Modeling and Reconfiguration of Solar Photovoltaic Arrays under Non-Uniform Shadow Conditions

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Abstract

Mass production and use of electricity generated from solar energy has become very common recently because of the environmental threats arising from the production of electricity from fossil fuels and nuclear power. The obvious benefits of solar energy are clean energy production and infinite supply of daylight. The main disadvantage is the high cost. In these photovoltaic systems, semiconductor materials convert the solar light into electrical energy. Current versus voltage characteristics of the solar cells are non-linear, thus leading to technical control challenges. In the first order approximation, output power of a solar array is proportional to the irradiance of sunlight. However, in many applications, such as solar power plants, building integrated photovoltaic or solar tents, the solar photovoltaic arrays might be illuminated non-uniformly. The cause of non-uniform illumination may be the shadow of clouds, the trees, booms, neighbor’s houses, or the shadow of one solar array on the other, etc. This further leads to nonlinearities in characteristics.
Because of the nature of the electrical characteristics of solar cells, the maximum power losses are not proportional to the shadow, but magnify nonlinearly [1]. Further, shadows of solar PV array can cause other undesired effects:

- The power actually generated from the solar PV array is much less than designed. At some systems, the annual losses because of the shadow effects can be reached 10%. Thus, the probability for “loss of load” increases [2].
- The local hot spot in the shaded part of the solar PV array can damage the solar cells. The shaded solar cells may be work on the negative voltage region and become a resistive load and absorb power. Bypass diodes are sometimes connected parallel to solar cells to protect them from damage. However, in most cases, just one diode is connected in parallel to group of solar cells [3], and this hidden the potential power output of the array.

This proposed research will focus on the development of an adaptable solar array that is able to optimize power output, reconfigure itself when solar cells are damaged and create controllable output voltages and currents.

This study will be a technological advancement over the existing technology of solar PV. Presently solar arrays are fixed arrays that require external device to control their output. In this research, the solar array will be able to self-reconfigure, leading to the following advantages:

- Higher efficiency because no external devices are used.
- Can reach maximum possible output power that is much higher than the maximum power of fixed solar arrays by arranging the solar cells in optimized connections.
- Elimination of the hot spot effects.

The proposed research has the following goals: First, to create a modeling and computing algorithm, which is able to simulate and analyze the effects of non-uniform changing shadows on the output power of solar PV arrays. Our model will be able to determine the power losses in each solar cell and the collective hot spots of an array. Second, to propose new methods, which are able to predict the performance of solar PV arrays under shadow conditions for long term (days, months, years). Finally, to develop adaptive reconfiguration algorithms to reconfigure connections within solar PV arrays in real time, under shadow conditions, in order to optimize output power.
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# Table of Contents

List of Figures ..................................................................................................................... 9  
List of Tables ...................................................................................................................... 11  
List of Acronyms ................................................................................................................ 12  

1. Introduction.................................................................................................................. 13  
   1.1 Background ........................................................................................................ 13  
      1.1.1 Photovoltaic becomes competitive ............................................................. 13  
      1.1.2 Various applications of solar PV systems ................................................... 15  
      1.1.3 I-V and P-V characteristic of the solar arrays ............................................. 21  
   1.2 Modeling and simulation solar PV system under non-uniform shadow conditions ...................................................................................................................... 25  
   1.3 Methods to improve the performance of solar PV array under partial shadow conditions ...................................................................................................................... 29  
   1.4 Maximum power point tracking ......................................................................... 32  
   1.5 Conclusion/Summary of thesis contributions .................................................... 34  

2. Modeling and Simulation Solar PV Array under Shadow Conditions ..................... 39  
   2.1 Introduction ........................................................................................................ 39  
   2.2 Simulation of solar PV array under a passing cloud .......................................... 43  
   2.3 Comparison between the proposed numerical model and linear model ............. 57  
   2.4 Simulation solar array with and without bypass diodes ..................................... 58  
      2.4.1 With bypass diode ....................................................................................... 59  
      2.4.2 Without bypass diode .................................................................................. 59  
   2.5 Solar PV arrays of different configurations ....................................................... 60  
   2.6 Conclusions ........................................................................................................ 63  

3. Solar PV Array Shadow Evaluation using Neural Network ..................................... 64  
   and On- Site Measurement .......................................................................................... 64  
   3.1 Introduction ........................................................................................................ 64  
   3.2 Performance evaluation for solar PV systems .................................................... 65  
      3.2.1 Numerical method....................................................................................... 70  
      3.2.2 Photogram metric method ........................................................................... 70  
      3.2.3 Neural network method ............................................................................... 71  
      3.2.4 The combined method .................................................................................. 72  
   3.3 Proposed method ............................................................................................... 74  
      3.3.1 Shadow evaluation using neural network without shading factor measurement ............................................................................................................. 74  
      3.3.2 Experimental set up ..................................................................................... 79  
   3.4 Neural network structure .................................................................................... 80  
      3.4.1 Neural network structure ............................................................................. 80  
      3.4.2 Input signals correlation analysis ................................................................ 82  
      3.4.3 The learning process ................................................................................... 83  
      3.4.4 The generalization check .......................................................................... 85  
      3.4.5 The performance analysis of the network response .................................... 85  
      3.4.6 Analysis and discussion .......................................................................... 86  
   3.5 Conclusions ........................................................................................................ 87  

4. A Adaptive Reconfiguration of Solar PV Arrays ..................................................... 89  
   4.1 Introduction ........................................................................................................ 89
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 1.1</td>
<td>Global PV market growth</td>
<td>14</td>
</tr>
<tr>
<td>Fig. 1.2</td>
<td>Photovoltaic becomes competitive</td>
<td>15</td>
</tr>
<tr>
<td>Fig. 1.3</td>
<td>The small scale stand-alone solar photovoltaic systems</td>
<td>16</td>
</tr>
<tr>
<td>Fig. 1.4</td>
<td>The photovoltaic system with battery storage</td>
<td>17</td>
</tr>
<tr>
<td>Fig. 1.5</td>
<td>The building integrated solar PV systems</td>
<td>19</td>
</tr>
<tr>
<td>Fig. 1.6</td>
<td>Solar PV power plant</td>
<td>20</td>
</tr>
<tr>
<td>Fig. 1.7</td>
<td>Experimental I-V and P-V curve of solar PV arrays with different irradiation levels</td>
<td>23</td>
</tr>
<tr>
<td>Fig. 1.8</td>
<td>Shadow configurations</td>
<td>24</td>
</tr>
<tr>
<td>Fig. 1.9</td>
<td>Photovoltaic systems with parallel strings and central inverter</td>
<td>29</td>
</tr>
<tr>
<td>Fig. 1.10</td>
<td>Photovoltaic systems with a) String inverters b) Module inverters</td>
<td>30</td>
</tr>
<tr>
<td>Fig. 1.11</td>
<td>P&amp;O for Maximum power point tracking</td>
<td>32</td>
</tr>
<tr>
<td>Fig. 2.1</td>
<td>Solar PV array from sub-modules, controlled switches</td>
<td>45</td>
</tr>
<tr>
<td>Fig. 2.2</td>
<td>An equivalent circuit of a solar cell</td>
<td>45</td>
</tr>
<tr>
<td>Fig. 2.3</td>
<td>A solar cell with bypass diode</td>
<td>48</td>
</tr>
<tr>
<td>Fig. 2.4</td>
<td>Solar PV array’s common interconnections</td>
<td>50</td>
</tr>
<tr>
<td>Fig. 2.5</td>
<td>The non-uniform and changed irradiation is the effect of a passing cloud</td>
<td>51</td>
</tr>
<tr>
<td>Fig. 2.6</td>
<td>Output power of solar PV array simulation is based on two different methods</td>
<td>58</td>
</tr>
<tr>
<td>Fig. 2.7</td>
<td>The sub-module of solar PV array with bypass diode</td>
<td>58</td>
</tr>
<tr>
<td>Fig. 2.8</td>
<td>Output power of solar PV arrays with and without bypass diode</td>
<td>59</td>
</tr>
<tr>
<td>Fig. 2.9</td>
<td>Output power of solar PV array depends on interconnection</td>
<td>61</td>
</tr>
<tr>
<td>Fig. 2.10</td>
<td>The losses of maximum power depend on the shaded area. In SP one cell in each column is fully shaded. In TCT, one cell in the same row is fully shaded.</td>
<td>62</td>
</tr>
<tr>
<td>Fig. 3.1</td>
<td>Example of annually global (total) irradiance on a horizontal surface and ambient temperature</td>
<td>66</td>
</tr>
<tr>
<td>Fig. 3.2</td>
<td>Annual average values for system parameters at 187 Japanese field test sites for 4/1995-12/2001[1]</td>
<td>69</td>
</tr>
<tr>
<td>Fig. 3.3</td>
<td>The correlation between the optimal power current and short-circuit current</td>
<td>71</td>
</tr>
<tr>
<td>Fig. 3.4</td>
<td>The correlation between the optimal power voltage and open-circuit voltage</td>
<td>72</td>
</tr>
<tr>
<td>Fig. 3.5</td>
<td>The sun’s position at specific time at day</td>
<td>77</td>
</tr>
<tr>
<td>Fig. 3.6</td>
<td>The input and output signals measurement circuit</td>
<td>79</td>
</tr>
<tr>
<td>Fig. 3.7</td>
<td>Neural network’s structure</td>
<td>81</td>
</tr>
<tr>
<td>Fig. 3.8</td>
<td>The squared error of the training process</td>
<td>84</td>
</tr>
<tr>
<td>Fig. 3.9</td>
<td>The network performance analysis</td>
<td>86</td>
</tr>
<tr>
<td>Fig. 3.10</td>
<td>The measured and predicted output powers of solar PV arrays</td>
<td>86</td>
</tr>
<tr>
<td>Fig. 4.1</td>
<td>Shading by collectors in solar field</td>
<td>93</td>
</tr>
<tr>
<td>Fig. 4.2</td>
<td>I-V curves with different irradiance level</td>
<td>97</td>
</tr>
<tr>
<td>Fig. 4.3</td>
<td>Parallel arrangement</td>
<td>97</td>
</tr>
<tr>
<td>Fig. 4.4</td>
<td>Series arrangement</td>
<td>98</td>
</tr>
<tr>
<td>Fig. 4.5</td>
<td>Series-parallel arrangement</td>
<td>99</td>
</tr>
<tr>
<td>Fig. 4.6</td>
<td>I-V curves for PV with series-parallel arrangement of full sun</td>
<td>100</td>
</tr>
<tr>
<td>Fig. 4.7</td>
<td>Practical circuit of the proposed reconfiguration: For m rows in the fixed solar array, we proposed m solar cells in the adaptive bank</td>
<td>104</td>
</tr>
<tr>
<td>Fig. 4.8</td>
<td>The switching matrix</td>
<td>105</td>
</tr>
</tbody>
</table>
Fig. 4.9 The flow chart of the control algorithm for “Bubble - Sort” method ............... 107
Fig. 4.10 The flowchart of the control algorithm for Model-based method ............. 111
Fig. 4.11 Solar array’s reconfiguration under non uniform illumination ............... 115
Fig. 5.1 Solar PV array outdoor test platform ......................................................... 118
Fig. 5.2 Output voltage of solar PV array before and after reconfiguration in Two – Bubble Sort Experiments ........................................................................ 120
Fig. 5.3 Output voltage of solar PV array before and after reconfiguration in Two Model-Based Experiments ........................................................................ 120
Fig. 5.4 Output voltage of solar PV array before and after reconfiguration when solar adaptive bank is partly shaded ......................................................... 124
Fig. 5.5 Output voltage of solar PV array when the number of shaded fixed solar cells is larger than the number of solar adaptive bank ........................................ 124
Fig. 6.1 Traditional solar PV array MPPT based on Buck converter topology ......... 128
Fig. 6.2 The I-V and P-V curves before and after reconfiguration .............................. 130
Fig. 6.3 Proposed MPPT based on Reconfiguration converter ................................. 132
Fig. 6.4 Two solar PV submodules are connected in series when S is turned ON .... 132
Fig. 6.5 Two solar PV submodules are connected in parallel when S is turned OFF ... 133
Fig. 6.6 The voltage stresses of the main switches .................................................... 134
Fig. 6.7 The input voltage and output voltage relationship ....................................... 135
Fig. 6.8 The voltage stress of transistor in a) buck converter and b) Reconfiguration converter .......................................................................................................... 137
Fig. 6.9 The voltage stress of main diodes in a) Buck converter and b) Reconfiguration converter .................................................................................................. 137
Fig. 6.10 The inductor current ripple in a) Buck converter and b) Reconfiguration converter ................................................................................................. 138
Fig. 6.11 The input capacitor voltage ripple a) Buck converter with one C=100uF, Vin b) Reconfiguration converter with two C=100uF, Vin/2 ......................... 138
List of Tables

TABLE 2.1 The parameters of solar PV array for simulation ............................................. 57
TABLE 3.1 The correlation between the inputs signals ................................................... 83
TABLE 4.1 Comparison of the Reconfiguration Methods ............................................. 114
(m=rows, n=columns in fixed array) .............................................................................. 114
TABLE 6.1 Simulation parameters of conventional and proposed configuration........... 136
List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_M$</td>
<td>output current of solar module</td>
</tr>
<tr>
<td>$I_C$</td>
<td>output current of solar cell</td>
</tr>
<tr>
<td>$V_M$</td>
<td>output voltage of solar module</td>
</tr>
<tr>
<td>$V_C$</td>
<td>output voltage of solar cell</td>
</tr>
<tr>
<td>$I_{SCM}$</td>
<td>short-circuit current of solar module</td>
</tr>
<tr>
<td>$I_{SC}$</td>
<td>short-circuit current of solar cell</td>
</tr>
<tr>
<td>$R_{SM}$</td>
<td>series resistance of solar module</td>
</tr>
<tr>
<td>$R_S$</td>
<td>series resistance of solar cell</td>
</tr>
<tr>
<td>$R_{SHM}$</td>
<td>shunt resistance of solar module</td>
</tr>
<tr>
<td>$R_{SH}$</td>
<td>shunt resistance of solar cell</td>
</tr>
<tr>
<td>$a_a_1$</td>
<td>ideality factor of bypass diode</td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzman’s constant.</td>
</tr>
<tr>
<td>$T$</td>
<td>cell operating temperature</td>
</tr>
<tr>
<td>$q$</td>
<td>electron charge</td>
</tr>
<tr>
<td>$s$</td>
<td>number of solar cells per column of a module</td>
</tr>
<tr>
<td>$p$</td>
<td>number of solar cells per row of a module</td>
</tr>
<tr>
<td>$I_0$</td>
<td>saturation current of the diode</td>
</tr>
<tr>
<td>$I_{OBP}$</td>
<td>saturation current of the bypass diode</td>
</tr>
<tr>
<td>$A_{ij}$</td>
<td>vertical element $(i, j$ running position index)</td>
</tr>
<tr>
<td>$B_{ij}$</td>
<td>horizontal element $(i, j$ running position index)</td>
</tr>
<tr>
<td>$I_{A_{ij}}$</td>
<td>current at element $A_{ij}$</td>
</tr>
<tr>
<td>$I_{B_{ij}}$</td>
<td>current at element $B_{ij}$</td>
</tr>
<tr>
<td>$V$</td>
<td>total output voltage</td>
</tr>
<tr>
<td>$I$</td>
<td>total output current</td>
</tr>
<tr>
<td>$R$</td>
<td>load resistance</td>
</tr>
<tr>
<td>$V_{A_{ij}}$</td>
<td>voltage at element $A_{ij}$</td>
</tr>
<tr>
<td>$V_{B_{ij}}$</td>
<td>voltage at element $B_{ij}$</td>
</tr>
<tr>
<td>$m$</td>
<td>number of vertical elements of a column</td>
</tr>
<tr>
<td>$n$</td>
<td>number of horizontal elements of a row</td>
</tr>
<tr>
<td>$R_{ON}$</td>
<td>resistance of turned $ON$ switches</td>
</tr>
<tr>
<td>$R_{OFF}$</td>
<td>resistance of turned $OFF$ switches</td>
</tr>
<tr>
<td>$t_p, t_{1...10}$</td>
<td>instant of time</td>
</tr>
</tbody>
</table>
1. Introduction

1.1 Background

1.1.1 Photovoltaic becomes competitive

The recent increase of energy demand from Asian countries as well as the traditional high energy demand from industrial countries causes many undesirable effects:

- First, oil prices have doubled in the last five years, increasing from 44 USD/barrel in 2003 to over 100USD/barrel in the beginning of 2008. In addition, there is a forecast that fossil fuel will still be available in 2030, but there is a geographical imbalance between the energy supply and demand that will eventually lead to the exhaustion of fossil fuel [1].

- Second, greenhouse effects and environmental threats are arising from the production of electricity from fossil fuels. The climate changes can cause floods or dissertations over the world. With more lightly effects, the long dry periods will lower water levels in hydro-electric facilities and may cause instability of the main electricity supply source in many countries.

One solution to these problems is obvious, mass production and use of electricity generated from solar energy, which is environmentally friendly. Benefits of solar energy include clean energy production and inexhaustible supply of daylight. The solar photovoltaic (PV) systems can supply energy without moving parts, operate noiselessly and have minimum maintenance cost. A disadvantage is the high manufacturing cost
because the semiconductor materials used to convert the solar light into electrical energy are scarce.

![Global PV market growth](image)

*Fig. 1.1 Global PV market growth*

That being said, the cost trend of photovoltaic is downwards, while fossil fuel price are rising. The cost of PV modules and associated system components depend on developing mass production techniques and facilities. A growing and stable market of PV system is developing. Fig. 1.1 shows the previous data and prediction data of the global market of PV from 1990 to 2013. The total Mega Watt Power of global solar PV market is doubled for the period from 2005 to 2008 [3].

The study [3] indicates that the cost of electricity produced by PV could match the retail price the domestic consumers pay for electricity by 2020, when the price of the consumer electricity in Germany rise in average 2% per year. In sunnier countries like Spain, the
solar PV systems work more efficiently, the price of PV electricity in Spain could be
match the retail price in 2010, as shown in Fig. 1.2.

![Graph showing the price of PV electricity in Germany and Spain](image)

*Fig. 1.2 Photovoltaic becomes competitive*

### 1.1.2 Various applications of solar PV systems

A solar cell generates the DC current from sunlight. A solar array is created by
connecting individual solar cells together. The output current of a solar array depends on
solar insolation, the ambient temperature, the size and the configuration of the solar array.
In general, the larger area solar panels will produce more energy, and smaller solar panels
produce less.

The solar PV system can be used to supply DC power to load or can be connected
through DC-AC inverters to supply AC power to loads.
Here are some examples of Photovoltaic applications:

**Stand-Alone Systems**

There are widespread applications using small-scale solar arrays, such as data solar disks, calculators, solar powered LED lights, to solar powered speedometers in the highways, etc, see Fig. 1.3. These systems usually have small power range: from few microwatts up to few hundred watts. The output voltages are in the range of few volts to tents of volts. Typical solar panels weights only 3.66 mg per square millimeter allowing mounting on a near portable electronics or consumer products without exceeding size of weights limitations [2].

*Fig. 1.3 The small scale stand-alone solar photovoltaic systems*
Battery Storage

The output power of solar PV systems depends on solar insolation and varies with daytime. In the night, solar PV systems do not generate energy [3]. To stabilize the output power, sometimes, the solar PV systems are connected to some type of battery. It allows the solar charger to be in the sun. The energy from the sun is collected by the solar panel and converted into electricity and sent to the battery charger. The electricity is produced and then used to charge a battery. This way equipment can be powered later by battery indoors, on a rainy day, or at night.

a) Small solar photovoltaic cell with battery storage

b) Water pump system using large photovoltaic with battery storage

Fig. 1.4 The photovoltaic system with battery storage
Fig. 1.4 (a) shows that some solar battery chargers work with simple AA batteries, like those that used to run a flashlight. Some work with special batteries, which can in turn be used to charge other equipment like cell phones, solar calculators, speedometers in the highways, LED, etc. Some charge the batteries within the electronics equipment, such as the battery in a laptop computer.

In the rural, high mountainous and forest areas where the cost of building and distributing conventional sources of energy is very high, solar photovoltaic systems are used to charge large battery systems to produce power in the order of kilowatts. Fig. 1.4( b) shows the water pump in a rural area is powered by a large photovoltaic system using large battery storage. Thus, the type of solar battery charger that a person would use depends in a large degree upon what the solar charger will be used for.

**Building Integrated Photovoltaic (BIPV) system**

The battery storage will increase the total cost of the solar PV system. One popular solution is to connect the solar PV system directly to the utility grid. The equipment is powered by the grid whenever there is insufficient solar insolation and the photovoltaic complements the grid in “high-demand electricity” hours, reducing the need for increasing the main power plant size to meet the load demand.

Sometimes conventional building materials such as the roof, skylights, or facades are replaced by photovoltaic materials in parts of the building envelope. In particular, they are increasingly being integrated in the construction of new buildings as a principal or
ancillary source of electrical power. Other existing buildings may also be retrofitted with BIPV modules. By using integrated photovoltaic systems, the initial cost can be reduced by saving the building materials and labor that would normally be used to construct the part of the building that the BIPV systems modules replace. In addition, since BIPV systems are an integral part of the design, they generally blend in better and are more aesthetically appealing than other solar options. These advantages make BIPV one of the fastest growing segments of the photovoltaic industry [3].

![Fig. 1.5 The building integrated solar PV systems](image)

**Utility Power Production**

Large-scale photovoltaic power plants can generate a wide range of powers up to few megawatts that can supply enough electricity for some thousand houses, as shown in Fig. 1.6.
Actually, solar arrays can be connected into standard modules, which consist of many PV arrays working together. Then these modules can be connected in parallel to generate required power. Because PV arrays are fairly easy to install and connect, there are many advantages of solar PV to utilities in comparison with other kind of power plants. Firstly, the solar PV plants can be built more quickly than conventional fossil or nuclear power plants as demand of electricity increase over planning. Because of unequal load demand of distributed electrical system, the PV power plants can be built where they are most needed in the grid. PV power plants consume no fuel and produce no air or water pollution while they silently generate electricity. So, they can be located in or very close to the population while meeting local environmental regulations.
And, unlike conventional power plants, modular PV plants can be expanded incrementally as demand increases. This makes PV power an attractive option for utilities that want or need to cut fuel costs [6].

1.1.3 I-V and P-V characteristic of the solar arrays

Fig. 1.7 shows the current versus voltage and power versus voltage for two different solar PV arrays: Global P3-30W and UNI-solar 15W taken in under indoor laboratory conditions. The artificial light source is the four 500W halogen lamps. From the above I-V and P-V curves, we can notice that:

- The performance of a solar PV array strongly depends on the irradiation levels.
- While the performance specifications of solar cell modules are available, the data provided for these arrays do not accurately reflect the amount of electric power that may be generated from the solar panel at time of use, i.e. these experimental results differ significantly than the characteristics provided by the manufacturer.
- I-V and P-V curves have strong non-linear characteristics.
- The output power and I-V curve of a solar panel vary significantly (in shape and power) depending on “the manufacturer”.

Current versus voltage characteristics of the solar cells are non-linear, thus leading to technical control challenges. In the first order approximation, output power of a solar array is proportional to the irradiance of sunlight.
a) V-I curve for Global P3-30 solar array

b) V-I curve for Unisolar 15W solar array
c) P-V curve for Global P3-30 solar array

d) P-V curve for Unisolar-15W solar array

Fig. 1.7 Experimental I-V and P-V curve of solar PV arrays with different irradiation levels.
However, in many applications, such as solar power plants, building integrated photovoltaic or solar tents, the solar photovoltaic arrays might be illuminated non-uniformly. The cause of non-uniform illumination may be the shadow of clouds, the trees, booms, neighbor’s houses, or the shadow of one solar array on the other, etc. This further leads to nonlinearities in characteristics.

![Shadow on portable solar array](image1.png)  ![Shadow from one array cast on another array](image2.png)

Fig. 1.8 Shadow configurations

For example, Fig. 1.8(a) shows a portable, flexible solar array that is embedded into fabric. These new generation solar arrays can be folded and carried by campers and soldiers to remote locations. Often, they are left alone to charge batteries near trees, fences, and have been reported to even be wrapped around telephone poles or trees [7].

Furthermore, for applications like BIPV and solar power plants in small spaces, as shown in Fig. 1.8(b), shadows from one solar PV array are commonly cast on another array. In conventional solar PV plants, the designer must solve the complex problem, the tradeoff between “maximum energy output” and “minimum produced energy cost” by varying the distance between the rows [8], [9].
For these new applications, it has been especially important to optimize performance of the arrays in shadowed conditions. Because of the nature of the electrical characteristics of solar cells, the maximum power losses are not proportional to the shadow, but magnify nonlinearly [10].

The shadow of solar PV array can cause many undesired effects:

- The real power generated from the solar PV array is much less than designed, so that the loss of load probability increases [11].
- The local hot spot in the shaded part of the solar PV array can damage the solar cells. The shaded solar cells may be work on the negative voltage region and become a resistive load and absorb power. Bypass diodes are sometimes connected parallel to solar cells to protect them from damage. However, in most cases, just one diode is connected in parallel to a group of solar cells [12] and this hides the potential power output of the array.

1.2 Modeling and simulation solar PV system under non-uniform shadow conditions

There are also other undesired effects of the shadows on solar PV arrays other than power drop. Dynamic modeling of the effect of clouds on solar array is a difficult task. Cloud conditions can dramatically change fast and the cost of such fluctuations with their effect on other systems is important to understand.
One method proposed by [17] measures the changes in solar insolation over a one minute time interval. With this method, solar insolation values may be measured in the horizontal plane and subsequently used to calculate insolation levels for any desired angle [18].

There have also been attempts to predict the solar PV array output power in clouds. An estimation method used in [18] proposes that the power output of a PV system is proportional to the insolation levels measured for the surface of a solar cell at any angular position. However, the output power of a solar array not only depends on changes in irradiance values, but also depends on other factors such as the interconnection of the individual solar cells, solar cells parameters, and the use of bypass diodes [19], [20]. Thus this modeling approach is not complete, and one goal of this thesis is to make improvement on it.

A shadowed solar cell acts like a load because it dissipates input current. In the presence of shadows, where there is no exposure to sunlight, a solar cell will heat up and develop a hot spot. To reduce the overall effect of shadows, bypass diodes are sometimes connected across shadowed cells to pass the full amount of current while preventing damage to the solar cell [12]. Thus, predicting the electrical characteristics of a solar PV array when experiencing passing clouds is more complex.
Mathematical models [19], [20] have been used to accurately characterize the electrical solar PV arrays. In [21] the effect of non-uniform illumination is considered on various configurations of solar PV arrays without a bypass diode.

The first objective of this project is to propose a modeling and computing algorithm that greatly expands on the ideas in [19], which simulates and analyzes the effect of non-uniform changing shadows (i.e. a passing cloud) on the output power of solar PV arrays. Our model will be able to determine the power losses in each solar cell and the collective hot spots of an array.

In order to include the effects of shadowing on solar PV arrays, conventional methods use an approach to determine the “shading factor,” which is defined as the ratio of the non-shaded area to the total area of the solar arrays.

In real operating conditions, solar PV arrays are connected with Maximum Power Point Trackers (MPPT) to track maximum output power. The MPP is often assumed linearly proportional to solar irradiance. So shading factors also can be used to calculate MPP power of shaded solar PV arrays. In reality, it is difficult to accurately estimate this shading factor because shadows change their shape and move with time.

This leads to several approaches to evaluate the shadow effects on those solar PV arrays:

- In the numerical method, the solar irradiance on all solar cells is modeled based on real time input data. The output power of the solar PV array at a given output
voltage is then received by solving differential equations on small time-scales (second, minutes) [19], [20]. This method requires unrealistic number of sensors to measure the irradiance in each solar cell. Furthermore, accurate prediction of the maximum output power of solar PV systems for long term (days, months, years), is more challenging, due to difficulties in modeling the shaded area in the solar PV systems.

- In the photogrammetric method, the position of obstacles and their shadow are estimated by using the triangulation with two photographs or more [21].
- Neural network method is used in [22], [23], [25] for predicting the dependence of maximum output power of solar PV arrays on environmental factors. However, these papers focus on estimating the performance of solar PV arrays under uniform illumination.
- In the combined method, the neural network prediction model uses training data created by the numerical method. The low accuracy is due to the low accuracy of the modeling shadow objects [26].

From the above discussion, there is not a simple and accurate method to define the shadow effects on shaded solar PV array for long term (seasonal or annual) in non-uniform illumination.

This thesis proposes a novel method to define the function of relationship between the maximum output power (MPP) of the shaded solar PV array and the environmental factors, such as the solar irradiation levels, the sun’s position angles and the ambient
temperature. This function, which is similar to the shading factor, can fully characterize
the shadow effects on the solar PV array for long term and is called the shading function.
As such, the shading function can eliminate the inaccuracy caused by the complexity of
the shading factor’s calculation.

1.3 Methods to improve the performance of solar PV array
under partial shadow conditions

Fig. 1.9 Photovoltaic systems with parallel strings and central inverter
Fig. 1.10 Photovoltaic systems with a) String inverters b) Module inverters
Fig. 1.9 shows a photovoltaic system with parallel strings and central inverter.

Solar cells PV$_1$, PV$_2$, ..., PV$_n$ are connected in parallel and/or series to create the solar submodule and/or strings. Photovoltaic inverters convert the dc voltage from solar arrays to ac voltage of a grid. The maximum power point (MPP) voltage of the solar array is different from the grid voltage, so the DC-DC converter (MPPT) usually is integrated in photovoltaic inverters [42].

For partly shaded solar arrays, or modules with different power outputs, the system with central inverter may have high losses, the parallel connection of string inverters or module inverters can reduce the losses [31], [32], [33]. Fig. 1.14 shows photovoltaic systems with two different classifications of inverters.

An emerging research field, and the part of this research thesis, is to adaptively reconfigure solar array connections in real time in order to track maximum output power. Traditionally fixed solar PV arrays have hard wired interconnections between their solar cells. These connections are not changed after installation. However, it is possible to continuously rearrange solar cells in series and parallel connections [34] to facilitate the photovoltaic system to work more as a constant power source even in different operating conditions, i.e. insolation, temperature, loads,...etc. Recent research studies in [35], [36] have started to develop methods to reconfigure solar cells to improve power output in shaded conditions.
The research of [35][36] focuses mostly on how to build the arrays, and does not propose real-time implementable control algorithm. Because of this, the methods proposed have unrealistic number of switches and sensors that must use complex control algorithms to determine when it turns the switch ON or OFF. Thus, there is a real need for more research to develop reconfigurable solar array that can actually be built.

### 1.4 Maximum power point tracking

The general idea of MPPT is that a solar panel behaves similarly to a nonlinear current source that has maximum power at a specific output voltage for each environmental condition (temperature, illumination, etc.) [37]. By inserting a DC-DC converter between the solar array and the load, it is possible to adjust the duty ratio of the converter to match the impedance of the array to the load, producing the maximum output power of the array.

![Fig. 1.11 P&O for Maximum power point tracking](image)

Several methods are utilized to achieve peak tracking of the solar PV array’s power [29]:
• In the Perturb & Observe method, the output power is measured and the duty ratio in a converter is changed. The duty ratio decreases when the output power of the array decreases. If the power increases, the direction is reversed. When the output voltage of the solar array changes around its MPP point, the duty ratio then fluctuates between positive increments and negative increments.

• There is another method that has a similar effect called Incremental Conductance. Sometimes the MPP point is estimated based on a solar panel’s open circuit voltage and/or short circuit current. However, this method is dependent on the PV array’s technology.

• In the conventional methods, the main assumption is that the solar PV system is uniformly illuminated. The remaining task of this research is to develop the topology that is able to track more power from non-uniformly illuminated solar PV systems. All these topologies can be derived from the basic canonical switching cell.

The large difference between the input and output current or voltage in each period/cycle will require the large energy storage elements (L and C). The size of the DC-DC converters strongly influenced the size of the energy storage elements.

In the above topologies, the buck converter has the smallest voltage stress and energy storage elements.
This thesis proposes a new topology based on Buck topology that is able to reduce the voltage stress of the main switches to half of the input voltage.

1.5 Conclusion/Summary of thesis contributions

This proposed research will focus on the modeling, development, and design of an adaptable solar array and system that is able to optimize power output, reconfigure itself when solar cells are damaged and create controllable output voltages and currents.

This study proposes a technological advancement over the existing technology of solar PV arrays. Presently solar arrays are fixed arrays that require external device to control their output. In this research, the solar array will be able to self-reconfigure, leading to the following advantages:

- Higher efficiency because no external devices are used.
- Maximum possible output power that is much higher than the maximum power of fixed solar arrays by arranging the solar cells in optimized connections.
- Elimination of hot spot effects.

The proposed research has the following goals: First, to create a modeling and computing algorithm, which is able to simulate and analyze the effects of non-uniform changing shadows on the output power of solar PV arrays. Our model will be able to determine the power losses in each solar cell and the collective hot spots of an array. Second, to propose new methods, this will predict the performance of solar PV arrays under shadow conditions for long periods of time (days, months, years). Finally, the thesis develops
adaptive reconfiguration algorithms to reconfigure connections within solar PV arrays in real time, under shadow conditions, in order to optimize output power. Alternatively, the reconfiguration algorithms can be used to improve performance when cells are damaged. The objectives are described in more detail in the followings

**Objective 1**

*Create a modeling and computing algorithm capable of accurately predicting the effects of non-uniform changing shadows, e.g., i.e. a passing cloud or a tree’s shadow on the output power of solar PV arrays.*

Chapter 2 develops a model that is able to determine the power losses in each solar cell and the collective hot spots of an array. The proposed procedure of modeling and simulation of solar PV array is the following:

First, when an accurate model is created for each solar cell, the proposed method will be able to define the parameters of the model for solar cells. Then, the model for horizontal elements in the network (the connection elements between solar cells) is created and the parameters of the horizontal elements are defined. Second, a system of equations between loops and nodes of the array is developed by using Kirchoff’s laws. The system of equations is solved by the Newton-Raphson method. Last, the proposed model is used to simulate the electrical behavior of the solar PV array under certain environmental factors: solar irradiance, temperature, and loads. The proposed model is applied to check the shadow effects on the solar PV arrays with different configurations. The accuracy of the proposed model with other conventional models is compared.
Objective 2

*Propose methods using neural networks that are able to predict the shadow effects on the solar PV arrays with low computational efforts.*

Chapter 3 develops a neural network method, combining the multilayer perceptrons feed-forward network with a back-propagation algorithm, to accurately predict maximum output power of solar photovoltaic arrays under shadow conditions. Using the solar irradiation levels, the solar photovoltaic array’s temperature, and the sun’s position angles as the input signals, and the maximum output power of the solar PV array as an output signal, the training data for the neural network is collected by one-day on site measurement. After training, the neural network model’s accuracy and generalization will be verified by using test data. The goal is to have the model to predict the shadow effects on solar PV arrays for long periods of time (days, months, years) with low computational efforts. The proposed method is able to define the main factors that influence the output power of the solar PV array under shadow conditions. The simple measurement procedure for each factor is described.

The appropriate neural network structure for this data is chosen. The random procedure to obtain the training data set and the test data set is described. The function of the relationship between the inputs and outputs from the training data set is derived. Last, the accuracy of the model is tested with the test data set. Thus, the function can be used to predict the output power of a solar PV array with the new input data set.
Objective 3

*Develop adaptive reconfiguration algorithms to reconfigure connections within solar PV arrays in real time, under shadow conditions, in order to optimize output power.*

Chapter 4 proposes to connect matrix switches between a “solar adaptive bank” and a standard TCT fixed solar PV array. Various control algorithm approaches are derived so the solar PV array reconfigures to produce optimal power. Control algorithms are implemented in real-time. Simple “bubble-sort” as well as model based control algorithm will be investigated. The method to measure the shadow patterns in the solar PV array with the smallest number of voltage sensor is described. The method also proposes the configuration that is most suitable to compensate the shaded cells by reconfiguration. Control algorithms for reconfiguration solar array first time (as our knowledge) are proposed.

Objective 4

*Validate all new models and reconfiguration algorithms in a small scale solar PV prototype system.*

Chapter 5 propose the procedure to build an experimental test bed with 10-15 solar cells and their necessary switch connections needed to test the reconfiguration algorithms in Objective 3. The tests with different shadow patterns and with each reconfigurable control algorithms derived. The advantages and disadvantages of proposed reconfiguration methods are derived.
Objective 5

*Develop an approach for solar array operation that merges features of external power electronics devices to be within the solar array itself. Next generation topology is proposed to continuously rearrange the two identical solar submodules in series and parallel connections by using high frequency switches to facilitate the photovoltaic system to work more as a constant power source in even in different operating conditions (i.e. irradiance, temperature, loads,...etc). The output of the solar PV array will be connected to the load through a high frequency filter without MPPT.*

Chapter 6 develops a class of DC-DC converter where the voltage stresses of the main switches will be reduced to a half of the input voltage, when the input sources are solar arrays. The difference between input and output voltage or current for each cycle will be reduced so that the size of storage elements (L and C) will be smaller in comparison with conventional topologies. A simulation reconfiguration PV system with the battery load is presented and is shown to verify the proposed topology. Chapter 6 will describe the proposed scheme in detail.
2. Modeling and Simulation Solar PV Array under Shadow Conditions

2.1 Introduction

As introduced in the Abstract, this thesis focuses on the research of two dominant fields of solar PV system: (1) modeling and simulation solar PV array under shadow conditions and (2) reconfiguration solar PV arrays to improve their performance under shadow conditions. This Chapter mainly discusses the modeling and simulation of solar PV systems under changing shadow conditions, a passing cloud.

Modeling and simulation solar PV arrays are important tasks in the design of solar PV system. The designs of solar PV system need to meet the demands with the consideration of applicable restrictions. The most important demand is the energy used per year, day and hour of the user. The restrictions may include the land area, the solar irradiation availability, the ambient temperature, the availability of the solar PV products in the market… etc.

The design of a solar PV system includes understanding the environmental effects on performance, and in particular the output power of the array under various shading conditions.

The solar cell is the semiconductor device that directly converts the light energy to the electrical energy. A solar cell has nearly the same behavior as a diode. Specifically, the
output power of a solar array strongly depends on the irradiance level of sunlight and ambient temperature. The most conventional model of a solar cell is the one diode model [37].

Because of low output current and output voltage of solar PV cell, in practice, solar cells are connected in series and/or in parallel to create a solar PV array that is able to meet the output voltage and/or output current requirement. In uniform illumination, the output power of the array is equal the total output power of all solar cells. It can be simply calculated by the multiplying the output power of one solar cell to the total number of solar cells in the array.

But, in some applications, such as solar power plants, building integrated photovoltaic systems (BIPV), and portable solar tents, it is common for the solar PV to become illuminated non-uniformly. The cause of non-uniform illumination may be shadows from: trees, booms, a neighbor’s houses, or even a shadow of one solar array to the other one.

The real power generated from the solar PV array may become significantly less than designed. At times, this may lead to a complete “loss of load”. A shadowed solar cell acts like a load because it dissipates input current. In the presence of shadows, where there is no exposure to sunlight, a solar cell will heat up and develop a hot spot. The local hot spot in the shaded parts of the solar PV array can damage the solar cells, and there can be a long-term decrease in annual system performance due to shading. To reduce the overall effect of shadows, bypass diodes are connected across shadowed cells to pass the
full amount of current while preventing damage to the solar cell. Thus, predicting the electrical characteristics of a solar PV array under non-uniform shadow conditions is more complex. It is vital to understand this prior to installation in order to effectively determine whether the system is sufficiently cost efficient enough to install [38].

There are also other undesired effects of the shadows on solar PV arrays other than power drop. Dynamic modeling of the effect of clouds on solar arrays is a difficult task. Cloud conditions can change fast dramatically and the cost of such fluctuations with their effect on other systems is important to understand.

One method proposed by [17], [39] measures the changes in solar insolation over a one minute time interval. With this method, solar insolation values may be measured in the horizontal plane and subsequently used to calculate insolation levels for any desired angle [18].

There have also been attempts to predict the solar PV array output power in clouds. An estimation method used in [18] proposes that the power output of a PV system is proportional to the insolation levels measured for the surface of a solar cell at any angular position. However, the output power of a solar array not only depends on changes in irradiance values, but also depends on other factors such as the interconnection of the individual solar cells, solar cells parameters, and the use of bypass diodes [19], [20]. Thus this modeling approach is not complete, and one goal of this research is to make improvement on it.
Mathematical models [19], [20] have been used to accurately characterize the electrical solar PV arrays. In [20] the effect of non-uniform illumination is considered on various configurations of solar PV arrays without a bypass diode.

This research propose a modeling and computing algorithm that greatly expands on the ideas in [19], which simulates and analyzes the effect of non-uniform changing shadows (i.e. a passing cloud) on the output power of solar PV arrays. The model will be able to determine the power losses in each solar cell and the collective hot spots of an array.

Specifically, our model has the following advantages:

- Creates an accurate model for each solar cell: The users can define the parameters of the model for solar cells for different type of solar cells.

- The model is applicable for any configurations of solar PV arrays: By modifying models for horizontal elements in the network (the connection elements between solar cells), define parameters of the horizontal elements: the wires and/or the switches.

- After inputting known parameters a system of equations between loops and nodes of the array, using the Kirchoff’s laws is created automatically: The Newton-Raphson method is applied for solving the system of equations. So, the simulation converges fast and accurately.
The proposed models can be used to simulate the electrical behavior of the solar PV array for different changing environmental factors: solar irradiance, temperature and load. The proposed model also is able to check the shadow effects on the solar PV arrays with different configurations. This model shows the higher accuracy in comparison with other conventional models.

### 2.2 Simulation of solar PV array under a passing cloud

From discussion in the Section 2.1., the modeling and simulation of solar PV systems are simple task under uniform irradiance level.

In non-uniform illumination conditions, when the solar cells are illuminated differently, the solar array is modeled as a network in Fig. 2.4 from vertical elements (solar cells) and horizontal elements (connectors, diodes).

The proposed model has the following advantages:

- Able to simulate all common types of solar PV cells and modules in the market, by inputting the solar cells parameters from manufactures or by curve fitting.
- Able to simulate solar PV system consisting from different types of solar cells or solar submodules.
- Able to simulate solar PV systems under non-uniform illumination with different shadow’s shapes or shadow’s moving direction.
• Converge fast enough.

Detailed analysis for modeling and simulation solar PV array under shadow conditions is provided in the below description. The following procedure is proposed for simulating a solar PV array under a passing cloud in MATLAB.

**Step 1**

The solar PV array is modeled as a matrix with dimension (m x n): m represents the number of solar cells connected in a series string, while n represents the number of strings connected in parallel. Fig 2.4 shows the two common solar PV array configurations that utilize the combinations of the connections. In this figure, each PV(i, j) is an individual solar cell. By inputting different solar cell’s parameters, we can model the solar arrays from the same kind of solar cells or the solar arrays from different kinds of solar cells.

The solar cells are connected in series and parallel to create a solar array. Fig. 2.1 shows a solar array: all the vertical components are solar cells or modules and all horizontal components are controlled switches.

By turn ON and turn OFF the horizontal switches B (i,j) we have different common configuration of solar PV array: the series-parallel configuration and total-cross-tied configuration.
**Modeling solar cells, the vertical elements of solar array**

The classical one diode model of a solar cell is shown in Fig. 2.2

The current source generates the photocurrent ISC, which is linearly proportional to the solar irradiance level.
The current goes through the solar cell diode varies with the junction voltage and the solar cell reverse-saturation current $I_0$. The series resistance of solar cell $R_S$ – characterize the voltage drop when the charge carries through the semiconductor junction to the external load. Series resistance of solar cell is small. The shunt resistance of solar cell $R_{SH}$ is large. The shunt resistance describes the leakage currents at the cell edges.

The relationship between the output current and output voltage of the solar cell is given by:

$$I = I_{PH} - I_0 (e^{V/R_T} - 1) - \frac{V + IR_S}{R_{SH}}$$  \hspace{1cm} (2.1)

Here, $I_{PH}$- Photo generated current proportional to illumination.

The threshold voltage of solar cell is defined by:

$$V_T = \frac{AKT}{q}$$  \hspace{1cm} (2.2)

Here
- $A$ is ideality factor;
- $K$ is Boltzman constant;
- $q$ is electron charge;
- $T$ is the solar cell temperature (K degree).

To simulate the characteristic (I-V curve) of a solar cell, the parameters $R_S$, $R_{SH}$, $I_0$ and $A$, have to be known. By changing environmental factors: solar irradiation levels and solar cell temperature, we can have the curves of different weather conditions.
Solar cell parameters approximation

For the simulation of a real solar cell, the parameters of solar cell or solar submodule are received by I-V curve fitting approximation from manufacturer’s datasheet. This I-V curve is received in standard test condition (STC) and the parameters of a solar cell will be changed in the real working conditions.

For more accurate approximation, [27] proposes method to extract the solar cell’s parameters based on experiment over wide range of operating conditions. The I-V curve of a solar PV cell is received by 300 measurements of the output current and output voltage over a wide range of solar irradiance level, ambient temperature and varied load.

After that, the parameters of solar cell and photo generated current in Eq. (2.1) are transformed to the coefficients a, b, c, d, f, according the following transformations:

\[
I_{ph} + I_s = a, \quad I_s = -b, \quad \frac{q}{A k T} = c, \quad \frac{q R_s}{A k T} = d, \quad R_{sh} = f
\]

This leads to the following simpler equation:

\[
I = a + b \times \exp(c U + d I) - (U + d I / c) / f \tag{2.2}
\]

The coefficients a, b, c, d and f are received by curve fitting the I-V curve received from the described experiment. The physical knowing the parameters quantities IPH, IS, n, RS, and RSH are found:
\[ I_{PH} = a + b, \quad I_s = -b, \quad \frac{q}{c k T} = A, \quad R_s = \frac{d}{c}, \quad R_{SH} = f \]

**Solar cell with bypass diode model**

![Solar cell with bypass diode diagram](image)

Fig. 2.3 A solar cell with bypass diode

Fig. 2.3 shows a solar cell with bypass diode. A shadowed solar cell acts like a load because it dissipates input current. In the presence of shadows, where there is no exposure to sunlight, a solar cell will heat up and develop a hot spot. To reduce the overall effect of shadows, (by creating low reverse breakdown voltage for a solar cell), bypass diodes are sometimes connected across shadowed cells to pass the full amount of current while preventing damage to the solar cell.

The relationship between the output current and output voltage of the solar cell with bypass diode is given by:

\[
I = I_{PH} - I_0(e^{\frac{V+I_{sh}}{V_T}} - 1) - \frac{V + IR_s}{R_{SH}} - I_{bypass}\left(e^{\frac{-V}{V_T}} - 1\right)
\]  

(2.3)
where, \( I_0 \) is the reverse-saturation current of the solar cell, \( I_{BYPASS} \) the saturation current of bypass diode.

_Modeling horizontal elements, the wires or switches_

In the above equation, \( R_{Bi,j} = R_{ON} \) if the relays are turned ON, \( R_{Bi,j} = R_{OFF} = 10^{30} \Omega \) if the relays are turned OFF.

_Different configurations of solar PV arrays and the maximum power losses of the shadow_

Fig. 2.4 shows the two common solar PV array configurations that utilize the combinations of the connections. In this figure, each PV(i, j) is an individual solar cell. The solar cells are connected in series and parallel to create a solar array.

_Simple series-parallel (SP) array: if all switches are OFF_

When all solar cells, for example, PV1,1, PV2,1, …, PV\(_{m-1,1}\), PV\(_{m,1}\), are connected in series creating strings. Then all these strings are connected in parallel, as shown in Fig. 2.4 (a).

_Total-cross-tied (TCT) array: if all switches are ON_

When all solar cells are connected in parallel, for example PV1,1, PV1,2, …, PV1,n-1, PV1,n creating modules. Then these modules are connected in series, as shown in Fig. 2.4 (b) [15].
Fig. 2.4 Solar PV array’s common interconnections
**Fig. 2.5** The non-uniform and changed irradiation is the effect of a passing cloud

**Step 2**

*Model a passing cloud*

The shadow of a passing cloud (and/or a tree’s shadow, boom’s shadow) will reduce current, resulting in non-uniform irradiance to solar PV array. The change of irradiance will change the short-circuit currents and open-circuit voltages of each cell. In this case we assume that the parameters and temperature of the solar cells are unchanged. The user specifies the ratio of the irradiance in each solar cell at each instant of time \((t_1...t_{10})\) according to irradiance standards (STC).
To simulate a moving cloud, we must first determine the distance, $D_{i,j}$, between the solar cell with index $i, j$ at instant of time $t_p$ and the center of a cloud. It can be defined by the following equation:

$$D_{i,j} = \sqrt{(i-t_p \times v)^2 + (j-t_p \times v)^2}$$  \hspace{1cm} (2.4)

Realizable values for the ratio of the irradiance in each solar cell will range from 0 to 1, and can be specified using the nominal distribution function in the following equation:

$$\frac{I_{SCE_i,j}}{I_{SCE_0}} = 1 - 4 \times e^{-\frac{(n_{i,j}-\mu)^2}{2\sigma^2}}$$  \hspace{1cm} (2.5)

where, ISC0 is the sort circuit current of the non-shaded solar cell and ISC{i,j} are short circuit current of the solar cell (i,j), $\mu$- is the mean, $\sigma$ – is the standard deviation.

In general, the two above equations model the cast of a moving shadow on a solar PV array for instant of time ($t_1 \ldots t_{10}$). The cloud is moving with the speed ($v=1$ solar cell/one second). The cloud is most darkness in the center and brighter in the bounds. For purpose of illustration, we will simulate as an example the followings: at the start point ($t_1$) the center of the cloud falls in the lowest left solar cell. At the end point ($t_{10}$) the center of the cloud falls in the highest right side solar cell.

The irradiance is approximately proportional to the short- circuit current, so that the effect of a passing cloud to a solar array may be modeled as the change of short circuit current through all elements of m x n matrix. Fig. 2.5 illustrates the graphical output of the MATLAB program. The resulting irradiation on each individual solar cell (10x10 cells in this example) represents a passing cloud.
Step 3

Inputting the irradiance data

Inputting the irradiance data \((I_{SC,i,j}, V_{OC,i,j})\) from Step 2, the numerical method of [5] (in MATLAB) can be used to determine the total current \(I\), sub-voltages \(U\) and sub-currents for each cell. In this method, Kirchhoff’s laws are applied to provide a system of equations relating all currents and voltages in the network. Each element has to be described by the mathematical relationship between current and voltage. The Newton-Raphson method is used to calculate the solution for the systems of equations.

Newton-Raphson numerical method [13].

In order to simulate the solar cell I-V curve for each specific solar irradiance level and ambient temperature, the current \(I\) must be computed individually for each given voltage \(V\).

To determine the characteristic curve numerical methods are normally used because of the non-explicit form of the equation of the solar cell curve. An equation for the solar cell is given in equation (2.1). For a given voltage \(V\), the current \(I\) is given by the root of equation (2.1), where \(I\) is expected to be a single root. In order to determine the single root, it is suggested to use the Newton-Raphson method. By using the first few terms of the Taylor series of a function \(f(x)\) in the vicinity of a suspected root this method has the following procedure to find a root.
The \( f(I) \) about the point \( I = I_0 + \varepsilon \) is presented in the Taylor series by:

\[
f(I_0 + \varepsilon) = f(I_0) + f'(I_0)\varepsilon + \frac{1}{2} f''(I_0)\varepsilon^2 + \ldots
\]

Using two terms only to first order,

\[
f(I_0 + \varepsilon) = f(I_0) + f'(I_0)\varepsilon
\]

Starting from an initial guess \( I_0 \), this expression can be used to estimate the amount of offset \( \varepsilon \) needed to land closer to the root, Setting \( f(I_0 + \varepsilon) = 0 \) and solving (2.1) for \( \varepsilon = \varepsilon_0 \) gives

\[
\varepsilon_0 = -\frac{f(I_0)}{f'(I_0)}
\]

which is the first-order adjustment to the root's position. By letting \( I_1 = I_0 + \varepsilon_0 \) a new \( \varepsilon_1 \) can be calculated. The offset in the \( n \) is:

\[
\varepsilon_n = -\frac{f(I_n)}{f'(I_n)}
\]

The algorithm can be applied iteratively to obtain

\[
I_{n+1} = I_n - \frac{f(I_n)}{f'(I_n)}
\]

For \( n=1, 2, 3, \ldots \), an initial point \( I_0 \), the process can be repeated until it converges to a fixed point, which is precisely a root.
This procedure can be unstable near a horizontal asymptote or a local extreme but it can be prevented a good initial choice of the root's position.

**System of equations for solar PV array**

The controlled switches shown in Fig. 2.4 may be relays or transistors; their switching action is described by the following equation:

\[
V_{Bi,j} = I_{Bi,j} \cdot R_{Bi,j}
\]  

(2.6)

Equation (2.6) has the form:

\[
f(I_{Bi,j}, V_{Bi,j}) = 0
\]

(2.7)

When a solar panel contains a large number of solar cells, computational time may be reduced by dividing the solar panel into modules. Assume that each module is uniformly illuminated. Each vertical element in Fig. 2.4 is a solar module, made up of (m x n) solar cells and protected by bypass diodes as shown in Fig. 2.7. Assume that all solar cells are illuminated by the same irradiance. In this case, the equation for the vertical components will be the following:

\[
f(I_M, V_M) = \frac{I_{SCM}}{pI_0} \left[ \exp \left( \frac{q(V_M + I_M R_{SM})}{sakT} \right) - 1 \right] \\
- \left( \frac{V_M + I_M R_{SM}}{R_{SHM}} \right) - I_M + I_{GBP} \left[ \exp \left( \frac{-qV_M}{a_1 kT} \right) - 1 \right] = 0
\]

(2.8)

$$I_M = pI_C, V_M = sV_C, I_{SCM} = pI_{SC}, R_{SM} = \frac{sR_S}{p}, R_{SHM} = \frac{sR_{SH}}{p}$$

The last component in (2.8) is the equation for the bypass diode. In this case, the bypass diode is connected in parallel to the whole module of the solar array and the irradiance of each instant of time ($t_1 \ldots t_{10}$)

The relationship between the current and voltage of the solar panel has the following form:

$$f(I_{Ai,j}, V_{Ai,j}) = 0 \quad (2.9)$$

From (2.8) and (2.9) we can define $\frac{df(V)}{dV}$ for each element of the solar PV array. Using MATLAB command in Appendix A, we can solve system of non-linear equations.

*Step 4*
Graphically display the influence of a passing cloud on the output power. Based on this curve, we can predict the maximum, minimum and average electrical power generated from a solar PV array for non-uniform and variable irradiance using MATLAB.

### 2.3 Comparison between the proposed numerical model and linear model

The proposed model is applied to simulate the solar PV array with the input data as shown in Table 2.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of solar cells</td>
<td>m x n</td>
<td>10x10</td>
<td></td>
</tr>
<tr>
<td>Series resistance</td>
<td>R_S</td>
<td>0.1</td>
<td>Ohm</td>
</tr>
<tr>
<td>Parallel resistance</td>
<td>R_SH</td>
<td>52</td>
<td>Ohm</td>
</tr>
<tr>
<td>Saturation current of solar cell diode</td>
<td>I_S</td>
<td>3.4e-07</td>
<td>A</td>
</tr>
<tr>
<td>Ideality factor</td>
<td>A</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>Cell temperature</td>
<td>T</td>
<td>25</td>
<td>°C</td>
</tr>
</tbody>
</table>

Fig. 2.6 shows the output power of a solar PV array for shadow conditions simulated by the linear approximation method, which assumes that the output power of solar PV array proportional to average irradiance level, and the numerical method.
2.4 Simulation solar array with and without bypass diodes

Using the above simulation methods, we can compare the simulated output powers of the solar PV array with and without bypass diode.

Fig. 2.7 The sub-module of solar PV array with bypass diode
2.4.1 With bypass diode

Assume that we have a solar module that is composed of solar cells, where each one is protected by a bypass diode. When current goes through a bypass diode, the solar cells that are in parallel (i.e. in the same row) will be shorted. The remaining solar cells will operate normally.

![Fig. 2.8 Output power of solar PV arrays with and without bypass diode](image)

2.4.2 Without bypass diode

In this case, the output current of a solar module will be limited by the most shadowed row. For conditions of shadow cover, using a bypass diode causes different voltage levels
to develop in a solar array. Alternatively, without the using of a bypass diode, different
current levels develop in a solar array. Assume that illumination conditions are the same
Fig. 2.1 shows that the average power of a solar array with bypass diode is higher than
the average power of a solar array without bypass diode, although the difference is very
small because bypass diodes will eliminate whole rows of solar cells in which they are
connected to parallel.

### 2.5 Solar PV arrays of different configurations

Fig. 2.4 shows the two common solar PV array configurations:

Simple series-parallel (SP) array, when all the controlled switches are OFF and modeled
as insulation resistance,

$$R_{Bi,j} = R_{OFF} = 10^{20} \Omega$$

(2.10)

Total-cross-tied (TCT) array, when all the controlled switches are ON and modeled as
conductance,

$$R_{Bi,j} = R_{ON}$$

(2.11)

In general, by combining different ON/OFF switching matrices, different configuration
and simulation results of the solar PV array may be obtained. In Fig. 18, the output power
of two configurations is shown. We can see that for this specific illumination condition
the total-cross-tied interconnection array gives more output power than the series-parallel
interconnection array.
The production cost of TCT interconnection solar PV array usually is higher than the production cost of SP interconnection solar PV array. Base on simulation results, the designer can trade off between the output energy of solar PV arrays and their production costs.

Fig. 2.9 Output power of solar PV array depends on interconnection

Fig. 2.10 shows a typical result of calculation of the power losses for SP and TCT for an array with 100 solar cells.

In this example, new simulation model can be used to simulate worst case shading effects on solar PV array. For SP connection, each solar cell in a different column completely shaded can cause up to 10% extra loss when shaded. The percent of lost
power depends on nonlinear functions, as described in Chapter 1. For example, if 6 solar
cells from different columns are completely shaded, the estimated power loss in Fig.
2.11, the point A, will be around 48%. On the other hand, if the 6 cells are in 3 different
columns, then the power loss, the point B, is reduced to about 17%.

For TCT connection, each solar cell in the same row completely shaded can cause up to
10% extra power loss. If two cells in different rows are shaded, the power loss is the
same as one row. Referring to Fig. 5 again, when the 6 solar cells in the same row
completely shaded, then the power loss of the array is around 48%, the point A. If the 6
shaded cells have only three shaded cells in the same rows, then the power losses is about
17%, the point B.

![Graph showing the losses of maximum power depending on the shaded area.](https://via.placeholder.com/150)

*Fig. 2.10  The losses of maximum power depend on the shaded area. In SP one cell in each
column is fully shaded. In TCT, one cell in the same row is fully shaded.*
In the worst case of 10 fully shaded solar cells (10% of the total number of solar cells in the solar PV array), the maximum output power can be reduced more than 90%. The result is the same for both SP and TCT.

### 2.6 Conclusions

A modeling and computing algorithm has been derived that simulates and analyzes the effect of non-uniform changing shadows (i.e. a passing cloud) on the output power of solar PV arrays.

The advantages and disadvantages of the topologies have been studied. The software implementation in MATLAB is shown to converge and is fast enough to be used within real time controllers. The model is able to determine the power losses in each solar cell and the hot spots of a shaded solar PV array as well as the PV output power. The model is flexible enough to simulate solar PV arrays with various configurations, with or without bypass diode.
3. Solar PV Array Shadow Evaluation using Neural Network and On-Site Measurement

3.1 Introduction

As introduced in the previous chapter, this thesis focuses on the research of two dominant fields of solar PV systems: (1) modeling and simulation of solar PV array under shadow conditions and (2) reconfiguration of solar PV arrays to improve their performance under shadow conditions. This chapter mainly discusses solar PV array performance evaluation under shadow conditions using neural network and on-site measurement.

This chapter proposes a novel method to define the function of relationship between the maximum output power (MPP) of the shaded solar PV array and the environmental factors, such as the solar irradiation levels, the sun’s position angles and the ambient temperature. This function, which is similar to the shading factor, can fully characterize the shadow effects on the solar PV array for long term and is called the shading function. As such, the shading function can eliminate the inaccuracy caused by the complexity of the shading factor’s calculation.

Specifically, our approach proposes the following procedure to define the shading function for the solar PV array under shadow conditions:

- The shadow ratio is characterized by the solar altitude and solar azimuth angles that are easily received from the information of the time of day for specific
Thus, the input signals of neural network are the solar irradiation levels, the sun’s position angles and the ambient temperature. The output signal of neural network is the maximum output power of the solar PV array.

- The input signals and output signal of neural network are measured for the one-day period, when the solar PV array is shaded partly by any nearby object. The measured data set is divided into a training set, and a test set.

- After the learning process of neural network, the test data prove the accuracy of the proposed model. The verified neural network model, the shading function, is able to predict the shadow effects on the solar PV arrays under any shadow conditions, i.e. with any solar irradiation levels, at any time of a day, when the solar array is shaded, and with different ambient temperature, for a long term and with low computational effort.

### 3.2 Performance evaluation for solar PV systems

A important step when designing large solar PV systems (BIPVs, solar power plants) is to evaluate the energy yield per year, month and day, etc. The system performance and the associated economic return can be calculated for the system based on this design constraint.

In practice, the conversion efficiency of a photovoltaic cell under outside operating conditions may be different from the one measured according to Standard Test Conditions procedures. In the Standard Test Conditions the PV module power ratings are
for of 1000 W/m² solar irradiance and 25°C cell temperature and 1.5 Air Mass. Fig. 3.1 shows an example of annually global (total) irradiance on a horizontal surface and ambient temperature.

![Solar Radiation/Temperature Comparison](image)

*Fig. 3.1 Example of annually global (total) irradiance on a horizontal surface and ambient temperature.*

As described in the previous chapter, the output energy of solar PV system heavily depends on the environmental factors. Specifically, typical irradiance levels and ambient temperatures must be known to estimate the energy generated by any solar PV system. Obviously, environmental conditions vary from an installation to an installation. In general, guidelines may be used to simplify estimation including the places with the same latitude should have similar solar irradiance levels and ambient temperatures.

In order to support the design of solar PV systems, the National Renewable Lab has been collecting irradiance levels, ambient temperatures, and wind speed from all US states. One of the Internet accessible tools for calculating solar PV system performance with
meteorological input data is PVWATTS. In this software the Typical Meteorological Year (TMY2) database is collected from 239 stations in United States. First, the PV systems designers have to select a location and according grid cells (40-km by 40-km) from the station map and sets of desired PV system parameters. Then, the PVWATTS will perform an hour-by-hour simulation that provides monthly and annually alternating current (AC) energy output in kilowatts and energy value in dollars [38]. The main limitation of PVWATTS is that this software cannot simulate solar PV systems more precisely, for example, minute-by-minute simulation.

[1] shows that the fundamental principle of the solar PV system sizing and evaluation is the energy balance between the generated energy and consumed load:

\[ H_A \times A \times \eta_{ps} \times K = E_L \times D_p \times R \]  

(3. 1)

Here, \( H_A \) = in-plane irradiation (kWh/m²); \( A \) = array area (m²); \( \eta_{ps} \) = PV efficiency at STC; \( K \) = performance ratio; \( E_L \) = load energy consumption (kWh); \( D_p \) = solar energy dependence; \( R \) = design redundancy for future load increase, safety margin.

The name plate d. c. power rating of the solar PV system equals the sum of all the module powers listed on the nameplates on the backsides of the individual PV modules.

The energy yield of grid-connected solar PV system is measured in kWh and evaluated for a specified solar PV system by the following equation:

\[ E_p = P_{AS} \times \frac{H_A}{G_S} \times K = P_{AS} \times Y_H \times K = P_{AS} \times Y_p \]  

(3. 2)
Here, $E_p$ = system generated electricity (kWh)

\[ K = K_H \times K_{PH} \times K_{PT} \times K_{PA} \times K_{PM} \times K_B \times K_C \]  

(3.3)

The system performance ratio $K$ is the most convenient value to evaluate the solar PV system performance. This parameter is normalized by site irradiation and system size. The system performance ratio $K$ consists of various parameters as shown in Fig. 3.2, such as the following:

- $K_H$ = irradiation modification factor that characterizes the shadows, soil age of surfaces;
- $K_{PH}$ = incident angle dependent factor, due to module glass structure reflection;
- $K_{PT}$ = cell temperature factor, due to the negative temperature coefficient of $P_{max}$;
- $K_{PA}$ = array circuit factor, consisting of series-connected model mismatch and wiring resistive losses;
- $K_{PM}$ = load matching factor, caused by mismatch operation apart from $P_{max}$ point;
- $K_B$ = battery circuit factor, including batteries and their peripheral losses;
- $K_c$ = power conditioner circuit factor, including power conditioner and their peripheral losses.

These parameters are only major parameters influencing the system performance ratio $K$ in actual PV systems, not all that can be considered theoretically. These parameters are usually calculated and evaluated in KWh, but KW.
To accurately define the above listed factors, modeling and performance prediction of solar photovoltaic (PV) arrays is an important task in the design of solar PV systems.

From the above discussion, the simple and reliable method to evaluate the shadow effects for long term (year, month and day) is necessary.

The shadows may be caused by the shadow from one submodule row on the other in the solar PV plants or by the nearby object such as trees, booms, or cloud passing... In order to include the effects of shadowing on solar PV arrays, conventional methods use an approach to determine the “shading factor,” which is defined as the ratio of the non-shaded area to the total area of the solar arrays.
So shading factors also can be used to calculate MPP power of shaded solar PV arrays. In reality, it is difficult to accurately estimate this shading factor because the shadows change their shape and move with time.

This leads to several approaches to evaluate the shadow effects on those solar PV arrays:

3.2.1 Numerical method

In the numerical method, the solar irradiance on all solar cells is modeled based on real time input data. The output power of the solar PV array at a given output voltage is then received by solving differential equations on small time-scales (second, minutes) [19], [20]. This method requires unrealistic number of sensors to measure the irradiance in each solar cell. Furthermore, accurate prediction of the maximum output power of solar PV systems for long term (days, months, years) is more challenging, due to difficulties in modeling the shaded area in the solar PV systems.

3.2.2 Photogrammetric method

In the photogrammetric method, the position of obstacles and their shadow are estimated by using the triangulation with two photographs or more [21].
3.2.3 Neural network method

Neural network method is used in [22], [23], [25] for predicting the dependence of maximum output power of solar PV arrays on environmental factors. However, these papers focus on estimating the performance of solar PV arrays under uniform illumination.

**Required data for identifying MPP**

The maximum power of solar PV system mainly depends on the insolation. In the reality, the sort circuit current $I_{SC}$, gives the most adequate information of the effective insolation. A linear correlation exits between the $I_{SC}$ and the optimal output current $I_{OP}$.

![Fig. 3.3 The correlation between the optimal power current and short-circuit current](image-url)
To estimate maximum output power from the solar PV system, the optimal voltage, \( V_{OP} \), is also required. The correlation between two parameters is non-linear and shown in Fig. 3.4.

![Fig. 3.4 The correlation between the optimal power voltage and open-circuit voltage](image)

### 3.2.4 The combined method

In the combined method, the neural network prediction model uses training data created by the numerical method. The low accuracy is due to the low accuracy of the modeling shadow objects [26].

From the above discussion, for the operation planning of solar power systems, there is a need of a simple and accurate method to define the shadow effects on shaded solar PV array for long term (seasonal or annual) in non-uniform illumination.
This research propose a model based on neural network that greatly expands on the ideas in [23], which use the insolation data and ambient temperature data to predict the output power of solar PV arrays under non-uniform shadow conditions.

Specially, the proposed model based on neural network has the following advantages:

- The model can define the *main environmental factors that result in reducing the output power* of the solar PV array under shadow conditions. By analysis the correlation between the input data, the dimension of the input vector can be reduced by eliminating the components of the vectors that are highly correlated (redundant).

- The simple experimental method is proposed to collect data necessary for the training neural network. The required experimental equipments is minimum and inexpensive.

- The appropriate neural network structure for these data by combining the multilayer perceptrons feed forward network with a back-propagation algorithm.

- By random selection technique, the training data set, the test data set can be received from the only one experimental data set. There is no need for repeating the experiment for many days. but the accuracy of the function of the relationship between the inputs and outputs from the training data set is verified by the test data set.

- The shading function proposed in this method is the most convenient form to store the information about the shadow effects in specific location. The conventional methods using the table to record the data of the shading factors for
hour, day, month, year that requires large memory space. To receive any conclusion about the shadow effects using tables would require more data analysis than our proposed approach.

3.3 Proposed method

3.3.1 Shadow evaluation using neural network without shading factor measurement

Detailed analysis for the proposed approach to obtain a neural network model for the shadow effects is provided in the following description.

In the numerical method, the shadow effects on the solar PV arrays are estimated by the shading factor, measured as the ratio of the shaded area to the total area of the solar PV array. In the proposed method based on neural network, instead of using the shading factor calculation, we directly find the shading function that characterizes the relationship between the maximum output powers of the shaded solar PV arrays and the environmental factors: the horizontal solar irradiance, the sun’s position, and the temperature:

$$P_{MAX} = f_{SHD}(Time, E, Temp) = f_{SHD}(\alpha_s, \gamma_s, I_{SC}, Temp) \quad (3.1)$$

Here, referring to (3.9) to define the following variables:

$P_{MAX}$- maximum output power of solar PV array, $E$-solar irradiation level, $I_{SC}$- short-circuit current, $\alpha_s, \gamma_s$- solar position’s angles, $Temp$- ambient temperature, $Time$- time of day, $f_{SHD}$- the shading function.
A neural network is an adaptive machine that resembles the human brain behavior. The neural network has a massively parallel distributed structure and the brain’s ability to learn and generalize. Neural network can be used to detect and derive the meaning from complicated or imprecise data. To derive the relationship in (3.1), the inputs of neural network are measured data from environmental factors: the horizontal solar irradiance, the sun’s position, and the ambient temperature. The output of neural network is the maximum output power of the shaded solar array. The neural network will process information, the large measured data of inputs and output, and learn from the data. The neural network will derive the function, which characterizes the relationship between the output and input signals in the form of matrix of weights. For future different environmental factors, the maximum output power of solar array under shadow conditions will be received in output of neural network by inputting the corresponding data of the time of day, solar irradiance and the ambient temperature.

The dependence of maximum output power of solar array on time, solar irradiation levels and ambient temperature is discussed below.

*The solar irradiance levels*

The average value, called the solar constant, $E_\circ$, of the solar irradiance measured outside the Earth’s atmosphere on a surface perpendicular to the solar irradiations, is:
The value of solar irradiance $E$ measured in the Earth’s surface is usually smaller than the solar constant due to reflection by the atmosphere, absorption in the atmosphere, and scatterings.

In the solar photovoltaic array, the photo generated current or a short-circuit current is linearly proportional to the solar irradiation levels $E$ and the coefficient $C_0$:

\[ I_{PH} \approx I_{SC} = C_0 E \]  \hspace{1cm} (3. 3)

**The position of the sun**

The sun’s position is defined by the two solar angles:

Sun’s height (solar altitude or elevation) $\gamma_s$, solar or sun azimuth $\alpha_s$ is shown in Fig. 3.5. These angles depend on the specific location of the solar PV array, the date, time, and time zone.
The angle of solar altitude is calculated by the following equation:

\[
\gamma_s = \arcsin(\cos \omega \cdot \cos \phi \cdot \cos \delta + \sin \phi \cdot \sin \delta)
\]  
(3.4)

The angle of solar azimuth:

If Solar time \(\leq 12.00\) hrs:

\[
\alpha_s = 180^\circ - \arccos \frac{\sin \gamma_s \cdot \sin \phi - \sin \delta}{\cos \gamma_s \cdot \cos \phi}
\]  
(3.5)

If Solar time \(\geq 12.00\) hrs:
Here $\delta$ is the solar declination, $\omega$ is the hour angle and $\phi$ is the latitude of the location.

In general, Eq. (3.4) to (3.6) can convert from the time to solar angles on the specific location of the solar PV array. These angels can be used as the input data for the neural network model.

**Temperature dependence**

With the rising ambient temperatures, the open circuit voltage decreases significantly and the short circuit current increases lightly. As a result, the maximum output power of the solar PV array will decrease.

**The maximum output power**

Maximum output power is measured by connecting the variable resistor $R$ to the external circuit of the solar PV array. The value of $R$ is defined by the following equation:

$$R_{LOAD} = \frac{V_{MPP}}{I_{MPP}}$$  \hspace{1cm} (3.7)

here, $V_{MPP}$ and $I_{MPP}$ are the maximum output power voltage and the maximum output power current.
3.3.2 Experimental set up

In this experiment, the solar PV array is outside and partly shaded by the nearby boom for some hours of day. Thus, the shadow is moving slowly with time.

![Diagram of input and output signals measurement circuit]

*Fig. 3.6 The input and output signals measurement circuit*

The signals are measured as shown in Fig. 3.6. Each diode presents the solar cell in total-cross-tied solar PV array. The darkened/colored diodes represent the shaded solar cells. Each shaded cell may be fully shaded or only partly shaded. So, the solar cells may have different shading factors. We assume that clouds have uniform effects on solar PV arrays and are not included in this experiment.
The shaded solar array is connected to the variable resistor $R_{LOAD}$ to track maximum output power from solar array. One un-shaded solar PV cell is connected to very small $R_{SENS}$ to measure the irradiation level (short-circuit current $I_{sc}$).

The input signals are the short circuit current $I_{SC}$, and ambient temperature. The output signal is maximum output power of the solar PV array

$$P_{MAX} = I_{MPP} \times V_{MPP}$$

(3. 8)

The signals are measured with interval of 30 seconds at particular time, when solar panel is shaded. Using PC, the time of each measurement is recorded. The positions of the sun, the two angles of the sun, are calculated from the time of day based on the MATLAB software.

All measured data are divided to the training set and test set for neural network.

### 3.4 Neural network structure

#### 3.4.1 Neural network structure

Fig. 3.7 shows multiple layers of neurons with nonlinear transfer functions that allow the network to learn nonlinear and linear relationships between input and the corresponding output value. This is a two layer feed-forward configuration.
The above experimentally measured data set includes the input data set: the time, the solar irradiance, the ambient temperature and the output data set: the maximum output power of solar PV array. This data set is divided into training, and test subsets. The design of the neural network is as follows:

First, the input layer consists of source nodes equal the number of input signals, the output layer consist of nodes with equal number of output signals. A subset of measured data (the training set) is used to train the network by the back propagation algorithm. This part of network design is called learning.

![Neural network’s structure](image_url)

*Fig. 3.7 Neural network’s structure*
Second, the performance of trained neural network is tested with the data from the test subset. The input signals of test subset are presented to the network. Then, the output of the network is compared with actual measured output.

In the specified neural network, the domain knowledge (here it is the relationship between the maximum output power of shaded solar PV array and the solar irradiation levels and the ambient temperature at a particular time) is captured by the value of free parameters (here they are the synaptic weights $w_i$ and $w_j$ and biases $b_i$ and $b_j$) of the neural network. The weights are adjusted by back-propagation algorithm. An effective procedure for performing this operation is illustrated in Fig. 3.7.

### 3.4.2 Input signals correlation analysis

In some situations, the dimension of the input vector can be reduced by eliminating the components of the vectors that are highly correlated (redundant).

Table 3.1 shows the correlation between the input signals of the neural network. The short circuit current and the solar altitude have the correlation coefficient 0.98, so we can remove the solar altitude from the input signals vector.
Table 3.1 shows that the input signals: the solar azimuth angle, the short circuit current, and the ambient temperature. The neural network has one output: maximum output power of solar PV array.

\[ \text{TABLE 3.1 The correlation between the inputs} \]

<table>
<thead>
<tr>
<th>Correlation</th>
<th>SOLAR ALTITUDE</th>
<th>SOLAR AZIMUTH</th>
<th>ISC</th>
<th>Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar altitude</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar azimuth</td>
<td>-0.8355</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isc</td>
<td>-0.9822</td>
<td>0.8580</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Temp.</td>
<td>-0.4120</td>
<td>-0.0559</td>
<td>0.3666</td>
<td>1</td>
</tr>
</tbody>
</table>

\[ \text{3.4.3 The learning process} \]

Once the network weights and biases have been initialized, the network is ready for training. The network is trained for function approximation. The training process requires a set of examples which include network inputs and target outputs. The experimental data is divided into training, and test subsets. We will take 70% of the data for the training set, 30% the test set.
During training, the weights and biases of the network are iteratively adjusted to minimize the network output estimation error. The default performance function for feedforward network is the mean square error MSE, the average squared error between the network outputs and the target outputs. Fig. 3.8 shows the squared errors after different epochs for training process. The error is calculated by equation:

\[
Er. = \frac{1}{N} \sum_{j=1}^{N} (e_j)^2 = \frac{1}{N} \sum_{j=1}^{N} (P_{\text{MEAS}} - P_{\text{EST}})^2
\]  

(3.9)

Here, \(P_{\text{MEAS}}, P_{\text{EST}}\) – the measured and estimated maximum output powers of solar PV array, \(N\) - the number of measurements in the training subset

The result here is acceptable, because the training set error and the test error have similar characteristics.
3.4.4 The generalization check

We can use data from the test subset to check the generalization of the network. The
generalization characterizes the ability of the network to correctly map the data that was
not involved in the learning. We can improve the generalization by using a larger
network or regularization and early stopping method.

3.4.5 The performance analysis of the network response

To investigating the network response, we will put the test data set through the network
and will perform a linear regression between the network outputs and the corresponding
targets. Then, we perform a regression analysis between the network response and the
 corresponding targets. We pass the network output (predicted maximum output power)
and the corresponding targets (measured maximum output power) to the linear regression
analysis function. It returns three parameters shown in Fig. 3.7. If we have a perfect fit,
the slope is close to 1, and y–intercept is near 0. The R=0.994 indicates that the output of
the neural network track the targets well.
3.4.6 Analysis and discussion

Fig. 3.9 The network performance analysis

Fig. 3.10 The measured and predicted output powers of solar PV arrays
Fig. 3.10 shows the two predicted curves, maximum output powers of shaded and non-shaded solar PV array, and measured maximum output power of shaded solar PV array. We can see that the predicted maximum output power is very close to the measured one (dashed) for the non-uniform shading. The trained neural network consequently may be used for predicting the maximum output power for any other shadow conditions at any time of a day, with any levels of solar irradiance or ambient temperature.

3.5 Conclusions

A neural network based model of the shadow effect on the maximum output power of the solar PV array is described. The maximum output power or maximum output power losses of the shaded solar PV array can be calculated based on shading function without a shading factor calculation.

We proposed to develop a neural network method, combining the multilayer perceptrons feed forward network with a back-propagation algorithm, to accurately predict maximum output power of solar photovoltaic arrays under shadow conditions. Using the solar irradiation levels, the solar photovoltaic array’s temperature, and the sun’s position angles as the input signals, and the maximum output power of the solar PV array as an output signal. The training data for the model, the shading function, can be easily collected on site by periodically measuring the maximum output power of solar PV arrays and measurable environmental factors over typical period of a day. The accuracy
and generalization of the network are checked by comparing the simulation data to the measured data.

The model/ shading function can be employed to accurately predict the maximum output power of the solar PV array over long periods of time with low computational efforts. The approach uses only readily available solar irradiation data at different times of a day, wherever the solar PV array is installed.
4. A Adaptive Reconfiguration of Solar PV Arrays

4.1 Introduction

This thesis generally can be categorized into two parts.

Mass production and use of electricity generated from solar energy has become more common recently, perhaps because of the environmental threats arising from the production of electricity from fossil fuels and nuclear power. However, in many applications, such as solar power plants, building integrated photovoltaic, or solar tents, the solar photovoltaic arrays might be illuminated non-uniformly. The cause of non-uniform illumination may be shadows from clouds, trees, booms, neighbor’s houses, or even the shadow of one solar array on the other, etc.

Furthermore, for applications like BIPV and solar power plants in small spaces, as shown in Fig. 4.1, shadows from one solar PV array are commonly cast on another array, [5]. In conventional solar PV plants, the designer must solve the complex problem, the tradeoff between “maximum energy output” and “minimum produced energy cost” by varying the distance between the rows For these new applications, it has been especially important to optimize performance of the arrays in shadowed conditions. Because of the nature of the electrical characteristics of solar cells, the maximum power losses are not proportional to the shadow, but magnify nonlinearly. The shadow of solar PV array can cause many undesired effects:

- The real power generated from the solar PV array is much less than designed, so that the loss of load probability increases [17].
• The local hot spot in the shaded part of the solar PV array can damage the solar cells

There are several approaches that have been proposed to reduce the effect of shadows on a solar PV array output power:

• Bypass diodes are connected across shadowed cells to pass the full amount of current while preventing damage to the solar cell. This method usually requires a great number of bypass diodes that are integrated in the solar arrays. The production of solar arrays with bypass diodes is more costly. Furthermore, the power losses of solar PV arrays are not prevented completely because there are the additional power losses when the current passes though the bypass diodes.

• In large systems, each of the solar sub-modules can be connected to its own maximum power point (MPP) tracking DC-DC converter and can individually operate near its own MPP. Thus, the efficiency of the whole system is increased, [42], but the method requires a large number of DC-DC converters (equal to the number of solar modules).

• An alternate research field, and the focus of this paper, is to adaptively reconfigure solar array connections in real time in order to track maximum output power. Traditionally fixed solar PV arrays have hard wired interconnections between their solar cells. These connections are not changed after installation. However, it is possible to continuously rearrange solar cells in series and parallel connections to facilitate the photovoltaic system to work more as a constant power source, even in different operating conditions (i.e. insolation, temperature,
loads,…etc). Research studies in have started to develop methods to reconfigure solar cells to improve power output in shaded conditions. This research focuses mostly on how to build the arrays, and does not propose real-time implementable control algorithms (the focus of this paper). Because of this, the methods proposed have unrealistic number of sensor and switches that must use complex control algorithms to determine when it turns the switch ON or OFF.

This chapter develops research for third approach above. Adaptive reconfiguration of solar arrays is proposed that requires significantly fewer voltages or current sensors and switches than [16-17]. Further, for the first time published, simple real time implementable control algorithms that determine how to adaptively reconfigure solar cell connections have been developed. The algorithms have been experimentally tested on a small scale solar reconfiguration system.

Specifically, this chapter presents the following research contributions:

- A new method for reconfiguration of solar PV arrays in real time under shadow conditions is presented. Solar cells from a (smaller) solar adaptive bank will be connected to the (larger) fixed part of the solar array. The maximum power point (MPP) of the whole array is tracked by a single common maximum power point tracker (MPPT), instead of many MPPTs as shown in [9-13]. Since only a small percentage of the solar arrays are reconfigurable, fewer switches and simplified control algorithms are possible. In the uniform illumination conditions, all these adaptive solar cells will be equally connected to all rows of the fixed part of solar
PV array. In non-uniform illumination conditions, the number of the adaptive solar cells connected to the shaded submodules depends on the shaded area of submodules. The configuration is executed through the proposed switching matrix.

- Simple control decision algorithms are presented to determine when and how to open and close switches between the fixed part and adaptive bank of the solar PV array. The algorithms rely on model predictions that can be implemented in real-time by a micro-controllers or Digital Signal Processors.

- An experimental adaptively reconfigurable solar PV has been built and tested to verify proposed reconfigurations. It is shown that the approach proposed is able to increase output power of solar PV array in real-time under shaded conditions by 30% for a typical experiment. The experimental results are presented in Chapter 5.

### 4.2 Shadow variation on photovoltaic collectors in a solar field

One of the new trends in solar PV energy is to install solar PV plants on the roof of big city buildings. The investment cost of Building integrated photovoltaic (BIPV) power plants is reduced because of the relatively low price of land and the minimum electrical transmission losses. On the other hand, the limited roof area of BIPV power plants causes additional unavoidable power losses from shadow cast by nearby trees, booms and other nearby buildings.
If there is no space limitation; the distance between the rows can be large, the shadow effects from one row to other is kept to a minimum. On the other hand, if the size of land is limited or economy calculation is taken into consideration, the tradeoff between the row’s distance and the shadow losses have to be considered [8], [9].

Fig. 4.1 shows the shading by collectors in a solar field. The solar field has fixed length $L$ and width $W$. $K$ is the number of solar collectors in the field. The use of many rows ($K$ is large) will increase both the solar PV area and the shadowing losses. A small number of rows will reduce the solar PV area and shadowing effects but the energy output from the solar field may be reduced. In the conventional solar PV plant design approach, the solar PV system’s designer has to solve the complex problem, the tradeoff between “maximum energy output” and “minimum produced energy cost” by varying $D$-parameter, the distance between the rows, as shown in Fig. 4.1.
The relative shaded area $a_s$:

$$a_s = \lambda_s \times h_s$$

(4.1)

The relative length of the shaded area $\lambda_s$:

$$\lambda_s = \frac{L_s}{L} = 1 - \frac{d \sin \beta + \cos \beta}{\lambda_s} \times \frac{\sin \gamma}{\cos \beta \tan \alpha + \sin \beta \cos \gamma_s}$$

(4.2)

Here, $\alpha \geq 0$ - the sun elevation angle, $|\gamma| \leq 90$ - the solar azimuth angle, $0 \leq \lambda_s \leq 90$

The relative height of the shaded area:

$$h_s = \frac{H_s}{H} = 1 - \frac{d \sin \beta + \cos \beta}{\cos \beta + \frac{\sin \beta \cos \gamma}{\tan \alpha}}$$

(4.3)

$$0 \leq h_s \leq 1$$

d is the normalized horizontal distance between the collectors:

$$d = \frac{D}{H \sin \beta}$$

(4.4)

And $\lambda$ is the normalized collector length

$$\lambda = \frac{L}{H \sin \beta}$$

(4.5)

4.3 Conventional methods of reconfiguration solar PV array

conventional methods

There are several approaches that have been proposed to reduce the effect of the shadow on the solar PV array output power:
• Bypass diodes are sometimes connected across shadowed cells to pass the full amount of current while preventing damage to the solar cell. This method usually requires a great number of bypass diodes that are integrated into the solar arrays, adding cost. The power losses in the solar PV array are only partially prevented due to the added shorts within the whole module.

• Alternatively, in large systems, each of the solar sub-modules can be connected to its own DC-DC converter and can individually operate near to its own maximum power point. Thus, the efficiency of the whole system is increased [37], [40], but the method requires a large number of DC-DC converters (equal to the number of solar modules).

• It is possible to continuously rearrange solar cells in series and parallel connections [34] to facilitate the photovoltaic system to work more constantly as the power source in specific design operating conditions (i.e. insolation, temperature, loads, etc). Recent research studies [35], [36] started to develop methods to reconfigure solar cells in shaded solar PV array. However, it has a drawback of requiring an unrealistic number of switches and sensors that must use a complex control algorithm to determine when it turns the switch ON or OFF [36].

In conventional methods, the solar PV array contains two parts: fixed part and adaptive part. The fixed part is main part of solar array. Solar cells in fixed part have fixed configuration, they are connected by wires.
The adaptive bank contains the reconfigurable solar cells. They can be connected together or connected in parallel or in series with the fixed part.

If adaptive solar cells are connected in parallel, the output current of solar array increases. If adaptive solar cells are connected in series with the fixed part, the output voltage increases. The photovoltaic solar arrays are neither constant current nor constant voltage source; therefore it needs special treatment when operating it as a power source. The combination of cells in series and parallel arrangements results in specific maximum power output under design operating conditions (i.e. insolation, temperature, loads, etc). It is of course required to get the maximum power output from the photovoltaic system as possible. So if we can let the photovoltaic system work as constant power source this will be the best solution. Fig. 4.2 shows the well known I-V characteristics of a solar array with superimposed a constant locus of maximum power points.

As shown in Fig. 4.2 it is clear that the locus of the maximum power points is nearly perpendicular to the constant power locus. The best solution of course is to let the locus of the maximum power points coincident with the maximum constant power locus.
Fig. 4.2 I-V curves with different irradiance levels

The possible arrangement of solar PV array:

Fig. 4.3 Parallel arrangement
Fig. 4.3 shows a parallel arrangement of solar PV array. The fixed part contains solar cells \((PV(1,1), PV(2,2), \ldots, PV(m,n))\). The adaptive part contains series-connected strings of solar cells \((APV(1,1), APV(1,2), \ldots, APV(m,1)) \ldots (APV(1,4), APV(2,4), \ldots APV(m,4))\). By turning switches \((B_1, B_2, B_3, B_4)\), these strings will be connected in parallel with the fixed part. The output current \(I_{OUT}\) will increase.
Fig. 4.4 shows a series arrangement of solar PV array. The fixed part contains solar cells (PV1(1,1), PV(2,2), …, PV(m,n)). The adaptive part contains parallel-connected submodules of solar cells (SPV(1,1), SPV(1,2), …, SPV(m,1))…(SPV(1,4), SPV(2,4), … SPV(m,4)). By turning switches (S1, S2, S3, S4), these strings will be connected in series with the fixed part. The output voltage $V_{OUT}$ will increase.

**Fig. 4.5 Series-parallel arrangement**

Fig. 4.5 shows a series-parallel arrangement of solar PV array. It is the combination of series arrangement and parallel arrangement. By turning switches (S1, S2, S3, S4) or (B1, B2, B3, B4), the strings or submodules of adaptive solar cells will be connected in series or parallel with the fixed part. Both the output voltage $V_{OUT}$ and output current will increase. The maximum output power point will be the intersections point between the I-V curves and the maximum output power locus. It is shown in Fig. 4.7.
Fig. 4.6 I-V curves for PV with series-parallel arrangement of full sun

Fig. 4.5 shows a fully reconfigurable solar PV array. The solar cells are continuously rearranged in series or parallel connections to get optimize connection. The drawback is that there is unrealistic number of switches and sensors. Furthermore, there are many possible configurations but a simple control algorithm to determine how and when to adaptively turn switch ON or OFF has yet to be developed.

This research project develops a new approach for adaptive reconfiguration of solar arrays. We propose methods that require significantly fewer switches and sensors than those in [35], [36] and also have simpler implementation of the real time control algorithm. Our methods will rely on model prediction from our new models from Chapter 2. This research develops adaptive reconfiguration algorithms to reconfigure connections within solar PV arrays in real time, under shadow conditions, in order to optimize output power.
We propose to connect a matrix switches between a “solar adaptive bank” and a standard TCT fixed solar PV array. Various control algorithm approaches, the solar PV array is reconfigured to produce optimal power. Control algorithms will be implemented in real-time. Implementation of neural network as well as model based control algorithm will be investigated.

The specific achievements of the proposed reconfiguration method are the followings:

- **Proposing a simple method to monitor the shadow pattern in the solar PV array:** the shadow pattern is defined by using just two monitoring voltage sensors instead of using one sensor for each solar cell.

- **Defining the configuration that solar cells can be reconfigured to compensate the shaded cell:** after analyzing the common configurations of solar PV arrays, we decided to choose the TCT configuration for the fixed part of the adaptive solar PV array, because in this type of configuration, the shaded solar cells of a row of fixed part can be compensated by connecting the illuminated solar cells in parallel to this row.

- **Proposing the two simple control algorithms for reconfiguration of the solar array:** the “bubble sort” control algorithm and the control algorithm based on the model developed in Chapter 2 can be applied for large solar PV system.
4.4 Proposed a adaptive reconfiguration method

This section proposes a system architecture that permits adaptive reconfiguration of the connections between solar PV arrays. A switching matrix that connects a small reconfigurable bank of PV arrays with a larger non-reconfigurable bank of solar PV arrays is proposed. Because only the adaptive bank is being reconfigured, the number of switches and reconfiguration time seems computationally efficient. We propose two different adaptive reconfiguration algorithms for the arrays, each of which will eventually produce the same increase in power under shadow conditions. The first method is simpler, and it relies on a serial “Bubble – Sort” approach, which switches the adaptive PV arrays in one at a time. After each switching, the power of the total system is analyzed and the next sort is implemented. In the second method, a model reference approach is proposed that is able to predict power levels in each of the rows of the fixed solar arrays and uses this prediction to simultaneously switch the connections of the adaptive bank.

These reconfiguration control algorithms are applicable even when the some of the solar cells of the adaptive photovoltaic bank are shaded: the control algorithms will automatically connect the most illuminated solar cells in the adaptive bank to the most shaded row of the fixed part. If a solar cell in the adaptive bank is shaded it will still be connected to the fixed solar array, perhaps to a more illuminated row. Since there is a parallel connection, the only implication is that there will be only a small amount of current/ power added from the shaded adaptive solar cell. In either case, the two different approaches eventually will produce the same increased power of the entire solar PV
system, and both are implementable on a Digital Signal Processor in real time. However, the second approach is quicker, as we later experimentally demonstrate. Fig. 4.10 shows the operation principle of the proposed method.

**The fixed part (m rows and n columns)**

The fixed part is the main part of the solar array and has most number of solar cells, as shown in the Fig. 4. 7. The fixed part contains (m x n) solar cells (the solar cells (1,1), (1,2), …(m, n-1), (m, n). All solar cells in the fixed part are connected by hard wire and have fixed configuration, with TCT, the total-cross-tied interconnection. We can consider that the fixed part of solar PV array has m PV “modules” connected in series.

**The solar adaptive bank of solar cells**

In this paper, the adaptive bank has m solar cells (the solar cells A₁, A₂, …, Aₘ) not connected together i.e. the number of adaptive solar cells is same as the number of rows in the fixed part.

These adaptive solar cells can be connected in parallel to any PV module, from PV₁ to PVₘ, as seen in Fig. 4.11. We remark that fewer than m adaptive solar cells can also be used. (The algorithms still work and there will still be power improvement after reconfiguration, as shown in experimental Chapter 5). However, by selecting m adaptive solar cells, there is the advantage that when there is uniform illumination and no need for reconfiguration, then the adaptive bank can form one additional column to the fixed part. In this case, the entire PV system will behave like an (m x (n+1)) array.
Fig. 4.7 Practical circuit of the proposed reconfiguration: For \( m \) rows in the fixed solar array, we proposed \( m \) solar cells in the adaptive bank

**The switching matrix**

The fixed part and solar adaptive bank are connected together through the switching matrix. The switching matrix, as shown in Fig. 4.8, contains switches \( S(1, 1) \), \( S(1, \ldots, m) \), and \( S(m, 1) \).
2), \( S(m-1, m-1), S(m, m) \) connect each solar cell in the adaptive bank to any row of solar cells in the fixed part of the PV array.

![Fig. 4.8 The switching matrix](image)

When the switch \( S(i, j) \) is ON, the solar cell \( A_i \) from the adaptive bank will be connected to row \( j \) of a fixed part. Thus, only one set of switches in a column can be ON at a time. The switches can be either relays or electrical switches. In the proposed method, each switch carries just the current of one solar cell (or one submodule), which is normally 1A \( \sim \) 5A, even for large solar power plants. Thus, if mechanical relays are selected, the arcing phenomena may not be burdensome since the current is so low. On the other hand, small electrical switches (in SO8 packages) are made at suitable power and voltage ratings for applications such as in Fig. 4.1. Furthermore, these small package sizes are easily embedded/sewn into the fabric already. So, it seems that these portable, foldable solar panels are prime candidates for this reconfiguration approach.
4.4.1 “Bubble - Sort” method

The flow chart of the “Bubble - Sort” method is shown in Fig. 4.9. In general, the solar array is reconfigured by the following principle: if the voltage of the one row is smaller than voltages of the other rows, it indicates that this row is the most shaded row. One solar cell from the adaptive bank will be switched in parallel to this row. The process will continue until all the solar cells of the solar adaptive bank are connected in parallel to the rows of the fixed part.

**Step 1**

The solar adaptive bank and fixed part of the solar array are connected together in the original configuration as in Fig. 4.9 (a). The voltage $V_1$ and $V_{OUT}$ are monitored, where $V_1$ is the voltage produced by row 1 of the solar array. In the uniform illumination, the output voltage: $V_{OUT} = m \times V_1$.

In the non-uniform illumination, two situations can occur:

The first case occurs when the first row is shaded and the other rows are non-shaded. In this case, the voltage of first row is reduced and it is less than the threshold voltage: $V_1 < \delta V$, the adaptive reconfiguration starts. The second case occurs, when the first row is non-shaded, and at least one of the other rows is shaded, the output voltage of the solar array is not equal to $m \times V_1$, but much less than that: $V_{OUT} - (m - 1) \times V_1 < \delta V$ In this case also the adaptive reconfiguration starts.
We propose to connect a matrix switches between a “solar adaptive bank” and a standard TCT fixed solar PV array. Various control algorithm approaches, the solar PV array is reconfigured to produce optimal power. Control algorithms will be implemented in real-time. Implementation of neural network as well as model based control algorithm will be investigated.

![Flow Chart](image)

*Fig. 4.9 The flow chart of the control algorithm for “Bubble - Sort” method*
Step 2

By the opening all switches S(1,1), S(2,2), …, S(m, m), all the solar cells in the solar adaptive bank are in the open circuits. Define, sort in the decreasing order: the open circuit voltages of all solar cells of the adaptive bank:

\[ V_{0,1} > V_{0,2} > \ldots > V_{0,m} \]

Step 3

Define the number of adaptive solar cells connected parallel to the shaded solar submodules in the fixed part.

Sorting: First, measure the voltages of all submodules of the solar fixed part. Next, the voltages of all submodules of the fixed part are sorted in increasing order:

\[ V_1 < V_2 < \ldots < V_m \]

the voltages of the fixed part. Thus, the rows of the fixed part and each adaptive solar cell have been renumbered according their sorting voltages.

Adding: Connect the solar cell with the maximum open circuit voltage of the solar adaptive bank in parallel to the most shaded sub-module of the fixed part, which has the smallest voltage. For example, if we switch solar cell A1 in parallel with the sub-module in row 1, then after the first switching, the solar adaptive bank becomes:

\[ V_{0,1} > V_{0,2} > \ldots > V_{0,m} \]

The fixed part might become:
Then the second switching occurs and the solar cell A2 is connected in parallel with the sub-module in the row 2. We continue the reconfiguration process until all the solar cells of the solar adaptive bank are connected parallel to the rows of the fixed part.

**Step 4**

When the shadow changes direction or shape, the voltage of the first row and the output voltage are continuously being measured and compared, and give the command to repeat the reconfiguration process, if the difference between them is above the fixed range, the control circuit repeats the procedure in Steps 2-3.

### 4.4.2 Model-based method

The flow chart of the model-based method is shown in Fig. 4.10. The control algorithm to determine how to connect and reconfigure the solar cells is based on a model-based control method and contains the following steps:

**Step 1**

It is the same as Step 1 in the “Bubble - Sort” method

**Step 2**

\[ V_2 < V_1 < \ldots < V_m \]
Define the photo generated currents of all solar cells of the solar adaptive bank and of all submodules of the fixed part.

We can use the model-based method to calculate the photo generated currents in Step 3. The benefits of this approach over the previous method is it defines photo generated currents of all solar cells of the solar adaptive bank and of all submodules of the fixed part, so all switches can be controlled synchronously at the same time.

*The photo generated currents of the solar adaptive bank:* By the opening all switches \( S(1,1), S(2,2), ..., S(m,m) \), all the solar cells in the solar adaptive bank are in the open circuits. By measuring the open circuit voltages of solar cells \( \{V_{OCA1}, V_{OCA2}, ..., V_{OCAm}\} \), the photo generated currents \( I_{PHAj} \) are estimated by the following equation:

\[
I_{PHAj} = \frac{V_{OCAj}}{R_{SH}} + I_S * \left( \exp \left( \frac{qV_{OCAj}}{akT} \right) - 1 \right) \tag{4.11}
\]

Here, \( R_{SH} \) - shunt resistance of solar cell, submodule, \( I_S \) - saturation current of the solar cell,

*The photo generated currents of the fixed part*

All submodules of the fixed part are still working with load. Their photo generated currents are calculated by the equation:

\[
I_{j} = I_{OUT} + I_S \left[ \exp \left( \frac{q(V_j + I_{OUT}R_{SM})}{akT} \right) - 1 \right] + \left( \frac{V_j + I_{OUT}R_{SM}}{R_{SHM}} \right) \tag{4.12}
\]

where, \( V_j = \{V_1, V_2, .., V_m\} \) - measured voltages of submodules, \( I_{OUT} \) – the output current of solar array, \( R_{SM} \) - series resistance of solar cell, submodule, \( R_{SHM} \) - shunt resistance of
solar cell, submodule, $I_S$ - saturation current of the solar cell diode, $n$ – number of solar cells in submodule.

Fig. 4.10 The flowchart of the control algorithm for Model-based method
These parameters of solar cell or solar submodule are received from manufacturers or extracted based on experiment by V-I curve fitting. By updating temperature and voltage parameters in the model (in real-time) it is possible to estimate photo generated currents $I_{PHAJ}$ and $I_{PHFj}$ of each solar cell or submodule by using[19] [20], and their dynamics multi-physics models[51].

**Step 3**

Define the number of adaptive solar cells connected parallel to the shaded solar submodules in the fixed part.

**Sorting:** First, the photo generated currents of all solar cells of the solar adaptive bank are defined and sorted in the decreasing order: $I_{A1} > I_{A2} > ... > I_{An}$, the current of the adaptive bank.

Next, the photo generated currents of all submodules of the fixed part are sorted in increasing order: $I_{F1} < I_{F2} < ... < I_{Fn}$, the currents of the fixed part.

Thus, the rows of the fixed part and each adaptive solar cell have been renumbered according their sorting predicted photo generated current.

**Adding:** Connect the solar cell with the maximum predicted photo generated current of the solar adaptive bank in parallel to the most shaded sub-module of the fixed part. For example, if we switch solar cell A1 in parallel with the sub-module in row 1, then after the first switching, the solar adaptive bank becomes: $I_{A2} > I_{A3} > ... > I_{An}$
The fixed part might become: \( I_{F2} < I_{F1} + I_{A1} < ... < I_{Fn} \)

Then the second switching occurs and the solar cell A2 is connected in parallel with the sub-module in the row 2. We continue the reconfiguration process until all the solar cells of the solar adaptive bank are connected parallel to the rows of the fixed part.

\textit{Step 4}

When the shadow changes direction or shape, the voltage of the first row and the output voltage are continuously being measured and compared, and give the command to repeat the reconfiguration process. If the difference between them is above the fixed range, the control circuit repeats the procedure in Steps 2-3.

Table 4.1 compares the previous reconfiguration structures [35][36] with the proposed method. In the previous reconfiguration approaches, it is assumed that all solar cells are “adaptive,” that is that they can all be reconfigured to each other. In our proposed approach, we assume that there is a fixed array and that this array has \( m \) rows and \( n \) columns of solar cells. Often the number of columns is made larger than rows, as the currents in each columns are added together to increase power.

Notice that the proposed method always uses fewer sensor, and in the case when the number of columns is significantly greater than the number of rows (\( n > m \)), as commonly
occurs, then there are significantly fewer sensors. Similarly, when n>m, the number of
switches also can be significantly decreased.

We remark that [16], [17] do not present methodologies to determine how to reconfigure
the solar arrays. Thus, we are unable to make comparisons in control algorithms.

### TABLE 4.1 Comparison of the Reconfiguration Methods

*(m=rows, n=columns in fixed array)*

<table>
<thead>
<tr>
<th>No</th>
<th>Item</th>
<th>Conventional</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Number of solar cells (submodules)</td>
<td>Fixed: 0</td>
<td>Fixed: m(n)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adaptive: m(n+1)</td>
<td>Adaptive: m</td>
</tr>
<tr>
<td>2</td>
<td>Number of voltage + current sensors</td>
<td>m(n+1)</td>
<td>2m+1</td>
</tr>
<tr>
<td>3</td>
<td>Number of switches</td>
<td>2m(n+1) to 3m(n+1)</td>
<td>2m^2</td>
</tr>
<tr>
<td>4</td>
<td>Control Algorithms</td>
<td>N/A</td>
<td>Bubble - Sort Model-based</td>
</tr>
</tbody>
</table>

One example of the reconfiguration method is shown in Fig. 4.11. The solar PV array
from 10x10 solar cells in the fixed part, 10 solar cells in the adaptive part has the
interconnection in 4.11(a), in the uniform illumination, in Fig. 4.12(b), in the non uniform
illumination. The figures show that by using the proposed adaptive reconfiguration
method, when the number of shaded solar cells is less than the number of solar cells in
one row, the maximum power loss is at most equals the power of the one row. If no
adaptive bank and TCT connection, the shade would have up to 30% reduction in
maximum output power (3 rows). With the adaptive bank, there is only 10% reduction in power.

Fig. 4.11 Solar array’s reconfiguration under non uniform illumination
4.5 Conclusions

This research develops a new method for reconfiguration of solar PV arrays under shadow conditions to maximize the possible output power.

A summary of the research contribution for the achievement of Objective 3 is as follows:

- A new method for reconfiguration of solar PV arrays in real time under shadow conditions has been developed: Solar cells from a (smaller) solar adaptive bank will be connected to the (larger) fixed part of the solar array. The maximum power point (MPP) of the whole array can be tracked by a single common maximum power point tracker (MPPT), instead of many MPPTs as in [37], [38], [39], [40]. Since only a small percentage of the solar arrays are reconfigurable, fewer switches and simplified control algorithms are required. In the uniform illumination conditions, all these adaptive solar cells will be equally connected to all rows of the fixed part of solar PV array. In non-uniform illumination conditions, the number of the adaptive solar cells connected to the shaded submodules depends on the shaded area of submodules. The reconfiguration is executed through the proposed switching matrix.

- Simple control decision algorithms to determine when and how the switches between the fixed part and adaptive bank of the solar PV array are open and closed. The algorithms will rely on predictive models that can be implemented in real-time by a micro-controllers or DSP. To our knowledge, it is the first time that such adaptive and implementable algorithms have been reported.
• The switching matrix is working in at relatively low switching frequency, so the
electromechanical relays can be used to increase the current going through panels.
The number of voltage sensors can be increased if it is desired to reduce the
calculation time. The simple sorting algorithm is applied to reduce the calculation
time.

• The proposed reconfiguration method helps avoid the local maximum power
points of solar PV arrays, thus the central maximum power point tracker can be
used to track the maximum output power of the whole solar PV array.
5. A Small Scale Solar Photovoltaic Test Bed

5.1 Introduction

Fig. 5.1 shows the solar PV array test platform. The experiment includes the following: The fixed solar array is from 9 solar cells, 3 rows (m) and 3 columns (n) (TCT connection). The solar adaptive bank combine from 3 solar cells (one string of 3 x1 cells) connected to the fixed part (3x3). The (3x3) switching matrix, controlled by Agilent Data Acquisition/Switch Unit 34970A, is connected between the fixed part and the solar adaptive bank. In total, we use 18 switches in the switching matrix and 6 voltage sensors (two of them are voltage monitors) for this test platform. The output load in all the experiments is 10 $\Omega$. 

Fig. 5.1 Solar PV array outdoor test platform
The voltages of solar cells in the solar adaptive bank and solar submodules in the fixed part are continuously measured and sent to PC running real-time MATLAB software. The sorting algorithm previously described is implemented by the PC in real-time.

### 5.2 Bubble-Sort method

Fig. 5.2 shows two separate experiments: Experiment 1 is from $0 < t < T_3$. In this time interval, the figure shows the output voltage of the solar array when 4 solar cells are partially shaded. From time equal 0 to $T_1$, the output voltage is under uniform illumination. From $T_1$, solar PV array is shaded. The interval $T_1 - T_2$ is time for measurement and control. After $T_3$, output voltage of solar array has been optimized and the reconfiguration has been completed. Notice that from $T_3$ to $T_4$, clouds move across the array and cause a change in the output voltage. However, no reconfiguration occurs since the clouds affect both the adaptive and fixed part of the solar array equally. Hence, this demonstrates a robustness of the proposed algorithms to falsely reconfigure when it is not necessary.

The output power of solar PV array is calculated by the following equation:

$$P_{out} = \frac{V_{out}^2}{R}$$  \hspace{1cm} (1)

For this Experiment 1, there is a 62.3% increase in output power from before to after the reconfiguration.
Fig. 5.2 Output voltage of solar PV array before and after reconfiguration in Two – Bubble Sort Experiments

Fig. 5.3 Output voltage of solar PV array before and after reconfiguration in Two Model-Based Experiments

Experiment 2 of the Bubble-Sort method is performed from $t > T_4$ in Fig. 5.2. At $t < T_4$, the solar system is in the configuration stage from the previous Experiment 1. All of a sudden at $t = T_4$, the shadow configuration is suddenly changed so that two cells in the
same row of the fixed part are **fully shaded**. The interval $T_4$-$T_5$ is time for measurement and control. After $T_6$, output voltage of solar array has been optimized and the Bubble-Sort reconfiguration has been completed. Using the data in Fig. 5.2 with (8), it is calculated that there is a 156% increase in output power from before to after the reconfiguration. In both experiments, the Bubble-Sort reconfiguration takes about 18 seconds.

### 5.3 Model-Based method

Fig. 5.3 shows another two experiments. Experiment 3 is from $0 < t < T_2$, and Experiment 4 is for $t > T_3$. In Experiment 3, the output voltage of the solar array when 4 solar cells are **partially shaded** is shown in the figure. From 0 to $T_1$, the output voltage is under uniform illumination. From $T_1$, solar PV array is shaded. The interval $T_1$-$T_2$ is time for measurement and control. After $T_2$, output voltage increases of solar array after reconfiguration. Notice that the voltage across the load is increased from $T_2$, by 20% indicating a 33% increases in power due to reconfiguration. The output voltage of solar array initially drops during real time reconfiguration (between $T_1$ and $T_2$). This is because the solar adaptive bank is disconnected from the load for short time to measure and sort. During the transition, though, the fixed part is still supplying power for the load.

In Experiment 4, shown in Fig. 5.3 for $t > T_3$, the shadow configuration suddenly changes so that three solar cells in the fixed part are completely shaded. The three solar cells in
the adaptive bank remain illuminated. The reconfiguration starts at \( t = T_3 \) from the previous reconfiguration connections of Experiment 3, but this provides no technical difficulties. From \( T_3-T_4 \), there is measurement and control. After \( T_4 \), the switches are controlled synchronously to reconfigure. For this experiment, the reconfiguration from \( T_3 \) to \( T_4 \) led to dramatic increases of power of a 3900% improvement from before to after reconfiguration.

5.4 Comparison between “Bubble - Sort” and “Model-based” methods

The second reconfiguration method takes about 8 seconds. This method is faster because all switches can be controlled synchronously at the same time, when the “Bubble - Sort” method switches one at a time instead of all at once. The final reconfiguration state does not differ between the two methods.

5.5 Partly shaded solar adaptive bank

At times, one can expect that the adaptive solar cells may also become shaded. As previously discussed, all the algorithms work when this occurs. For the case when there are still more illuminated adaptive solar cells than shaded fixed solar cells, there will still be significant power improvements after reconfiguration. Fig. 5.4 shows the output voltage of the solar cells when 2 fixed solar cells and one adaptive solar cell are fully shaded. (Thus there are still 2 adaptive solar cells fully illuminated.) As in the previous two experiments, from 0 to \( T_1 \), the output voltage is under uniform illumination. After \( T_1 \),
two fixed solar cells in the same row and one adaptive solar cell are fully shaded. The interval $T_1-T_2$ is time for measurement and control. At $T_2$ three illuminated adaptive solar cells are connected in parallel with the shaded row at the same time. Using the data in Fig 5.4 with (8), it is calculated that there is a 65% increase in output power from before to after the reconfiguration.

5.6 The number of shaded fixed solar cells is larger than the number of solar adaptive bank

It is possible that many adaptive solar cells become shaded and that there will not be sufficient number of them to compensate for all the shaded solar cells in the fixed part.

Alternatively, this could also occur if fewer adaptive solar cells are used, as we only are recommending “m” number of adaptive cells. Still, there is benefit of the reconfiguration algorithms to add power to the system, and both reconfiguration algorithms will still work. Of course, less power can be added to the system.

Fig. 5.5 shows the output voltage of the solar cells when 4 fixed solar cells are fully shaded, 3 of which are in the same row. There remain 3 fully illuminated adaptive solar cells.

From 0 to $T_1$, the output voltage is under uniform illumination. After $T_1$, four fixed solar cells in the same row are fully shaded. The interval $T_1-T_2$ is time for measurement and control. At $T_2$, three illuminated adaptive solar cells are connected in parallel with the
shaded row at the same time. For this experiment, the reconfiguration from T₁ to T₂ led to dramatic increases of power of a 4125% improvement from before to after reconfiguration.

Fig. 5.4 Output voltage of solar PV array before and after reconfiguration when solar adaptive bank is partly shaded

Fig. 5.5 Output voltage of solar PV array when the number of shaded fixed solar cells is larger than the number of solar adaptive bank
5.7 Conclusion

A new approach for adaptive reconfiguration of solar PV arrays under shadow conditions is described. A matrix of switches is used to connect a “fixed” total-cross-tied array with an adaptive array that can be reconfigured. Simple control algorithms are presented that determine how to control the switches to optimize output power. An experimental adaptively reconfigurable solar PV array has been built and tested to verify the proposed configurations.

The switching matrix may still require a large number of switches, and this represents a disadvantage of the approach. However, we show that when the number of rows in the solar array is not too large, the number of switches and sensors is significantly reduced. Further, we present four separate experiments which demonstrate the technical feasibility of two different reconfiguration algorithms. The reconfiguration methods are shown to be effective in improving solar array power, even when the number of shaded arrays is more than the power provided by the adaptive solar modules to be switched into the system. The Model-Based sorting algorithms have reduced calculation time.
6. Single - Stage Two - Input DC-DC Converter for MPPT Solar PV Arrays

6.1 Introduction

In general, a solar array consists of many solar PV submodules, which are connected in parallel and/or series to meet the output requirements. Insolation on each solar module may be different, because of incident angle of solar light, the mismatch of solar submodule parameters, and shadows of nearby objects or clouds.

In the parallel connection, a single shadow over a solar cell does not affect the power delivered by the other solar cells in the submodule. Thus, it is the most robust configuration for solar array under shadow conditions. However, the output voltage is very low (~0.5V).

In the series connection, all the solar cells share the same current, $I_{OUT}$. Thus, when one solar cell becomes shaded, it directly affects the power delivered by the other cells. That is, output current decreases throughout all the cells and there is a significant power drop.

As previously discussed, there are several approaches that have been proposed to reduce the effect of shadows on a solar PV array output power:

In large systems, each of the solar sub-modules can be connected to its own maximum power point (MPP) tracking DC-DC converter and can individually operate near its own
MPP. Thus, the efficiency of the whole system is increased [42], but the method requires a large number of DC-DC converters (equal to the number of solar modules).

In this chapter, we propose the new class of DC-DC converters which is to adaptively reconfigure solar array connections in real time in order to track maximum output power.

Specifically, this chapter presents the following research contributions:

Developing new topology to continuously rearrange the two non-uniform illuminated solar submodules in series and parallel connections by using high frequency switches to facilitate the photovoltaic system to work more as a constant power source even in different operating conditions (i.e. insolation, temperature, loads,…etc). The output of solar PV array will be connected to the load through high frequency filter without MPPT.

The new topology is single-stage two-input DC-DC converter. In this topology the voltage stresses of the main switches will be approximately reduced to a half of the input voltage.

The difference between input and output voltage or current for each cycle will be reduced so that the size of output inductor will be smaller in comparison with conventional buck topology.
6.2 Solar PV array’s model and the conventional MPPT based on Buck-converter topology

6.2.1 Conventional MPPT based on Buck converter

Fig. 6.1 shows the traditional solar PV array MPPT based on Buck converter topology. In this topology, two solar PV sub-arrays PV1 and PV2 are connected in series.

These are the most common topologies used as MPPT’s

- Down or Buck converters
- Up or Boost converters
- Up-Down or Buck-Boost converters

All these topologies can be derived from the basic canonical switching cell.

Fig. 6.1 shows the conventional solar PV array MPPT based on Buck converter. In this topology, two solar PV sub-arrays PV1 and PV2 are connected in series.
a) I-V curve before configuration

b) I-V curve after reconfiguration
Fig. 6.2 The I-V and P-V curves before and after reconfiguration

c) P-V curves

Fig. 6.2 shows the I-V curves and P-V curves for two PV modules connected in series before and after reconfiguration by the proposed method. In the operating lines b and c, the non-shaded solar module PV\(_1\) cannot generate the full power because the current of this module is limited by the current of the shaded module PV\(_2\). So, for example, on operating line b, the non-shaded PV\(_1\) operates at I-V point S\(_{b1}\) and the shaded PV\(_2\) operates at (I-V) point S\(_{b2}\). In series, the total array will operate at their voltage sum, while at the same fixed current, i.e. operating point S\(_b\).

In the operating line a, the non-shaded module PV\(_1\) generate full power, but the operating point of the shaded module PV\(_2\) moves to the negative region. The PV\(_2\) works as a load and causes losses in the system.
The output power is decreased:

$$P_{out} = P_{out1} - P_{loss2}$$  \hspace{1cm} (6.1)$$

From above discussion, the main reason to cause the losses in the solar PV array is that the currents of the series connected solar cells or solar submodules are limited by the current of the shaded solar cell or the shaded solar submodule.

After reconfiguration, the operating point of the solar PV array moved from the point $S_b$ in Fig. 6.2(a) to the point $S_{bmax}$ in Fig. 6.2(b). The maximum output power of the whole solar PV array increases from the point $P_{S_b}$ to $P_{S_{bmax}}$ in Fig. 6.2(c).

### 6.3 Proposed MPPT based on reconfiguration converter

In the proposed scheme, the solar submodules will be reconfigured from series connection to parallel connection in each cycle. The output of solar PV array will be changed from $2V_{pv}$ in ON time to $V_{PV}$ in OFF-time. The voltage stress of high frequency switches will be a half of input voltage ($V_{PV}$). In the OFF-time, the solar PV array does both things: charge capacitor and supply current to the load.

**Interval 1 (0- DT):**

The condition of this period is shown in Fig. 6. 5. In this interval, $S$ is turned ON: $V_{32}>0$ and $V_{14}>0$, the $D_1$ and $D_2$ are turned OFF. The subarray PV$_1$ and PV$_2$ are connected in series. The current goes through: PV$_2$, switch $S$, PV$_1$, output filter (Lo and Co) and load.
Fig. 6.3 Proposed MPPT based on Reconfiguration converter

Fig. 6.4 Two solar PV submodules are connected in series when S is turned ON
The detail will be described below:

**Interval 2 (DT-T)**

As shown in Fig. 6.6, the S is turned OFF during this interval: D₁ and D₂ turn ON, PV₁ and PV₂ are connected in parallel. The current $I_{L0}$ goes through the two solar parallel solar PV₁ and PV₂ submodules, two diodes D₁ and D₂, the output filter (Lo and Co) and load.

The voltage stresses of the main switches are shown in Fig. 6.7. They equal a half of input voltage

$$V_{SW} = \frac{V_{IN}}{2} = V_{PV}$$  \hspace{1cm} (6.1)
6.4 The relationship between the input current and voltage with the output current and voltage

In the steady state, the average voltage of input capacitor equals zero, so we have the following equation:

\[ <V_{c1}> = 0 \]

\[
\frac{1}{C_1} \int_{0}^{T} I_{c1} dt = \frac{1}{C_1} \int_{0}^{DT} (I_0 - I_{IN}) dt + \int_{DT}^{T} (I_{IN} - \frac{I_0}{2}) dt = 0
\]

(6.2)

\[
I_0 = \frac{2I_{IN}}{1 + D}
\]

(6.3)

Here, \( I_{IN} \) - the output current of each solar submodule
If we assume that the converter operates in steady state, the energy stored in each component at the end of a commutation cycle $T$ is equal to that at the beginning of the cycle. That means that the current $I_L$ is the same at $t=0$ and at $t=T$ (see figure 4).

Therefore:

$$\Delta I_{LON} + \Delta I_{LOFF} = 0 \quad (6.4)$$

We have:

$$\frac{V_{IN} - V_0}{L} \times DT + \frac{V_{IN}}{2} - \frac{V_0}{L} \times (1 - D)T = 0 \quad (6.5)$$

From (12) we have:

$$V_0 = \left(\frac{1+D}{2}\right)V_{IN} \quad (6.6)$$
6.5 Simulation result

The parameters of solar PV array (submodule) and the battery are shown in the Table.6.1.

<table>
<thead>
<tr>
<th>No</th>
<th>Item</th>
<th>Symbol</th>
<th>Unit</th>
<th>Con.</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Open circuit voltage</td>
<td>$V_{OC}$</td>
<td>V</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>Short-circuit current of first submodule</td>
<td>$I_{SC1}$</td>
<td>A</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Short-circuit current of second submodule</td>
<td>$I_{SC2}$</td>
<td>A</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Series resistance</td>
<td>$R_S$</td>
<td>Ohm</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>Parallel resistant</td>
<td>$R_{SH}$</td>
<td>Ohm</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>Battery voltage</td>
<td>$V_{BAT}$</td>
<td>V</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>Battery resistance</td>
<td>$R_{BAT}$</td>
<td>Ohm</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>Switching frequency</td>
<td>$F_{SW}$</td>
<td>kHz</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>9</td>
<td>Filter inductor</td>
<td>$L$</td>
<td>uH</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>10</td>
<td>Input capacitor</td>
<td>$C_{IN}$</td>
<td>uF</td>
<td>100</td>
<td>100x2</td>
</tr>
<tr>
<td>11</td>
<td>Output capacitor</td>
<td>$C_{OUT}$</td>
<td>uF</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

In the first simulation schematic, the two solar PV submodules are connected in parallel. The configuration is fixed. The solar PV array charges the battery through the buck converters.
In the second simulation schematic, the two solar PV submodules are reconfigurable, connected by the proposed topology. The solar PV array charges the battery through the buck converters.

**Fig. 6.8** The voltage stress of transistor in a) buck converter and b) Reconfiguration converter

**Fig. 6.9** The voltage stress of main diodes in a) Buck converter and b) Reconfiguration converter
Fig. 6.10 The inductor current ripple in a) Buck converter and b) Reconfiguration converter

Fig. 6.11 The input capacitor voltage ripple a) Buck converter with one $C=100\mu F$, $V_{in}$ b) Reconfiguration converter with two $C=100\mu F$, $V_{in}/2$
6.6 Conclusion

A new topology of the reconfiguration converter of solar PV arrays under shadow conditions is described.

The voltage stress is reduced to a half of input voltage. The size of the energy storage elements is reduced without using more switches.

One disadvantage, may be, the second solar PV array is switched between ground voltage and output voltage of first solar PV array that can be the EMI source.

This thesis only analytically proposes then simulates the new topology. Simulations verify the principles, but to fully understand the capabilities of the approach, experiments should be performed (see Chapter 7 for future research).
7. Conclusions

7.1 General description

With the mass production and use of solar PV energy, the new goal for solar PV research field is to have the breakthrough cost for solar energy. The optimized problem for “maximum output power” and “minimum cost of energy” creates new challenges for solar PV system research. With unlimited space, the solar PV array can be installed in locations without worries from shading objects: trees, booms… and the collectors in solar field installed with the large distance between the rows. With economy calculation, the solar arrays are forced to work in the non-uniform illumination to increase the gross solar photovoltaic area in the limited land, roof area.

In uniform illumination, the large solar PV array is a simple system of “scaled-up” solar cells: the output voltage is equal the voltage of solar cell, multiplied by the number of solar cell in series. The current equals the current of solar cell, multiplies the number of parallel solar cells.

In the non-uniform illumination, the picture is changed. The solar array become the system of mxn solar cells, each solar cell is presented by a source with non-linear characteristics. Although the solar cells may have identical parameters, they still create mismatch losses when they are connected in series/parallel. Because of nonlinear characteristics in the solar cells, non-uniform illumination dramatically reduces the output power of solar PV system. The maximum output power losses (%) are much larger
than the shading factors. The shadows move and change their shape with time. The modeling the solar PV system under dynamic change of illumination is more difficult task.

The shaded cell, in the worst case, becomes the resistor that consumes energy instead of supplying. Because the breakdown voltage of solar cell is large, the shaded cell can create the local hot spot caused damage solar cells. The need of accurate model to analyze and simulate the solar system under shadow conditions is apparent.

Under a passing cloud, the output power of solar array is reduced greatly. In utility grid connected PV systems, the fast reduction in supply power can cause instability of the whole system. This requires the modeling and computing algorithm that simulates and analyzes the effect of non-uniform changing shadows (i.e. a passing cloud) on the output power of solar PV arrays. The software must also be fast enough to be used within real time controllers.

This thesis, in Chapter 2, proposes the software implementation in MATLAB that meets the above requirements. The model also model is flexible enough to simulate solar PV arrays with different scale, various configurations, with or without bypass diode, from different manufacturers.
When the parameters of solar system are changed with the time and environmental conditions, such as temperature, wind speed, humidity…The model is easily updates new parameters in real time, so that simulation of solar PV system is closer to the real system.

The model is able to simulate and detect the local hot spots of solar PV system that is caused by mismatch of solar cells parameters or non uniform illuminations of solar insolation. The local hot spots of solar PV systems are the most reason that causes damage the solar cells or solar submodules or even whole systems. The solar cells under shaded conditions act like loads. They dissipate heat and the semiconductors junctions may be damaged. When the solar cells become fully illuminated, they cannot generate the full power as designed and block the current of the strings subsequently reducing system output power. The solar systems under non-uniform illumination may have much shorter lifetime than normal systems. The proposed model in Chapter 2 can simulate the power dissipation on each shaded solar cell which help define the solar cell temperature is in range of normal working condition or not.

Chapter 3 proposes another approach to simulate and analyze the solar PV system performance based on neural networks. The performance of a solar PV system under any working conditions, uniform illumination or non-uniform illumination, can be predicted using acquired data for short term. Then the collected data are used to generate the functions to characterize the relationship between the performance of the solar PV system and the influence of environmental factors. The main advantages of the proposed neural
network method are that it is possible to simulate and analyze the solar PV system performance, without knowing the parameters of solar cells, or the system configuration.

Chapter 3, uses the solar irradiation levels, the solar photovoltaic array’s temperature, and the sun’s position angles as the input signals, and the maximum output power of the solar PV array as an output signal. The maximum output power or maximum output power losses of the shaded solar PV array can be calculated based on shading function without a shading factor calculation. A neural network structure is proposed, combining the multilayer perceptrons feed-forward network with a back-propagation algorithm that can accurately simulate maximum output power of solar photovoltaic arrays under shadow conditions.

The detailed procedures to collect the training data for the model and to check the accuracy and generalization of the network are described. By using only readily available solar irradiation data at different times of a day, wherever the solar PV array is installed the proposed approach can be employed to accurately predict the maximum output power of the solar PV array over long periods of time with low computational efforts. The disadvantage of proposed neural network method is the collected data needs to be cleaned and checked their possible correlation before input to the neural network simulation tools.

Chapter 4 of this thesis proposes a practical reconfigurable solar array. The previous approaches of reconfigurable solar PV array are unrealistic because of large number of required sensors, switches and complicated control algorithm.
This thesis proposes a reconfiguration method of solar PV array that requires fewer switches and simplified control algorithms by choosing the appropriate configuration of main fixed part of solar array and reconfiguring only a small percentage of the solar arrays. The reconfiguration is executed through the proposed switching matrix. In uniform illumination, both fixed and adaptive parts are equally connected in parallel so they can generate full power to the load. In non-uniform illumination, the number of the adaptive solar cells connected to the shaded submodules depends on the shaded area of submodules. They create the paths for currents in the non-shaded solar cells in the same string and bypass the shaded cells. The output power will just be reduced by the amount proportional to the shaded area. Two simple control decision algorithms are proposed to determine when and how the switches between the fixed part and adaptive bank of the solar PV array are open and closed. The algorithms will rely on predictive models that can be implemented in real-time by a micro-controllers or DSP. To our knowledge, it is the first time that such adaptive and implementable algorithms have been reported. For large solar PV system, we propose using the switching matrix the electromechanical relays to increase the current going through panels. The proposed reconfiguration method helps avoid the local maximum power points as well as the local hotspots of solar PV arrays, thus the central maximum power point tracker can be used to track the maximum output power of the whole solar PV array.

In the proposed reconfiguration method, to define the shadow pattern of large solar PV system, we propose the algorithm that use only minimum number of voltage sensors
(two). This algorithm can be used for monitoring shaded solar PV system in other applications.

In Chapter 5, a small test experimented platform was created to validate the proposed solar PV array reconfiguration methods and control algorithms. The experiment includes the following: The fixed solar array is from 9 solar cells, 3 rows (m) and 3 columns (n) (TCT connection). The solar adaptive bank combine from 3 solar cells (one string of 3 x1 cells) connected to the fixed part (3x3). The (3x3) switching matrix, controlled by Agilent Data Acquisition/Switch Unit 34970A, is connected between the fixed part and the solar adaptive bank. In total, we use 18 switches in the switching matrix and 6 voltage sensors (two of them are voltage monitors) for this test platform. The experiments demonstrate the technical feasibility of both control algorithms. The model-based algorithm have reduced calculation time and show advantage over bubble sort method when applying for large solar PV system because in model based method all solar cells in the adaptive bank are reconfigured synchronously.

Four experiments with different possible shadow patterns are demonstrated and shown to be effective in improving solar array power, even when the number of shaded arrays is more than the power provided by the adaptive solar modules to be switched into the system.
In the next section, the future work of this thesis is to build new topology of the reconfiguration converter of solar PV arrays under shadow conditions. From first investigation and analyzing of new topology, there may be many possible advantages:

- The voltage stress is reduced to a half of input voltage.
- The size of the energy storage elements is reduced without using more switches.
- The total output power may be higher than power output of shaded solar array with only one central dc-dc converters.
- One disadvantage, may be, the second solar PV array is switched between ground voltage and output voltage of first solar PV array that can be the EMI source.

### 7.2 Future research: Design of proposed reconfiguration converter

To build a prototype to verify the advantage of the proposed single stage two-input dc/dc converters for tracking MPP of solar PV array

The power source from a solar panel GP 3-30 is considered a "current-limited" voltage source. The solar panel is divided in two parts, each part has the same number of solar cells (6 solar cells) connected in series. Before the design we firstly set the input DC voltage range. We define

- $V_{P_{\text{MAX}}}$ as the maximum input voltage, $V_{P_{\text{MIN}}}$ as the minimum input DC voltage: $V_{P_{\text{MAX}}}=16\text{V}$; $V_{P_{\text{MIN}}}=8\text{V}$; $V_{\text{OUT}}=12\text{V}$
- Input power: $P_{P_{\text{MAX}}}=15\text{W}$; $P_{\text{IN MAX}}=30\text{W}$
- Maximum output current of solar PV array: $I_{\text{OUT}}=2.3\text{A}$
The maximum power from the solar panel to charge a 12V Li-Ion battery can be achieved by regulating the system bus voltage around the MPP through charge current reduction when the total current demand from the system and battery charging exceeds the output current capability from the solar panel. System power and battery charging power control architecture are critical elements for designing a reliable solar panel powered system.

The switching frequency is 50 kHz, switching period is 20 $\mu$s. The duty ratio: $D=0.5$

Main switches:

*Transistor S*, the voltage stress is $V_{PV\text{MAX}}=8V$ and maximum current is 20V, 2A, MTM862270LBFC-ND

*Rectifier diodes*: D1-D2, maximum current is 1.2 A, MURA105T3, 2A, 50V.

### 7.2.1 Input capacitor design for proposed converter. The comparison with conventional Buck converter

*For the Buck converter:*

The minimum size of input filter capacitors is defined by:

$$C \geq \frac{I_{IN}(1-D)T}{\Delta v_{IN}}$$  \hspace{1cm} (7.1)

*For the proposed converter:*

Current relation: With ripple frequency, the capacitor is assumed to be sorted, the average voltage of capacitor equal zero. We have:

$$I_{C1} = C_1 \frac{dV_{C1}}{dt}$$  \hspace{1cm} (7.2)
The minimum size of capacitor that ripple of the input voltage $V_{pv1}$ less than requirement:

$$C_i \geq \frac{I_{IN}\times D\times (1-D)T}{(1+D)\times \Delta V_{PVM}}$$  \hspace{1cm} (7.3)

The comparison the size of capacitors of the both schemes:

If $I_{IN}=0.75 \times I_{OUT}$, $D=0.75$ for buck converter:

$$C \geq \frac{I_{IN}(1-D)T}{\Delta V_{IN}} = \frac{I_{IN} \times 0.25}{\Delta V_{IN}} T$$  \hspace{1cm} (7.4)

*For proposed converter:*

$D=0.5$

$$C_i \geq \frac{I_{IN}\times D\times (1-D)T}{(1+D)\times \Delta V_{PVM}} = \frac{I_{IN} \times 0.25}{1.5 \times \Delta V_{PVM}} T$$  \hspace{1cm} (7.5)

$$C_{1\text{MIN}} = \frac{C_{MIN} \times \Delta V_{IN}}{1.5 \times \Delta V_{PVM}}$$  \hspace{1cm} (7.6)

Input capacitor: $C1 = C2 = 100 \ \mu F$, 135D506X9025F2CAP, WET TANT 50UF 10% 60V AXIAL

### 7.2.2 Output inductor design:

A rule of thumb, which we will use later for selecting a value of inductance in an LC filter, is to start with an inductor value that results in a peak-to-peak inductor current that
is 10% of the full load current. For our example of a 12 V output, 2.4 A load, and 50 kHz switching frequency, the inductor can be calculated from the formula $V = L \cdot (di/dt)$.

*For the Buck converter:*

The energy storage elements are sized by the following equation:

The minimum size of output inductor is defined by:

$$L_{\text{Buck}} \geq \frac{V_{\text{OUT}} (1-D)T}{\Delta i_L}$$

(7.7)

*For the proposed converter:*

The minimum size of output inductor is defined by:

$$L_p \geq \frac{(V_{\text{OUT}} - V_{\text{IN}}/2)(1-D)T}{\Delta i_L}$$

(6.7)

*Comparison:*

If for both converter $V_{\text{OUT}} = 0.75 \, V_{\text{IN}}$, with the same current ripple requirement:

$$L_{\text{PMIN}} = \frac{2L_{\text{BUCKMIN}}}{3}$$

(7.8)

Output inductor: 0.5 mH, LHL13NB101K-ND, INDUCTOR 100UH 2.0A RADIAL

### 7.2.3 Output capacitor design

Both buck and proposed converter have the same equation for output filter capacitor design:
\[ C_{OUT} \geq \frac{I_{OUT} (1 - D) T}{\Delta V_{OUT}} \]  \hspace{1cm} (7.9)

Output capacitor: 135D506X9025F2CAP, 50UF 10% 60V AXIAL
APPENDIX A MATLAB source code for modeling solar PV arrays under shadow conditions

MAIN
function [P] = main(Isc)
Isc=Isc
% % Short circuit current
[y,x] = size(Isc);
m = (x-1)*y;
n = x*(y-1);
z = m+n+1;
z1 = x*y; % indexes for VA
z2 = (x-1)*(y-1); % indexes for VB
z3 = 1; % indexes for I
V =20;
I= 14;
%VA =2.1*ones(y,x);
VA =2.1*ones(y,x);
VB = zeros(y-1,x-1);
Res = 0.01*ones(y-1,x-1);
u(1:z1,1) = reshape(VA',1,z1)
u(z1+1:z1+z2,1) = reshape(VB',1,z2)
u(z1+z2+z3,1) = I
% Algorithm
% start with u0
epsilon = 1e-4; Error = 1;
while (Error > epsilon)
dU = Jacobian(u, Res, Isc);
[ru] = r_f(u, V, Isc, Res);
u = u - 0.04*inv(dU)*ru
Error = norm(inv(dU)*ru);
end
Cout=u(z1+z2+z3,1);
% Power output
P=Cout*V

CLOUD SIMULATION
[X,Y] = meshgrid(0:1:9,0:1:9);
for i=1:10
R = sqrt((X-(i-1)).^2 + (Y-(i-1)).^2) + eps
Z = (0.5 + sin(R)./(1+R))
figure
Xlabel('m')
Ylabel('n')
Zlabel('Irradiation (Isc/Isc0)')
mesh(X,Y,Z,'EdgeColor','black')
surf(X,Y,Z)
colormap hsv
colorbar
az = -132;
el = 7;
view(az, el);
end
CURRENT CALCULATIONS
function \[ C = \text{Curr}(\text{Isc}, V) \]
\[
q = 1.6022 \times 10^{-19}; \\
a = 6.55; \\
k = 1.3806 \times 10^{-23}; \\
T = 300; \\
I0 = 3.403 \times 10^{-7}; \\
Rsh = 53; \\
Rs = 0
\]
% Open circuit output voltage
\[
mVT = \frac{a \times k \times T}{q}; \\
Voc = mVT \times \log(Isc/I0+1) \\
b = \frac{q \times Voc}{(a \times k \times T)}; \\
sigma = Voc/(Rsh \times Isc); \\
bbd = b; \\
lodb = 15e-13; \\
Vt = 0.026; \\
C = Isc - \left( Isc \times \frac{(1-sigma)}{(exp(b)-1)} \times \left( exp(b \times V/Voc) - 1 \right) \right) - (IsceV/Voc\times sigma)
\]
function \[ dI = dIdV(\text{Isc}, V) \]
\[
q = 1.6022 \times 10^{-19}; \\
a = 6.55; \\
k = 1.3806 \times 10^{-23}; \\
T = 300; \\
I0 = 3.403 \times 10^{-7}; \\
Rsh = 53; \\
Rs = 0
\]
% Open circuit output voltage
\[
mVT = \frac{a \times k \times T}{q}; \\
Voc = mVT \times \log(Isc/I0+1) \\
b = \frac{q \times Voc}{(a \times k \times T)}; \\
sigma = Voc/(Rsh \times Isc); \\
bbd = b; \\
lodb = 15e-13; \\
Vt = 0.026; \\
dl = -(Isc \times (b\times Voc) \times (1-sigma)/(exp(b)-1) \times \left( exp(b \times V/Voc) \right)) - (sigma\times IsceV/Voc)
\]
function \[ dI = dIdV_B(\text{R}, V) \]
\[
dl = 1/R;
\]
JACOBIAN MATRIX
% Return the Jacobian matrix of r(u)
function \[ dU = \text{Jacobian}(u, \text{Res}, \text{Isc}) \]
\[
[y, x] = \text{size}(\text{Isc}); \\
m = (x-1)\times y; \\
n = x\times(y-1); \\
z = m+n+1; \\
dU = \text{zeros}(z+1, z+1);
\]
\[
z1 = x\times y; \text{ indexes for VA} \\
z2 = (x-1)\times(y-1); \text{ indexes for VB}
\]
% for i = 1: (y)
%     for j = 1: (x)
%         VA(i,j) = u( (i-1)*x+j );
%         IA(i,j) = Curr(Isc(i,j), VA(i,j));
%     end
% end

for i , j = 1:(x-2)
    VA(i,j) = u( (i-1)*x+j );
    IA(i,j) = Curr(Isc(i,j), VA(i,j));
end

for i = 1: (y-1)
    for j = 1: (x-1)
        VB(i,j) = u( (i-1)*(x-1)+j +z1 );
        IB(i,j) = VB(i,j)/Res(i,j);
    end
end

%ru(1) = sum(VA(:,1)) - V;
for i = 1:y
    dU(1,1+x*(i-1)) = 1;
end

%for loops on the 1st row
i = 1;
for j = 1: (x-1)
    index = (i-1)*(x-1) + (j-1) + 2;
    %ru(index) = VA(i,j) - VB(i,j) - VA(i,j+1);
    dU(index, (i-1)*(x)+j ) = 1;
    dU(index, z1 + (i-1)*(x-1)+j ) = -1;
    dU(index, (i-1)*(x)+j+1 ) = -1;
end

%for middle loops
for i = 2: (y-1)
    for j = 1: (x-1)
        index = (i-1)*(x-1) + (j-1) + 2;
        %ru(index) = VA(i,j) - VB(i,j) - VA(i,j+1) + VB(i-1,j);
        
    end
end
\[ dU(index, (i-1)*(x)+j ) = 1; \]
\[ dU(index, z1 + (i-1)*(x-1)+j ) = -1; \]
\[ dU(index, (i-1)*(x)+j+1 ) = -1; \]
\[ dU(index, z1 + (i-2)*(x-1)+j ) = 1; \]
\[ \text{end} \]
\[ \text{end} \]
\[ \% \text{for loops on the last row} \]
\[ i = y; \]
\[ \text{for } j = 1:(x-1) \]
\[ \text{index} = (i-1)*(x-1) + (j-1) + 2; \]
\[ \% ru(index) = VA(i,j) - VA(i,j+1) + VB(i-1,j); \]
\[ dU(index, (i-1)*(x)+j ) = 1; \]
\[ dU(index, (i-1)*(x)+j+1 ) = -1; \]
\[ dU(index, z1 + (i-2)*(x-1)+j ) = 1; \]
\[ \text{end} \]
\[ \text{%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %} \]
\[ \% ru(index+1) = \text{sum}(IA(1,:)) - I; \]
\[ \text{for } j=1:x \]
\[ dU(index+1, j) = dldV(Isc(1,j), VA(1,j)); \]
\[ \text{end} \]
\[ dU(index+1, z+1) = -1; \]
\[ \text{start} = index+1; \]
\[ \% \text{for nodes in the 1st column} \]
\[ \text{for } i = 1:(y-1) \]
\[ j=1; \]
\[ \text{index} = \text{start} + (i-1)*x + (j-1) + 1; \]
\[ \% ru(index) = IA(i,j) + IB(i,j) - IA(i+1,j); \]
\[ dU(index, (i-1)*x+j ) = dldV(Isc(i,j), VA(i,j)); \]
\[ dU(index, z1 + (i-1)*(x-1)+j ) = dldV_B(Res(i,j), VB(i,j)); \]
\[ dU(index, (i)*x+j ) = -dldV(Isc(i+1,j), VA(i+1,j)); \]
\[ \text{end} \]
\[ \% \text{for middle nodes} \]
\[ \% \text{for } i = 1:(y-1) \]
\[ \% \text{for } j = 2:(x-1) \]
\[ \% \text{index} = \text{start} + (i-1)*x + (j-1) + 1; \]
\[ \% \% ru(index) = IA(i,j) + IB(i,j) - IA(i+1,j) - IB(i,j-1); \]
\[ dU(index, (i-1)*x+j ) = dldV(Isc(i,j), VA(i,j)); \]
\[ dU(index, z1 + (i-1)*(x-1)+j ) = dldV_B(Res(i,j), VB(i,j)); \]
\[ dU(index, (i)*x+j ) = -dldV(Isc(i+1,j), VA(i+1,j)); \]
\[ \% \text{end} \]
\[ \% \text{end} \]
\[ \% \text{Unidentical} \]
\[ \% \text{---------------------------------------------------------------} \]
\[ \text{for } i = 1:(y-1) \]
\[ \text{for } j = 2:(x-2) \]
\[ \text{index} = \text{start} + (i-1)*x + (j-1) + 1; \]
\[ \% ru(index) = IA(i,j) + IB(i,j) - IA(i+1,j) - IB(i,j-1); \]
\[
dU(index, (i-1)*x+j) = dIdV(Isc(i,j), VA(i,j));
\]
\[
dU(index, z1 + (i-1)*(x-1)+j) = dIdV_B(Res(i,j), VB(i,j));
\]
\[
dU(index, (i)*x+j) = -dIdV(Isc(i+1,j), VA(i+1,j));
\]
\[
dU(index, z1 + (i-1)*(x-1)+j-1) = -dIdV_B(Res(i,j-1), VB(i,j-1));
\]
\end{verbatim}

\begin{verbatim}
end
end
for i = 1:(y-1)
for j = (x-2):(x-1)
    index = start + (i-1)*x + (j-1) + 1;
    \%ru(index) = IA(i,j) + IB(i,j) - IA(i+1,j) - IB(i,j-1);
    dU(index, (i-1)*x+j) = dIdV1(Isc(i,j), VA(i,j));
    dU(index, (i)*x+j) = -dIdV1(Isc(i+1,j), VA(i+1,j));
    dU(index, z1 + (i-1)*(x-1)+j-1) = -dIdV_B(Res(i,j-1), VB(i,j-1));
end
end
%----------------------------------------------------------------------------
%for nodes in the last column
% for i = 1:(y-1)
%   j = x;
%     index = start + (i-1)*x + (j-1) + 1;
%     \%ru(index) = IA(i,j) - IA(i+1,j) - IB(i,j-1);
%     dU(index, (i-1)*x+j) = dIdV(Isc(i,j), VA(i,j));
%     dU(index, (i)*x+j) = -dIdV(Isc(i+1,j), VA(i+1,j));
%    dU(index, z1 + (i-1)*(x-1)+j-1) = -dIdV_B(Res(i,j-1), VB(i,j-1));
% end
%Unidentical
%---------------------------------------------------------------------------------
for i = 1:(y-1)
    j = x;
    index = start + (i-1)*x + (j-1) + 1;
    \%ru(index) = IA(i,j) - IA(i+1,j) - IB(i,j-1);
    dU(index, (i-1)*x+j) = dIdV1(Isc(i,j), VA(i,j));
    dU(index, (i)*x+j) = -dIdV1(Isc(i+1,j), VA(i+1,j));
    dU(index, z1 + (i-1)*(x-1)+j-1) = -dIdV_B(Res(i,j-1), VB(i,j-1));
end
%Return the Jacobian matrix of r(u, V, Isc). Isc is a vector
%u = [VA, VB, I];

function [ru] = r_f(u, V, Isc, Res)

[y,x] = size(Isc);
z1 = x*y; %indexes for VA
z2 = (x-1)*(y-1); %indexes for VB
z3 = 1; %indexes for I

for i = 1:(y)
    for j = 1:(x-2)
        VA(i,j) = u((i-1)*x+j);
        IA(i,j) = Curr(Isc(i,j), VA(i,j));
    end
end

155
end

for i = 1:y
  for j = (x-1):x
    VA(i,j) = u((i-1)*x+j);
    IA(i,j) = Curr1(Isc(i,j), VA(i,j));
  end
end

for i = 1:(y-1)
  for j = 1:(x-1)
    VB(i,j) = u((i-1)*(x-1)+j+z1);
    IB(i,j) = VB(i,j)/Res(i,j);
  end
end

I = u(z1+z2+z3);

ru(1,1) = sum(VA(:,1)) - V;

% for loops on the 1st row
i = 1;
  for j = 1:(x-1)
    index = (i-1)*(x-1) + (j-1) + 2;
    ru(index,1) = VA(i,j) - VB(i,j) - VA(i,j+1)
  end

% for middle loops
for i = 2:(y-1)
  for j = 1:(x-1)
    index = (i-1)*(x-1) + (j-1) + 2;
    ru(index,1) = VA(i,j) - VB(i,j) - VA(i,j+1) + VB(i-1,j)
  end
end

% for loops on the last row
i = y;
  for j = 1:(x-1)
    index = (i-1)*(x-1) + (j-1) + 2;
    ru(index,1) = VA(i,j) - VA(i,j+1) + VB(i-1,j)
  end

% index - 1 - (x-1)*y
ru(index+1,1) = sum(IA(1,:)) - I
start = index + 1; % numbers of equations r(u) before node equations

% for nodes in the 1st column
for i = 1:(y-1)
  j=1;

index = start + (i-1)*x + (j-1) + 1;
ru(index,1) = IA(i,j) + IB(i,j) - IA(i+1,j)
end
%for middle nodes
for i = 1:(y-1)
    for j = 2:(x-1)
        index = start + (i-1)*x + (j-1) + 1;
        ru(index,1) = IA(i,j) + IB(i,j) - IA(i+1,j) - IB(i,j-1)
    end
end
%for nodes in the last column
for i = 1:(y-1)
    j = x;
    index = start + (i-1)*x + (j-1) + 1;
    ru(index,1) = IA(i,j) - IA(i+1,j) - IB(i,j-1)
end
APPENDIX B MATLAB code for modeling solar PV array using neural network method

Input data file

load Irradiance_Time
[Poutmax]= xlsread('NN_05_07','Poutmax')
Isc=Isc;
Ishadow=Ishadow;
Vout=Vout;

Main file

location.longitude = -71.09177;
location.latitude = 42.34153;
location.altitude = 10;
[m,n]=size(Time)
for i=1:m
    time.year = Year(i);
    time.month = Month(i);
    time.day = Day(i);
    time.hour = Hour(i);
    time.min = Minute(i);
    time.sec = Second(i);
    time.UTC = -4;
    sun = sun_position(time, location);
end
load Time_Isc_Poutmax
clear x1 x2 x3 y;
[m,n]=size(Time)
for i=1:m
    x1(i)=z(i).zenith;
    x2(i)=z(i).azimuth;
    x3(i)=Isc(i);
    x4(i)=Ktemp(i);
    y(i)=Poutmax(i);
end
X = [x2; x3; y]
save allresults.csv, X'

p = [x2; x3; x4];
t= [y];

%Step 1: Normalized the inputs and target
[n,meanzh,stdz,tn,meant,stdt] = prestd(p,t)
[pn,meanzh,stdz] = prestd(p);
[ptrans,transMat] = prepca(pn,0.001);
%Step 2: Chek size of transformed data
\[ R, Q \] = size(ptrans)
\[ ptrans, tn \] = randomize(ptrans, tn)

% ________________________________________________________________________
% \[ R, Q \] = size(p)
% \[ ptrans, tn \] = randomize(p, t)

% Step3: The next step is to divide the data up into training and test subsets. We will take one fourth of the data for the validation set, one fourth for the test set and one half for the training set. We pick the sets as equally spaced points throughout the original data.
Trnumber = round(Q * 0.7);
\[ ptr, ttr, ptest, ttest \] = randpick(ptrans, tn, Trnumber, t)
\[ ptr, ttr, ptest, ttest \] = randpick(p, t, Trnumber, t)
% iitst = [2:4:Q];
% iiitr = [1:4:Q 3:4:Q 4:4:Q];
% test.P = ptrans(:, iitst); test.T = tn(:, iitst);
% ptr = ptrans(:, iiitr); ttr = tn(:, iiitr);
% test2 = ptrans(:, iitst);

% Training net
net = newff(minmax(ptr), [3 1], {'tansig', 'purelin'}, {'trainlm'});
[net, tr] = train(net, ptr, ttr, [], []);
net.performFcn = 'msereg';
net.performParam.ratio = 1;
net.trainParam.show = 5;
net.trainParam.epochs = 300;
net.trainParam.goal = 2e-2;

% net.performFcn = 'msereg';
% % net.performParam.ratio = 0.5;
% % net.trainParam.show = 5;
% % net.trainParam.epochs = 200;
% % net.trainParam.goal = 1e-5;
% % net.trainParam.show = 5;
% % net.trainParam.lr = 0.05;
% % net.trainParam.epochs = 235;
% % net.trainParam.goal = 1e-10;
% Test
plot(tr.epoch, tr.perf)
legend('Training', '-1');
ylabel('Squared Error'); xlabel('Epoch')

% plot(tr.epoch, tr.perf, tr.epoch, tr.vperf)
% legend('Training', 'Test', '-1');
% ylabel('Squared Error'); xlabel('Epoch')
% figure
% %plot(tr.epoch, tr.tperf)
% plot(tr.epoch, tr.perf)
% legend('Training', 'Test', '-1');
% ylabel('Squared Error'); xlabel('Epoch')
% plot(tr.epoch, tr.perf, tr.epoch, tr.tperf)
% legend('Training', 'Test', '-1');
% ylabel('Squared Error'); xlabel('Epoch')
% Test data set
% an = sim(net,ptrans);
a = sim(net,ptest);
% a = poststd(an,meant,stdt);

figure
[m,b,r] = postreg(a,ttest);
ylabel('Predicted power(W)'); xlabel('Measured power(W)')

---

**Sun position**

function sun = sun_position(time, location)
% sun = sun_position(time, location)
%
% This function compute the sun position (zenith and azimuth angle at
% the observer
% location) as a function of the observer local time and position.
% It is an implementation of the algorithm presented by Reda et Andreas
% in:
%   radiation application. National Renewable Energy Laboratory (NREL)
%   Technical report NREL/TP-560-34302.
% This document is avalaible at www.osti.gov/bridge
%
% This algorithm is based on numerical approximation of the exact
equations.
% The authors of the original paper state that this algorithm should be
% precise at +/- 0.0003 degrees. I have compared it to NOAA solar table
% (http://www.srrb.noaa.gov/highlights/sunrise/azel.html) and to USNO
% solar
% table (http://aa.usno.navy.mil/data/docs/AltAz.html) and found very
% good
% correspondance (up to the precision of those tables), except for
% large
% zenith angle, where the refraction by the atmosphere is significant
% (difference of about 1 degree). Note that in this code the correction
% for refraction in the atmosphere as been implemented for a
temperature
% of 10C (283 kelvins) and a pressure of 1010 mbar. See the subfunction
% «sun_topocentric_zenith_angle_calculation» for a possible
modification
% to explicitley model the effect of temperature and pressure as
describe
% in Reda & Andreas (2003).
%
% Input parameters:
%   time: a structure that specify the time when the sun position is
% calculated.
%     time.year: year. Valid for [-2000, 6000]
%     time.month: month [1-12]
%     time.day: calendar day [1-31]
time.hour: local hour [0-23]
% time.min: minute [0-59]
% time.sec: second [0-59]
% time.UTC: offset hour from UTC. Local time = Greenwich time +
% This input can also be passed using the Matlab time format ('dd-
% mmm-yyyy HH:MM:SS').
% In that case, the time has to be specified as UTC time (time.UTC =
% 0)
%
% location: a structure that specify the location of the observer
% location.latitude: latitude (in degrees, north of equator is
% positive)
% location.longitude: longitude (in degrees, positive for east of
% Greenwich)
% location.altitude: altitude above mean sea level (in meters)
%
% Output parameters
% sun: a structure with the calculated sun position
% sun.zenith = zenith angle in degrees (angle from the vertical)
% sun.azimuth = azimuth angle in degrees, eastward from the
% north.
% Only the sun zenith and azimuth angles are returned as output, but a
% lot
% of other parameters are calculated that could also extracted as
% output of
% this function.
APPENDIX C MATLAB code for control solar PV array reconfiguration

function []=main2()
% Step 1: Origin State
% [Org]=Origin State2()
% Step 2: Check shadow ratio
% Start control
cont=0
for k=1:5
[Vmin,Vmax]=StartDC2()
range=0.03*Vmax;
[Y1,Z1]=Scan()
if Vmin<range
% Step 3: Define the photogenerated currents
% Step 4:
% Disconnect fixed and added parts
[Open]=Open_State()
SW=zeros(3,3);
for i=1:3
% a) Measure
[Vfix]=StartDC1()
[SW]=Switches1(Vfix,i,SW)
% b) Adding: Switching command
[T]=Switches(SW)
[Y2,Z2]=Scan()
end
[Y5,Z5]=Scan()
else
end
end
% Step 5: Check shadow ratio after reconfig
[Y6,Z6]=Scan

function [SW]=Switches1(Vfix,i,SW)
SW=SW
[A1,indexV]=sort(Vfix,'ascend');
m=i;
n=indexV(1);
SW(m,n)=1;

function [Iadd, Ifixed, Iout]=getVDC2(RA, RF, R)
s = serial('COM1');
set(s,'BaudRate',9600)
get(s,{'BaudRate','DataBits','Parity','StopBits'})
set(s,'Timeout',60); % to avoid long waiting when there is a problem...
 fopen(s);
 fprintf(s,'ABOR'); % abort running scan
 query(s,'R?'); % delete data from the buffer
 fprintf(s,'ROUT:OPEN (@ 311:338)');% Open all channels
 fprintf(s,'ROUT:SCAN (@101:109)'); % set the channels to be scanned
 % Measure the ladd

162
fprintf(s,'ROUT:CLOS (@ 341)')
fprintf(s,'MEAS:VOLT:DC? (@101)')
fprintf(s,'ROUT:OPEN (@ 341)

fprintf(s,'ROUT:CLOS (@ 342)')
fprintf(s,'MEAS:VOLT:DC? (@101)')
fprintf(s,'ROUT:OPEN (@ 342)

fprintf(s,'ROUT:CLOS (@ 343)')
fprintf(s,'MEAS:VOLT:DC? (@101)')
fprintf(s,'ROUT:OPEN (@ 343)

% Measure the Ifix

fprintf(s,'ROUT:CLOS (@ 341)')
fprintf(s,'MEAS:VOLT:DC? (@101)')
fprintf(s,'ROUT:OPEN (@ 341)

fprintf(s,'ROUT:CLOS (@ 342)')
fprintf(s,'MEAS:VOLT:DC? (@101)')
fprintf(s,'ROUT:OPEN (@ 342)

fprintf(s,'ROUT:CLOS (@ 343)')
fprintf(s,'MEAS:VOLT:DC? (@101)')
fprintf(s,'ROUT:OPEN (@ 343)

%--------------------------------------------------

x=str2num(fscanf(s))

%Sense resistors
Iadd=x(1,1:3)./RA
Ifixed=Iout .+ x(1,4:6)./RF

% Chanel 107 measure the current
% Chanel 108 measure the total output voltage
Iout=x(1,8)./R
fclose(s)

function [Y]=Monitor2()

s = serial('COM1');
set(s,'BaudRate',9600)
get(s,{'BaudRate','DataBits','Parity','StopBits'})
set(s,'Timeout',60);       % to avoid long waiting when there is a problem...
fopen(s);
fprintf(s,'ABOR');         % abort running scan
query(s,'R?');            % delete data from the buffer
for i=1:20
fprintf(s,'MON:VOLT:DC? (@107)')
y(i)=str2num(fscanf(s));
end
Y=y
fclose(s)

% Step 1: Original state
% Each cell connects to each row

function [Open]=Open_State()
\texttt{s = serial('COM1');}
\texttt{set(s,'BaudRate',9600)}
\texttt{get(s,{'BaudRate','DataBits','Parity','StopBits'})}
\texttt{set(s,'Timeout',60); \hspace{1cm} \% to avoid long waiting when there is a problem...}
\texttt{fopen(s);}
\texttt{fprintf(s,'ABOR'); \hspace{1cm} \% abort running scan}
\texttt{query(s,'R?'); \hspace{1cm} \% delete data from the buffer}
\texttt{fprintf(s,'ROUT:OPEN (@311:338)')}
\texttt{Open=1}
\texttt{fclose(s)}

\texttt{% Step 1: Original state}
\texttt{% Each cell connects to each row}
\texttt{function [Org]=Origin_State2()}
\texttt{s = serial('COM1');}
\texttt{set(s,'BaudRate',9600)}
\texttt{get(s,{'BaudRate','DataBits','Parity','StopBits'})}
\texttt{set(s,'Timeout',60); \hspace{1cm} \% to avoid long waiting when there is a problem...}
\texttt{fopen(s);}
\texttt{fprintf(s,'ABOR'); \hspace{1cm} \% abort running scan}
\texttt{query(s,'R?'); \hspace{1cm} \% delete data from the buffer}
\texttt{fprintf(s,'ROUT:OPEN (@311:338)')}
\texttt{fprintf(s,'ROUT:CLOS (@313;324;335)') \% To origin state}
\texttt{Org=1}
\texttt{fclose(s)}
\texttt{function [Vout,I]=Scan()}
\texttt{s = serial('COM1');}
\texttt{set(s,'BaudRate',9600)}
\texttt{get(s,{'BaudRate','DataBits','Parity','StopBits'})}
\texttt{set(s,'Timeout',60); \hspace{1cm} \% to avoid long waiting when there is a problem...}
\texttt{fopen(s);}
\texttt{fprintf(s,'ABOR'); \hspace{1cm} \% abort running scan}
\texttt{query(s,'R?'); \hspace{1cm} \% delete data from the buffer}
\texttt{fprintf(s,'TOT:CLE:IMM (@101:108)');}
\texttt{fprintf(s,'ROUT:SCAN (@101:108)');}
\texttt{fprintf(s,'ROUT:MON (@107)');}
\texttt{fprintf(s,'ROUT:MON:STATE ON');}
\texttt{\%Enable monitoring}
\texttt{for i=1:10}
\texttt{fprintf(s,'ROUT:MON:DATA?');}
\texttt{Vout(i)=str2num(fscanf(s));}
\texttt{end}
\texttt{fclose(s);}
\texttt{fclose(s);}
\texttt{fprintf(s,'ROUT:MON (@108)');}
\texttt{fprintf(s,'ROUT:MON:STATE ON ');}
\texttt{\%Enable monitoring}
\texttt{for i=1:10}
\texttt{fprintf(s,'ROUT:MON:DATA?');}
\texttt{I(i)=str2num(fscanf(s));}
\texttt{end}
\texttt{Vout=Vout;}
\texttt{I=I;}

\texttt{164}
fclose(s)
%Step2: Check shadow ratio
function [V]=StartDC1()

s = serial('COM1');
get(s,{'BaudRate','DataBits','Parity','StopBits'})
set(s,'Timeout',60); % to avoid long waiting when there is a problem...
fopen(s);
fprintf(s,'ABOR'); % abort running scan
query(s,'R?'); % delete data from the buffer
fprintf(s,'ROUT:OPEN (@ 311:338)');% Open all channels
fprintf(s,'ROUT:CLOS (@313,324,335)')%Go to original state
fprintf(s,'ROUT:SCAN (@104:106)') ; % set the channels to be scanned
fprintf(s,'MEAS:VOLT:DC? (@104:106)')% Measurement of rows voltage
fprintf(s,'MEAS:TEMP TC,J,(@109)')% Measurement of temperature
x=str2num(fscanf(s));
[m,n]=size(x);
V=x
fclose(s)
% Adding: Matrix switches
function [T]=Switches(SW)
s = serial('COM1');
get(s,{'BaudRate','DataBits','Parity','StopBits'})
set(s,'Timeout',60); % to avoid long waiting when there is a problem...
fopen(s);
fprintf(s,'ABOR'); % abort running scan
query(s,'R?'); % delete data from the buffer
if SW(3,1) == 1
    fprintf(s,'ROUT:CLOS (@333)')
end
if SW(3,2)==1
    fprintf(s,'ROUT:CLOS (@323)')
end
if SW(3,3)==1
    fprintf(s,'ROUT:CLOS (@313)')
end
if SW(2,1)==1
    fprintf(s,'ROUT:CLOS (@334)')
end
if SW(2,2)==1
    fprintf(s,'ROUT:CLOS (@324)')
end
if SW(2,3)==1
    fprintf(s,'ROUT:CLOS (@314)')
end
if SW(1,1)==1
    fprintf(s,'ROUT:CLOS (@335)')
end
if SW(1,2)==1
    fprintf(s,'ROUT:CLOS (@325)')
end
if SW(1,3)==1; fprintf(s,'ROUT:CLOS (@315)'); end; fclose(s); T=1
References

[7] F. Jeffrey, Power Film Inc., Private communication


[38] Energy Trust Program http://www.energytrust.org/TA/solar/charts/How_to_use.html


169