22nd International Conference on Renewable Energies and Power Quality (ICREPQ'24)
Bilbao (Spain), 26th to 28th June 2024

ISBN: 978-84-09-60656-6

Determination of conditions for the optimal power generation PV system for energy community and citizen's energy in Ukraine by criterion programming method

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Abstract. The paper presents the main benefits of the implementation of energy community, for example, Ukraine.

The main expected issues of the creation of renewable energy sources for Ukrainian energy communities are highlighted. For finding of optimal condition of photovoltaic (PV) system operation is used criteria method.

Design, simulation and improving of PV system and householder was in PV*SOL Premium. The paper considers the features of mathematical modeling of the optimal decision-making process in PV complex dynamical systems in terms of analysis and evaluation of their sensitivity. The perspective of the application of criterion modeling in problems of optimal control, in particular for the analysis of the sensitivity of optimal decisions, is shown.

Next, is devoted to forming mathematical models to analyze the sensitivity of the optimality criterion. Models of optimal control with eigenvalues and vectors are considered.

Key words. Energy community, renewable energy sources, photovoltaic system, criterion optimization, objective function.

1. Introduction

It is becoming increasingly difficult for Ukraine to maintain the planned growth of renewable energy sources. In the context of the two-year war, energy dependence is definitely a priority for the economy of Ukraine and most European countries. The world's experience of developed countries in creating and operating an energy community can be useful for the post-war reconstruction of Ukraine [1, 2]. The main goals of the implementation of energy communities are:

- to popularize the creation of a distributed power generation system in Ukraine [3, 4];
- to promote the growth of investment in renewable energy;
- to justify the role of civil society in this energy community development process;
- to focus on the green recovery of Ukraine;
- to mitigate climate change;
- sustainable development of local communities;
- improve power quality [4, 5];
- increase energy safety;
- develop and popularize the prosuming model [6].

In Ukraine, there is still no clear simply understanding and efficiency mechanism for the creation and operation of an energy community. Government and non-government organizations (for example, Non-government organization Agency Sustainable Development SYNERGY, Ecoclub, and so on) are already working in this direction, and the first project will be visible soon [7-9].

Many problems must be solved for efficient renewable energy source implementation in community energy. It is necessary to take into account not just current financial, legal, and social preconditions for the emergence of a movement to create green energy communities in Ukraine at the local level. Developing a roadmap for communities and renewable energy supporters are relevant. Technical tasks like design RES, develop of recommendation for operation and so on has high priority [10]. For example, the optimization of the accumulation system for the renewable energy sources (RES) energy community can be more crucial than for the industry PV system [13-14]. In [15] noted that PV systems are more popular in Ukraine than wind or small hydropower plants.

Mathematical modeling in the problems of energy community PV system operation optimizing the conditions of such systems has specific features, exactly technical, metrological, economic, law, and social. In the paper more paid attention to a mathematical model common criterion optimality [16]. It is necessary to take into account the fact that energy community PV system is dynamic systems. On stage design is importantly take into account maximization of power generations and minimalization consumption from grid by the way optimization power consumption.

The final technical and economic effect of the dynamic systems operation conditions control assesmented by the results of the practical implementation in energy community can be:

- how much money they saved for bill in energy,
- how much citizens start use energy more saivly,
- how much kWh is generated by their RES.

Observed objective task has two aspects: mathematical modelling and practical simulation. Mathematical modelling of optimal control of a complex system (PV generation and citizen consumption) can be decided with helping criterion method. Practical simulation operation PV system and developing recommendations for citizens is possible realize in PV*SOL Premium software.

In the problems of optimal control of a complex PV system with a quadratic quality criterion during the determination of sensitivity of optimal solutions there are certain difficulties. This is caused, first of all, by the incorrectness of the inverse sensitivity problem [16]. [17] proposed an effective method for solving such problems. It is based on criterion modeling.

2. Implementation of mathematical model

In this paragraph algorithm for sensitivity analysis of optimal control RES and citizen consumption system whose criterion model includes eigenvalues and eigenvectors are discussed. Criteria modeling involves the transformation of the original mathematical model into a dimensionless or criterion form of writing, where all the values involved in the control process have the meaning of similarity criteria.

Mathematical modeling in the problems of optimizing the conditions of such systems has specific features. Optimization function is posinom. Criterion programming method has good results for decided optimization task of posinom with limitations [18, 19, 20]. Simplex method, linear programing methods and other work with variables, criterion method works with criterion similarity. Criterion similarity doesn't have units and compares influences different paraments on the objective function. When developing a mathematical model, it is necessary to take into account the fact that the final technical and economic effect of the control of conditions of dynamic systems is determined by the results of the practical implementation of the optimal conditions that are planned [21, 22].

The optimization task RES control in the war environment with complex criterion optimality can be presented in mathematical (Eq.1-2) and graphical interpretations (Fig.1):

minimize the control function

$$F(u) = \int_{t_0}^{t_k} [\boldsymbol{x}_t(t)\boldsymbol{Q}\boldsymbol{x}(t) + \boldsymbol{u}_t(t)\boldsymbol{R}\boldsymbol{u}(t)]dt. \quad (1)$$

in the area of limitations

$$\frac{dx}{dt} = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t); \boldsymbol{x}(t_0) = \boldsymbol{x}_0;$$

$$\boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t) + \boldsymbol{D}\boldsymbol{u}(t), \quad (2)$$

where

x(t), u(t), y(t) are respectively the vectors of limitations, control, and observation;

A; B; C; D; Q; R are matrix of constant index;

t_0, t_k are time interval beginning and end;

x_0 is the initial value of the condition vector.

The first equation in system (2) is the equation of condition of the system, and its solution satisfying the initial requirement $x_0 = x(t_0)$, gives the vector of condition $x(t)=\psi[x(t_0), u(t)]$. The second equation in (2) determines the output parameters depending on x(t) and u(t). The criterion of normal conditions control optimality of the EPS can be an economic criterion – a minimum of costs or losses, provided that the specified requirements for reliability and quality. If the problem of optimal control of the conditions of system is set in such a way that at the stage of formation of the goal function, the purpose is to obtain control laws in the form convenient for their further automatic realization, then the solution (1), taking into account (2), has the form [20].

$$\mathbf{u}(t) = -\mathbf{w}\,\mathbf{y}(t), \quad (3)$$

where w is the feedback matrix.

Expression (3) is the law of optimal control, the implementation of it allows us to achieve the minimum of function (1). The most famous direction of deterministic functional-adaptive control systems is the control with an etalon model [20].

The scheme of such an adaptive system with a reference model is shown in Fig. 1. In the case under consideration, when the objective function of the optimal control problem has a quadratic shape, it is necessary to pre-transform the latter. Information of observation vector **y** is compared with parameters etalon model (that simulated in PV*Sol Premium). In case, when deviation between etalon model parameters and current state of the object is more than error measurement devices and under limit sensitivity objective function, parameters of control vectors $\mathbf{u}_m$ are calculated and implemented. Corrective crion influence after calculation u(t) impact to the system. Obtained vector of observation in main counter will compare with observation vector of adaptation counter, and algorithm will repeat.

If the target optimal control function is written as [18] (Fig.1):

$$F = \boldsymbol{x_t Q x} + \boldsymbol{u_t R u}, \tag{4}$$

then after the transformation of the quadratic form it will look like:

$$F = \textstyle\sum_{i=1}^{m} q_i\, X_i^2 + \sum_{i=1}^{m} r_i\, U_i^2. \tag{5}$$

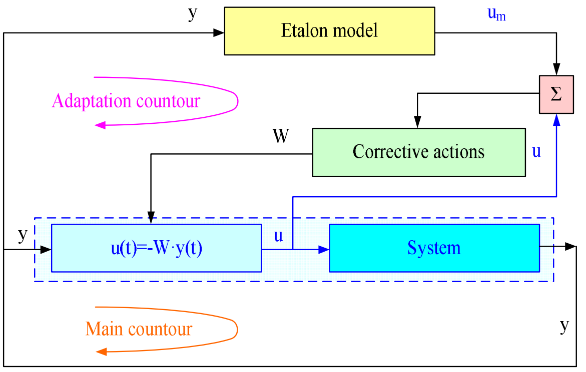

Fig. 1. Adaptive control system with a etalon model

In (1): **x** and **u** are the vectors of state and control of the system; **Q** and **R** are symmetric matrices of constant coefficients. In (2): q_i and r_i are the eigenvalues of the matrices **Q** and **R**, respectively; **X** = $\mathbf{S}_t$**x**, **U** = $\mathbf{T}_t$**u**, where $\mathbf{S}_t$ and $\mathbf{T}_t$ are the transposed eigenvector matrices of the matrices **Q** and **R**, respectively.

Convert (2) into a criterion form. Since (6) is valid for any values of the variables X and U, is written:

$$F_{min} = \sum_{i=1}^{m} q_i X_{i0}^2 + \sum_{i=1}^{m} r_i U_{i0}^2 . \tag{6}$$

Criteria for the similarity of the process that is optimized and described (6) are determined by the method of integral analogues [16]:

$$\pi_i^x = \frac{q_i X_{i0}^2}{F_{min}}, \quad \pi_i^u = \frac{r_i U_{i0}^2}{F_{min}} . \tag{7}$$

From (7) it follows that

$$F_{min} = \frac{q_i X_{i0}^2}{\pi_i^x} \quad or \quad F_{min} = \frac{r_i U_{i0}^2}{\pi_i^u} . \tag{8}$$

Dividing the left and right parts (7) by F_{min} and substituting the value of F_{min} from (7) in the right part, is obtained the criterion relation between the optimality criterion and the parameters:

$$\frac{F}{F_{min}} = \sum_{i=1}^{m} \frac{q_i X_i^2}{F_{min}} + \sum_{i=1}^{n} \frac{r_i U_i^2}{F_{min}} = \sum_{i=1}^{m} \frac{q_i X_i^2}{\frac{q_i X_{i0}^2}{\pi_i^x}} + \sum_{i=1}^{n} \frac{r_i U_i^2}{\frac{r_i U_{i0}^2}{\pi_i^u}}$$

or

$$F_* = \sum_{i=1}^{m} \pi_i^x X_{i*}^2 + \sum_{i=1}^{m} \pi_i^u U_{i*}^2 , \tag{9}$$

where $F_* = F/F_{min}$, $X_{i*} = X_i/X_{i0}$, $U_{i*} = U_i/U_{i0}$.

The peculiarity of the application of criterion relation (9) for the analysis of the sensitivity of optimal solutions is that the similarity criteria (8) are determined including by the eigenvalues and vectors of the matrices of the initial mathematical model of the optimized process. Therefore, consider the sensitivity of eigenvalues, using the method described in [16]. The essence of this analysis is to determine the reaction of the system when the eigenvalues q and r change to Δq and Δr.

Let the matrices **Q** and **R** be positively defined and have different eigenvalues and their corresponding eigenvectors. This is true, for example, for the power system [17]. Consider the matrix

$$\mathbf{Q}(\Delta q) = \mathbf{Q} + \Delta q \boldsymbol{\alpha},$$

where $\boldsymbol{\alpha}$ is a real matrix. Similar actions can be given in relation to the eigenvalues r_i of the matrix **R**.

The eigenvalues of the new matrix **Q**+$\Delta q\boldsymbol{\alpha}$ are denoted as $q_i(\Delta q)$, and the eigenvectors are $\mathbf{S}_i(\Delta q)$, $i=\overline{1,m}$. The quantities q_i (Δq) and $S_i(\Delta q)$ are inseparable and differentiated functions of the small parameter Δq. There are convergent power series:

$$q_i(\Delta q) = q_i + \sum_{j=1}^{\infty} \frac{1}{j!} \cdot \delta q_{ij} \cdot \Delta^j q, \tag{10}$$

$$S_i(\Delta q) = S_i + \sum_{j=1}^{\infty} \frac{1}{j!} \cdot \delta S_{ij} \cdot \Delta^j q, \tag{11}$$

where

$$\delta q_{ij} = \left(\frac{\partial^j q_i(\Delta q)}{\partial \Delta^j q} \right) \Bigg|_{\Delta q = 0} ;$$

$$\delta S_{ij} = \left(\frac{\partial^j S_i(\Delta q)}{\partial \Delta^j q} \right) \Bigg|_{\Delta q = 0} .$$

For eigenvalue (9) and eigenvector (10) have:

$Q(\Delta q) \cdot S_i(\Delta q) = q_i(\Delta q) \cdot S_i$ $Q(\Delta q) \cdot S_i(\Delta q) = q_i(\Delta q) \cdot S_i(\Delta q)$. (Δq).

Differentiating the last relation by Δq and multiplying it scalarly by the eigenvector Z_i of the transposed matrix Q, is obtained:

$$(\alpha S_i, Z_i) + \left(\frac{\partial S}{\partial \Delta q}, Q_t Z_i - q_i Z_i \right) = \frac{\partial q_i}{\partial \Delta q} (S_i, Z_i),$$

As a result, for the sensitivity coefficient of the first order, taking into account the fact that the vectors of the original and transposed matrix are orthogonal, is obtained:

$$\delta q_{i1} = \frac{(\alpha S_i, Z_i)}{(S_i, Z_i)} . \tag{12}$$

Thus, to determine the sensitivity coefficient δq_{ij} of the first order eigenvalue q_i by formula (12) it is necessary to know the derivative of the matrix **Q** (Δq) by q and the corresponding vectors S_i and Z_i. All these values are determined at $\Delta q = 0$ [18-20].

Often in practical problems varies one of the elements of the matrix **Q**, such as q_{kl}. Then $\Delta q = q_{kl}$ and the matrix α has only one nonzero element α_{kl}. With

$$\delta q_{i1} = \frac{\partial q_i}{\partial \Delta q_{kl}} = \frac{s_{il} z_{ik}}{\sum_{j=1}^{m} s_{ij} z_{ij}} , \tag{13}$$

where s_{ij}, z_{ij} are the appropriate components for the vectors $\mathbf{S}_i$ and $\mathbf{Z}_i$.
When the diagonal element of the matrix **Q** varies, for example q_{kk}, have:

$$\delta q_{i1} = \frac{\partial q_i}{\partial \Delta q_{kk}} = \frac{s_{ik} z_{ik}}{\sum_{j=1}^{m} s_{ij} z_{ij}} . \quad (14)$$

When the matrix Q is symmetric, the source and ransposed matrices coincide, then, as shown in [18],

$$\delta q_{i1} = \frac{(\alpha S_i, Z_i)}{(S_i, Z_i)}$$

and, respectively, (9) and (11) are transformed:

$$\frac{\partial q_i}{\partial \Delta q_{k1}} = \frac{s_{i1} z_{ik}}{\sum_{j=1}^{m} s_{ij}^2}, \qquad \frac{\partial q_i}{\partial \Delta q_{kk}} = \frac{s_{ik}^2}{\sum_{j=1}^{m} s_{ij}^2}.$$

If the eigenvectors of a symmetric matrix are normalized, then the equations for the sensitivity coefficients δq_{i1} are simplified because their denominators are equal to one. Similarly, are determined the sensitivity coefficients for the study using (3) the relative influence on the criterion of optimality of the component, which is determined by the control variables. Accordingly, it is obtained that the general expression of the sensitivity factor

$$\delta r_{i1} = \frac{\partial r_i}{\partial \Delta r_{k1}} = \frac{t_{i1} y_{ik}}{\sum_{j=1}^{n} t_{ij} y_{ij}} , \quad (15)$$

and for a symmetric matrix R [18]

$$\frac{\partial r_i}{\partial \Delta r_{kl}} = \frac{t_{il} y_{ik}}{\sum_{j=1}^{n} t_{ij}^2}, \quad \frac{\partial r_i}{\partial \Delta r_{kk}} = \frac{t_{ik}^2}{\sum_{j=1}^{n} t_{ij}^2}.$$

In the last expressions t_{ij} and y_{ij}, respectively, components of the vector $\mathbf{T}_i$ and eigenvector $\mathbf{Y}_i$ of transposed matrix **R**. Taking into account (3), (14) and (15) the criteria of similarity of the optimized process are determined

$$\pi_{i1}^{x} = \frac{(q_i + \delta q_{i1}) X_{i0}^2}{F_{min}}, \qquad \pi_{i1}^{u} = \frac{(r_i + \delta r_{i1}) U_{i0}^2}{F_{min}} . \quad (16)$$

These values of the similarity criteria are used in (8) for the criterion analysis of the sensitivity of the optimal solutions to the system parameters. If the optimal solution of the task (3) is realized by means of an automatic control system, the law of optimal control is realized, the latter taking into account (8) and (16) takes the form:

$$u_j(t) = -\sum_{i=1}^{n} \left(\pi_i^u + \delta \pi_{i1}^u \right) x_i'(t), \quad (17)$$

where

$$\delta \pi_{i1}^u = \frac{\delta r_{i1} U_{i0}^2}{F_{min}}.$$

Thus, the considered method of estimating parametric sensitivity together with the method of sensitivity analysis of the criterion of optimality to change of control variables u, described in [19], allow building an effective algorithm for studying the quality of functioning of the system that implements optimal solutions, provision, and operating conditions. Successful cases of application PV system in power grids, which possible use for energy community, expected problems and ways of solutions are presented in papers [23-26]. In [27] noted hybrid solution for PV system with take into account type of load. Authors in [27, 28] shown how possible increase efficiency PV modules.

3. Verification on model community power engineering system

3 properties belonging to the local authority were chosen for purpose of the model community power engineering project. The precise location is under information embargo because of strategic objects in war conditions in Ukraine.
Location 1 consists from 1029 modules installed on unshaded parts of flat roofs of the complex with installed capacity 524,79 kWp. Location 2 contains 271 modules on flat roof with installed capacity 140,92 kWp and Location 3 has the installed capacity 380,12 kWp consisting from 731 modules on unshaded parts of flat roofs. Fig. 2 demonstrates the situation for Location 1.

Fig. 2. Location 1 (PV*Sol Premium)

Location 1 supplies the community including some municipality properties, school and hospital. The Location 2 and Location 3 are in parallel to production in Location 1.

Fig. 3 shows the annual load chart of the model community.

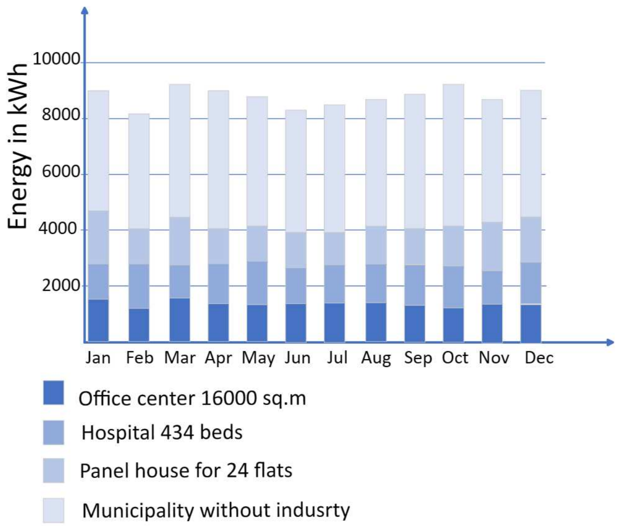

Fig. 3. Community load chart (PV Sol Premium)

Location 1, 2, and 3 are pointed out on the rooftop on the Fig. 2. Module capacity and type 1 is Trina Solar 510 W Triple Cut PERC Mono Solar Module Vertex-SP.V. cell. For Location 2 and 3 used 520 W Solar Panel TFL-210X30_10_36. Parameters considered for optimization of the same building are meteorological parameters (irradiation, humidity, wind speed and so on) and technical characteristics building. Tilt angle is used for orientation is 39 degree.

4. Simulation of the model community power generation and consumption

Power generation and consumption simulation were calculated respecting different conditions to verify the mathematical model presented in the first chapter. Fig. 4 demonstrates the basic consumption and its coverage without any optimization of consumption and without any accumulation. It allows to find the criterion relation according to equation (16).

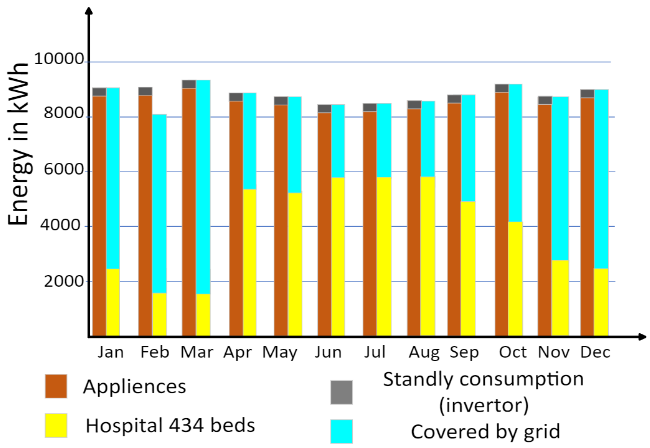

Fig. 4. Non optimized energy coverage (PV Sol Premium)

Fig. 5 demonstrates the daily load chart and its coverage after optimization of the system using eigenvectors according to equations (8) and (9). In the figure 5 red curve is PV energy (DC) without inverter down-regulation [W]; blue curve is rated PV energy [W]; yellow curve is consumption [W].

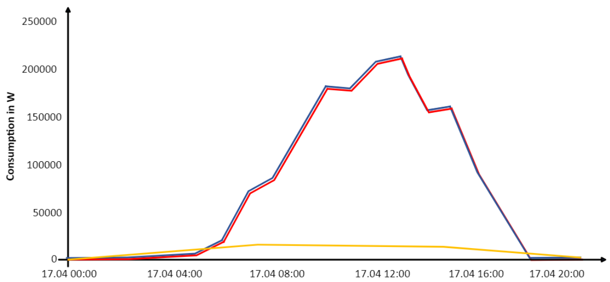

Fig. 5. Daily load chart and coverage (PV Sol Premium)

In future research, will be study energy storage system.

4. Conclusion

1. The similarity of characteristics of automatic optimal control devices for PV system and energy community consumption is established. The possibility of representation of transfer functions in the criterion form is shown. Thus, criterion models can be used to solve optimal control problems between PV system and regulation householdres consumption.

2. Mathematical models of process optimization are constructed, which connect the criterion of optimality with the parameters of control and observation for cases when as a result of transformation of the quadratic form of the objective function into canonical coefficients contain eigenvalues of matrices. It is shown that eigenvaluesare included in the expressions of similarity criteria.

3. A method for estimating the sensitivity of a mathematical model of optimal control using eigenvalues and vectors has been developed. The expressions of sensitivity coefficients of eigenvalues and vectors, which are included in the criterion model of the studied process, are obtained.

4. A method for determining the sensitivity coefficients of similarity criteria has been developed. In the automatic implementation of the optimization results, the control actions are determined taking into account these sensitivity factors.

5. PV system model and demand of householder was simulated in PV*SOL Premium.

Acknowledgement

This result was supported by project MSCA4Ukraine ID number 1233365, 24-PKVV-UM-007, 24-PKVV-UM-006

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