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doi:10.15199/48.2017.03.23

Optimization of the functioning of the renewable energy sources in the local electrical systems

***Abstract**. The paper proposes a new solution of actual scientific and applied problem of optimization of the renewable energy sources in the local electrical systems, which is to determine the optimum installed capacity of RES and the choice of optimal schemes connection and also the automation of optimal control of their work in the electrical system. The application of these developments will allow reducing the power losses on electrical energy transmission and improving its quality.*

***Streszczenie.** Artykuł proponuje nowe rozwiązanie aktualnego naukowego i praktycznego problemu optymalizacji odnawialnych źródeł energii (OZE) w lokalnych systemach energetycznych, który determinuje optymalnie zainstalowaną ilość OZE i wybór optymalnego schematu połączeń, a także automatyczne optymalne sterowanie ich pracą w systemie energetycznym. Zastosowanie tego rozwiązania pozwoli zredukować straty mocy przesyłu energii elektrycznej i podwyższy jej jakość. (**Optymalizacja funkcjonowania odnawialnych źródeł energii w lokalnych systemach energetycznych**).*

Keywords: renewable energy, local electrical systems, electrical networks, optimal control, energy losses, Smart Grid.
Słowa kluczowe: energia odnawialna, lokalne systemy energetyczne, sieci energetyczne, kontrola optymalna, straty energii Smart Grid.

Introduction

The development of renewable energy stimulates the research on the design and operation of renewable energy sources (RES) to enhance energy security and reduce the impact of energy on the environment. These sources directly operate in the local electrical systems (LES), which are an electrical distribution network, which takes the features of the system because it has the energy sources. As has been demonstrated in the relevant literature [see bibliography 1–3], this leads to a gradual transition from centralized power supply to combined when the part of electrical energy produced by renewables.

Today was not fully explored the projecting and operation issues of RES in modern conditions, the questions of their impact on the electrical energy networks modes (EN), some problems of nominal parameters inconsistency in main equipment with the needs of such sources. The absence of standard solutions and remedies in relation to automate the process of electrical energy production will lead to complications efficient functioning of renewables in the LES. Primarily this is due to the instability of the generation of renewable energy through their natural dependence on the environment. Therefore there is a necessity of coordinated power supply of RES and substations of electric power system (EPS), which provides the centralized power supply. It is necessity to comply the reliability of power delivery and the connected sources as close to the centers of power consumption as possible. This fact will reduce transportation costs of electrical energy and ensure adequate quality. As a result of the above, the aim of this paper is to solve the design problem – the determine the optimal installed capacity, and operational problem –the optimization daily modes for generating renewable electrical energy and power delivery scheme in the local electric networks with RES.

A growing share of renewables raises the question of a gradual shift from traditional technologies, which involve the use of centralized electrical energy generation, new solutions that focus on the widespread use of renewables and active networks that can provide services for transmission, storage and conversion of electrical energy. Nowadays, all aspects of such "intelligent" power systems are considered in the concept of Smart Grid – the most well-known concept of modernization of electric networks. Nowadays, all aspects of such "smart" power systems are considered in the concept of Smart Grid – the most well-known concept of modernization of electric networks. In the literature [4, 5] noted that many countries have used the series standards for Smart Grid, which are used for relay protection, control and monitoring of transmission and distribution networks.

The research and analysis methods of RES optimization in local electric systems have shown that reducing energy losses and improving its quality advisable to move on to solving complex optimization problem of LES scheme, which provides for the implementation of effective design and implementation of operational reconfiguration schemes of joining RES using Smart Grid technologies, as shown in [6–12].

Optimization of RES in local electric systems by reconfiguring involves the use of automated control systems. Thus, it is necessary to explore the possibility and feasibility of using an automated system optimal control of complex renewable energy to improve the efficiency of distribution of EN technology Smart Grid. The use of adaptive automatic control system helps maintain proper quality process under conditions of incomplete and imperfect initial information, which is typical for the operation of RES in local electric systems.

To solve the complex problems of optimization of renewable energy in LES, establishing uniform criteria and conditions for optimality is inappropriate. The functioning of renewables should use the laws of controls that are derived general concept, but depending on the operational situation.

The definition of optimal power generation of renewable energy sources into the local electrical system

Given the specificity of ensuring profitability LES expedient to solve the problem of determining the optimal power of the conditional controlled renewable energy P_{jRES}, j = 1,2 ... n using complex criteria taking into account the conditions of the multi-tariff energy market and performance indicators functioning LES. As components of of complex criteria to ensure maximum revenue from the sale electrical energy of RES appropriate to use the indexes of power quality and power loss on its transportation networks of LES. Depending from the goal specified problem can be solved, as design problem – to determine the optimal installed capacity of RES and as operational – to optimize daily modes of renewables, according to the projected schedule of load LES [13].

To solve the first problem it is advisable to use an expression of total income from operation of renewable energy which are connected in parallel work in LES:

(1) $$B^{RES} = \sum_{j=1}^{n} \left[c_j \cdot P_j^{RES} \cdot k_{P_j} \cdot T \right],$$

where P_j^{RES} – installed capacity RES; c_j – electrical energy tariff for j RES ("green tariff"); k_{Pj} – coefficient of using installed capacity j RES; T – the duration of the reporting period.

Considering (1), the objective function of optimization installed capacity of renewable energy in LES presented as:

(2) $$\mathrm{F} = B^{RES} \cdot e^{-z_1} \cdot e^{-z_2} \to \max,$$

including restrictions:

(3) $$\sum_{j=1}^{n} P_j^{RES} - \sum_{g=1}^{m} P_{l_g} \le P_{\lim},$$

where e^{-z_1}, e^{-z_2} – regression equationї, which characterized the impact optimality criterion functioning components; $z_1 = k_1 \cdot (1 - \overline{P}(U\mathrm{y}_{per}, T))$ – the regression equation exponent, which considers limiting profits from operation of renewable energy for power quality criteria; $z_2 = k_2 \cdot (1 - \overline{P}(\Delta W_{per}, T))$ – the regression equation exponent, which considers limiting profits from operation of renewable energy including the criterion electrical energy consumption for its transportation; k_1, k_2 – weights regression equations, intended for harmonizing the impact of partial optimality criteria on optimization results; $\overline{P}(U_{n\,per}, T)$ – probability ensure normative voltage deviation for a given reporting period T; $\overline{P}(\Delta W_{per}, T)$ – probability ensuring normative power losses for a given reporting period T; P_{lg} – power load of consumption g node, $g = 1,2\ldots m$; P_{lim} – capacity of electric network, which limited to the most "weak" section of network.

The solution of the optimization problem (2) – (3) will be the optimal value of installed capacity of RES in the network in conditions of multi-tariff energy market and compliance with the restrictions on the capacity of transmission lines and quality of electrical energy in the LES.

In order to solve the optimization problem of daily modes of renewable energy $P_j^{\mathrm{RES}}(t)$, $j = 1,2\ldots n$ (such as small hydro power plants – SHPP) according to the projected schedule of LES load with an interval of time [t_0; t_k] taking into account the modes of the conditional controlled RES, equation (1) takes the form:

(4) $$B^{RES}(t) = \int_{t_0}^{t_k} \left[\sum_{j=1}^{n} c_j \cdot P_j^{RES}(t) \right] dt + \sum_{t} M_{\mathrm{F},t},$$

where $M_{F,t}$ – mathematical expectation of total profit from the operation of totality the conditional controlled RES, such as wind power plant and solar power plant (WPP and SPP).

The solution to the optimization problem (2) – (3) using the (4) will be the optimal values of generation capacity of some RES P_j^{RES} according to the projected schedule of load LES using complex criteria optimal the operation. For the numerical solution of these problems for a given aggregate of initial data was used the coordinate-wise descent method.

The determining the optimal placement renewable energy using the criterion of minimum power losses in the local energy systems

For determining the optimal placement of res, its capacity is calculated from (2) – (3), was developed a method of optimization connection renewable sources in distribution electrical networks using the criterion of minimum power losses. This method uses matrix coefficients of power losses distribution $\dot{\mathbf{T}}$ in branches of equivalent circuit between the network nodes [14]. To ensure the uniqueness of ranking potential nodes connection RES matrix $\dot{\mathbf{T}}$ expedient to convert the vector weighting coefficients, they represent a total coefficients of distribution power losses in the circuit branches LES:

(5) $$\dot{\mathbf{T}}_{\Sigma} = \dot{\mathbf{T}}_t \cdot \mathbf{n}_{\mathbf{B}},$$

where $\dot{\mathbf{T}}_t$ – transposed matrix coefficients of distribution power losses; $\mathbf{n}_{\mathbf{B}}$ – unit vector column that has the dimension on the number of threads schemes EN. Vector $\dot{\mathbf{T}}_{\Sigma}$ has the dimension on the number of nodes in LES. Each element of the vector corresponds to the percentage of losses, which caused by the flow of power RES from the corresponding node EN to the main center of power supplies (basic node).

Using vector weighting coefficients (5) allows to determine node EN, in which the connection RES given power will lead, with certain assumptions, to the smallest changes of power losses or to minimize losses.

Vector $\dot{\mathbf{T}}_{\Sigma}$ consists of the elements $\dot{T}_{\Sigma j}$, which are the sensitivity coefficients. They establish a connection between an increase of power losses in LES and power changes in RES nodes. The coefficients of sensitivity $\dot{T}_{\Sigma j}$ is actually constant in conditions of proportional change of generation and load nodes LES, according to the schedule load of its daily mode. The increase sensitivity coefficient $\delta \dot{T}_{\Sigma j}$ for a given value of power by changing the voltages in the nodes by means of regulation will not exceed 5%. Therefore, considering the achievable accuracy of initial data on mode parameters LES and passport information of electrical equipment, for the design problems, specified accuracy is allowable and sufficient to choose the optimal placement of RES in the LES.

Thus, the relative static of coefficients sensitivity $\dot{T}_{\Sigma j}$ allows, at the stage of selection variants the design decisions, to determine the optimal nodes of connection RES capacity, which practically does not depend on mode of local electrical systems and renewable energy in it.

Under certain conditions RES connection can lead to a shift the point of flow in LES and thus to change the numerical coefficients of distribution power losses $\dot{\mathbf{T}}_{\Sigma}$ in a wide range. In such cases it is necessary to clarify conditions of optimal configuration LES with renewable energy using the criterion of minimum power losses. To solve the problem was used vector coefficients of distribution power losses, formulated and solved the problem of reconfiguration of the local electrical system with RES using the specified criteria:

minimize:

(6) $$\Delta P = \sum_{j=1}^{n} P_j (T'_{\Sigma j} - T''_{\Sigma j} \cdot tg\varphi_j) + \Delta P_{CPS} + \Delta P_{CC} \to \min$$

taking into account the balance limits:

(7) $$\sum_{j=1}^{n} P_j - P_{CPS} = 0; \quad \sum_{j=1}^{n} (P_j \cdot tg\varphi_j) - Q_{CPS} = 0,$$

where P_j – capacity of controlled RES or consumer, $j = 1,2\ldots n$; $tg\varphi_j$ – expedient ratio of reactive and active power energy or consumer; ΔP_{CPS} – active power losses in EN, caused by overflow from the center of power supplies; ΔP_{CC} – active power losses in EN, caused by the flow from the conditional controlled RES; $T'_{\Sigma j}$, $T''_{\Sigma j}$ – real and imaginary components of the distribution coefficient of active power losses for the node j; P_{CPS}, Q_{CPS} – active and reactive power, which coming to the electrical energy supply from the main power supplies center. Solving the problem (6) – (7) by the Lagrange multiplier method allowed to receive analytical conditions of optimal configuration LES using the criterion of minimum power losses, consisting in equal coefficients of distribution power losses for individual nodes EN:

(8) $$T'_{\Sigma j} = -\lambda_P = idem, \; T''_{\Sigma j} = \lambda_Q = idem.$$

From the resulting solution we can see that optimal configuration changes LES or RES mode operation on the specified criteria are those that approximate the power distribution coefficients to the average value. Since the proposed indicators $\mathbf{T'}_\Sigma$, $\mathbf{T''}_\Sigma$ are multidimensional, without additional conditions do not allow definitive evaluation of the effectiveness reconfiguration. It was therefore proposed generalized indicator to select options by bringing vectors to form the number Euclidean norm:

(9) $$dP' = |\mathbf{T}'_\Sigma| = \left[\sqrt{\sum_{j=1}^{n} T'^2_{\Sigma j}}\right]; \; dP'' = |\mathbf{T}''_\Sigma| = \left[\sqrt{\sum_{j=1}^{n} T''^2_{\Sigma j}}\right].$$

The lengths of the vectors dP', dP'' are measured in relative units and have the physical meaning of modules loss, which caused by overflows of active and reactive power RES respect to these components of capacity. They can be used as an indicator impact parameters of an individual node or branch of equivalent circuit EN with RES on its optimal operation.

The optimal placement RES with given installed capacity, for example, calculated by the developed method is determined by the criterion of minimum power losses. The algorithm is to use the power distribution coefficients for the possible connection of nodes as weight coefficients of these nodes.

Flowchart of the algorithm for determining the optimal placement of RES shows on Fig. 1. The algorithm provides the input of initial data characteristic LES to create a calculation model and formation of the list of nodes mode θ_n, which possible connection of RES.

Depending on the installed capacity RES was provided for two options for determining the optimal place of connection. If the installed capacity of renewable energy does not exceed the total power load consumers LES ΣP_l, an optimum place connection selected by the criterion of minimum power losses distribution coefficients. Otherwise, the flow of RES will be directed to the center of power, leading to increased power losses in LES. Then an optimum place connection determined by the criterion of minimum generalized indicator of the effectiveness dP' of active power flows.

This approach provides a solution that does not depend on changes in EN mode and decreases power losses and improving voltage quality for a set of possible modes of LES.

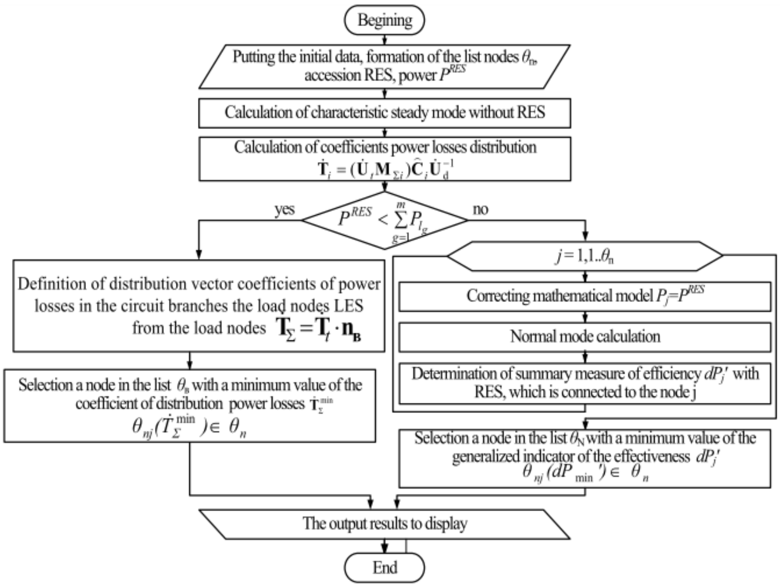

Fig.1. The algorithm for determining the optimal placement of connection RES in LES

The method of harmonization schedules of generating renewable energy and energy consumers in the local electric systems

To coordinate schedules to generate SPP from the local power consumption is provided a method of operating control scheme inverter connection, to wit changes the scheme of issuing power to EN. Depending on the current power of SPP and consumers load at regulated bus system (BS) connected the number of inverters, that can provide consumption in LES with compliance of quality indicators and minimal power losses. Excess electrical energy produced is provided toward the center of power supplies, which is a separate feeder connected to another unregulated bus system. To implement the method provides for the use of electronic keys corresponding power or controlled switching equipment 0.4 kV, installed in the switch box (SB). Furthermore it is necessity to install the automatic inverse power (AIP). The main scheme of SPP connections shown of Fig. 2, allow operative coordinate schedules of issuing power on one bus system with local load by automatically redistributing power from outputs inverters between sections bus. Therefore, using the microprocessor device of local automatic control system and a communication channel with operational and information complex LES [15].

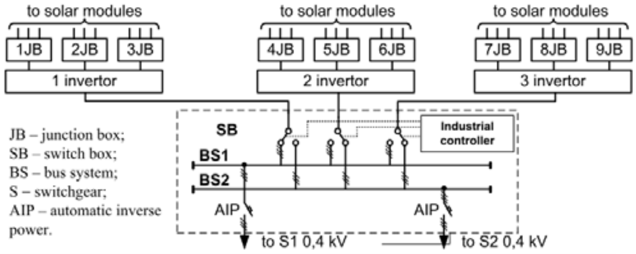

Fig.2. The main scheme of SPP connections with reserved and controlled power issue

For implementation of the proposed method of harmonization graphs generation of solar power to the local electrical energy consumption in the article was proposed the optimal control law of switching equipment reconfiguration system scheme of issuing power. To reduce electrical energy losses in the electrical network proposed measure current on high voltage buses of SPP depending on the value of optimal power, which is defined by the algorithm of optimization daily modes of RES generation, it is necessary to change the number of inverters N_i, which are connected to the first or second bus system for maintain the voltage on the buses in the allowable values.

Each additional inverter will turn on the regulated bus system if the current deviation $\Delta i(t)$ will be below the lower limit of insensitivity zone ($\Delta i(t)$ = -6A, and i_{nz} = -5A), voltage is less than the maximum, number of taps does not exceed the maximum, and the measured current of renewable energy tends to decrease. Conversely, if the current deviation will be above the upper limit of insensitivity zone ($\Delta i(t)$ = -6A, and i_{wz} = +5A), the voltage higher than the maximum, number of taps does not less than the minimum, and the measured current of renewable energy will tend to increase, will perform inverter switching from regulated to unregulated bus system. In accordance with the above substantiation the control law has the form of expression (10):

$$\Delta i(t) = K_1\left[(I(t) - I_{set}) - K_2(U(t) - U_{set})\right];$$

$$N_i = \begin{cases} n(t)+1, \quad if \quad \begin{cases} \Delta i(t) \le i_{l.z}; \\ \Delta i(t-\tau_d) \le i_{l.z}; \\ U(t) \le U_{\max}; \\ \dfrac{dI_{en}}{dt} \le 0; \\ n(t)+1 \le n_{\max}; \end{cases} \\ n(t), \quad at \quad i_{l.z} < \Delta i(t) < i_{l.z}; \\ n(t)-1, \quad if \quad \begin{cases} \Delta i(t) \ge i_{h.z}; \\ \Delta i(t-\tau_d) \ge i_{h.z}; \\ U(t) \ge U_{\min}; \\ \dfrac{dI_{\text{en}}}{dt} \ge 0; \\ n(t)-1 \ge 0; \end{cases} \end{cases} \tag{10}$$

where N_i – the number of inverters, which are connected to the regulated bus system; I_{set} – setpoint current, which corresponds to the RES optimum capacity and adjusted depending on the LES mode parametrs, selling price, etc; U_{set} – setpoint voltage on the buses, which equals to nominal voltage or to other value, if RES are involved in regulating the voltage in LES; $I(t)$, $U(t)$, $n(t)$ – measurements of current and voltage, and the number of enabled inverters at the moment t; K_1 – the gain coefficient which that determines the sensitivity of the regulator to the deflection current; K_2 – equivalent conductivity intended for calculation of voltage deviation from the set point in the equivalent current deviation from optimal (this ensures the system response to exceeding voltage when current meets the optimal value); $\Delta i(t)$ – current deviation from optimal taking into account the voltage change on the buses RES; I_{en} – envelope of total current inverters $I(t)$; τ_d – signal delay time; t – moment of time for which capacity should be regulated; $n_{\max}$ – the maximum number of inverters that can be enabled on the regulated BS.

The results of the optimization of renewable energy sources in the local electrical systems

To determine the installed capacity for renewable energy with using the complex optimality criteria on which considers the quality of electrical energy and minimize losses, was used the developed method on the example Tsekynivska SPP. The latter was launched into operation by three lines: Tsekynivska SPP No 1: 1.43 MW; Tsekynivska SPP No 2: 1.43 MW; Tsekynivska SPP No 3: 0.25 MW. Electrical energy is generated directly to the electrical network 10 kV through the feeders F-31 (the first line) F-35 (the second and third line) (Fig. 3). The calculation results are presented in table. 1.

Table 1. The calculation results of optimal installed capacity of the first line Tsekynivska SPP with using the complex criteria

Tsekynivska SPP No 1, kW	$B_{RES,}$ mln $/year	$\overline{P}(U_n, T)$ r.u.	$\overline{P}(\Delta W_{per}, T)$ r.u.	ΔW_{fac}, %	F, mln $/year
1430	2.93	1	0.38	8.47	2.65
1680	3.44	1	0.42	8.21	3.14
2080	3.75	1	0.47	7.9	3.44
2710	4.22	0.6	0.35	9.2	3.39

As seen from the results of research the optimal value of installed capacity is 2080 kW. The increasing of installed capacity can lead to a possible decrease of voltage quality and can worsen conditions for the functioning of the local electrical system.

For the purpose of checking the efficiency of the method of harmonization schedules generation of RES and LES energy consumers and the optimal control law of reconfiguration scheme issuing RES capacity in local electrical systems, were calculated the daily operation modes of Tsekynivska SPP in electrical networks of Yampolsky region.

The ratio of daily generation modes of Tsekynivska SPP (all lines together) and energy consumption in the mode of maximum load feeder No 31 (SS 35/10 "Sloboda Pidlisivska") shown on Fig. 4.

By analyzing dependence, which shown in Fig. 4, we can see, that when the power flow from Tsekynivska SPP (from 11.00 to 17.00) will be directed to the center of power supply, then this mode will increase the power losses in the LES. In order to test the feasibility of optimization power flows with using the method of harmonization schedules of generating renewable energy and energy consumers in the local electric systems were calculated the schemes of issuing capacity in the local electric systems.

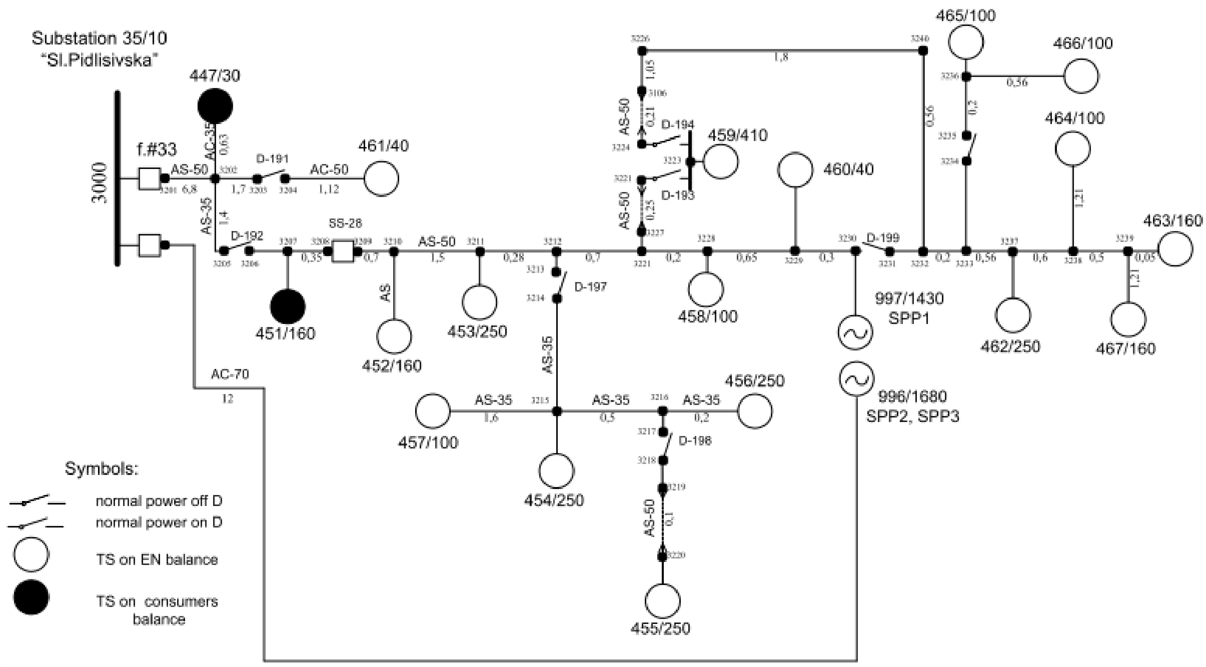

Fig.3. Substation 35/10 "Sloboda-Pidlisivska" and electric scheme of feeders No 31 and No 35

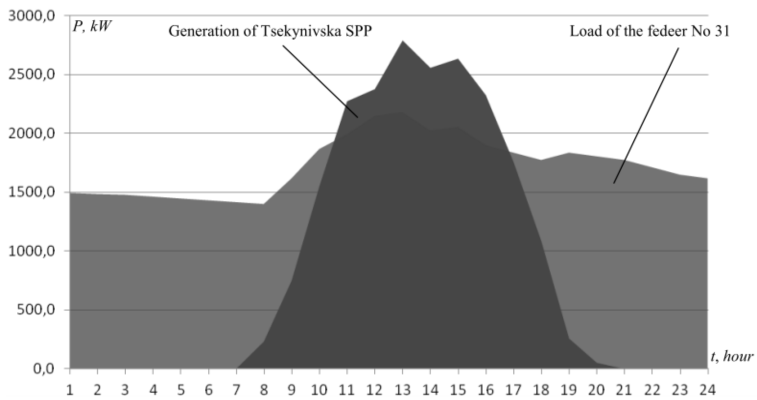

Fig.4. The ratio of power losses F-31 and covering of its load (SS 35/"Sloboda Pidlisivska")

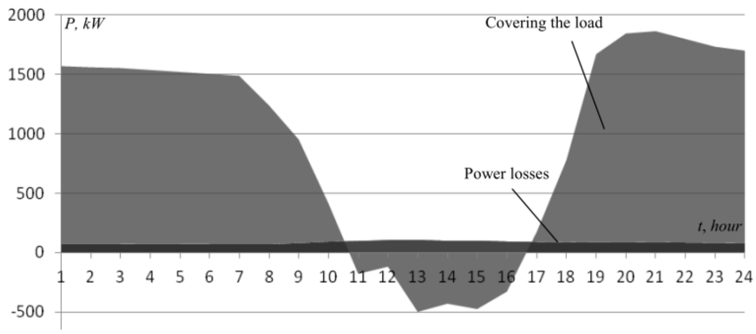

Fig.5. The ratio of daily generation modes of Tsekynivska SPP and energy consumption in LES

a) b)

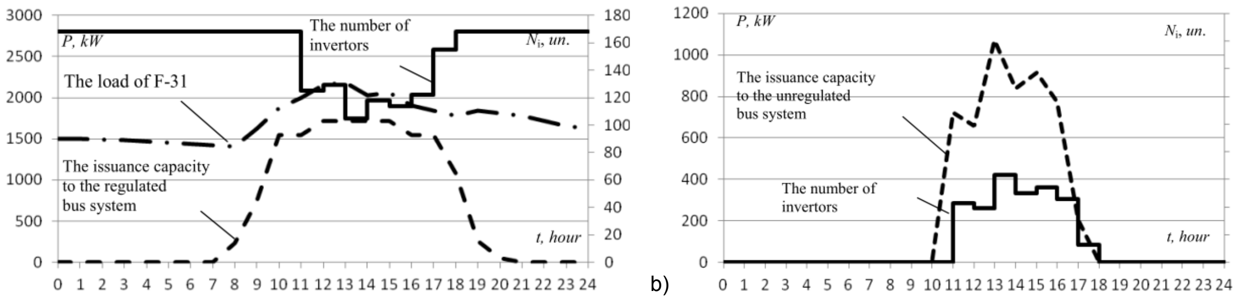

Fig.6. The results of the optimization the daily generation modes of Tsekynivska SPP and energy consumers (SS 35/"Sloboda Pidlisivska"): a) F-No 31 б) F-No 35

The calculation results of power losses for the mode of maximum load for feeder F-31 SS 35/10/"Sloboda Pidlisivska" and the schedule of the covering power consumption from the center power supply shown on Fig. 5.

The calculation results of optimal controlling influences are presented like a schedule of change the number of inverters, which can be switched on the regulated bus system (feeder F-31) during the day (Fig. 6a) and on unregulated bus system (feeder F-35) (Fig. 6b).

Conclusions

In the article it was shown that as the optimality criteria of LES modes appropriate to use the complex criterion of maximum profit from the sale of RES electrical energy, taking into account their impact on the operating of EN. The applications of developed methods of optimizing the installed capacity of RES for set placement in the local electrical system and the method of optimizing the daily RES schedules allows to solve the problem of determining the optimal capacity of the conditional controlled RES on the both stages – on the design stage and on the operating stage, taking into account the quality indicators of electrical energy. The using of general indicators of the efficiency of the electric network allows to obtain the quality schematics on the connection renewable energy sources. The article also developed a method of reconciliation schedules generation of renewable energy and the local electric systems consumption, which provides the reconfiguration of schemes issuing capacity and increases operational efficiency electrical networks without reduce the profitability of energy companies and an algorithm of determine the optimal installed capacity for the set placement of RES in the LES.

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