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MATRIX ANALYSIS OF THE TOPOLOGY OF ELECTRIC CIRCUITS FOR SOLAR PANELS AND POWER PLANTS USING CONTROLLED CONNECTIONS

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The work is devoted to the use of matrix theory to represent the topology of electric circuits in photovoltaic panels and photovoltaic power stations and their modeling and calculation. When creating the electric circuits in photovoltaic devices, the controlled connections between photovoltaic cells in photovoltaic panels or photovoltaic panels in photovoltaic power stations are used. The advantages of using the dynamic controlled connections instead of fixed ones are noted. The expediency of using the field-effect transistors as a switching element is mentioned. The incidence matrices with elements responsible for series connection, parallel connection and shunt connection are created. That is, by selecting the elements of the matrix, the corresponding connection is implemented. It is noted that these elements can be parametric and change in time that leads to the implementation of a dynamic system. It is shown that using a matrix presentation it is also convenient to calculate the cascade connections of photovoltaic cells or photovoltaic panels, for which the input values are the output values calculated for the previous cascade. It is also shown that it is convenient to separate a unified calculation matrix to a generation matrix, a matrix of parametric processes and a matrix of connections. It is noted that the use of matrix analysis to the calculation of electric circuits allows the use of algorithms for model computer creation and computer simulation. The conclusions were made and it was shown that it is advisable to develop a matrix approach for use in the calculation of hybrid energy systems. References 23, figures 3.
Keywords: matrix analysis, topology, photovoltaic, solar panels, solar power plants, controlled connections.

Introduction. The relevance and widespread use of photovoltaic energy sources make it necessary to develop and improve the generating devices and systems [1, 2], namely, photovoltaic (PV) panels and solar photovoltaic power plants (PVP). One of the aspects of improvement is the creation of an optimal topology of photovoltaic cells in panels or panels in solar power plants. To improve the various topological solutions, it is possible to use both fixed connections and dynamic connections [3]. It is necessary to pay attention to study of dynamic switching. It should be noted that to create the optimal technical solutions and to carry out the effective modeling, it is advisable to use the matrix analysis [4, 5].

The tasks of the work are to create a theoretical tool for analysis, calculations and simulation of the topology of electric circuits of photovoltaic cells connected in panels and photovoltaic panels connected in solar power stations, based on the mathematical approaches of matrix theory.

Objectives of the work are to create a matrix representation of the elementary cell that connects photovoltaic elements; using the matrix representation to show the parallel and series connections in solar panels and photovoltaic power plants, and also to analyze the variety of elements in the topological matrix.

Basic topology of electric circuits of solar cells. The solar cells in panels or solar panels in power plants are connected in electric circuits to produce the photovoltaic generators with different electrical parameters, namely, operating voltage and operating current. For this, the fixed connections using the conductors with various configurations are used, but it is mainly a metal tape that creates the parallel and serial links of a circuit, such as serial-parallel connections, total cross tide connections, bridge link connections, honeycomb connection [6–8]. Such a design is stationary and cannot be changed.

The fixed connections are especially inefficient when the abnormal situations (such as shading) occur. In this case, the flexibility of the design reveals itself due to dynamic connections. [9–11].

In contrast to fixed connections, the work proposes to use the dynamic connections. The electrical implementation of dynamic connections can use the various switching elements, but the most appropriate

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and modern of them are MOSFET-transistors [12, 13]. To control the dynamic switching the application of programmable logic controllers based on microcontroller technology are needed. The combination of microcontrollers and MOSFET-transistors makes it possible to develop a wide range of topological solutions and create the devices with various operating conditions.

Topology based on a parallel-serial cell. The use of the unified element as a block of dynamic switching is a universal and optimal solution. The paper [14] proposes the use of a parallel-serial cell, in which two generating elements are connected by four commutating elements (Fig. 1): elements P1 and P2 for parallel connection, element S for series connection and element Z for complete shunt of generating elements. Such a cell can be as the basic unit of a photovoltaic panel or a solar power plant, which form a certain range of operating voltages and currents.

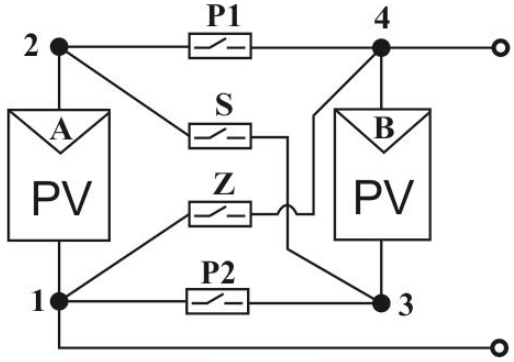

Fig. 1

It is convenient to present the circuit in Figure 1 in the form of a graph for currents (Fig. 2).

The graph shown in Fig. 2 can be described by equations (1)–(4) according to Kirchhoff's current law [15]:

$$I_{10} = I_{11} + I_{12} + I_{13} + I_{14}\,, \quad (1)$$

$$0 = I_{21} + I_{22} + I_{23} + I_{24}\,, \quad (2)$$

$$0 = I_{31} + I_{32} + I_{33} + I_{34}\,, \quad (3)$$

$$I_{10} = I_{41} + I_{42} + I_{43} + I_{44}\,, \quad (4)$$

where I_{11}=I_{22}=I_{33}=I_{44}=0, I_{13}=-I_{31}=I_{24}=-I_{42}, I_{23}=-I_{32}, I_{12}=-I_{21}=$I_{\rm A}$; I_{34}=-I_{43}=$I_{\rm B}$; $I_{\rm A}$ is the current generated by element *A* (Fig.1); $I_{\rm B}$ is the current generated by element *B* (Fig. 1).

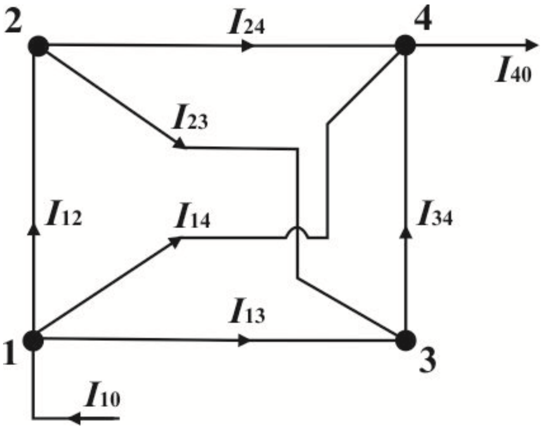

Fig. 2

Taking into account the switching elements from Figure 1 and for the system of equations (1)–(4) we create the topological matrix of currents (5), which acts on the vector of generalized currents I_1, I_2 , I_3, I_4.

The nodal topological matrix is:

$$\begin{pmatrix} I \\ 0 \\ 0 \\ I \end{pmatrix} = \begin{pmatrix} 0 & a & p & z \\ a & 0 & s & p \\ p & s & 0 & b \\ z & p & b & 0 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \mathbf{X} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix}. \quad (5)$$

Considering the vectors and matrix (5), we see that the current *I* is the current of two combined PV elements using a cell. I_1, I_2 , I_3, I_4 are the generalized currents of the corresponding nodes. The coefficients of matrix **X** describe the connection options and generating circuits. Namely, *a* and *b* act on the current of the link according to the current generation by elements *A* and *B*, *p* acts on the current of the links at parallel connection, *s* acts on the current of the links at series connection, *z* acts on the current of the link at short circuit.

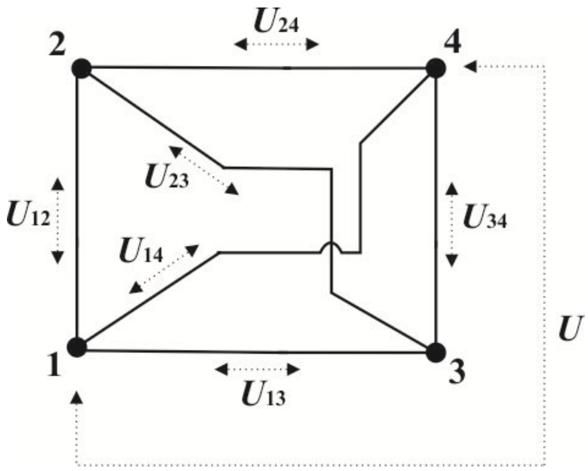

Fig. 3

It is also convenient to present the circuit in Figure 1 in the form of a graph for voltages (Fig. 3).

The graph given in Figure 3 has four closed loops and can be described by equations (6)–(9) according to Kirchhoff's voltage law [15].

Loop 1 (Nodes *1*, *2*, *4* in Fig. 3):

$$0 = U_{11} + U_{12} + U_{24} + U_{14}\,, \quad (6)$$

Loop 2 (Nodes *1*, *2*, *3* in Fig.3):

$$0 = U_{21} + U_{22} + U_{23} + U_{13}\,, \quad (7)$$

Loop 3 (Nodes *2*, *4*, *3* in Fig.3):

$$0 = U_{42} + U_{32} + U_{33} + U_{34}\,, \quad (8)$$

Loop 4 (Nodes *1*, *4*, *3* in Fig.3):

$$0 = U_{41} + U_{31} + U_{43} + U_{44}\,, \quad (9)$$

where $U_{11}=U_{22}=U_{33}=U_{44}=0$, $U_{13}=-U_{31}=U_{24}=-U_{42}$, $U_{23}=-U_{32}$, $U_{12}=-U_{21}=U_A$; $U_{34}=-U_{43}=U_B$; U_A is the voltage at the output of element *A* (Fig.1); U_B is the voltage at the output of element *B* (Fig.1).

We take into account the switching elements in Fig. 3 and for the system of equations (6)–(9) and form the topological matrix of voltages (10) that has an influence on the vector of generalized voltages U_1, U_2, U_3, U_4.

The closed loop topological matrix is as follows:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0+U_{12}+U_{13}+U_{14} \\ U_{21}+0+U_{23}+U_{24} \\ U_{31}+U_{32}+0+U_{34} \\ U_{41}+U_{42}+U_{43}+0 \end{pmatrix} = \begin{pmatrix} 0 & a & p & z \\ a & 0 & s & p \\ p & s & 0 & b \\ z & p & b & 0 \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{pmatrix} = \mathbf{X} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{pmatrix}. \quad (10)$$

Considering the vectors and matrix (10), we see that voltage U is the voltage of two combined PV elements by a cell. U_1, U_2, U_3, U_4 are the generalized voltages of the corresponding closed loops. Matrix **X** is described in the same way as for currents.

Parallel connection. When implementing a parallel connection, we will use equations (5) and (10) in matrix form to calculate the current and voltage. In the equations the coefficients for currents: p=1; s=0; z=0; $aI_1=aI_2=I_A$; $bI_3=bI_4=I_B$. Then for currents we get:

$$\begin{pmatrix} I \\ 0 \\ 0 \\ I \end{pmatrix} = \begin{pmatrix} 0 & a & 1 & 0 \\ a & 0 & 0 & 1 \\ 1 & 0 & 0 & b \\ 0 & 1 & b & 0 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \begin{pmatrix} 0+I_A+I_{13}+0 \\ I_A+0+0+I_{24} \\ I_{31}+0+0+I_B \\ 0+I_{42}+I_B+0 \end{pmatrix}. \quad (11)$$

Solving the system of equations obtained from (11) and understanding that $I_{13}=I_{31}$ and $I_{24}=I_{42}$, we have:

$$I = I_A + I_B \ . \quad (12)$$

The coefficients for voltages: p=0; s=1; z=1; $aU_1=aU_2=U_A$; $bU_3=bU_4=U_B$. We get for voltages:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & a & 0 & 1 \\ a & 0 & 1 & 0 \\ 0 & 1 & 0 & b \\ 1 & 0 & b & 0 \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{pmatrix} = \begin{pmatrix} 0+U_A+0+U_{14} \\ U_A+0+U_{23}+0 \\ 0+U_{32}+0+U_B \\ U_{41}+0+U_B+0 \end{pmatrix}. \quad (13)$$

Solving the system of equations obtained from (13) and taking into account that $U_{13}=U_{31}=0$ and $U_{24}=U_{42}=0$, we have:

$$U = U_{14} = U_A = U_B \ . \quad (14)$$

Series connection. When implementing a series connection, we will also use the equations in matrix form (5) and (10) to calculate the current and voltage. The coefficients are determined as follows: p=0; s=1; z=0; $aI_1=aI_2=I_A$; $bI_3=bI_4=I_B$. For currents we get:

$$\begin{pmatrix} I \\ 0 \\ 0 \\ I \end{pmatrix} = \begin{pmatrix} 0 & a & 0 & 0 \\ a & 0 & 1 & 0 \\ 0 & 1 & 0 & b \\ 0 & 0 & b & 0 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \begin{pmatrix} 0+I_A+0+0 \\ I_A+0+I_{23}+0 \\ 0+I_{32}+0+I_B \\ 0+0+I_B+0 \end{pmatrix}. \quad (15)$$

Solving the system of equations obtained from (15) and understanding that $I_{23}=I_{32}$, we have:

$$I = I_A = I_B \ . \quad (16)$$

The coefficients for voltages are equal to: p=1; s=0; z=1; $aU_1=aU_2=U_A$; $bU_3=bU_4=U_B$. Then for voltages we get:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & a & 1 & 1 \\ a & 0 & 0 & 1 \\ 1 & 0 & 0 & b \\ 1 & 1 & b & 0 \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{pmatrix} = \begin{pmatrix} 0+U_A+U_{13}+U_{14} \\ U_A+0+0+U_{24} \\ U_{31}+0+0+U_B \\ U_{41}+U_{42}+U_B+0 \end{pmatrix}. \quad (17)$$

Solving the system of equations obtained from (17) and understanding that U_{24}=U_{42} and U_{13}=U_{31} we have:

$$U = U_A + U_B \,. \tag{18}$$

Short circuit. Implementing the short-circuit or in other words, the shunting of PV cells or panels, we will again use the equations in matrix form (5) and (10) to calculate the current and voltage. In the equations the coefficients are equal to: p=0; s=0; z=1; aI_1=aI_2=I_A; bI_3=bI_4=I_B, but in this case a=0 and b=0. Hence we get for currents:

$$\begin{pmatrix} I \\ 0 \\ 0 \\ I \end{pmatrix} = \begin{pmatrix} 0 & a & 0 & 1 \\ a & 0 & 0 & 0 \\ 0 & 0 & 0 & b \\ 1 & 0 & b & 0 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \begin{pmatrix} 0+0+0+I_{14} \\ 0+0+0+0 \\ 0+0+0+0 \\ I_{41}+0+0+0 \end{pmatrix} . \tag{19}$$

Solving the system of equations obtained from (19), we have:

$$I = I_{14} = I_{41} \,. \tag{20}$$

Therefore the current of the PV cells or panels has no effect on the input and output current.

The coefficients for voltages are as follows: p=1; s=1; z=0; aU_1=aU_2=U_A; bU_3=bU_4=U_B. For voltages we get:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & a & 1 & 0 \\ a & 0 & 1 & 1 \\ 1 & 1 & 0 & b \\ 0 & 1 & b & 0 \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{pmatrix} = \begin{pmatrix} 0+U_A+U_{13}+0 \\ U_A+0+U_{23}+U_{24} \\ U_{31}+U_{32}+0+U_B \\ 0+U_{42}+U_B+0 \end{pmatrix} . \tag{21}$$

Considering (21), we have:

$$U = U_{14} = 0 \,. \tag{22}$$

Parametric connections. The coefficients of matrix **X** in (5) and (10) can be parametric. For example, the coefficients p and s can depend on the output voltage (27) or change in time (28), or coefficient z depends on ambient temperature T (29)

$$\begin{pmatrix} I \\ 0 \\ 0 \\ I \end{pmatrix} = \begin{pmatrix} 0 & a & p(U) & z \\ a & 0 & s(U) & p(U) \\ p(U) & s(U) & 0 & b \\ z & p(U) & b & 0 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \mathbf{X}(U) \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} , \tag{27}$$

where, for example, p=0, s=1 at U<U_{max} and p=0, s=1 at U>U_{max}.

$$\begin{pmatrix} I \\ 0 \\ 0 \\ I \end{pmatrix} = \begin{pmatrix} 0 & a & p(t) & z \\ a & 0 & s(t) & p(t) \\ p(t) & s(t) & 0 & b \\ z & p(t) & b & 0 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \mathbf{X}(t) \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} , \tag{28}$$

where, for example, $p \sim \sin(\omega t)$ and $s \sim \sin(\omega t + \pi/2)$.

$$\begin{pmatrix} I \\ 0 \\ 0 \\ I \end{pmatrix} = \begin{pmatrix} 0 & a & p & z(T) \\ a & 0 & s & p \\ p & s & 0 & b \\ z(T) & p & b & 0 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \mathbf{X}(T) \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} , \tag{29}$$

where, for example, z=0 at T<T_{max} and z=1 at T>T_{max}.

In this way, the dynamic system with the parameters depending on internal or external factors and changing in time can be implemented.

Cascade connection. When calculating a multi-element system [14], it is advisable to use the cascade embedding for matrix calculations. Then the topological matrix of currents, which represents the connection of four previously connected elements in pairs, has the form:

$$\mathbf{X}_{(2)} = \begin{pmatrix} 0 & a_{(2)} & p & z \\ a_{(2)} & 0 & s & p \\ p & s & 0 & b_{(2)} \\ z & p & b_{(2)} & 0 \end{pmatrix}, \tag{30}$$

where $a_{(2)}$ proportionally depends on $I_{(A1)}$; $b_{(2)}$ is proportionally with $I_{(B1)}$; $a_{(2)}$ and $b_{(2)}$ are the energy sources of the next level; $I_{(A1)}$ and $I_{(B1)}$ are the output currents, which are calculated using the topological matrix of currents (5) at the previous level. Thus the entire system is calculated step by step. In this case the input values are the output values calculated for the previous cascade.

Separation of matrices. For more convenient calculation and modeling, it is useful to separate the various factors and elements of the circuit into their own matrices. So, it is possible to form a generation matrix, a matrix of parametric or nonlinear factors of the circuit, and a matrix of connections, and then to combine them into one expression:

$$\begin{pmatrix} I \\ 0 \\ 0 \\ I \end{pmatrix} = \left(\begin{pmatrix} 0 & A & 0 & 0 \\ A & 0 & 0 & 0 \\ 0 & 0 & 0 & B \\ 0 & 0 & B & 0 \end{pmatrix} \begin{pmatrix} \cos(\omega t) & 0 & 0 & 0 \\ 0 & \cos(\omega t) & 0 & 0 \\ 0 & 0 & \sin(\omega t) & 0 \\ 0 & 0 & 0 & \sin(\omega t) \end{pmatrix} + \begin{pmatrix} 0 & 0 & p & z \\ 0 & 0 & s & p \\ p & s & 0 & 0 \\ z & p & 0 & 0 \end{pmatrix} \right) \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix}. \tag{31}$$

Features of using the MOSFET transistors for connection of photocells and solar panels. The use of MOSFET transistors instead of diodes and fixed metallic connections offers several advantages. For instance, the unique feature of using MOSFETs in photovoltaic elements is that, the MOSFET in the ON state does not exhibit a significant voltage drop due to the induced channel with the same conductivity as the source and drain [16]. Also the MOSFET has only ohmic (d.c.) resistance. This is crucial because the generated voltages in photovoltaics are low and a substantial voltage drop is unacceptable. However the drawback of MOSFETs consists in the presence of a parasitic diode connected in parallel to the source and drain of the transistor [17]. Then under certain voltage values and polarities across the transistor terminals, the current can flow through this diode and cause the voltage drop. To prevent this negative effect, the complementary pair of transistors is used. In this configuration, the system acts as an ideal diode–with no voltage drop in forward-biased state and completely blocks the current in reverse-biased state.

It should be noted that when connecting the solar panels in unified block-at using of complementary transistor pairs, it is convenient to apply the transistor assemblies, such as two MOSFETs in single SO-8 case [18]. However, when connecting photocells within a panel, it is more practical to use a surface-mount MOSFET and place it inside the photovoltaic panel between the photocells, but it is needed to ensure the adequate heat dissipation.

Conclusion. Using the matrix representation of the circuit by a switching cell, it is possible to quickly and conveniently implement the calculations of the series and parallel connections of photovoltaic elements as well as their shunting. Namely, choosing the coefficients S, P and Z that are equal to zero or one, we connect the corresponding links. In addition, these coefficients can have other values, simulating the processes of the current limitation and amplification. Also note that these coefficients can be parametric and change in time. This leads to the implementation of a dynamic system in which the output voltage and current vary in time. This approach will lead to alternating current at the output of the system. And we can make the waveform of this alternating current by introducing of a certain time-dependent function instead of the coefficient. So, for example, the introduction of harmonic function, such as a sine or cosine, can cause the harmonic signal at the output of a photovoltaic generator system. Using the matrix presentation, it is convenient to calculate the cascade connections of photovoltaic cells or photovoltaic panels, especially by computer algorithms for formation of topological matrices [19, 20] and computer simulation [21, 22].

It should also be noted that the further development of the matrix approach will make it possible to calculate the connections not only of photovoltaic generating devices, but also of hybrid energy generators [23].

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УДК 621.31

МАТРИЧНИЙ АНАЛІЗ ТОПОЛОГІЇ ЕЛЕКТРИЧНИХ КІЛ В СОНЯЧНИХ ПАНЕЛЯХ ТА СТАНЦІЯХ З ВИКОРИСТАННЯМ КЕРОВАНИХ З'ЄДНАНЬ

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Роботу присвячено використанню теорії матриць для представлення топології електричних кіл в фотоелектричних панелях і фотоелектричних станціях та проведення їхнього моделювання і розрахунку. Під час побудови електричних кіл в фотоелектричних пристроях використано керовані з'єднання між ПВ-комірками в фотоелектричних панелях або ПВ-панелей в фотоелектричних станціях. Відмічено переваги використання динамічних керованих з'єднань замість фіксованих. Згадано про доцільність використання польових транзисторів як комутуючих елементів. Побудовано матриці інциденцій з елементами, які відповідають за послідовне, паралельне та шунтувальне з'єднання. Тобто, вибираючи елементи матриці, реалізовується відповідне з'єднання. Відмічено, що ці елементи можуть бути параметричними і змінюватися у часі, що призводить до реалізації динамічної системи. Показано, що використовуючи матричне відображення також зручно розраховувати каскадні з'єднання фотоелементів чи фотопанелей, де під час розрахунку вхідними значеннями є вихідні значення, розраховані для попереднього каскаду. Також показано, що зручно розділяти єдину розрахункову матрицю на генерувальну матрицю, матрицю параметричних процесів та матрицю з'єднань. Відмічено, що використання матричного аналізу під час розрахунку електричних кіл дає змогу використовувати алгоритми комп'ютерного створення моделей та проведення комп'ютерного моделювання. Зроблено висновки та показано, що доцільно зробити розвиток матричного підходу на використання до розрахунку гібридних енергетичних систем. Бібл. 23, рис. 3.

Ключові слова: матричний аналіз, топологія, фотоелектрика, сонячна панель, сонячна станція, керовані з'єднання.

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