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WAYS AND METHODS OF IMPROVING THE EFFICIENCY OF OVERHEAD POWER LINES

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Abstract: At this article, existing methods and ways to increase the efficiency of electricity transmission in overhead power lines were analyzed. The role and place of electric energy in the general structure of energy consumption, methods of its transportation, types of losses that occur during transportation of electric energy and ways to reduce these losses were considered. On the basis of literature sources the structure of losses in transmission lines was investigated. A literature review indicates that a certain type of losses has been overlooked, that is, losses occurring due to the mismatch of the load with the line. The ways of achieving and possibilities of maintaining the operation of lines in a matched load mode were analyzed. New method of reducing losses by creating a matched load mode in power lines is proposed.

Key words: losses in power lines, primary and secondary parameters of power lines, characteristic impedance, unmatched load mode, matched load mode, controlled power lines.

1. Introduction

Today, any daily human activity is anyhow related to the use of electricity. Electricity is converted into other types of energy, namely: thermal, mechanical (potential or kinetic) or chemical; being based on the type of energy, goals and objectives were set. But there is a reverse transformation, i.e. to obtain a certain amount of electricity requires conversion from some other type of energy. Electricity is produced at power plants: thermal, nuclear, wind, solar, hydroelectric etc.

One of disadvantages of electricity is the inability to store it in large quantities and store these reserves for a long time. Stocks of electric energy in accumulators, galvanic cells and capacitors are enough only for operation of rather low-power devices, however, terms of such storage are limited. Electricity should be produced only when it is required by consumers, and in the amount in which they need it. Therefore, there is a problem with rational usage of non-renewable and renewable sources, and, in addition to generating electricity, transferring it to users. The locations of these electricity sources and their consumers are often far apart, at a distance of hundreds or even thousands kilometers. Currently, the problem of rational use of energy resources is relevant all over the world, i.e., getting as much “useful” energy as possible for the same amount of fuel used. Therefore, in the power industry, one of the pressing issues in this direction is the possibility of improving the efficiency of electricity transmission through networks.

According to the data provided by the Ministry of Energy of Ukraine, technological losses in the electricity networks of Ukraine during the transportation of electricity increase to 19.11 % of the total amount of electricity consumed. Moreover, in some regions of Ukraine electricity losses reach almost 30 %.

For the transmission of electricity in the United Energy Systems of Ukraine (UESU), a network of main power transmission lines of different voltage classes is used [1]. According to data [2], in 2018, 70 % of all overhead power lines (OPL) in Ukraine have been in operation for more than 40 years.

2. The role and place of electricity in the overall structure of energy consumption

In total, there are two forms of energy in the world:

- primary energy is an energy form that occurs in nature and has not undergone any engineering impact or transformation process. This is the energy contained in raw fuel.
- secondary energy is an energy form that is derived from the previous form, namely, it is produced or obtained by conversion from a primary energy source. These include thermal, mechanical, chemical energy, electricity, etc.

Electricity is generated at power plants, which are located as close as possible to primary energy sources.

World energy consumption is the total amount of energy that has been used by mankind. It is usually measured over some period of time, such as a year. This energy consists of all the energy consumed from each energy source used by mankind in every industrial or technological field in all countries of the world. According to the statistics presented in [3], the world's annual electricity consumption is growing from year to year. In 2020 it was 23 177 TWh, which is much larger than in 2007 (18 231 TWh) and in 1997 (12 892 TWh). The analysis of these data shows that every 10 years the value of the world's annual electricity consumption increases on average by more than 5000 TWh, or 500 TWh per year. Thus, we can predict that by 2030 the value of global annual electricity consumption will exceed 30,000 TWh, and by 2040 – 35.000 TWh.

3. Methods of transporting electricity

Power plants are connected to each other and to consumers by electric networks by means of cable or wire lines which unite them in the centrally controlled power systems. The transmission of electricity over such distances is most often performed by OPL. Cable lines (CL) are used to transmit electricity over shorter distances, or based on certain technical conditions of laying the line.

The main disadvantages of CL compared to OPL are:

- Laying the cable is much more expensive due to the greater complexity of construction and repair, high costs of materials and requirements for higher qualification of service personnel.
- Due to the influence of insulation temperature restrictions, CLs have a lower throughput per unit cross section.
- Determining the exact location of CL damage can take much longer.

The main advantages of the CL over the OPL include:

- Ability of electrical cables of the required voltage class to cross highways and utilities in required quantity (there are certain regulated restrictions), as well as the ability to lay these lines along highways.
- A large area is not required for laying CLs.
- The cable laid in the ground is not subjected to atmospheric influences.
- Damage to the CL is not so dangerous to people.
- Physical access to the CL route is not available to third parties.

The main advantages of the OPL include:

- Relative cheapness in comparison with the CL.
- Better maintainability due to the fact that earthworks are not needed to replace the wire. It is easy to conduct a visual inspection of line condition seeking for physical damage and checking the integrity of the line.

The main disadvantages of the OPL include:

- Wide exclusion zone: in the regulated zone along the OPL it is forbidden to build any structures and plant trees and, before laying a line through the forest, trees must be cut down along the entire width of the exclusion zone.
- Vulnerability to external influences, for example: trees falling on the line, or wires being stolen. Despite lightning protection devices, it also suffers from lightning strikes. Due to such threats, two circuits, main and backup, are often equipped on one overhead line.

The transmission of electricity over any distance is inevitably accompanied by losses.

The source [4] notes that the amount of power lost depends on certain factors, namely:

- distance from generators and consumers: the greater the distance between them, the more power is lost;
- voltage and resistance in transmission line: the so-called “quality” of line, which depends on the correctly selected parameters of conductors depending on the load of consumers, their number and time when they consume transmitted electricity;
- how much power passes through the line: the more loaded line emits more heat and has more losses. According to [5], electricity transmitted through power systems must be of a certain quality. That is, there are certain regulated indicators of electricity quality which have their permissible limits.

4. Types of losses in the transportation of electricity and ways to reduce them

According to [6], the total amount of energy produced worldwide in 2018 is 26,733 TWh, and losses in electricity transmission – 1994 TWh, which is 7,5 %. That is, 8 % of all energy produced is lost due to the design of power lines, namely, the heating of metal in the conductors. Furthermore, we should take into account the losses of electricity occurring due to the technological process in the equipment of stations and substations for generation and transformation of electricity, as well as self-service, equal to 2355 TWh, which is almost 8.6 % of the total. Thus, the total amount of energy lost is already 4415 TWh, i.e. almost 16.3 %, and consumers get only 83.7 % of all electricity produced.

But what economic effect can be obtained by reducing the global loss rate by at least 1 % or 2 %?

Taking into account, that the average European price of 1 kWh of electricity is 0.2159 euro, the economic effect of electricity transmission losses is 953.7 billion euros. 1 % reduction in losses will lead to global savings of 57.7 billion euros and a 2 % reduction – to 115 billion euros.

In 2018, losses due to the transmission and distribution of electricity in Ukraine amounted to 19.1 TWh, or 13.3 % of the total electricity supply to the network of 143.6 TWh. The electricity price for consumption of 1 kWh is 0.05 euro / kWh. Thus, the economic losses during the transfer in 2018 amounted to 972 million euros. According to the Ministry of Finance of Ukraine, Ukraine's GDP in 2018 amounted to 130 billion euros, and 0.58 % of GDP was lost due to the losses in electricity transmission. Reducing these costs by at least 0.5 % will return 36 million euros to the economy, 1 % will give already 73 million euros and 2 % will recover about 146 million euros.

First of all, it is necessary to understand what these transmission losses are, where they come from, how this 17 % global figure occurs, what it consists of, how it was calculated, and what methods are available to calculate these losses.

In [7–9] authors give a classification of all possible losses in power supply systems. They identify 4 main groups, namely:

1) commercial losses

2) electricity losses due to instrumental errors of their measurement

3) electricity losses for own needs of substations

4) technical losses of electricity.

After analyzing these groups and understanding possibilities, due to which loss reduction will be possible, it becomes clear that losses in each of these groups have unique properties and origins.

- The solution to the problem of losses in the first and second group can be found by upgrading the network and systems of devices performing measurements in certain parts of the power supply system.
- Own-account losses can be reduced by upgrading equipment, as well as automating and optimizing certain production processes.
- Technological losses in networks are the most significant. There are many ways and methods to reduce these losses, but this topic is still relevant, and scientists around the world are looking for ways to reduce losses in electricity transmission.

The instructions [10] divide measures of reducing electricity losses during transmission into the following groups:

- organizational measures;
- technical measures;
- measures to improve systems of settlement and technical accounting of electricity.

The paper also provides a list of typical measures to reduce technological losses of electricity during the transmission in electrical networks.

In [11], measures which can essentially reduce active losses in electric networks are resulted.

In [12], the possibility of reducing electricity losses in the power supply system of an industrial enterprise is considered. Authors note that the regulation of active loads in power supply systems of electricity consumers is essential.

In [13], a list of measures to save electricity, which can be divided into structural and operational ones, is provided.

In [14], one of the existing variants of a constructive measure to reduce losses is given, namely, the development of uninsulated cables for the transmission of a voltage class of 6–35 kV with an increased side surface, which allows increasing the rate of heat exchange of the cable with environment, and as a consequence, to increase line capacity.

In [15], the authors classify the methods of reactive power compensation by the type of compensation device (the type of equipment with which the compensation is performed), by the method of inclusion, and by the location of the compensation device. The description of compensating devices is given, which allow improving energy characteristics, reducing electricity losses and increasing the capacity of power supply systems.

In [16], measures and methods for reducing electricity losses in power supply systems are presented. After analyzing all existing methods, it becomes clear that all of them can be divided into 2 major groups of measures:

1) management of operating modes and development of electrical networks.

2) management of operating modes and development of end user networks.

However, such type of losses as those caused by the mismatch of the load with line, fell out of consideration.

5. Losses from the unmatched load mode

It is well known that in theoretical power engineering a long-distance power line is considered as a line with distributed parameters. In [17], the substitution scheme for such lines is given (Fig. 1)

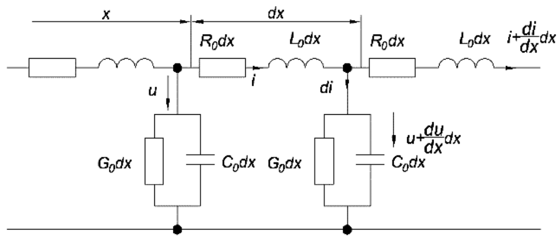

Fig. 1. Π- figurative substitution OPL scheme.

From [17] it is also known that all parameters of the OPL are divided into primary and secondary ones.

Primary parameters of the OPL include specific resistance R_0, specific inductance L_0, specific conduction G_0, specific capacitance C_0.

Secondary parameters include impedance and constant propagation.

The constant propagation of γ is calculated as

$$\gamma = \sqrt{\left(R_0 + j\omega L_0\right)\left(G_0 + j\omega C_0\right)}. \tag{1}$$

Wave resistance $\underline{Z}_C$ of a single transmission line is calculated by the formula:

$$\underline{Z}_c = \sqrt{\frac{R_0 + j\omega L_0}{G_0 + j\omega C_0}} \tag{2}$$

It is known [18], that when an electric signal propagates along such a line, two types of waves occur, namely, incident and reflected ones. The reflected wave occurs due to a mismatch between the load resistance and wave resistance of the line. The presence of the reflected wave leads to decrease in efficiency of the line, since part of the energy from the incident wave does not aproach the load.

In [19], the authors consider operation of power lines in matched load mode to be one of the possible ways to increase the efficiency of electricity transmission. As it is shown in [20], there is no reflected wave in this mode, and the value of the load resistance is equal to the value of the wave resistance. Comparing the results of calculations for two different options, it becomes clear that matched load mode gives the chance to transfer more energy via the same line (with efficiency in the range of 97–99 %, according to data from source [19]), unlike a normal operating mode.

It is possible to ensure the mode of coordinated operation of the line with distributed parameters only when the wave resistance of the line will be equal to its load resistance.

Here the question arises what the possibilities for changing the impedance are due to the complexity of ensuring the operation of the OPL in the mode of coordinated load.

This issue was studied thoroughly enough at the laboratory of controlled transmissions of the Institute of Energy of the Republic of Moldova. The research on the controlled power lines was carried out by a large team of authors under the leadership of Academician Vitaly Postolatiy. Different PLs were developed and tested for different voltage classes, and the theoretical foundations of controlled power high-voltage lines (CPHVL) are described in detail in a series of works [21–25].

It is known that the total power transmitted in the line consists of active and reactive components. These power components are characterized by the values of the active and reactive resistance of the line, voltage at the beginning and at the end of the line, and the phase angle of the shift between these voltages. The active resistance can be influenced only constructively, namely, by changing one of the following indicators: brand and cross-section of the wire/cable, PL length. The other 4 quantities can be influenced without changing the properties of the PL itself.

In work [21], the parameters, characteristics and technical and economic indicators of the USVL are presented. In work [22], diagrams are shown and the structure of the CPHVL is described. In work [23], the structural and circuit differences of the CPHVL from the conventional PL. Schematically, the CPHVL differs from the usual ones, because the circuits of three-phase bus systems at the starting and receiving ends are connected in such a way that a certain angular displacement θ is provided between the voltage vectors of the adjacent phases. The value of the angle θ can vary depending on the OPL load in the range of 0-180º, or is established as a fixed one (0; 120º). In [24], the authors note that the main parameter influenced in the CPHVL is the wave resistance. Controlling the magnitude of the wave impedance is possible only by controlling the angular shift θ, without changing the values of the primary and secondary PL parameters. In work [25], a scheme for continuous regulation of the angle θ in the range from 0 º to 180º is proposed. This scheme is implemented by connecting transformer or autotransformer types of phase control devices with the use of controlled shunt reactors.

In work [26], the principles of operation and other similar methods of influencing the parameters and indicators of PL are considered. Devices for parallel compensation of reactive power (static thyristor compensators, STCs; controlled shunt reactors, CSRs) affect the voltage at the beginning and at the end of the PL; devices for consistent compensation (DCCs) affect the value of reactance; phase control devices (PFDs) affect the value of the phase angle shift of the stress vectors; combined power flow controllers (CPFCs) can affect all four quantities.

In the book [27] methods for increasing the transmission capacity of overhead lines and controlling power flows, means of voltage regulation increasing the static and dynamic stability of EPS through the use of FACTS technology are presented.

Such flexible systems make it possible to regulate power flows in entire interconnected electric power systems (IEPS) and within large distribution networks. They allow more efficient use of intersystem communications, taking into account their resources, optimize the use of power equipment. The use of phase control means in combination with controllable compensation devices makes it possible to regulate the wave impedance of the power transmission line in a wide range for all operating modes. This ultimately leads to a positive economic effect through the use of such IEPSs.

In power supply systems (PSS), the most urgent task is to regulate the flows of active power, since all electrical installations consume exactly active/useful energy calculated by formula (1). One of the ways to regulate active power is to change the angle θ, which is achieved by using the PFD. The purpose of the PFD is to create an additional phase shift between the voltage of the primary buses and the secondary buses, as well as its change depending on the need for the transfer of EE over the PL. Such a change in the angle θ will allow controlling, redistributing the flows of active and reactive power in PL, as well as reducing losses during this transmission.

$$P = \frac{U_1 U_2}{R + jX} \sin\theta, \qquad (3)$$

where P is active power, W; U_1 is voltage at the beginning of PL, V; U_2 is voltage at the end PL, V; R is active resistance PL, Ohm; X is reactance PL, Ohm; Θ is phase shift angle between voltage vectors at the beginning and at the end PL.

An additional phase shift from the PFD can be obtained by introducing a boost voltage between the PFD input and output at the points of its connection to the line. There is a direct relationship between the boost voltage and the angle θ.

Sources [28–31] consider the use cases for the PFD. The authors distinguish 3 ways of adjusting the PFD to change the boost voltage:

- transverse – injected boost voltage offset ± 90º relative to the voltage at the PFD input; the voltage at the output increases in amplitude and changes in phase;
- longitudinal-transverse – input boost voltage as the sum of two components: longitudinal (offset by ±180º relative to the voltage at the PFD input) and transverse (offset ±90º relative to the voltage at the PFD input). With this adjustment, the output voltage can be either higher, or lower, or equal to the voltage at the PFD input, depending on the load transmitted through the PL);
- symmetrical regulation – the input boost voltage is offset by ±90º relative to the voltage at the PFD input, but the output voltage changes only in phase and does not change in amplitude.

The authors note that the existing PFD models with on-load control devices (OLTC) of network parameters (change in voltage amplitude or phase angle) are not fast due to the presence of mechanical switches and sequential voltage phase change. As it is known, performance is an important factor, since the PFD must quickly respond to changes in the network and change the boost voltage depending on the required values for optimal operation of the EPS. With a sufficient level of performance, PFD also increases the resistance of the EPS to external influences. Increasing the PFD performance is an important technical task, along with the possibility of fully automating these processes, since it will reduce the values of losses from the transfer of energy and more efficiently manage the flows of the transmitted power to the UEPS.

In a series of works [32–37], the authors present various schemes for the execution of the PFD: "Two-bar polygon"; "single transformer PFD with neutral regulation"; "polygon"; "triangle"; "star". Their main elements, principle of operation, technical characteristics are described. Also in [37], the authors performed a comparative analysis of the energy characteristics of the PFD. After analyzing the results, the scheme "polygon" (the schematic diagram is shown below in Fig. 2) was chosen as the most optimal scheme. The analysis was carried out according to the results of determining the effectiveness of the device in question, namely, according to 2 characteristics: coefficient characterizing the installed (thermal) power of the device; and the coefficient characterizing the control power. That is, the value of the ratio of the installed power of the transformer to the throughput is one of the smallest indicators. This PFD has also the lowest cost indicator for a phase angle control system.

The main elements of the device are two power three-winding transformers, one of which performs the functions of a parallel (or magnetizing) element and the other operates as a serial (or phase-shifting) element. An index "p" marks the windings and the corresponding electrical quantities characterizing the mode of the magnetizing transformer, an index "q" is for the windings and the electrical quantities of the phase-shifting transformer.

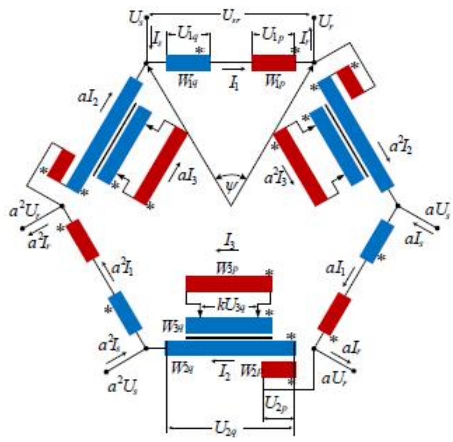

Fig. 2. PFD schematic diagram with winding designation.

The common disadvantages of existing models and versions include the low speed of the PFD control system when changes in the values of the line loads occur in normal and emergency operation modes. This disadvantage can be eliminated by introducing PFD monitoring and control systems into the existing PL. The first system will provide real-time data on load parameters and PL parameters, as well as calculate the optimal values of the angle θ for maximum efficiency in power transmission. The second system is intended to actually change the parameters based on the required values.

This paper analyzes the possibility of introducing information technologies into the OPL parameter adjustment system to create an autonomous OPL control system. The main tasks of this system are speed, accuracy and autonomy in deciding on the regulation of the angle θ.

The PFD control system is most rational and economically promising one to be installed at higher voltage classes. As a rule, lines from 110 kV and above are double-circuit. In this work, we will consider such double-circuit lines, as well as the possibility of introducing a PFD monitoring and control system into them. Let us start with considering the control system.

To carry out continuous regulation of the angular shift of the voltage vector systems of the CPHVL circuits, the angle θ being changed within the range of $0 \div 180°$, it is necessary to install the PFD at the ends of the CPHVL. The work [21] shows a circuit for adjusting the angle θ for a double-circuit PL.

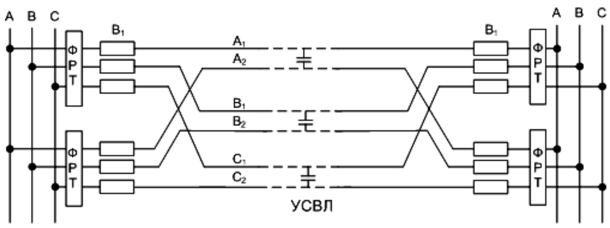

Fig. 3. Wide range continuous angle control circuit with PFD and FACTS devices.

In this OPL scheme, phase-shifting transformers are installed in front of the high-voltage switches, due to the use of which the adjustment process is carried out.

In work [19], the authors consider the possibility of OPL operation in the matched load mode and come to the conclusion that the use of this mode of operation gives the maximum value of the line efficiency during power transmission. As it is known from the theoretical foundations of electrical engineering, a consistent mode of operation of a line is a mode in which the value of the characteristic impedance is equal to the value of the load resistance.

Let us return to wave resistance formula (2).

The specific active resistance of the phases for the selected wire brand remains an independent value. In the absence of corona losses, the value of the active transverse conductance of the wires (phases) of the line can be $g_0 = 0$.

Returning to the diagram shown in Fig. 3, it can be observed that the main fundamental difference between the CPHVL and the conventional double-circuit is in the maximum possible convergence of three-phase circuits, due to which an increased electromagnetic influence of the circuits is achieved, and the change in the angular displacement of three-phase voltage systems of one circuit with respect to another determines the sign of this influence on the equivalent parameters of the phases. The presence of a significant and adjustable electromagnetic mutual influence of the circuits creates the effect of interchain self-compensation of the line parameters, thanks to which increase in the throughput of each circuit and the line as a whole is achieved, as well as new properties of the controlled parameters of the line itself.

Thus, in the CPHVL, the resulting phase parameters are calculated as follows:

$$\underline{Z}_{CE} = \underline{Z}_{C0} + \underline{Z}_{CM} e^{j\theta}, \quad (4)$$

where $\underline{Z}_{C0}$ are eigenvalue parameters of phases of traditional overhead lines; $\underline{Z}_{CM}$ are mutual components of the parameters that appear after phase convergence (in compact overhead lines);
$\underline{Z}_{CE}$ are resulting parameters of phases.

Analyzing formulas 3 and 4, the relationship between the transmission active power of the line P, wave resistance $\underline{Z}_C$ and angle θ will become clear, where the bigger the value θ, the less the value $\underline{Z}_C$ and the bigger the value P. (When $\theta = 0$ º, $\underline{Z}_C$ has a maximum value; when $\theta = 180$ º, $\underline{Z}_C$ has a minimum value).

Thus, the task of this system is changing the angle θ, and as a consequence of this, also the wave resistance, so that the system might work in the most optimal mode, namely in the mode of matched load.

Thus, the calculation in [19] allows us to conclude that the provision of a matchload mode of operation allows significant reducing losses in the transportation of electricity. If all power transmission lines of Ukraine operated in this mode with an efficiency of 98 %, it would reduce energy losses from the existing 19 TWh to 2.9 TWh only in 2018, i.e., almost 6.6 times less! At an estimated price of €0.1 per 1KWh (in 2021 for Ukrainian industrial enterprises), the savings will be around 826 million euros per year. Morover, taking into account the steady rise in electricity prices, the savings will be even bigger.

6. Conclusion

The method for creating and maintaining a matched load mode is proposed, which is provided by the use of the CPHVL.

In modern power supply systems, there are problems associated with losses in the transmission of electricity from sources to consumers.

Electricity is transmitted through engineering systems that originate in methods and areas of activity developed a hundred years ago. Transmission systems are part of the high voltage network. They work as interdependent networks, using a small amount of standardized voltages.

The urgency of modernization of existing OPL UEPS of Ukraine is not only to replace, but also to be able to use new technologies of the OPL themselves. Currently, new developments of high-voltage OPLs, different from traditional ones, are increasingly used. One of the most effective means of developing electrical networks is the use of the compact OPL in combination with FACTS devices, including phase control devices (compact controlled OPL).

The construction of managed energy systems should be carried out at the state level, not in local regions. The economic effect of the implementation of controlled power systems will be felt only on long lines and with big amounts of power. For relatively low-power transmission lines of regional importance, the implementation of managed power systems is not economically justified.

The introduction of a system that would maintain a matchload mode for the transmission line throughout Ukraine will reduce transmission losses by more than 6 times, and will save almost 826 million euros per year.

Directions for further researches are as follows:

1) definition of methods accurate determination of load resistance by measuring current and phase rms values;

2) development of a method for transmitting information about the parameters of the load along the line over long distances;

3) creation of an automated control system for phase-shifting transformers;

4) verification of the proposed method for reducing transmission losses in real conditions.

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ШЛЯХИ ТА МЕТОДИ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ПОВІТРЯНИХ ЛІНІЙ ПЕРЕДАЧІ ЕЛЕКТРИЧНОЇ ЕНЕРГІЇ

Артем Савєльєв

В роботі проаналізовано використовувані методи та шляхи підвищення ефективності передачі електроенергії в повітряних лініях електропередачі. Розглянуто роль та місце електричної енергії в загальній структурі енерго-споживання, способи її транспортування, види втрат, які виникають під час транспортування електричної енергії, та шляхи зменшення цих втрат. На підставі літературних джерел досліджено структуру втрат в лініях передачі. У проведеному огляді літератури вказується, що не роз-глядався такий вид втрат, як втрати за рахунок неуз-годженості навантаження з лінією. Проаналізовано шляхи досягнення та можливості підтримання роботи лінії в режимі узгодженого навантаження.

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