримані при дослідженні в ділянці тягового електропостачання Придніпровської залізниці, дозволяють стверджувати, що запропонований спосіб визначення коротких замикань є досить ефективним. Його можливо використовувати як додаткову (дублюючу систему) в загальній релейній-захисній апаратурі. Це підвищить надійність систем електропостачання тягових мереж. Загалом розглянутий спосіб визначення коротких замикань може бути використаний у будь-якій електроенергетичній системі постійного струму

Ключові слова: коротке замикання, напруга фідера, швидкість зміни напруги, релейний захист, тривалість спаду напруги, селективний захист

UDC 681.5

DOI:10.15587/1729-4061.2019.186485

CONSTRUCTION OF A METHOD TO PROTECT A TRACTION ELECTRIC NETWORK AGAINST SHORT-CIRCUIT CURRENTS, BASED ON THE NEW ATTRIBUTE

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Received date 03.10.2019

Accepted date 04.12.2019

Published date 23.12.2019

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1. Introduction

It is known that all kinds of protection of electrical systems from emergency modes of operation are based on

certain attributes. Comparing values of these attributes under the normal and emergency states of an electrical system underlies the principle of operation of protective devices.