






Optimal Management of Small Hydroelectric Plants Power Generation in Local Electrical Systems

Petro Lezhnuk , Olexander Rubanenko ^(✉) , and Iryna Hunko 

Vinnytsia National Technical University,
93 Khmelnytske Shose St., Vinnytsia 21021, Ukraine
rubanenkoae@ukr.net

Abstract. The number of renewable energy sources (photovoltaic power plants, small hydroelectric power plants and others) is growing rapidly. They transfer the generated electrical energy through the distribution networks of power supply companies. Therefore, the problem of calculating the normal modes of such electrical networks is urgent. This makes it possible to investigate the influence of renewable energy sources on the losses of electric power in distribution electrical networks. The given paper presents a mathematical model of active power losses of local electrical systems - electrical systems of power supply companies. The sources of electricity for such systems are not only powerful electric stations, but also renewable energy sources. Often these are distributed sources of energy. That is why optimal management of such sources is complex. The article shows the determination of insensitivity zones of the optimal points deviations in which the power fluxes are distributed to the change in the load power and generation in the nodes of local electrical systems. The mathematical expression is proposed where similarity criteria are used, it allows to analyze the influence of generation of the investigated renewable energy source on the losses of active power. The significance of these similarity criteria can be determined from the optimality conditions of the dual criterion programming problem with respect to the direct problem. It is expected that the account of calculation results of dead zones will enable to determine a renewable energy source, for instance, a small hydroelectric power station. Control of the generated power of the selected power plant at this time provides minimal losses of electrical energy of distributed electric networks.

Keywords: Renewable energy sources · District electric networks
Power lines · Distributed sources of energy · Electricity losses
Mathematical model · The country's energy · Matrix of branches in the nodes

1 Introduction

A sign of today is the ever-increasing use of renewable energy sources (RES) which are considered as one of the most promising ways to solve growing energy supply problems. Often, such features of RES as ecological cleanliness and inexhaustible resource

base become crucial to their benefits in the face of increasing rates of environmental pollution and a rapid reduction of organic fuel resources.

Ensuring the country's energy independence and joining the European Union are two of the most important strategic tasks for the development of modern Ukraine. One of the conditions for a successful solution to both tasks is the maximum increase in the share of energy in the strategic balance, produced at the expense of its own energy resources, including RES. Ukraine has a great potential for a variety of RES.

It is also known that there are problems in Ukraine due to the use of traditional energy sources. The reasons are outdated technologies and the exhaustion of equipment resources in the power industry which, together with the low efficiency of fuel usage, lead to considerable increase of harmful emissions. The significant losses during transportation, distribution and use of electricity and heat, as well as a monopoly dependence on imports of energy carriers, complicate the situation on the energy markets of Ukraine. However, an increase in the generation of distributed energy sources (DES) without taking into account the peculiarities of their operation in power grids can lead to the deterioration of the electric energy quality, and sometimes to deterioration of equipment reliability indices in local electrical systems.

Consequently, the reduction of electricity losses in local electrical systems by means of coordinated control over the generation of solar power stations and small hydroelectric stations and the optimization of power flows in local electrical systems (LES) with RES are relevant, designed to ensure reduction of electricity losses in electrical networks, maintain balance reliability and improve the quality of electric energy supply.

A characteristic feature of today is the ever-increasing use of renewable energy sources (RESs) which are considered to be one of the most promising ways of solving growing energy supply problems. Such features of RES as ecological cleanliness and inexhaustible resource base become their main advantages in the conditions of increasing rates of environmental pollution and a rapid reduction of organic fuel resources.

Providing the country's energy independence and joining the European Union are two of the most important strategic tasks of the development of modern Ukraine. One of the conditions of a successful solution of both tasks is the maximum increase in the strategic balance of the share of energy produced at the expense of its own energy resources, including RES. Ukraine has a great potential of various RES.

It is also known that there are problems in Ukraine due to the use of traditional energy sources. The reasons of this are outdated technologies, the exhaustion of equipment resources in power industry, and all of this, together with the low efficiency of fuel use, leads to significant amounts of harmful emissions. Significant losses in the process of transportation, distribution and use of electric energy and heat, as well as a monopoly dependence on imports of energy carriers, complicate the situation in the energy markets of Ukraine. However, an increase in the generation volume of distributed energy sources (DESs) without taking into account the peculiarities of their operation in power grids can lead to the deterioration of electric energy quality, and sometimes to the deterioration of reliability indices of the equipment of local electrical systems.

2 Literature Review

In [1] Anand et al. state that in order to reduce electric energy losses and improve its quality indices, it is expedient to pass to solution of the complex problem of district electric grids (DEG), which involves the implementation of efficient design solutions and the introduction of operational reconfiguration systems of RES connection by means of Smart Grid.

Consequently, the reduction of electric energy losses in local electrical systems by means of coordinated control of the generation by solar power plants and small hydroelectric power stations, and the optimization of power flows in local electric systems (LES) with RES, are urgent, intended to provide the reduction of electric energy losses in power grids, maintain balance reliability and improve the quality of power supply

For example, in [2] the need for coordinated control of automated devices and photovoltaic generators in order to reduce the negative impact of the voltage increase in circuits of DESs by RES sources is substantiated, and an algorithm for reducing power losses and voltage stabilization by using voltage regulators and reactive power compensation devices in a microcontroller is suggested. In [3], an overview of the literature on optimal energy management and control modes of DES is presented and a hierarchical energy management architecture that requires a telecommunications infrastructure for the connection of distributed control on the level of DES with the upper level of control of the energy supply company where the optimization of grid operation mode is carried out, is analyzed. In [4], the issues of autonomous operation of DEG in the directions of symmetric load distribution between parallel operating inverters and compliance with the requirements of electric power quality are studied. In [5], the issue of influence optimization of the share of RES in the balance of reactive power of DEG of wind and solar power plants is discussed. The issue of estimating the forecast characteristics of solar power plants generation is a subject of scientific work in [6]. The article proposes new economic indices for the forecasting of the production of electric energy at solar power plants, considering the consequences of forecasting errors. In [7] a methodology was proposed for the development of equivalents of electric grids of low and medium voltage electric networks to study their impact on the reliability of power systems. In [8], the attention was paid to the creation of intelligent electric grids based on the SMART GRID concept, considering the features of the energy market and RES. The ways of compensating seasonal variations of RES generation are analyzed. In [9], it is shown that the grid configuration depends on the choice of individual generators' modes which allows to reduce the power losses in the system. Inconsistencies in operating modes can lead to excessive losses. In [10], it is said that the integration of RES in the distribution grid of rural areas can significantly improve the reliability of electric energy supply. Thus, the problem of optimal control of power generation by small hydroelectric power stations in local electrical systems is relevant and actively studied in foreign and domestic scientific works.

3 Research Methodology

In order to calculate the losses of active power in District Electric Networks the node voltage method [10] is chosen. The matrix of branches in the nodes, the matrix of the branches resistance and the matrix of currents in the nodes are used as the input parameters.

To calculate the steady-state DEN with DES, the mathematical model based on the node voltage method is adapted to the form of the output data of such networks, as well as to the tasks that are solved. The method and corresponding algorithm allow counting modes when the circuit of the network is closed and open, but some of the lines (those with the RES) are lines with two-way power supply. Moreover, the individual power lines can combine several different types of DES.

The mathematical model in the matrix form, depending on the output data, is used in the form where \mathbf{Y}_n – is a matrix of nodal conductivity;

$$\mathbf{Y}_n \cdot \dot{\mathbf{U}} = \hat{\mathbf{U}}_d^{-1} \hat{\mathbf{S}} - \mathbf{Y}_b \cdot \dot{\mathbf{U}}_b \text{ or } \mathbf{Y}_n \cdot \dot{\mathbf{U}} = \dot{\mathbf{J}} - \mathbf{Y}_b \cdot \dot{\mathbf{U}}_b \quad (1)$$

\mathbf{Y}_b – is a matrix-column of nodal conductivity relative to the balancing node with voltage $\dot{\mathbf{U}}_b$; $\hat{\mathbf{S}}$ is a vector of conjugated complex capacities of nodes; $\hat{\mathbf{U}}_d^{-1}$ – inverse diagonal matrix of nodal voltage complexes; $\dot{\mathbf{J}}$ – is a vector of nodal currents.

Capacities or currents in nodes are provided as the sum of nodal loads and generation of RES:

$$\dot{\mathbf{S}} = \dot{\mathbf{S}}_1 - \dot{\mathbf{S}}_{gHES} - \dot{\mathbf{S}}_{gSES} \text{ or } \dot{\mathbf{J}} = \dot{\mathbf{J}}_1 - \dot{\mathbf{J}}_{gHES} - \dot{\mathbf{J}}_{gSES} \quad (2)$$

To study the effect of the generation of RES on power losses in DEN and its selected fragments, an algorithm based on the matrix of the distribution of power losses on the circuit branches, depending on the power in its nodes, is used [10]:

$$\Delta \dot{\mathbf{S}}_b = \dot{\mathbf{T}} \cdot \dot{\mathbf{S}}, \quad (3)$$

where $\dot{\mathbf{S}}_1, \dots, \dot{\mathbf{S}}_{gHES}$; $\Delta \dot{\mathbf{S}}_b$ – is a vector of losses in the branches of the circuit, which are determined by the capacities.

Each matrix τ line is defined as

$$\dot{\mathbf{T}}_i = (\dot{\mathbf{U}}_i \mathbf{M}_i) \widehat{\mathbf{C}}_i \mathbf{U}_d^{-1}, \quad (4)$$

where \mathbf{M}_i – is branches matrix of connection in the nodes; $\widehat{\mathbf{C}}_i$ – is the i line of the matrix for the distribution of currents in the nodes $\dot{\mathbf{J}}_1, \dot{\mathbf{J}}_{gHES}, \dot{\mathbf{J}}_{gSES}$ on the branches of the circuit. For a fragment of a network with dedicated HES, expression (4) is converted to

$$\Delta \dot{S}_{bf} = \dot{T}_f \cdot \dot{S}_{gHES}, \quad (5)$$

where $\dot{T}_f = \dot{T}_{fa} + \dot{T}_{fr}$ – is the power loss distribution matrix in the fragment of the network. As a rule, the dependence of losses of active power and electricity from generation of hydroelectric power stations is interesting. If the power of HES tires is balanced in such a way that it does not consume or generate reactive power, then the expression (5) for the analysis of the impact of HES on the loss is considerably simplified:

$$\Delta P_b = T_{fa} \cdot P_{gHES}. \quad (6)$$

Expressions (1÷6) are a mathematical model of LES modes that enables to study the impact of HES and SES capacities on power losses in them and determine the optimal power generated by the losses criterion taking into account voltage constraints, transmission capacities and installed HES power.

Unplugging the network trunk at the point of flow distribution provides a minimum of power losses [11]. However, network segmentation at this point is associated with a number of problems. First, optimal location of power losses may not coincide with the location of the segmentation determined from the conditions of reliability. Secondly, the point of flow distribution in the network can “float”, depending on the load, in addition, the point of flow distribution of active and reactive power may not coincide. The task is to ensure that a power network, open in accordance with the requirements of reliability, provides power fluxes that correspond to the point of flow distribution in a closed network. Thus, a reduction of electric power losses in DEN without reducing its reliability is achieved. In DEN with RES, it is possible to influence the power flows by modifying the generation of small HES and SES [11, 12]. However, considering that the optimal point of power flow and, accordingly, the calculated optimal power flows may change, this task can only be realized with the help of Industrial control system (ICS).

To create the normal conditions for the functioning of ICS it is necessary to establish for it a zone of insensitivity to the input parameters, which are the power load of consumers and the generation of DES.

By its physical content, this zone of insensitivity corresponds to the optimality region of electric energy losses in DEN when the power load of consumers and the generation of DES change [13, 14].

4 Results

The insensitivity zone of the functioning of ICS can be determined in relative units in accordance with the procedure outlined in [15]. To obtain a criterial model that relates the relative total active power losses in DEN with currents set in the nodes, the following equation is written in matrix form:

$$\Delta P = \dot{\mathbf{I}}_t \mathbf{r} \hat{\mathbf{I}}. \tag{7}$$

Let us express the losses ΔP by the currents in the nodes. The currents in the network branches, if emf is missing, are defined as $\dot{\mathbf{I}} = \dot{\mathbf{C}} \mathbf{J}$, where $\dot{\mathbf{C}}$ – is matrix of current distribution coefficients, \mathbf{J} – is current in the nodes of load and DES generation. Then (7) will be rewritten:

$$\Delta P = \dot{\mathbf{J}}_t \left(\dot{\mathbf{C}}_t \mathbf{r} \hat{\mathbf{C}} \right) \hat{\mathbf{J}} \tag{8}$$

Rewrite (8) as follows: $\mathbf{B}_a = Re \left(\dot{\mathbf{C}}_t \mathbf{r} \hat{\mathbf{C}} \right)$; $\mathbf{B}_p = Im \left(\dot{\mathbf{C}}_t \mathbf{r} \hat{\mathbf{C}} \right)$ are valid symmetric matrices.

$$\Delta P = \dot{\mathbf{J}}_t \mathbf{B}_a \hat{\mathbf{J}} + j \dot{\mathbf{J}}_t \mathbf{B}_p \hat{\mathbf{J}}. \tag{9}$$

Further, according to the method described in [8], expression (9) is rewritten in a canonical quadratic form and by the method of integral analogues [7] the value of power losses in relative units is written:

$$\Delta P_* = \sum_{i=1}^m \pi_{ja} \bar{J}_{ja}^2 + \sum_{i=1}^m \pi_{jp} \bar{J}_{jp}^2 \tag{10}$$

Or

$$\Delta P_* = \sum_{j=1}^m \pi_{ja} \left(\sum_{i=1}^m v_{jia} \frac{J_{jao}}{J_{jao}} J_{ia} \right)^2 + \sum_{j=1}^m \pi_{jp} \left(\sum_{i=1}^m v_{jip} \frac{J_{jpo}}{J_{jpo}} J_{ip} \right)^2 \tag{11}$$

$\pi_{ja}^J = \frac{b_{ja} \bar{J}_{jao}^2}{\Delta P_{min}}$; $\pi_{jp}^J = \frac{b_{jp} \bar{J}_{jpo}^2}{\Delta P_{min}}$ where is caused by the active and reactive components of currents in the nodes, respectively from the general expression for DEN with DES (11), we can obtain the expression for analysis of the effect on relative power losses P_* in the network, caused by the generation of DES. For example, for j-th DES with (11) we obtain:

$$\Delta P_{*j} = \pi_{ja} v_{aj}^2 J_{ja}^2 + \pi_{jp} v_{jp}^2 J_{jp}^2 \tag{12}$$

where v_{aj} , v_{pj} – are weight coefficients of the influence of the relative change of the current in the j-th node, expressed through the branches parameters.

Another possibility of determining relative power losses, depending on the power of a small hydroelectric power station, is the usage of expression (6). In this case, the influence of HES capacity on the losses of power is determined in the part of the electrical network on which this HES is operating. In practice, as a rule, the task is set

precisely because it is necessary to determine the zone of insensitivity for ICS of HES, corrective effects of which are determined by the local parameters of the mode [8].

To construct the dependence of power losses on the power of HES and further analysis of the sensitivity, calculations are carried out according to (6). Dependence is formed in tabular form. When using the criterion method as the basis of the algorithm for assessing the sensitivity of optimal solutions, the dependence of losses on the power of HES is approximated in the criterial form. In particular, we obtain certain advantage if the dependence $P_f(P_g \text{ HES})$ is approximated in the form of a binomial polynomial:

$$\Delta P_{*j}(P_{g \text{ HES}^*}) = a_j P_{g \text{ HES}^*}^{\alpha_j} + b_j P_{g \text{ HES}^*}^{\beta_j}, \tag{13}$$

where $\Delta P_{*j}(P_{g \text{ HES}^*})$ – is the value of the target function (minimum losses of active power in the network or its part) in relative units; $P_{g \text{ HES}^*j} = P_{g \text{ HES} j} / P_{g \text{ HES} j_0}$ generation capacity of HES, with the help of which the LES modes are optimized, in relative units. (taken as the basic optimal values of generating capacity of HES); $a_j, b_j, \alpha_j, \beta_j$ – are constant coefficients reflecting the dependence and the degree of influence of HES generation on the value ΔP_{*j} . The advantage of approximating the target function in the form (13) lies in the fact that the direct and inverse task of sensitivity is solved in a simplified manner [16]. If there is no problem with the direct task – $\Delta P_{*j}(P_{g \text{ HES}^*})$ in the right side of Eq. (13) the set deviation of the generation is substituted and the corresponding value of the losses is calculated, then the inverse task of sensitivity ΔP_* is more difficult. Since the Eq. (13) is nonlinear, the inverse problem of sensitivity refers to incorrect problems [15].

Figure 1 illustrates the determination of optimal solutions area, i.e., the inverse problem of sensitivity.

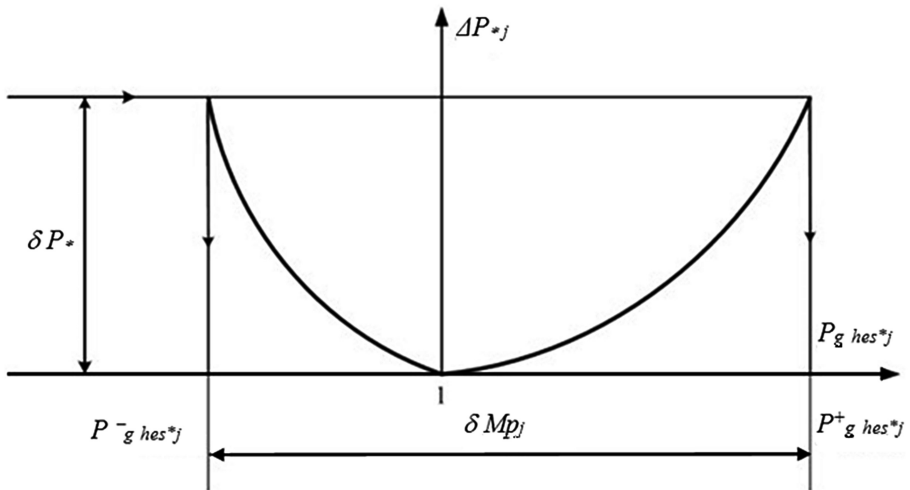


Fig. 1. Definition of optimal solution area (inverse sensitivity problem).

Limiting values of generating power with a given allowable deviation of power δP_* losses in a selected fragment of DEN [8]:

$$P_{g\text{HES}^*j}^- = \left(\frac{1}{\pi_{j1}} \cdot \frac{a_j}{1 + \delta P_*} \right)^{-1/\alpha}, \quad P_{g\text{HES}^*j}^+ = \left(\frac{1}{\pi_{j2}} \cdot \frac{b_j}{1 + \delta P_*} \right)^{-1/\beta}. \quad (14)$$

The values of similarity criteria can be determined from the optimality conditions of the dual problem of criterion programming relative to the direct problem [15]. For (15):

$$\begin{cases} \alpha_j \pi_{j1} + \beta_j \pi_{j2} = 0; \\ \pi_{j1} + \pi_{j2} = 1. \end{cases} \quad (15)$$

From the system of Eqs. (15) we obtain

$$\pi_{j1} = \frac{-\beta_j}{\alpha_j - \beta_j}, \quad \pi_{j2} = \frac{\alpha_j}{\alpha_j - \beta_j}. \quad (16)$$

Substitute in (14) the value of the similarity criteria (16) and finally observe:

$$P_{g\text{HES}^*j}^- = \left(\frac{\alpha_j - \beta_j}{-\beta_j} \frac{a_j}{1 + \delta P_*} \right)^{-1/\alpha}, \quad P_{g\text{HES}^*j}^+ = \left(\frac{\alpha_j - \beta_j}{\alpha_j} \frac{b_j}{1 + \delta P_*} \right)^{-1/\beta}. \quad (17)$$

The resulting δM_P area of the allowable deviations of the variables from their optimal values, in essence, contains a set of possible equally-economical variants of HES generation with the set accuracy. The δM_P area is used to make decisions regarding the implementation of optimal modes, using HES.

It should be noted that the implementation of this approach is achieved by the reduction of the calculated number of impacts on DES. This is essential for GRAM systems of hydroelectric plants, since it makes the implementation of the control laws that are set for them real. In DEN, automating the process of optimal control of power flows is made possible by changing the allowable deviation of active power losses from the optimum value P to control the intensity of DES operation in order to increase the efficiency of their use. The values of the insensitivity zone of the optimality criterion P are established, based on the desire to maximize the effectiveness of each corrective effect of DES.

5 Conclusions

Since, in order to create the normal conditions for the functioning of ICS, it is necessary to establish for it a zone of insensitivity to the input parameters, which are the power load of consumers and the generation of DES, the method of determining insensitivity

areas of active power loss in DEN with RES to the change of the generated DES power was further developed. This method allows to determine the limits of insensitivity zones of active power losses in DEN with DES to the change of power generated by each HES, and choose the most influential one for reducing the losses of the hydroelectric power station.

References

1. Anand, M. P., Ongsakul, W., Singh, J. G., Golshannavaz, S.: Economic operational Scheduling of a smart distribution network considering demand response, electric vehicles and network reconfiguration. In: 2015 IEEE Eindhoven, pp. 1–6. PowerTech, IEEE (2015)
2. Jung, J., Onen, A., Arghandeh, R., Broadwater, R.: Coordinated control of automated devices and photovoltaic generators for voltage rise mitigation in power distribution circuits. *Renew. Energy* **66**, 532–540 (2014)
3. Minchala-Avila, L., Garza-Castanon, L., Vargas-Martinez, A., Zhang, Y.: A review of optimal control techniques applied to the energy management and control of microgrids. In: The 5th International Conference on Sustainable Energy Information Technology (SEIT-2015), pp. 780–787. Elsevier, London (2015)
4. Han, H., Hou, X., Yang, J., Wu, J., Su, M., Guerrero, J.M.: Review of power sharing control strategies for islanding operation of AC microgrids. *IEEE Trans. Smart Grid* **7**(1), 200–215 (2016)
5. Shengqi, L., Lilin, Z., Yongan, L., Zhengping, H.: Optimal reactive power planning of radial distribution systems with distributed generation ISDEA. In: 2013 Third International Conference on Intelligent System Design and Engineering Applications, pp. 1030–1033. IEEE, Hong Kong (2013)
6. Bracale, A., Carpinelli, G., Rizzo, R., Russo, A.: Advanced method and cost-based indices for probabilistic forecasting the generation of renewable power. In: 3rd Renewable Power Generation Conference (RPG 2014), pp. 1–6. IET, Naples (2014)
7. Ilie, I., Hernando-Gil, I., Djokic, S. Z.: Reliability equivalents of LV and MV distribution networks. 2012 IEEE International Energy Conference and Exhibition (ENERGYCON), pp. 343–348. IEEE, Florence (2012)
8. Kirilenko, O.V., Pavlovskiy, V.V., Luk'yanenko, L.M., Trach, I.V.: The problem of integration of renewable source of energy into the “weak” electrical networks. *Tech. Electrodyn.* **3**, 25–26 (2012)
9. Tugay, Yu.I., Kozirskiy, V.V., Gay, O.V., Bodunov, V.M.: The integration of renewable energy sources in rural distribution electrical networks of village regions. *Tech. Electrodyn.* **5**, 63–67 (2011)
10. Lezhniuk, P.D., Hunko, I., Kravchuk, S., Komada, P., Askarova, N., Arman, A.: Influence of distributed power sources on active power loss in electric grid. *Przegląd Elektrotechniczny* **93**(3), 107–112 (2017)
11. Komar, V.O., Kovalchuk, O.A., Kuzmyk, O.V.: Impact of distributed generation on the quality of distributed electric grids operation. *Tech. Electrodyn.* **2**, 34–35 (2012)
12. Keane, A., Ochoa, L., Vittal, E., Dent, C., Harrison, G.: Enhanced utilization of voltage control resources with distributed generation. *IEEE Trans. Power Syst.* **26**(1), 252–260 (2011)

13. Ardesbna, N. K., Chowdhury, B. H.: Supporting islanded microgrid operations in the presence of intermittent wind generation. In: Power and Energy Society General Meeting, pp. 1–8. IEEE, Providence (2010)
14. Keane, A., Ochoa, L. (N.)F., Vittal, E., Dent, C.J., Harrison, G.P.: Enhanced utilization of voltage control resources with distributed generation. In: Power and Energy Society General Meeting, pp. 1–8. IEEE, Providence (2010)
15. Medeiros, R., Xu, X., Makram, E.: Assessment of operating condition dependent reliability indices in microgrids. *J. Power Energy Eng.* **4**, 56–66 (2016)