Matlab/Simulink Interface Design and Implementation for PV Arrays Reconfiguration

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Abstract One of the major problems in photovoltaic (PV) arrays operation is the mismatching effect due to partial shading; it produces significant drops in the power delivered by the PV system. The power losses due to partial shading for a given operating condition can be mitigated in part by changing the scheme connection of the PV array. This paper introduces a solution to reconfigure a 3×3 PV array by means of a graphic interface using Matlab and Simulink. A mathematical model is used to calculate the configuration which provides the maximum power under a given operating condition. Then, a connection matrix is identified and the connections on the PV array are implemented by using an ARDUINO DUE and a relay based reconfiguration board. The proposed solution is validated by comparing the power vs voltage ($P - V$) characteristics of different configuration schemes obtained from experimental tests.

1 Introduction

The interest of the scientific community in the development and implementation of renewable energies, especially, solar energy, has increased gradually through the last few years: in 2017, the power generation capacity increased an estimated 178 GW globally, with photovoltaic (PV) capacity as the main addition [1]. To improve the efficiency in PV systems, the study of the losses which affect the extraction of the maximum power is imperative. One of the main causes of power drops is mismatching: different modules parameters or partial shading [2]. Partial shading occurs when part of a PV array is shaded (due to passing clouds, parts of other

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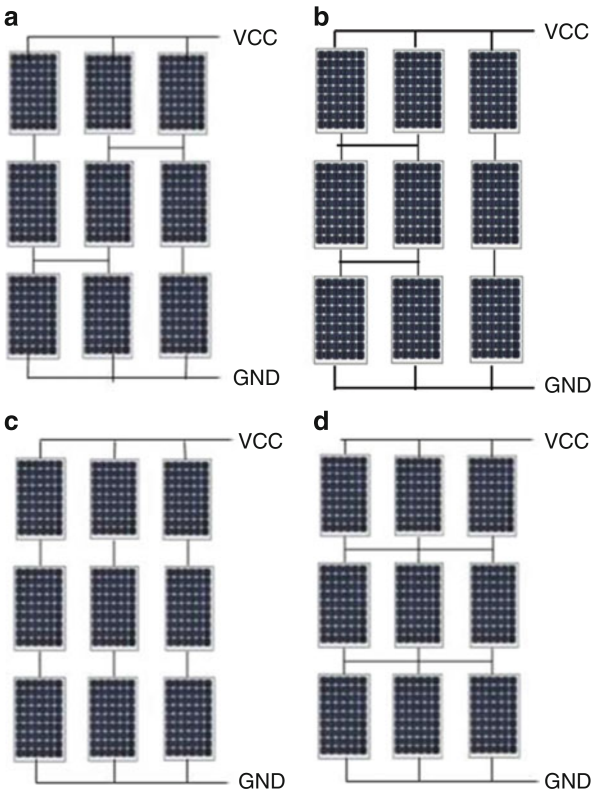
buildings, trees, adjacent PV panels, etc.) while the rest of the array remains fully illuminated [3], this producing the activation of the bypass diodes connected in antiparallel to the PV modules. When that happens, the power vs voltage ($P - V$) characteristic exhibits multiple power peaks which can introduce errors in the operation of the algorithms used to track the global maximum power point (*GMPP*).

1.1 Reconfiguration of Photovoltaic Arrays

The process of rearranging solar PV panels either physically or electrically is known as reconfiguration. Such a process is carried out to mitigate the effects of partial shading on the power provided by the PV system [4, 5]. However, a large number of switches and sensors are required to implement different techniques reported in literature [4] and the high complexity of some algorithms increases the cost of such applications [6]. On the other hand, another form of reconfiguring a PV array can be considered, this by performing changes in the connection scheme of the array, i.e., changing the connection of the array using conventional configurations also called *regular configurations* which follows a defined pattern as illustrated in Fig. 1 where

Fig. 1 PV configurations example. (**a**) HC (**b**) Irregular (**c**) SP (**d**) TCT



item (a) represents a Honey-comb configuration (HC), item (c) a serial-parallel configuration (SP), and item (d) a total-cross-tied configuration (TCT). Moreover, other configurations known as irregular or hybrids [7, 8], illustrated in Fig. 1 item (b), which are connected randomly or without a pattern, can also be considered. This kind of reconfiguration requires less number of switches reducing the cost and complexity of its implementation. One of the requirements for performing the reconfiguration between conventional or irregular structures is a technique to calculate the best configuration (in terms of produced power) for a given operating conditions.

For this purpose, procedures as the one introduced in [7] can be used. Such a procedure is able to calculate the currents and voltages and then the power of a PV system with any configuration operating under uniform or partial shading conditions. In this way, it is possible to know which connection is more suitable for mitigating the effects of partial shading; this information can be used in a switching board to perform the physical connections in the PV array. This paper presents the application of the modeling procedure introduced in [7] implemented in Matlab environment, adapting it in order to evaluate every possible configuration, conventional and irregular, for a 3×3 PV array, finding the best connection that delivers the highest MPP. The different connections in the PV array are performed through a switching matrix which is managed by means of a graphic interface designed in Simulink, using an Arduino DUE. This paper is organized as follows: In Sect. 2 the main algorithm of the modeling procedure and the application proposed will be described. Section 3 is dedicated to define the elements of the experimental setup: Sect. 3.1 elements that are used to implement the reconfiguration process and in Sect. 3.2 the experimental results are presented. Finally, in Sect. 4 conclusions close the paper.

2 Proposed Application of Modeling Procedure

2.1 Modeling Procedure

The algorithm described in [7] calculates the current of any conventional or irregular PV array, with N rows and M columns of panels ($N \times M$), operating under uniform or partial shading conditions, to obtain the *I-V* and *P-V* curves of the PV array. The model is based on the single diode model (*SDM*) including bypass diode; such a model requires seven parameters: photovoltaic current I_{ph}, saturation current I_{sat}, ideality factor n, series resistance R_s, parallel resistance R_{sh}, bypass diode saturation current $I_{sat,db}$, and bypass diode ideality factor n_{db}. In order to represent the ties (connections between the array strings), the procedure makes use of a $(N-1) \times (M-1)$ matrix known as *connection matrix*; such matrix is filled with “0” or “1”: a “0” indicates no connection between strings and a “1” indicates connection. As an example, connection matrices (M_{conn}) corresponding to HC and the irregular configuration described in Fig. 1 are shown in (1). For TCT and SP, the connection matrices $M_{conn-TCT}$ and $M_{conn-SP}$ are a matrix filled with ones and a matrix filled with zeros, respectively.

$$M_{conn-Irregular} = \begin{bmatrix} 1 & 0 \\ 1 & 0 \end{bmatrix} \quad M_{conn-HC} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{1}$$

In this work, the modeling procedure reported in [7] will be used to evaluate the *I-V* characteristics of all the possible connections, that means, the switches states corresponding with the regular or irregular configurations for a 3×3 PV array under a given irradiance profile in order to acquire the scheme which mitigates best the partial shading effect. In this way, the connection matrix concept will be used for obtaining the signals which will be sent to the switching matrix to perform the suitable connection in the PV array.

2.2 *Identification of Connection Matrices*

The automation of the connection matrices calculation and the recognition of all possible configuration schemes regular and irregular have been added to the procedure in [7] by changing the manual entry of connection matrices for an automated process developed in this application and represented in Algorithm 1. In the next sub-sections these contributions will be explained.

Algorithm 1 Identification and creation of connection matrices

INPUT: N, M, array dimensions
OUTPUT: *Nt*, *Tco*
1: Set gu=1
2: Calculate *Nm* with (2)
3: **For** j=1 **to** *Nm* **do**
4: Calculate *F(j)* with (3)
5:**end for**
6: Calculate *Tco* with (6)
7:**For** i=1 **to** *Nm* **do**
8: Set *Array*(1,i)=1
9: Save in *Fr* all possible permutations of the elements of the vector *Array*
10: **end for**
11:**For** ij=1 **to** length of the largest array dimension in F **do**
12: Identify $nF_{(ij,1)}$ and a= rows of $nF_{(ij,1)}$
13:**For** mm=1 **to** a **do**
14: Set Nodo(gu)=reshape $nF_{(ij,1)}$ into (N-1)x(M-1)=*Nt* and set gu=gu+1
15:**end for**
16:**end for**
17: **Return** *Nt* and *Tco*

To identify the possible configurations in an $N \times M$ PV array, first the amount *Nm* of elements in the connection matrix needs to be settled [9], for this purpose, (2) is applied and referenced in line 2 of the pseudocode:

$$Nm = (N-1)(M-1) \tag{2}$$

The connection matrix depends on the number of ties or ("1") in it, then, it is necessary to place one tie ("1") in all the position in the matrix while the rest of the positions are ("0") then with two until *Nm* ties, and calculate the possible combinations *F* that can be obtained with every configuration; *for* loop in lines 3–5 of the pseudocode and (3) where *j* is the variable of iteration inside the *for* loop, the number of these possible combinations can be known. An example of the position change inside the matrix is shown in (4) and (5).

$$F(j) = \frac{Nm!}{(Nm-j)!j!} \tag{3}$$

$$M_{conn-(1,1)} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} -- > M_{conn-(1,2)} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \tag{4}$$

$$M_{conn-(1,1;1,2)} = \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix} -- > M_{conn-(1,1;2,1)} = \begin{bmatrix} 1 & 0 \\ 1 & 0 \end{bmatrix} \tag{5}$$

The total number of possible configurations *Toc* is the result of adding together the *F* of every iteration as is shown in (6); the plus 1 is the SP configuration which has no ties between strings.

$$Tco = \sum_{j=1}^{Nm} F(j) + 1 \tag{6}$$

The connection matrix has to be created for each possible configuration; the *for* loop in lines 7–10 of the pseudocode go over an initial vector *Array* that will set the elements and a vector *Fr* that will process them, both of dimensions $(1 \times Nm)$, making permutations in a similar process as described above, the first element will be the first tie ("1"), i.e., (3). Each resulting permutation is a different configuration of the connection matrix; therefore, these vectors will be saved in a cell *nF* of dimensions $(Nm \times 1)$, as indicated in line 9.

To get the final connection matrices associated with the PV array, the vectors *Fr* inside *nF* must be reformed into a $(N-1)$ rows and $(M-1)$ columns matrices $((N-1) \times (M-1))$, based on the dimensions of the photovoltaic array. The process is carried out by means of *for* loops in lines 11–16 and 13–15 of the pseudocode, in charge of re-arrange and save the outcoming matrices in an auxiliary cell *Nt*; the auxiliary variables *a*, *gu* and the cell *Nodos* are introduced to simplify the code.

2.3 Obtainment of the Optimum Configuration Scheme

The recognition of the connection matrices makes possible to evaluate regular and irregular configurations schemes: *For* loops traverse the *Nt* cell within the modeling procedure in [7], where it is possible to calculate the voltage *V* and current *I* values for every configuration found. Now, by making use of the Ohm's law (7), the power can be calculated.

$$P = VI \tag{7}$$

The proper configuration scheme is the one with the highest power, then, the maximum values of each connection matrix are saved in a vector *Pconf* of dimensions (1×Toc), by using a simple comparison between the vector data to find the maximum, the GMPP can be found, and because of the indexed of the *Nt* cell, also the optimum configuration. It is simple to identify whether it is a regular or an irregular configuration, with the connection matrices defined above for regular configurations (SP, TCT, and HC) and *if* conditionals, the comparisons between the connection matrices in *Nt* cell and the known configuration schemes will define which regular configuration matches or in case of irregular configuration will only display such connection matrix.

The corresponding connection matrix is deployed through a specific code that communicate Matlab and Simulink environment where the electrical reconfiguration will be made by sending the proper digital signals through the Arduino DUE to the reconfiguration board.

3 Performance of the Proposed Application

3.1 Experimental Setup

An illustrative diagram of the experimental setup is shown in Fig. 2. The optimal configuration scheme is deployed in a reconfiguration board based on a switches matrix, also, connected in series with the solar panel there is a blocking diode whose purpose is to avoid wrong connections inside the photovoltaic array. The graphic interface allows to communicate the algorithm with the experimental platform through the Arduino and has a fast identification of the type of configuration scheme, regular or irregular, that reached the GMPP.

3.1.1 Reconfiguration Board

In order to implement the application proposed in this paper, a proper system has been designed at Universidad Nacional of Colombia and produced at the

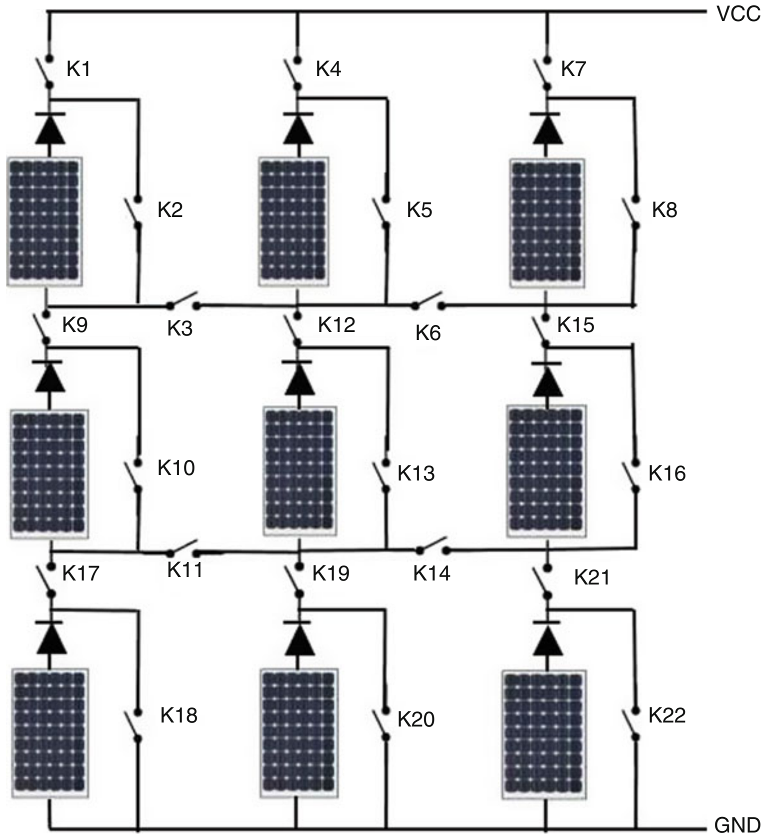


Fig. 2 Experimental setup

Instituto Tecnologico Metropolitano to reconfigure nine solar panels (3×3 matrix). The system described is an electronic board shown in the photograph of Fig. 3 that contains IN and OUT elements, switches (relays), and protection elements:

- Twenty two relay NO (normally open) with a control stage,
- Terminal blocks that provide direct connection with the photovoltaic array and the power supply for the relays,
- Contact pins for the Arduino board,
- Blocking diodes and transistors,
- LED diodes

The relay control stage consists of a transistor whose base is connected to a digital output from the Arduino, this energizes the coil inside the relay and acts as a current amplifier. A LED has been incorporated to verify visually the relay state, and a freewheeling diode which absorbs the current peak from the coil when

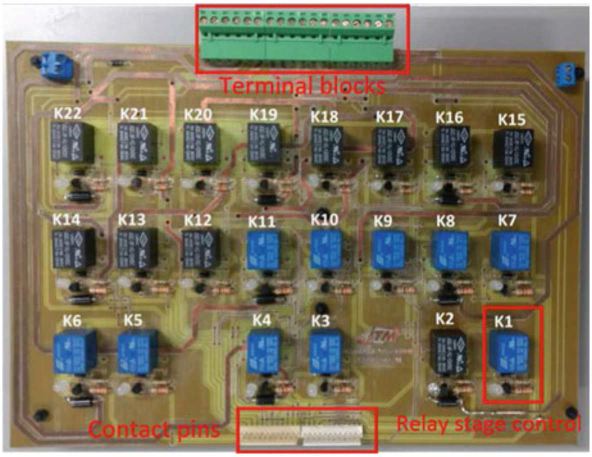


Fig. 3 Reconfiguration board

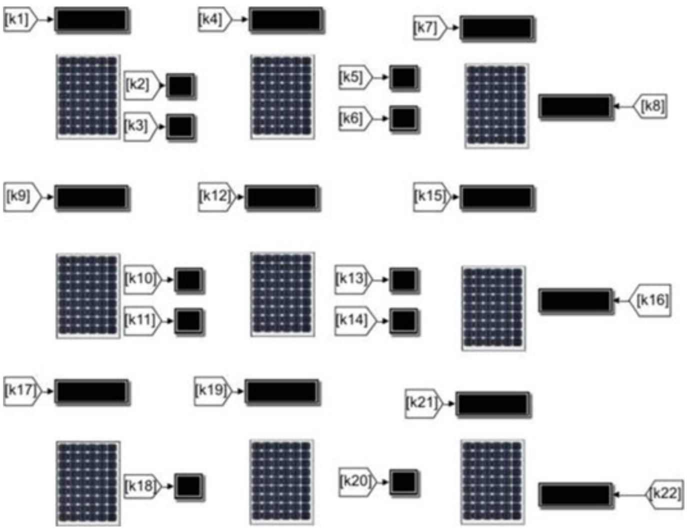


Fig. 4 Graphic interface in Simulink

is connected or disconnected, due without it, the transistor will be exposed to overvoltages that eventually will damage it.

3.1.2 Interface Design with Arduino

A graphic interface in Simulink has been designed to visualize which configuration scheme has been implemented on the board, showing the state of every single relay as is illustrated in Fig. 4. Using the Simulink libraries that allow to communicate Matlab and Simulink with Arduino via serial port. Each relay has attached a digital output of the Arduino, enumerated from K1 until K22, corresponding also with the diagram exposed in Fig. 2. K1, K6, K11, and K14 are the equivalent of the elements in the connection matrix. The graphic interface has 22 displays that show the state of each relay (one for ON and zero for OFF) and 9 solar panels, with the aim of facilitating the view of the actual configuration scheme.

3.2 Experimental Results

In order to evaluate the system described above, a 3×3 PV array has been employed, simulation and experimental results were founded using nine ERDM 10 solar panels, whose main electrical characteristics are: $P_{max} = 10$ W, $I_{mp} = 0.58$ A, $V_{mp} = 17.40$ V, $V_{oc} = 21.8$ V, and $I_{sc} = 0.63$ A. The effectiveness of the implementation of the graphic interface on the reconfiguration target was tested considering one irradiance profile (i.e., Fig. 5) under solar irradiance conditions without significant changes.

For the 3×3 PV array, 16 possible configurations have been found; after calculating the I and V values for each one of them, a comparison has been made for 3 regular configurations, as is shown in Fig. 6 the $P - V$ characteristic curves of the HC, SP, and TCT configurations show an inflection point due to the bypass diode enabling. This result shows TCT as the optimum configuration with 28.9387 W for this irradiance profile with a 34.54% of improvement over HC configuration (18.9424 W) and 38.54% over SP configuration (17.7856 W). The connection matrices for the regular configurations worked are shown in Figs. 7, 8 and 9; where items (a) of each figure represent the digital signals ("0" for OFF and "1" for ON) for the corresponding outputs to the Arduino and the state of the relays K3, K6, K11, and K14 in the reconfiguration board that allows the connection between strings, items (b) display the interface once the correct ties between strings are deployed.

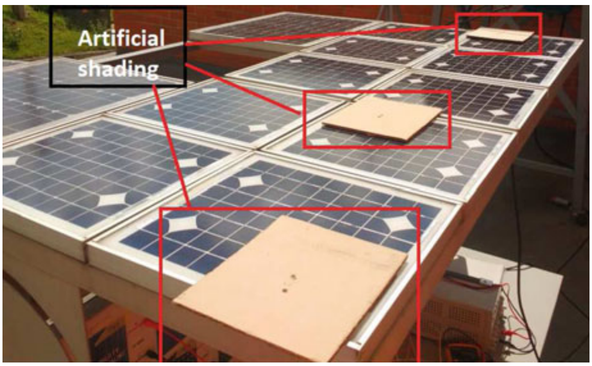


Fig. 5 Experimental test

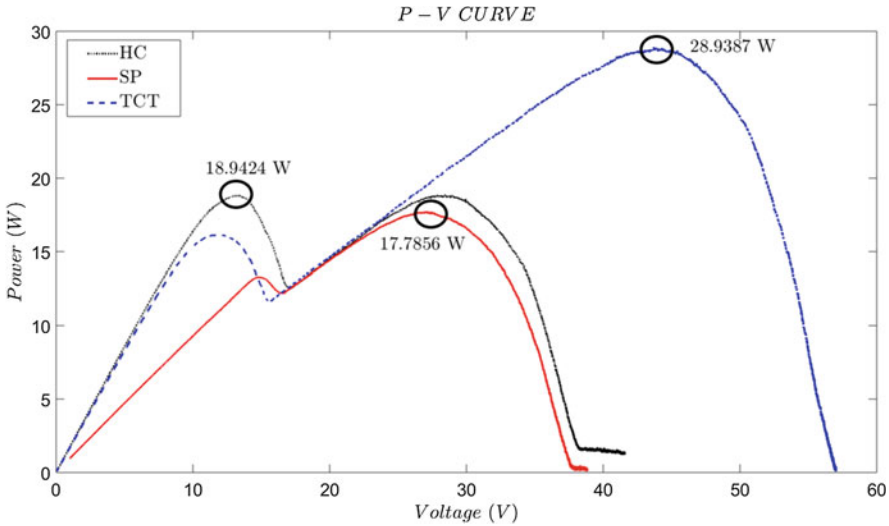


Fig. 6 HC, SP, TCT experimental $P - V$ curves

4 Conclusion

An application of the modeling procedure reported in [7] has been designed and implemented. The identification of all configuration schemes and the automation of the connection matrices calculation for a $(N \times M)$ PV array introduced in this work make possible to consider them for an appropriate evaluation of the I and V characteristics. In this way, a suitable configuration scheme that reaches the GMPP to ensure the maximum power extraction can be found. This application shows high compatibility between Simulink, Matlab, and Arduino, also, is an affordable and more suitable setup for PV systems efficiency modeling. The proposed solution has been validated by experimental tests consisting in the evaluation and comparison of three conventional configurations (HC, SP, and TCT) exposed to the same irradiance profile. The results showed that TCT configuration was the suitable connection providing higher power at the GMPP of 34.54% and 38.54% in comparison with HC and SP configurations, respectively. The evidence of the deployment of the connection matrices related with the regular configurations worked has been illustrated in the graphic interface with the correct ties between strings, also, the designed reconfiguration board can be utilized for PV arrays of a maximum power of 296.055 W. As a future work, the proposed application can be developed in a neuronal network to make real-time identifications with less processing time, also, a proper shading profile characterization is under investigation to improve the accuracy of the prediction of the power in PV arrays. This could be a previous stage that can be added to the solution presented in this paper.

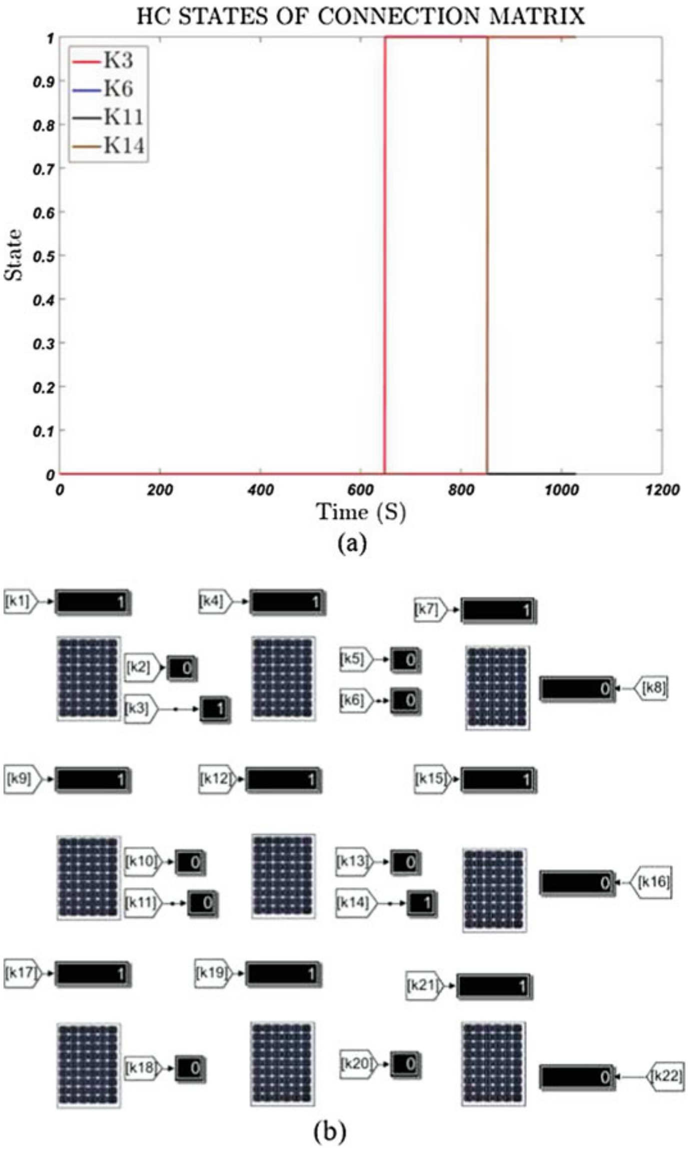


Fig. 7 Result from HC configuration. (**a**) Representation of the digital signals in HC configuration. (**b**) HC configuration in graphic interface

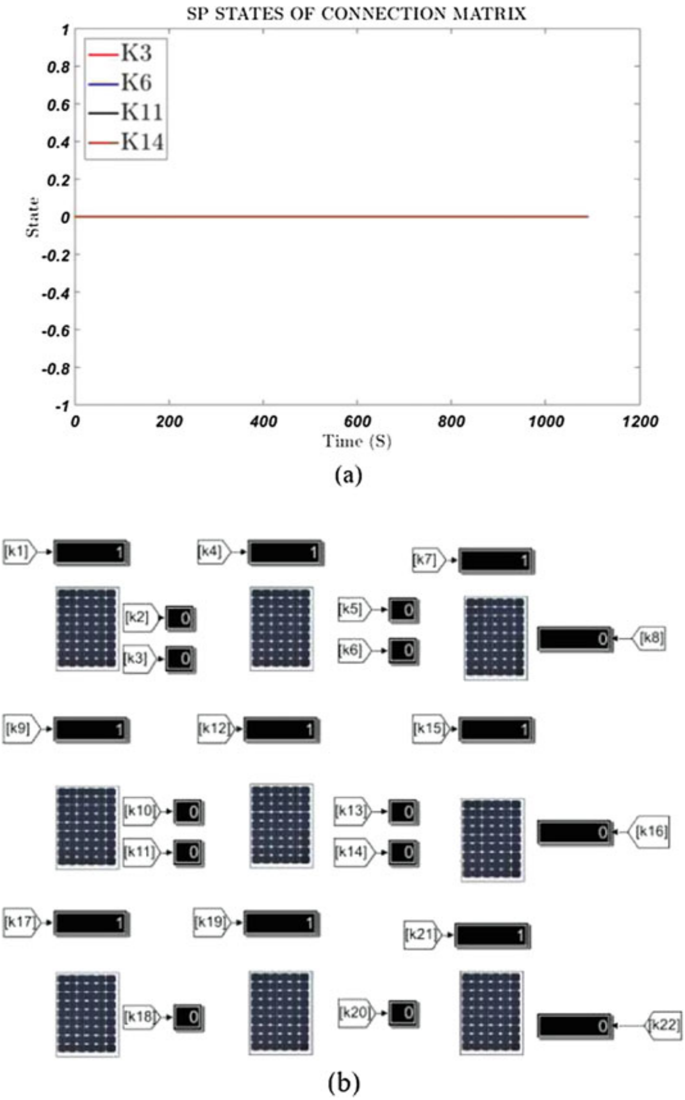


Fig. 8 Result from SP configuration. (**a**) Representation of the digital signals in SP configuration. (**b**) SP configuration in graphic interface

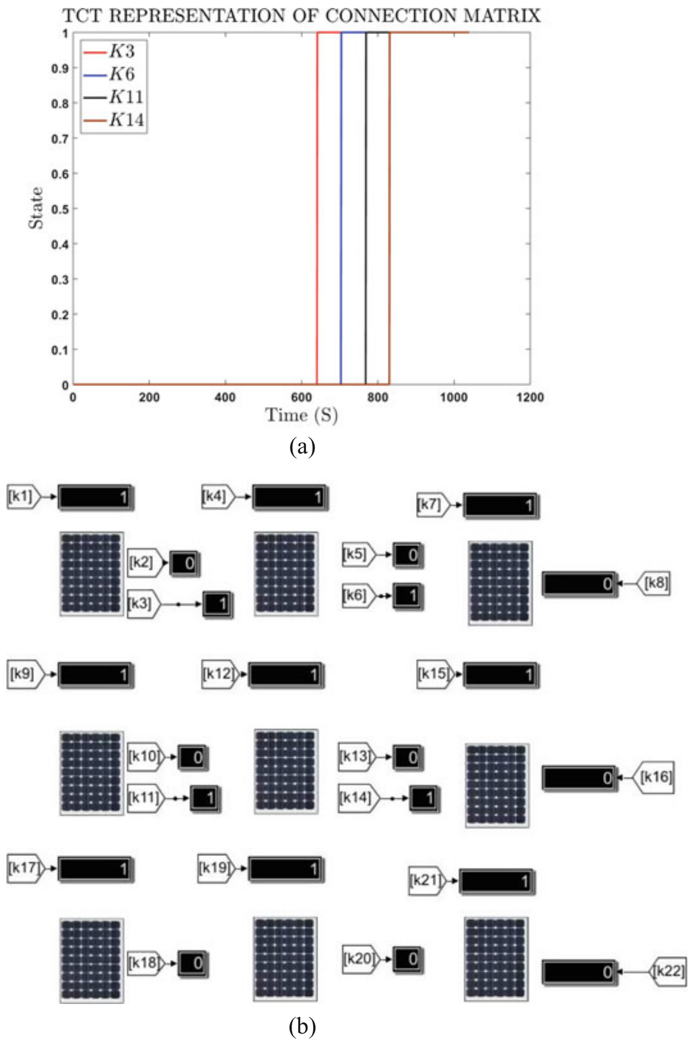


Fig. 9 Result from TCT configuration. (**a**) Representation of the digital signals in TCT configuration. (**b**) TCT configuration in graphic interface

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