Research of the Impact of Energy Storage Systems on the Electrical Distribution Networks Operations

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***Abstract*—An analysis was made of the energy storage systems that can be used to improve the efficiency of the electrical distribution network. Features of work of various systems of energy storage and their influence on a mode of work of distributive electric networks are considered. A criterion for determining the economic efficiency of energy storage systems in power distribution networks has been developed.**

***Keywords*—energy storage system, electrical distribution network, load diagram, flywheel, efficiency criterion**

I. Introduction

Distribution electric networks are a very special and important link in the power system. Distributive electric networks are carried out at low voltage classes, have a considerable length, a large number of consumers with rapidly changing and non-stationary schedules of electricity consumption are connected to them. This leads to higher power losses in such electrical networks compared to the power supply and backbone networks, which are carried out at higher voltage classes.

The development trend of power distribution networks in recent years is an increase in the number of distributed generation sources, which include renewable energy sources. They are connected directly to the distribution electric networks and are characterized by a strong dependence of the generated power on climatic conditions and environmental conditions. To solve this problem in the world are increasingly using various systems of accumulation of electrical energy, which have specific features and affect the modes of operation of distribution electrical networks.

Analysis of the development of modern trends in energy storage technologies and systems of energy storage shows that the capacity and number of such systems are increasing significantly both in the world and in Ukraine. Delivery of surplus generated capacity from renewable energy sources to the centralized energy system is carried out directly through the distribution electric networks. It leads to increase of influence of electric energy storage devices both on operating modes of distribution electric networks, and on operating modes of power system as a whole.

Thus, to date, the study of the impact of energy storage systems on the operation of distribution electrical networks is an important and actual task for the energy sector.

Scientists from different countries dealt with the use of energy storage systems in networks of different voltage classes. Considerable attention has been paid to the use of energy storage systems in distribution networks. So in [1], the authors have analyzed the main power storage systems used in distribution networks. The authors of [2] dealt with the issues of automation of storage systems in a distributed network using various storage systems together with renewable energy sources.

In addition to using various energy storage systems to reduce losses in a 0.4 kV distributed electrical networks in the world often use different methods that are introduced at the design stage or already at the time of network operation. In [3], the authors have reduced losses in the electrical network that supplies the hospital using the increase in power supply electrical cable cross-section and the installation of synchronous compensators on the buses.

Besides in work [4], authors for decrease in losses in distributive networks and increase of quality of the electric power offer to use sources of distributive generation being in proximity to the consumer.

It should be noted that a great deal of research is devoted to the modelling of energy storage systems, as well as to analysing the specifics of the integration of such systems into electrical networks of various voltage classes [5] - [7]. The authors [8] substantiate the advantages of distributed generation using radial distribution networks by using modern software for modelling. In constructing the structure of the electricity network in this way, the authors achieve an improvement in the quality of electric energy as well as a reduction in technical losses.

It is important to investigate the impact of distributed generation on the protection systems of power distribution networks against various damages, as the solution of these tasks contributes to the reliability of power distribution networks [9], [10]. Work [11] presents an approach to creating a protection scheme for a radial distribution network with distributed generation sources that well coordinates the behaviour of relay-operated reclosers and sectionalizers, as

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well as allows the effect of distributed generators in a radial network to be controlled using a short-circuit current limiter.

At the same time, the issues of researching the impact of energy storage systems on the operation of electricity distribution networks do not lose their relevance, as the development of technologies and introduction of new technical solutions require constant consideration of the specifics of both the development of the electricity network structure and the specifics of the storage systems used.

II. Justification of the Energy Storage Systems Type for Use in the Distribution Electric Network

The rationale for the type of energy storage systems and the location of their connection to the power distribution network is an important task, as these factors have a strong impact on the operating modes of the power network and the efficiency of the energy storage systems.

To investigate the impact of energy storage systems on the operation of electric distribution networks, a 0.4 kV electrical network was considered, which is located in an urban area in Ukraine (Kharkiv). The scheme of this electrical network is radial and is shown in Fig. 1.

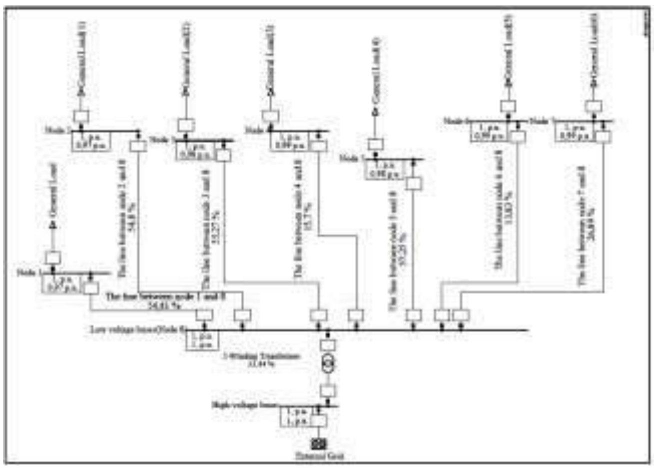


Fig. 1. The scheme investigated electric distribution network.

The electricity network under investigation consists of a transformer substation with a voltage of 10/0.4 kV, as well as 0.4 kV cable lines, which are made using cables of the AASHV brand. Municipal, administrative and household consumers with very different daily load schedules are connected to the considered electricity network. According to [12], the majority of these consumers are electricity receivers of category 3 in terms of supply reliability. The main consumer parameters for the electrical distribution network under investigation are presented in Table. I.

A total load diagram for the consumers of the investigated electric network has been drawn, which is shown in Fig. 2. As can be seen from Fig. 2, this specific nature of the load dependence can greatly impact the operation of the entire power supply system, leading to voltage dips during a sharp decrease in consumption. To eliminate this negative factor in the event of a reduction in electricity consumption, it is advisable to use energy storage systems to smooth out the level of power imbalance in the network, since it is dangerous in this case to turn off generating units from the point of view of energy security.

TABLE I. Main Parameters of Consumers in the Investigated Electrical Distribution Network

Node number	Customer name	Number of floors	Estimated load of residential buildings		
			***P*, kW**	***Q*, kVar**	***S*, kVA**
1, 2, 3	Dwelling house	9	470.7	152.2	494.7
5	Dwelling house	9	482.0	168.4	510.5
4,6	Dwelling house	5	117.0	33.9	121.8
7	School	4	140	46.2	147.4

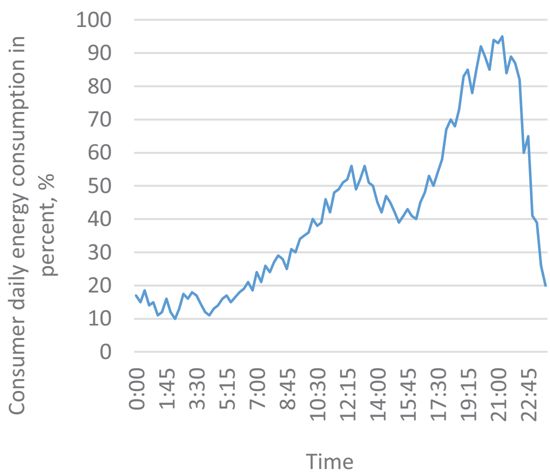


Fig. 2. Total load diagram for the consumer in investigated distribution network.

According to the international standard [13], the deviation value of the voltage over a certain time interval must not exceed the limit value for any load changes in the electrical network.

Modeling of operating mode parameters for the investigated electrical network when the load changes was performed using the DigSILENT PowerFactory software and computing complex [14].

On the basis of data on the magnitude and character of changes in the total load of consumers in the investigated electrical network, a graph of the total planned capacity that comes from the external power system to the investigated electrical network was drawn to cover the resulting consumption graph (Fig. 3).

In order to reduce power losses in the investigated electric network, it is advisable to use energy storage systems, taking into account the prospects for further development and the trend of increasing the number of distributed generation sources connected to the electric distribution networks, as well as global experience in using energy storage systems. It should be noted that different types of energy storage systems, including flywheels, can be used for such an electrical network, as there are such systems among consumers that allow them to use the kinetic energy of their movements.

Thus, an important task is to determine the type and location of energy storage systems in the investigated electrical distribution network.

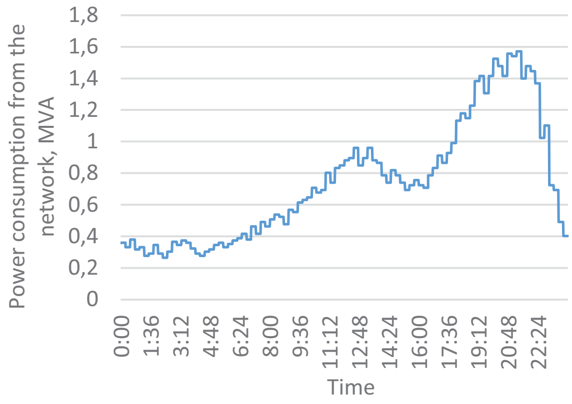


Fig. 3. Graph of the total planned capacity that is supplied from the external energy system to the investigated distribution electrical network to cover the resulting load consumption graph.

III. The Use of Energy Storage Systems in Distribution Networks

In order to solve this task, two options were considered for locating energy storage systems in different parts of the electric distribution network. In the first option, the energy storage devices are located in the nodes of the electricity network where consumers are directly connected. In the second option, the connection of energy storage systems was made at the distribution network power supply centre.

A. The use of Energy Storage Systems in Consumer Nodes

The scheme of the investigated electrical distribution network for the first option of connecting energy storage systems is shown in Fig. 4. In this case, the energy storage systems, each of which has a capacity of 0.04 MW, are located on 0.4 kV buses in the nodes of the electricity network where consumers are directly connected. These are nodes 1-5 in the presented scheme of the electrical distribution network under investigation.

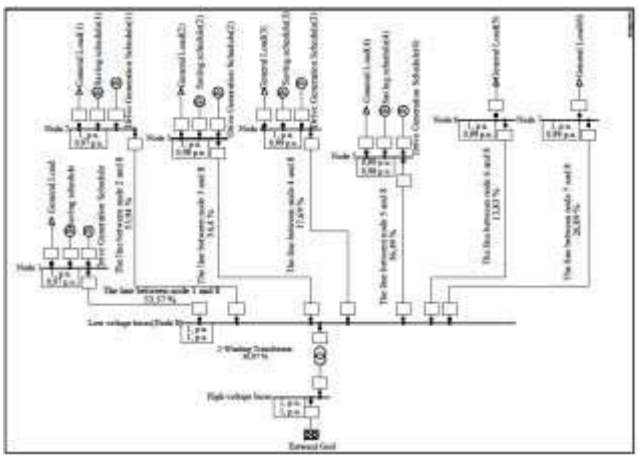
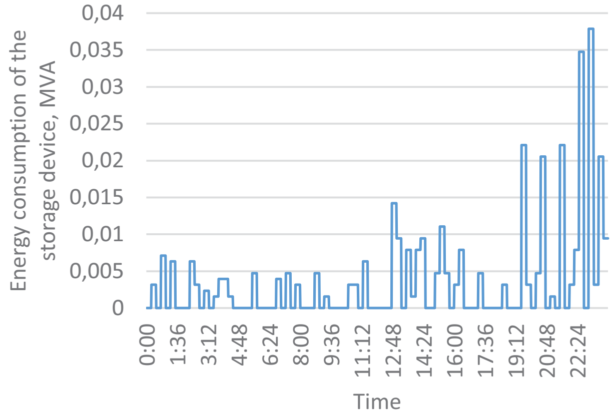


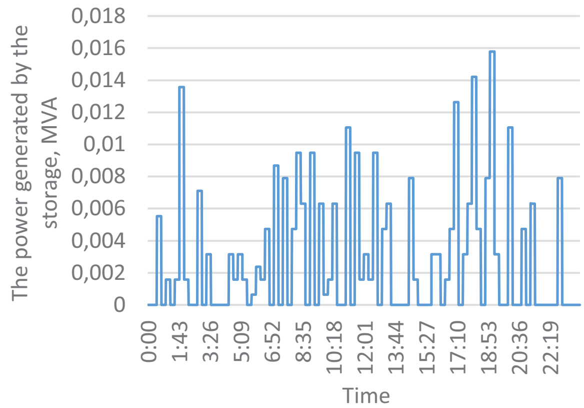
Fig. 4. Scheme of the investigated distribution electric network with energy storage systems for option I (located in consumer nodes).

Different types of energy storage systems can be used for this individual connection method: batteries, flywheels, capacitors and others. The flywheels were considered as energy storage systems for the investigation electricity network. In such a system, the drive is used in the form of two modules, one is an engine that stores energy, and the second generator, which at the right time supplies power to the network.

After the energy storage systems in investigated electrical network are connected, the load schedule changes, which is supplied from the energy system to cover the load of consumers in the investigated electrical network. Schedules of power output by energy storage systems for each of the nodes of the considered electrical network were obtained using the drive and power generation schedules. One of them is shown in the Fig. 5. On the basis of the graphs constructed, a summary graph of power consumption from the power supply system was obtained after the connection of the energy storage systems in the electrical distribution network under investigation, which is shown in the Fig. 6.



a)



b)

Fig. 5. Power graphs when the energy storage system is running for option I: a - graph of accumulated power; b - graph of accumulated power generation.

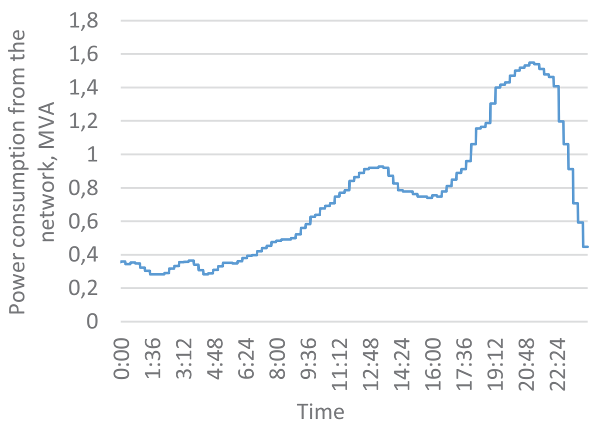


Fig. 6. Graph of the power consumed by distribution network from the power system when using the energy storage system for the first connection option.

B. *Using the Energy Storage System on the Buses of the Power Substation*

The scheme of the investigated electric distribution network for the second option of connecting energy storage systems is shown in the Fig. 7. In this case, the energy storage systems were located on 0.4 kV busbars of the transformer substation, from which all consumers are supplied with electrical energy. This is node number 8 on the presented scheme of the distribution electrical network under investigation. The energy storage system has a capacity of 0.04 MW and consists of six individual storage units.

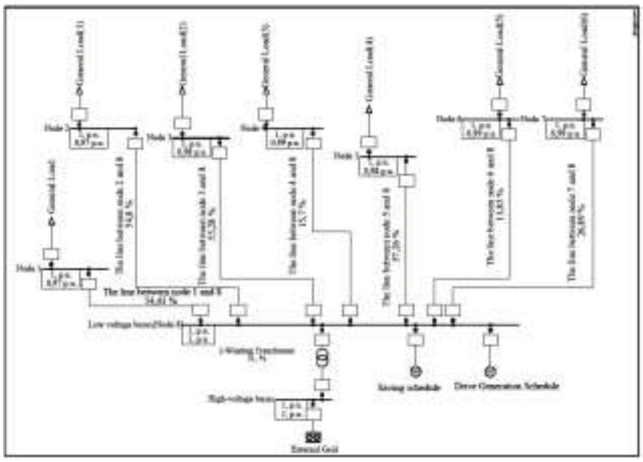
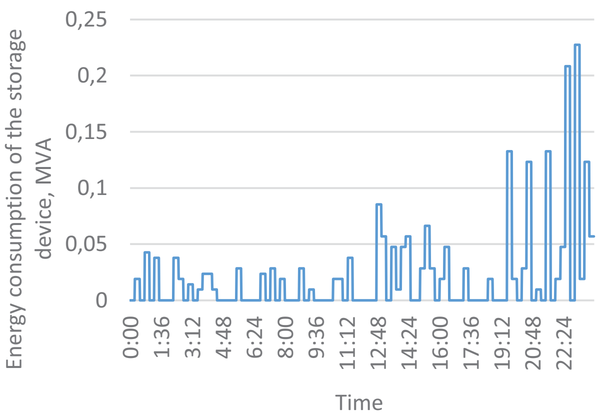


Fig. 7. Scheme of the investigated distribution electric network with energy storage for option II (located on the buses of the power substation).

This group connection method also allows the use of different types of low and medium power storage systems, except for flywheels, due to the lack of easily accessible mechanical power generation methods at the connection point. Accumulator batteries were considered as energy storage systems for investigated electrical network.

The summary graphs of energy storage and power output for the energy storage system in the electrical network under consideration are presented in Fig. 8. The summary graph of power consumption from the energy system after the connection of the energy storage systems in the electricity distribution network under investigation for the second option was obtained taking into account the graph of power output from the energy storage system and is presented in Fig. 9.



a)

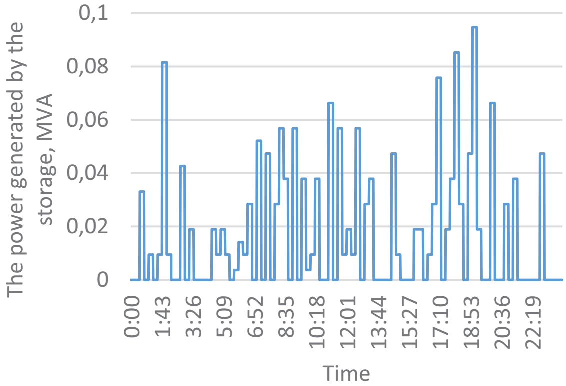


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Fig. 8. Power graphs when the energy storage system is running for option II: a - graph of accumulated power; b - graph of accumulated power generation.

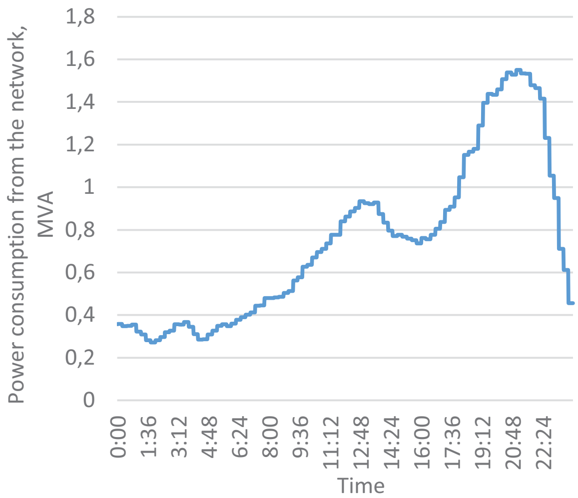

Fig. 9. Graph of the power consumed by distribution network from the power system when using the energy storage system for the second connection option.

IV. Cost-Effective Use of Energy Storage Systems to Improve the Efficiency of Electrical Distribution Networks

Analysis of the graphs shown in Fig. 5 and Fig. 8, showed that the drive produces on average more than 50 cycles of discharge of accumulated energy per day. This number of trips is random, but depending on the number of trips, the drive may waste a lifetime of reliability, which will affect the reliability and efficiency of the electrical distribution network.

Therefore, in order to justify the choice of the location for connecting the energy storage systems in the electricity distribution network, it is necessary to take into account the factors affecting the operation of the energy storage system used and assess the technical and economic performance of the electricity network.

A. *Factors Affecting the Operation of the Energy Storage Systems Used*

One of the weakest links in a flywheel energy storage device is bearings. In many applications, it is assumed that the service life of such an energy storage device depends on how long the bearings have a service life under normal operating conditions. In [15], a method for calculating the service life of a bearing, which is calculated by the formula:

$$L_{nm} = a_1 \cdot a_{SKF} \cdot \left(\frac{C}{P}\right)^3, \qquad (1)$$

where a_1 – life correction factor for reliability, which is 0.55 for 96% reliability; a_{SKF} – SKF life correction coefficient, which can be found in the tables in the SKF catalog [16]; C – nominal basic dynamic load, kN; P – equivalent dynamic bearing load, kN.

According to studies conducted in [15] and [17], the authors determined that if the number of generation cycles per day does not exceed 100 (+ 20%) times, then the average service life of such an energy storage device will be 15 years.

In addition, one of the basic characteristics for the flywheel energy storage is the amount of energy it stores:

$$E = \frac{1}{2} \cdot I \cdot \omega^2, \qquad (2)$$

where E – accumulated kinetic energy; I – moment of inertia; ω – angular velocity.

As can be seen from formula (2), the energy stored in the system is equal to half the moment of inertia and the square of its angular velocity. This allows us to conclude that the features of the flywheel design determine the efficiency of its operation. As a result, these parameters have a significant impact on the amount of energy stored and the operating mode of the electricity distribution network in which the flywheel is used.

The strength limit of the flywheel is determined as:

$$\sigma_{max} = \rho \cdot r^2 \cdot \omega^2, \qquad (3)$$

where σ_{max} – maximum tensile strength; ρ – material density; r – radius; ω – angular.

According to formula (3), the design of such energy storage devices focuses on the choice of flywheel design and angular speed of its rotation. In most cases, the angular speed depends on the material from which the flywheel was designed [18]. Based on formula (3), it is possible to determine the maximum allowable angular speed for different types of flywheels.

Therefore, when using the flywheels to operate in the electricity distribution network, it is necessary to take these features into account when selecting the design of such storage devices in order to maximise the efficiency of the electricity distribution network.

B. Technical and Economic Criterion for the Efficient Using of Energy Storage Systems During Operation in Electrical Distribution Networks

In order to quantify the efficiency of the use of energy storage systems in electrical distribution networks, a technical and economic criterion has been developed which takes into account the type, specifics of operation, the location where the energy storage systems are connected, the reliability of the power supply to consumers and the characteristics of electrical distribution networks:

$$\begin{aligned} K_{ef}(x) = &\sum_{m=1}^{M} w_{R_m} \cdot R_m(x) + w_P \cdot P(x) + \\ &+ w_C \cdot C(x) + w_K \cdot K(x) + w_{\eta_{CHE}} \cdot \eta_{CHE}(x) \end{aligned}, \qquad (4)$$

where x – number of the measures group for improving the efficiency of the operation of electrical distribution networks, which is characterised by the type, quantity and location of energy storage systems; $R_m(x)$ – electricity distribution network reliability index (SAIDI, SAIFI, MAIFI, ENS and others), the value of which is determined in accordance with [19]; M – the quantity of electrical network reliability indices that are taken into account in the calculation; $P(x)$ – total power losses when transmitting electricity to consumers in the electrical distribution networks; $C(x)$ – total costs of the power supply system for measures to improve the efficiency of the electrical distribution network operation; $K(x)$ – the amount of compensation to consumers for failure to meet guaranteed quality standards for the provision of electricity services that the distribution system operator counts and provides to the consumer in accordance with [20]; $\eta_{CHE}(x)$ – the efficiency of energy storage systems of different types; w_{R_m}, w_P, w_C, w_K, $w_{\eta_{CHE}}$ – weighting factors which take into account the significance of the indices of electrical network reliability, total power losses in the electrical network $P(x)$, the cost of measures to improve the efficiency of the operation of electrical distribution networks $C(x)$ and compensation to consumers for failure to comply with quality standards for the provision of electricity supply services $K(x)$ in accordance with the current state of the electricity market, as well as the efficiency factor of the energy storage systems used $\eta_{CHE}(x)$.

In order to select an economically feasible measure to improve the efficiency of the operation of the electrical distribution network, which depends on the type, quantity, capacity and location of the energy storage systems:

- to develop options for such measures to improve the efficiency of the electrical distribution network operation;
- to define for each group of measures the value of the technical and economic criterion for improving the efficiency of the electrical distribution network operation $K_{ef}(x)$;
- to select from the developed measures list one that meets the minimum of the calculated performance criteria according to the expression:

$$\mathrm{K}_{\mathrm{ef}}(\mathrm{x}) \to \min. \qquad (5)$$

Such technical limitations must be taken into account when solving the task required:

$$\begin{aligned} &SAIDI(x) \le SAIDI_{max}, \quad SAIFI(x) \le SAIFI_{max}, \\ &MAIFI(x) \le MAIFI_{max}, \quad ENS(x) \le ENS_{max}, \\ &I_{EEQ}(x) \le I_{EEQ\,mp}, \qquad P_M(x) \le P_{M\,mp}, \end{aligned} \qquad (6)$$

where $\mathrm{SAIDI}_{\max}$, $\mathrm{SAIFI}_{\max}$, $\mathrm{MAIFI}_{\max}$, $\mathrm{ENS}_{\max}$ – maximum values of electricity distribution network reliability indices that correspond to the required level of power supply services provision; $I_{EEQ_{mp}}$ – maximum permissible values for electrical energy quality indicators; $P_{M_{mp}}$ – maximum permissible values for the parameters of the electrical distribution network mode (voltages in the electrical network nodes, currents in power transmission lines, etc.).

The calculation of this criterion for the electricity network under consideration (Table. II) has shown that the most efficient way to connect the energy storage systems is to use the first option.

TABLE II. EVALUATION OF MEASURES TO IMPROVE THE EFFICIENCY OF THE OPERATION OF ELECTRICAL DISTRIBUTION NETWORKS

Number of the measure group	Characteristics of the measure group	Efficiency coefficient $K_{ef}(x)$, rel. units
1	Installation of flywheels in consumer nodes	0,64
2	Installation of accumulator batteries on buses of the power substation	0,83

Thus, the proposed technical and economic criterion for the efficiency of the use of energy storage systems when operating in electrical distribution networks takes into account the total cost of connecting the storage systems, the amount of power losses during the transportation of electricity from the supply network, indicators of the reliability of electrical distribution networks and the quality of electrical energy supplied to consumers. The application of this criterion makes it possible to quantify the feasibility of the cost of using energy storage systems in the electricity distribution network.

CONCLUSIONS

According to the results of the study for the distribution network of 0.4 kV, the use of a kinetic (flywheel) drive is advisable when installing it on consumer buses with maximum load. Since the number of triggering cycles per day is close to 50, and according to the results of the research conducted by the authors of other works and suppliers of such energy storage systems, for normal operation of the energy storage systems for 15 years, the average number of cycles per day should be 100 (+20%) times. Therefore, the use of such a drive in such distribution networks is one of the most optimal ways to balance the load schedule and ensure that the quality of electrical energy is improved.

In order to quantify the efficiency of the application of energy storage systems in electrical distribution networks, a technical and economic efficiency criterion has been developed, which takes into account the type, specifics of operation, the place of connection of the energy storage systems, the specifics of the electrical network structure, the costs of connection of the electrical network storage and maintenance systems, the amount of power losses during transportation of electricity from the electrical supply network, indicators of the reliability of the electrical distribution network operation and the quality of electrical energy supplied to consumers.

The application of the developed technical and economic criterion made it possible to compare different options for the connection of electric energy storage devices in the electrical distribution network under investigation and to substantiate the expediency of using 5 groups of flywheel storage devices connected in the consumer nodes, as compared to 6 groups of batteries located on 0.4 kV buses of the transformer substation.

REFERENCES

[1] A. Alhamali, M.E. Farrag, G. Bevan, and D.M. Hepburn, "Review of Energy Storage Systems in electric grid and their potential in distribution networks," In 2016 Eighteenth International Middle East Power Systems Conference (MEPCON), Cairo, pp. 546-551, 2016.

[2] S.S. Sami, M. Cheng, J. Wu, and N. Jenkins, "A virtual energy storage system for voltage control of distribution networks," *Journal of Power and Energy Systems*, vol. 4, no. 2, pp. 146-154, 2018.

[3] O.F. Odiasea and O. Agbonayeb, "Technical power losses reduction on distribution network of university of benin teaching hospital," *International Journal of Renewable Energy and Environment*, vol. 3, pp. 12- 27, 2018.

[4] A.M. Eltamaly, Y.S. Mohamed, A.M. El-Sayed, and A.N. Elghaffar, "Impact of Distributed Generation (DG) on the Distribution System Network," *International Journal of Engineering Science*, vol. 1, no. 17, pp. 165-170, 2019.

[5] M. Rampazzo, M. Luvisotto, N. Tomasone, I. Fastelli, M. Schiavetti, "Modelling and simulation of a Li-ion energy storage system: Case study from the island of Ventotene in the Tyrrhenian Sea," *Journal of Energy Storage*, vol. 15, pp. 57-68, 2018.

[6] T. Xia, M. Li, P. Zi, L. Tian, X. Qin, and N. An, "Modeling and simulation of Battery Energy Storage System (BESS) used in power system," in *2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, Changsha, China, 2015, pp. 2120-2125.

[7] J. Stuchly, S. Misak, and L. Prokop, "A Simulation of Energy Storage System for Improving the Power System Stability with Grid-Connected PV using MCA Analysis and LabVIEW Tool," *Advances in Electrical and Electronic Engineering*, vol. 13, no. 2, pp. 127-136, 2015.

[8] A.O. Ekwue and O.A. Akintunde, "The Impact of Distributed Generation on Distribution Networks," *Nigerian Journal of Technology*, vol. 34, no. 2, pp. 325-331, 2015.

[9] J. Dong, Y.J. Rong, and C.J. Zhang, "Analysis of the Impact of Distributed Generation on Distribution Network Protection," *Advanced Materials Research*, vol. 433-440, pp. 5924-5929, 2012.

[10] M.A. Gana, U.O. Aliyu, and G.A. Bakare, "Integration and Evaluation of the Impact of Distributed Generation on the Protection System of Distribution Network with DG Using Etap," *Engineering and Applied Sciences*, vol. 4, no. 2, pp. 44-51, 2019.

[11] R.W. Osabohien and R. Uhunmwangho, "Assessing the Impacts of distributed generation on the protection scheme of a distribution network: Trans Amadi 33 kV distribution network as a case study," *Nigerian Journal of Technology (NIJOTECH)*, vol. 37, no. 1, pp. 209–215, 2018.

[12] Ministry of Energy and Coal Industry of Ukraine, *Rules of arrangement of electrical installations*. Kiev, 2017.

[13] EN 50160:2010, "Voltage characteristics of electricity supplied by public electricity networks," 2010.

[14] DIgSILENT PowerFactory, User Manual, 2018.

[15] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Applied Energy, Elsevier*, vol. 137, pp. 511-536, 2015.

[16] N. Leijtens, "Design of an Energy Storage System for Pacific Islands," University of Twente, Enschede, Netherlands, Internship Research, Aug.–Nov., 2015.

[17] SKF, "Rolling Bearings Catalog 2012," PUB BU/P1 10000 EN, Oct. 2012.

[18] F.J.M. Thoolen, "Development of an advanced high speed flywheel energy storage system," Doctoral Thesis, Dept. of Mechanical Engineering, Eindhoven University of Technology, Netherlands, 1993.

[19] Verkhovna Rada of Ukraine, "Forms of reporting on the electricity supply quality and instructions on how to fill them out," *Verkhovna Rada of Ukraine*, Legislation of Ukraine, 2018. [Online]. Available: https://zakon.rada.gov.ua/laws/show/v0374874-18#n18. [Accessed Aug. 19, 2020].

[20] Verkhovna Rada of Ukraine, "The procedure for ensuring the electricity supply quality and providing compensation to consumers for non-compliance," *Verkhovna Rada of Ukraine*, Legislation of Ukraine, 2018. [Online]. Available: https://zakon.rada.gov.ua/laws/show/v0375874-18. [Accessed Aug. 19, 2020].