Fault Analysis in Solar Photovoltaic Arrays

A Thesis Presented

by

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to

The Department of Electrical and Computer Engineering

in partial fulfillment of the requirements

for the degree of

Master of Science

in

Electrical Engineering

Northeastern University
Boston, Massachusetts
December, 2010
Abstract

Fault analysis in solar photovoltaic (PV) arrays is a fundamental task to increase reliability, efficiency and safety in PV systems. Conventional fault protection methods usually add fuses or circuit breakers in series with PV components. But these protection devices are only able to clear faults and isolate faulty circuits if they carry a large fault current. However, this research shows that faults in PV arrays may not be cleared by fuses under some fault scenarios, due to the current-limiting nature and non-linear output characteristics of PV arrays.

First, this thesis introduces new simulation and analytic models that are suitable for fault analysis in PV arrays. Based on the simulation environment, this thesis studies a variety of typical faults in PV arrays, such as ground faults, line-line faults, and mismatch faults. The effect of a maximum power point tracker on fault current is discussed and shown to, at times, prevent the fault current protection devices to trip. A small-scale experimental PV benchmark system has been developed in Northeastern University to further validate the simulation conclusions.

Additionally, this thesis examines two types of unique faults found in a PV array that have not been studied in the literature. One is a fault that occurs under low irradiance condition. The other is a fault evolution in a PV array during night-to-day transition. Our simulation and experimental results show that overcurrent protection devices are unable to clear the fault under “low irradiance” and “night-to-day transition”. However, the overcurrent protection devices may work properly when the same PV fault occurs in daylight. As a result, a fault under “low irradiance” and “night-to-day transition” might be hidden in the PV array and become a potential hazard for system efficiency and reliability.
First of all, I would like to show my gratitude to my research advisor, Prof. Brad Lehman, who gave me this great research opportunity. I am heartily thankful to Prof. Lehman for his tireless guidance, extraordinary patience and constant encouragement to my research. His knowledge, creativity and passion always inspire me during this work.

I am grateful to Mersen USA Newburyport-MA, LLC. (former Ferraz Shawmut) for the research grant that funded my work. I would like to thank the people at Mersen, Jean-François de Palma, Jerry Mosesian and Robert Lyons, who gave me valuable suggestions in my research.

I would like to thank all my friends from the research group: Song, Renato, Chung-Ti, Stephanie, Peng and Su, who provided me with their friendly help.

Furthermore, I am grateful to all my family members, especially my wife, Ling Yang, for her continuous supporting and encouraging me to pursue this degree. This thesis would not have been possible without their constant love and support.

Finally, I want to express my gratitude again to Prof. Brad Lehman for his confidence and trust in my work.
Contents

Abstract ................................................................................................................................................... 2

Acknowledge .......................................................................................................................................... 3

List of Figures ......................................................................................................................................... 7

List of Tables ......................................................................................................................................... 11

1. Introduction ................................................................................................................................... 12

1.1 Rapid growth of photovoltaic industry .............................................................................. 12

1.2 Fundamentals of photovoltaic systems ............................................................................. 13

1.2.1 How solar cells work ............................................................................................. 13

1.2.2 Solar cell technologies .......................................................................................... 15

1.2.3 How to scale up solar cells to a PV array .............................................................. 16

1.2.4 Typical PV systems ............................................................................................... 19

1.2.5 Maximum power point tracker (MPPT) ................................................................. 22

1.3 Challenges to fault analysis in PV arrays .......................................................................... 23

1.4 Conclusion/Summary of thesis contributions ................................................................... 24

2. Modeling and Simulation of PV Modules ..................................................................................... 28

2.1 Introduction ....................................................................................................................... 28

2.2 Modeling and simulation of PV modules .......................................................................... 30

2.2.1 Models for solar cells ............................................................................................ 30

2.2.2 Modeling algorithm ............................................................................................... 32

2.2.3 Simulation in MATLAB/Simulink ........................................................................ 34

2.3 Validating the model for PV modules ................................................................................. 36

2.3.1 Mono-crystalline silicon modules ......................................................................... 37

2.3.2 Amorphous silicon modules .................................................................................. 39

2.4 PV benchmark systems ..................................................................................................... 41
2.4.1 Mono-crystalline silicon PV system ................................................................. 42
2.4.2 Amorphous silicon PV system ........................................................................ 43
2.5 Conclusions ........................................................................................................... 46

3. Typical Faults in PV Arrays ..................................................................................... 47
3.1 Introduction ............................................................................................................ 47
3.2 Approaches of fault analysis ................................................................................ 50
  3.2.1 I-V characteristics analysis ........................................................................... 52
  3.2.2 KCL analysis .................................................................................................. 54
  3.2.3 Conservation of power analysis .................................................................... 55
3.3 Ground faults in a PV array under STC ............................................................... 56
  3.3.1 Simulation results of ground faults under STC............................................. 56
  3.3.2 Summary of ground faults .......................................................................... 65
3.4 Line-line faults in a PV array under STC ............................................................. 66
  3.4.1 Simulation results of line-line faults under STC ........................................... 66
  3.4.2 Summary of line-line faults ......................................................................... 75
3.5 Mismatch faults in a PV array .............................................................................. 77
  3.5.1 Open-circuit fault in a PV array ................................................................... 78
  3.5.2 Degradation faults within PV modules ........................................................ 81
3.6 Experimental verification in real working conditions .......................................... 85
  3.6.1 Experiments of a ground fault ..................................................................... 85
  3.6.2 Experiments of a line-line fault ................................................................... 88
  3.6.3 Experiments of mismatch faults .................................................................. 92
3.7 Conclusions ........................................................................................................... 96

4. Unique Faults in PV Arrays ................................................................................... 99
4.1 Introduction ........................................................................................................... 99
4.2 Overview of a line-line fault in the PV array ....................................................... 101
4.3 The line-line fault in the PV array under low irradiance .................................... 104
  4.3.1 Simulation results ........................................................................................ 106
4.4 The line-line fault in the PV array during night-to-day transition ..................... 109
4.4.1 Simulation results........................................................................................................ 110

4.5 Experimental verification............................................................................................. 114

4.5.1 Experimental set-up ............................................................................................ 115

4.5.2 Experimental results of the line-line fault under low irradiance ......................... 116

4.5.3 Experimental results of the line-line fault during night-to-day transition.............. 117

4.5.4 Summary of experiment results........................................................................... 123

4.6 Conclusions............................................................................................................... 124

5. Conclusion and Future Work......................................................................................... 128

5.1 Conclusion ............................................................................................................... 128

5.2 Future work: Development of fault detection and protection in PV arrays............. 132

References....................................................................................................................... 134
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Historical development of world cumulative PV power installed in main geographies [2]</td>
<td>13</td>
</tr>
<tr>
<td>Figure 1.2</td>
<td>Picture of a solar cell [7]</td>
<td>14</td>
</tr>
<tr>
<td>Figure 1.3</td>
<td>The structure of solar cells [8]</td>
<td>14</td>
</tr>
<tr>
<td>Figure 1.4</td>
<td>Illustrations of cell, module and array</td>
<td>16</td>
</tr>
<tr>
<td>Figure 1.5</td>
<td>Photovoltaic system components [12]</td>
<td>17</td>
</tr>
<tr>
<td>Figure 1.6</td>
<td>I-V curve of a PV module</td>
<td>17</td>
</tr>
<tr>
<td>Figure 1.7</td>
<td>I-V curve of a PV string with $m$ modules in series</td>
<td>18</td>
</tr>
<tr>
<td>Figure 1.8</td>
<td>I-V curve of a PV string with $n$ modules in parallel</td>
<td>18</td>
</tr>
<tr>
<td>Figure 1.9</td>
<td>I-V curve of a PV array with combined series and paralleling modules</td>
<td>19</td>
</tr>
<tr>
<td>Figure 1.10</td>
<td>P-V curve for the P&amp;O MPPT algorithm for a typical PV module/array</td>
<td>23</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>I-V curve of a solar cell [22]</td>
<td>28</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Equivalent circuits for (a) the one-diode model, (b) the double-diode model</td>
<td>30</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>The one-diode model for a PV module (a) equivalent circuits, (b) numerical model</td>
<td>32</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Numerical model for PV modules</td>
<td>35</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Simulation model for PV modules in MATLAB/Simulink</td>
<td>35</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>“Numerical solution” subsystem in MATLAB/Simulink</td>
<td>36</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>Primary input parameters for PV model in MATLAB/Simulink</td>
<td>36</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>A picture of SHARP NT-175UC1 PV module [31]</td>
<td>37</td>
</tr>
<tr>
<td>Figure 2.9</td>
<td>The I-V curves of simulation model and the manufacturer’s datasheet for SHARP module</td>
<td>39</td>
</tr>
<tr>
<td>Figure 2.10</td>
<td>Picture of PowerFilm R7 PV module (a) open module, (b) bundled module [32]</td>
<td>40</td>
</tr>
<tr>
<td>Figure 2.11</td>
<td>I-V curves of simulation model and the manufacturer’s datasheet for PowerFilm module</td>
<td>41</td>
</tr>
<tr>
<td>Figure 2.12</td>
<td>Schematic diagram of PV system of crystalline silicon modules</td>
<td>42</td>
</tr>
<tr>
<td>Figure 2.13</td>
<td>I-V curves of crystalline silicon PV array and PV module at STC</td>
<td>43</td>
</tr>
<tr>
<td>Figure 2.14</td>
<td>Schematic diagram of PV system of amorphous silicon modules</td>
<td>44</td>
</tr>
<tr>
<td>Figure 2.15</td>
<td>I-V curves of amorphous silicon PV array and PV module at STC</td>
<td>45</td>
</tr>
<tr>
<td>Figure 2.16</td>
<td>Picture of amorphous silicon PV system set up on Dana building at Northeastern University, Boston</td>
<td>45</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Three states of fault evolutions in power systems</td>
<td>48</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>A schematic diagram of a grid-connected PV system with $m \times n$ modules</td>
<td>51</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Modified schematic diagram of a PV system under fault</td>
<td>52</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>I-V characteristics of array under fault on a clear day</td>
<td>54</td>
</tr>
<tr>
<td>Figure 3.5</td>
<td>Conservation of power in a PV array under fault</td>
<td>55</td>
</tr>
</tbody>
</table>
Figure 3.6  Schematic diagram of a lower ground fault under STC ........................................... 57
Figure 3.7  Simulated fault current ($I_{fault}$) of a lower ground fault under STC ......................... 58
Figure 3.8  Simulated top String #1 current ($I_{1a}$) of a lower ground fault under STC .......... 58
Figure 3.9  Simulated results of entire PV array under a lower ground fault under STC .......... 59
Figure 3.10 I-V characteristics of PV array under a lower ground fault ..................................... 60
Figure 3.11  Schematic diagram of an upper ground fault ............................................................. 61
Figure 3.12  Simulated fault current ($I_{fault}$) of an upper ground fault ........................................ 62
Figure 3.13  Simulated top String #1 current ($I_{1a}$) of an upper ground fault ......................... 62
Figure 3.14  Simulated results of entire PV array under an upper ground fault ....................... 63
Figure 3.15 I-V characteristics of PV array under an upper ground fault ................................. 64
Figure 3.16 Schematic diagram of a line-line fault with small voltage difference ....................... 67
Figure 3.17 Modified schematic diagram of a line-line fault ...................................................... 68
Figure 3.18 Simulated fault current ($I_{fault}$) of a line-line fault with small voltage difference ....... 69
Figure 3.19 Simulated top current of String #1 ($I_{1a}$) in a line-line fault with small voltage difference ................................................................................................................. 69
Figure 3.20 Simulated top current of String #2 ($I_{2a}$) in a line-line fault with small voltage difference ................................................................................................................. 70
Figure 3.21 Simulated results of entire PV array under a line-line fault with small voltage difference ................................................................................................................. 70
Figure 3.22 I-V characteristics of PV array under a line-line fault with small voltage difference ................................................................................................................. 71
Figure 3.23 Schematic diagram of a line-line fault with large voltage difference ......................... 72
Figure 3.24 Simulated fault current of a line-line fault with large voltage difference ............... 73
Figure 3.25 Simulated top current of String #1 ($I_{1a}$) in a line-line fault with large voltage difference ................................................................................................................. 73
Figure 3.26 Simulated top current of String #2 ($I_{2a}$) in a line-line fault with large voltage difference ................................................................................................................. 74
Figure 3.27 Simulated results of entire PV array under a line-line fault with large voltage difference ................................................................................................................. 74
Figure 3.28 I-V characteristics of PV array under a line-line fault with large voltage difference ................................................................................................................. 75
Figure 3.29 Schematic diagram of an open-circuit fault in PV array ........................................... 79
Figure 3.30 Simulated faulted string current $I_{1a}$ under an open-circuit fault ......................... 80
Figure 3.31 Simulated results of entire PV array under an open-circuit fault ......................... 80
Figure 3.32 I-V characteristics of PV array of an open-circuit fault ........................................... 81
Figure 3.33 Schematic diagram of a degradation fault in PV array ........................................... 82
Figure 3.34 Simulated currents of a degradation fault in the PV array ................................. 83
Figure 3.35 Simulated results of the entire PV array under a degradation fault ......................... 83
Figure 3.36 I-V characteristics of the PV array of a degradation fault ........................................ 84
Figure 3.37 Photograph of the outdoor experiments on Dana building at Northeastern University, Boston ................................................................................................................. 85
Figure 3.38  Schematic diagram of PV system under a ground fault ................................. 86
Figure 3.39  Experimental results: \( V_{sys} \) and \( I_{sys} \) at a ground fault without interruption........... 86
Figure 3.40  Experimental results: \( V_{sys} \) and \( I_{fault} \) at a ground fault without interruption .......... 87
Figure 3.41  Schematic diagram of PV system under a line-line fault........................................... 89
Figure 3.42  Experimental results: \( V_{sys} \) and \( I_{1a} \) at a line-line fault without interruption ........... 89
Figure 3.43  Experimental results: \( I_{sys} \) and \( I_{1a} \) during a line-line fault and normal conditions .... 90
Figure 3.44  Experimental results: \( V_{sys} \) during a line-line fault and normal conditions ............. 90
Figure 3.45  Schematic diagram of PV system under an open-circuit fault ................................. 92
Figure 3.46  Experimental results: \( I_{sys} \) and \( I_{1a} \) during an open-circuit fault and normal conditions .............................................................. 92
Figure 3.47  Experimental results: \( V_{sys} \) during an open-circuit fault and normal conditions .......... 93
Figure 3.48  Schematic diagram of PV system under a degradation fault ................................. 94
Figure 3.49  Experimental results: \( V_{sys} \) and \( I_{sys} \) during a degradation fault .............................. 95
Figure 3.50  Experimental results: \( V_{sys} \) and \( I_{1a} \) during a degradation fault .............................. 95
Figure 4.1  Schematic diagram of a line-line fault with large voltage difference ......................... 102
Figure 4.2  Irradiance data for a cloudy day [50]............................................................................ 103
Figure 4.3  The I-V curve analysis of PV array under a line-line fault at low irradiance .............. 105
Figure 4.4  The P-V curve analysis of PV array under a line-line fault at low irradiance .............. 106
Figure 4.5  The P-V curve analysis of the faulted PV array under a line-line fault at low irradiance ........................................................................................................ 106
Figure 4.6  Simulated fault current of a line-line fault under low irradiance .............................. 107
Figure 4.7  Simulated top current of String#1 (\( I_{1a} \)) of a line-line fault under low irradiance .. 107
Figure 4.8  Simulated top current of String #2 (\( I_{2a} \)) of a line-line fault under low irradiance . 108
Figure 4.9  Simulated voltage, current and output power of the PV array of a line-line fault under low irradiance ........................................................................ 108
Figure 4.10  The P-V curve analysis of the faulted PV array under different irradiance................. 110
Figure 4.11  Simulated fault current of a line-line fault during night-to-day transition .......... 111
Figure 4.12  Simulated top current of String #1 (\( I_{1a} \)) of a line-line fault during night-to-day transition ........................................................................................................ 111
Figure 4.13  Simulated top current of String #2 (\( I_{2a} \)) of a line-line fault during night-to-day transition ........................................................................................................ 112
Figure 4.14  Simulated voltage, current and output power of the PV array of a line-line fault during night-to-day transition ........................................................................ 112
Figure 4.15  Schematic diagram of PV system under a line-line fault.......................................... 114
Figure 4.16  Picture of PV system experimental set-up at Northeastern University, Boston .... 115
Figure 4.17  Experimental results of a line-line fault under low irradiance .................................. 116
Figure 4.18  P-V curves of the faulted PV array with increasing irradiance during night-to-day transition ........................................................................................................ 118
Figure 4.19  Experiments: the faulted PV array voltage (\( V_{sys} \)) during night-to-day transition... 119
Figure 4.20  Experiments: the faulted PV array current (\( I_{sys} \)) and String #1 top current (\( I_{1a} \)) during night to day transition .............................................................................. 119
Figure 4.21 Experiments: the faulted PV array output power ($P_{sys}$) during night to day transition
.................................................................................................................................................. 120

Figure 4.22 Experiments: the faulted PV array current ($V_{sys}$) during day-to-night transition... 121

Figure 4.23 Experiments: the faulted PV array current ($I_{sys}$) and String #1 top current ($I_{1a}$) during day-to-night transition........................................................................................................... 121

Figure 4.24 Experiments: the faulted PV array output power ($P_{sys}$) during day to night transition
.................................................................................................................................................. 122
List of Tables

Table 1.1 Summary of solar cell technologies [9-11] ............................................................... 15
Table 2.1 Parameters at STC for SHARP NT-175UC1 PV module [29, 31] ........................... 38
Table 2.2 Parameters at STC for PowerFilm R7 PV module ................................................... 40
Table 2.3 Summary of two benchmark PV systems ..................................................................... 41
Table 2.4 Parameters of main components in the 5.25kW mono-crystalline silicon PV system ........................................................................................................ 43
Table 2.5 Parameters of PV modules and the inverter in the amorphous silicon PV system .... 46
Table 3.1 Simulation results of a lower ground fault under STC ............................................. 57
Table 3.2 Simulation results of a upper ground fault under STC ............................................. 61
Table 3.3 Simulation results of upper ground faults under STC ............................................. 65
Table 3.4 Simulation results of a line-line fault with small voltage difference ...................... 68
Table 3.5 Simulation results of a line-line fault with large voltage difference ...................... 72
Table 3.6 Simulation results of line-line faults under STC ...................................................... 76
Table 3.7 Simulation results of an open-circuit fault at STC .................................................. 79
Table 3.8 Degraded parameters of a PV module in simulation ............................................... 82
Table 3.9 Simulation results of a degradation fault at STC .................................................... 83
Table 3.10 Experimental results of a ground fault in the PV array ........................................ 87
Table 3.11 Experimental results of a line-line fault in the PV array .................................... 90
Table 3.12 Experimental results of an open-circuit fault in the PV array .............................. 93
Table 3.13 Experimental results of a degradation fault in the PV array .............................. 95
Table 4.1 Parameters of PV components in the 5.25kW benchmark PV system ................ 102
Table 4.2 Simulation results of a line-line fault at low irradiance ...................................... 107
Table 4.3 Simulation results of the line-line fault during night-to-day transition .................. 110
Table 4.4 Simulation results of the line-line fault under low irradiance .............................. 117
Table 4.5 Simulation results of the line-line fault during night-to-day transition .................. 122
Table 4.6 Summary of experimental results ................................................................. 124
1. **Introduction**

1.1 **Rapid growth of photovoltaic industry**

The solar photovoltaic (PV) industry has grown since the oil crises of the 1970s, but has especially been in rapid development in recent years. According to the International Energy Agency (IEA) [1], the world PV industry has developed at average annual growth rates of 15% to 20% from 1991 to 2007 - a growth rate comparable to that of the semiconductor and computer industries. In the recent 10-year period from 2000 to 2009, world cumulative installed PV power has been increasing from 1,428 MW to 22,893 MW (see Fig. 1.1), with an average annual growth rate 36.7%, making it the world’s fastest-growing energy technology [2]. The rapid growth rate is mainly due to the need for alternatives to fossil fuel-based electricity generation, concerns over the global environment, reduced photovoltaics costs, and interests in distributed energy sources to improve power system reliability [3-4].

For instance, during the past decades, thanks to the new discovered materials, devices and fabrication methods, as well as improved solar-cell efficiency and reliability, the cost of photovoltaics has been reduced by several orders of magnitude. According to the International Energy Agency (IEA) [1], PV system costs in reported countries has come down from 16 USD per watt in 1991 to 8 USD per watt in 2007.

For the next several decades, the PV industry has the capability to keep a double - digit annual growth. In a solar PV roadmap of IEA [5-6], it is estimated that by 2050, the solar PV power will supply around 11% of global electricity generation and reduce 2.3 gigatonnes (Gt) of CO2 emissions per year. As a leading role in world PV industry, the U.S. photovoltaic industry roadmap [3] has a long-term goal for 10% of U.S. peak
electricity generation capacity by 2030 be supplied by PV power. It is reasonable to predict that the PV industry has the potential to play a significant role in world electricity generation in the future.

Figure 1.1   Historical development of world cumulative PV power installed in main geographies[2]

1.2   Fundamentals of photovoltaic systems

1.2.1   How solar cells work

A solar cell (see Fig. 1.2) is essentially a photodetector containing a p-n junction that is illuminated to generate DC current. A typical silicon solar cell is composed of a thin wafer layer of n-type (e.g. phosphorus-doped) silicon on top, and a thicker layer of p-type (e.g. boron-doped) silicon at bottom (see Fig. 1.3). The contact between the two materials forms the p-n junction, which has a built-in electrical field in the depletion region.
The photovoltaic process of current generation in a solar cell involves two key steps (see Fig 1.3). The first step is the absorption of incident photons to generate electron-hole pairs. Electron-hole pairs can be created only if the incident photons have energy greater than the semiconductor band gap. The second step is that electrons and holes are separated by the electrical field in the junction depletion region and flow through the external circuit.

However, the detailed study of the physics of solar cells is considerably complicated and
is beyond the scope of this thesis. Knowing the electrical characteristics of solar cells, modules, and array in different environment (irradiance and temperature) is sufficient for the fault studies of PV systems.

### 1.2.2 Solar cell technologies

Photovoltaic cells and modules vary in their basic materials, output efficiency, and costs. The following Table 1.1 summarizes a comparison of available solar cell technologies.

<table>
<thead>
<tr>
<th>Picture</th>
<th>Crystalline Silicon</th>
<th>Thin Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module types and module efficiency</td>
<td>Mono-crystalline Silicon (15-18%)</td>
<td>Amorphous Silicon (5-7%)</td>
</tr>
<tr>
<td></td>
<td>Poly-crystalline Silicon (13-16%)</td>
<td>Copper Indium Diselenide (CIS) (9-11%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cadmium Telluride (CdTe) (7%)</td>
</tr>
<tr>
<td>Advantages</td>
<td>More efficient</td>
<td>Less manufacturing costs</td>
</tr>
<tr>
<td></td>
<td>Requires less space</td>
<td>Very versatile</td>
</tr>
<tr>
<td></td>
<td>Long track record</td>
<td>More shade tolerant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Less temperature sensitive</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Costly</td>
<td>Shorter track record</td>
</tr>
<tr>
<td></td>
<td>Limited applications</td>
<td>Lower module efficiency</td>
</tr>
<tr>
<td></td>
<td>Shade intolerant</td>
<td>Requires more space</td>
</tr>
<tr>
<td></td>
<td>Temperature sensitive</td>
<td></td>
</tr>
<tr>
<td>Applications</td>
<td>Grid-connected PV systems</td>
<td>More used in standalone PV systems, such as portable solar chargers</td>
</tr>
<tr>
<td></td>
<td>Standalone PV systems (off-grid)</td>
<td>Grid-connected PV systems</td>
</tr>
<tr>
<td>Market share</td>
<td>78 - 80%</td>
<td>18 - 20%</td>
</tr>
</tbody>
</table>

Table 1.1 Summary of solar cell technologies [9-11]
This research mainly focuses on the electrical characteristics and interconnection studies of PV modules under normal and fault working conditions. Two types of PV systems using the aforementioned solar cell technologies are set up in simulation and experiments. The first PV system is composed of mono-crystalline silicon PV modules by SHARP Electronics Corporation. The second PV system is built by amorphous silicon PV module by PowerFilm Inc.

1.2.3 How to scale up solar cells to a PV array

PV technologies are versatile and widely used to generate electricity for many applications, from small to large power levels. Individual solar cells are used for powering small appliances such as electronic calculators. Large PV arrays are utilized to generate power to the utility grid, such as PV plants.

As basic photovoltaic devices, solar cells are often electrically connected and encapsulated in an environmentally protective laminate as a PV module (see Fig. 1.4). The main components in PV systems are illustrated in Fig. 1.5.

![Illustrations of cell, module and array](image.png)
Solar cells are also usually connected in series in PV modules, generating an additive voltage. As shown in Fig. 1.6, a PV module has a non-linear current vs. voltage (I-V) curve that contains all the possible operation points along with it. There are three important points on the I-V curve, named short-circuit current ($I_{sc}$), open-circuit voltage ($V_{oc}$) and maximum power point (MPP), which represent the maximum possible current, maximum possible voltage and maximum possible power, respectively, that the module can provide under a specific environmental condition.

PV technology is modular and scalable that can be built incrementally to match growing electricity demands. As the fundamental building block of PV systems, PV modules can be assembled in series and/or parallel to build a PV array. For instance, each PV module
has a short-circuit current ($I_{sc}$) and an open-circuit voltage ($V_{oc}$). In Fig. 1.7, connecting $m$ modules in series will yield a PV string with a higher open-circuit voltage ($m \times V_{oc}$). In Fig. 1.8, putting $n$ strings in parallel will create a PV array with a larger short-circuit current ($n \times I_{sc}$).

Furthermore, using the topological methods shown above, a large PV array can be developed. If a string has $m$ identical modules, $n$ identical PV strings can be in parallel to build a PV array containing ($n \times m$) PV modules. Therefore, the PV array has a short-circuit current $n \times I_{sc}$ and an open-circuit voltage $m \times V_{oc}$ (shown in Fig 1.9).
A typical grid-connected PV system mainly consists of a PV array with bypass diodes, a grid-connected inverter, connection wirings and protection devices, such as overcurrent protection devices (OCPD) and ground fault protection devices (GFPD).

**PV array**

A PV array is a complete DC power-generating unit, consisting of any number of PV modules wired in series and/or parallel to deliver particular voltage and amperage that a system requires. The array can be as small as several modules, or large enough to cover acres as a utility PV plant.

**Bypass diodes**

Usually each PV module will be equipped with bypass diode(s) to avoid the destructive effects of hot-spot heating caused by non-uniform irradiance, mismatch of solar cells’ characteristics, or other types of faults. A bypass diode is connected in parallel but opposite polarity with a number of solar cells (usually 18-24 cells) within the PV module. Under normal working conditions, each solar cell will be forward biased and therefore
the bypass diode will be reverse biased. But if solar cells are reverse biased due to the mismatch among PV modules, then the bypass diode will conduct, thereby allowing the extra current from the good solar cells to flow in the external circuit rather than forward biasing bad cells.

**Grid-connected inverter**

The grid-connected inverter is the equipment that is used to feed DC input energy from PV to utility grid. The grid-connected inverter usually has the maximum power point tracker (MPPT) algorithm that can harvest the maximum output power from PV array.

**Grounding issues**

Grounding is “a conducting connection, whether intentional or accidental between an electrical circuit or equipment and the ground or some conducting body that serves in place of the ground” [13]. The general purpose of grounding is to minimize electrical shock hazards, minimize fire hazards caused by faults, protect equipments from faults and induced surges, and reduce the electromagnetic interference effects [14]. The grounding issues of PV systems need some special consideration because PV systems are very different from conventional power source and, sometimes, fault PV currents may not be cleared properly by conventional protection devices.

There are two types of grounding in PV systems[12]:

- **System grounding**: some points of one current carrying conductor (usually the negative conductor) of a 2-wire PV system, or the reference (center tap) conductor of a bipolar PV system should be intentionally connected to ground;
- **Equipment grounding**: Exposed non-current carrying conductive parts, such as metallic module frames, equipment, and conductor enclosures, should be grounded.
Equipment grounding is required in all countries. However, system grounding varies widely with application among different countries.

- **Grounded system**: the US National Electrical Code (NEC) [12] requires that PV system voltage (open-circuit PV voltage times a temperature-dependent constant) over 50V should have system grounding [12];
- **Ungrounded system**: European and Japanese codes do not require system grounding in PV installations so that most of the PV systems do not have grounded current-carrying conductors on the DC side.

Regarding line-line fault (a short-circuiting fault between current-carry conductors with different voltage difference), the fault analysis approach is the same in grounded and ungrounded systems since the fault does not involve any ground points. However, grounded and ungrounded systems are different at ground faults. For instance, a single ground fault can lead to fault currents in a grounded system but cannot lead to any fault currents in an ungrounded system. Specifically, more than one ground fault is needed to cause a ground current in an ungrounded system.

Although this thesis discusses PV faults based on grounded systems in accordance with the US codes [12], the simulation platforms and fault analysis approaches in this thesis can also be applied in an ungrounded systems in European countries and Japan. For example, two ground faults in an ungrounded system have the same fault characteristics as the ones in a grounded system.

**Ground fault protection devices (GFPD)**

Ground fault protection devices (GFPDs) provide fire hazard prevention in PV systems. The GFPD should be capable of ground fault detection, fault current interruption, and fault indication according to National Electrical Code (NEC) [12]. In practice, these
GFPDs (either inside the inverter or externally mounted) actually are installed between the negative current-carrying conductor and system grounding point [15]. Under normal conditions, since the negative conductor is connected to ground at only one point, current will flow in the negative conductor, but will not flow in any of the system grounding. In the case of a ground fault (positive conductor is accidentally connected to ground), the ground-fault current will flow through GFPD on its way from the ground-fault point back to the PV array [16]. The GFPD usually is a circuit breaker or a fuse with rated current 0.5A. If the ground-fault current through the GFPD exceeds 0.5A, the circuit breaker or the fuse may trip or melt and clear the ground fault.

**Overcurrent protection devices (OCPD)**

Fuses are often used as overcurrent protection devices for modules and conductors in PV systems. The US *NEC* requires that a single overcurrent protection device shall be used in series-connected strings of two or more modules [12]. The rating current of overcurrent devices shall be no less than 156 percent of module rated short-circuit current ($I_{sc}$) [12].

1.2.5 **Maximum power point tracker (MPPT)**

A MPPT is an algorithm is often integrated with the DC-AC inverter (or DC-DC converter) to harvest the maximum output power of PV arrays. Since the MPPT keeps optimizing output power of a PV array (system) for given environmental conditions and array configurations (normal or faulted), the MPPT plays an important role in determining the normal current as well as the fault current.

The most commonly used MPPT algorithm is the Perturb and Observe (P&O) method, which is developed and tested in this research. Fig. 1.10 shows the nonlinear power vs. voltage (P-V) curve of a PV array, which has a maximum power point (MPP). The P&O perturbs the operating voltage of an array in a certain direction and observes changes in
its output power. From Fig. 1.10, it can be seen that if the change of power is in the same
direction of voltage perturbation \((dP/dV>0)\), then the operation point is on the left of the
MPP, and the operating voltage should be increasing to reach the MPP. Otherwise, if the
change of power is in the opposite direction of voltage perturbation \((dP/dV<0)\), then the
operation point is on the right of the MPP, and the operating voltage should be decreasing
to approach the MPP. This P&O algorithm is processed iteratively until the MPP is
reached and then, the PV array will oscillate around its present MPP in steady-state
operation.

![P-V curve for the P&O MPPT algorithm for a typical PV module/array](image)

**Figure 1.10** P-V curve for the P&O MPPT algorithm for a typical PV module/array

### 1.3 Challenges to fault analysis in PV arrays

Faults in PV arrays impact the output power performance as well as lead to critical and
possibly hazardous situations. In this thesis, it is considered that the PV array is the only
source of fault current. For fault detection and protection in a PV array, conventional
approaches usually add fuses or circuit breakers in series with PV components [17-19].
These protection devices are able to trip faults and isolate faulty circuits only if they carry
the large faulty current. For example, according to the US NEC [12], the nominal currents
of serial fuses with PV modules are rated no less than 1.56 times the short circuit current
\((I_{sc})\) of PV modules. However, because of the non-linear I-V characteristics and the
current-limiting nature of PV arrays, faults may not cause significant overcurrent. In
addition, fault analysis in PV may become more complicated caused by the following
factors:

- Environmental conditions, such as varying irradiance level and temperature on the PV array;
- Types of faults can differ based on the number of solar PV modules, PV array configurations and fault locations;
- Aging, hot-spot and other mismatch faults in PV array are unique to PV technology;
- MPPT effects of the PV inverter can influence fault currents.

These factors can cause the fault currents to become lower than expected. Thus, conventional protection devices may not be able to clear faults correctly. These fault protection issues are discussed in Chapter 3 and Chapter 4 in this thesis.

1.4 Conclusion/Summary of thesis contributions

Unlike conventional power generation sources, e.g., generators and batteries, PV arrays are unique and have their own output characteristics. To better understand the fault issues described in the previous sections, this thesis focuses on the modeling, development, and analysis of varied faults in a grid-connected PV system. The main contributions of this thesis are:

- A simulation platform has been developed that can accurately predict the normal output performance of PV arrays with different scales, various solar-cell technologies and different array configurations. The same simulation platform is used to simulate typical PV faults, including ground faults, line-line faults, mismatch faults and others;
- An experimental test-bed has been built in real working conditions and used to verify the simulation results of faults in PV arrays;
- Based on simulation and experimental results, this thesis summarizes the fault characteristics of typical faults in PV arrays, such as ground faults, line-line faults,
and mismatch faults. The research results show that a line-line fault with small-voltage difference could result in low fault current and might be difficult to clear by conventional protection devices;

- It is discovered that the MPPT in the inverter can significantly effect the fault current in a PV system. This leads to new protection issues in PV arrays that have not previously been documented;

- Unique faults in PV arrays have been discovered: fault under low irradiance conditions and fault evolutions in PV array during night-to-day transition. These types of fault may not generate enough fault current to trip the conventional protection devices, but still may be large enough to cause arcing or fire hazards in the fault path. Consequently, it may bring new challenges to conventional protection methods that have not yet been reported in the literature.

The proposed research has several objectives: First, we create a modeling algorithm of PV modules that is suitable for fault analysis. Taking the solar irradiance level and PV module temperature as inputs, the simulation model has accurate steady-state performance compared with the manufacturer’s datasheet. Second, we simulate and experimentally verify the PV array performance under typical fault conditions. The approaches of fault analysis are given in detail, and the effects of the MPPT on the fault current are discussed. Third, we introduce and analyze unique faults in PV arrays that may bring challenges to existing PV protection approaches. The objectives are discussed in more detail as follows.

**Objective 1 (in Chapter 2)**

Create a modeling algorithm capable of accurately predicting the steady-state performance of PV modules in different fault conditions. Build two PV benchmark
systems with different technologies (mono-crystalline and amorphous silicon) and various scales in both simulation and experiment.

Chapter 2 develops a simulation model that is able to use the solar irradiance level and PV module temperature as inputs to predict steady-state performance accurately compared with the manufacturer’s datasheet. The numerical model of PV modules relies on the one-diode model that is widely used in PV industry. This model is flexible and robust, and it can be adopted into any circuit simulator, such as Pspice and MATLAB/Simulink. As the fundamental building block of PV arrays, our simulation model can be assembled in any series-parallel configuration to build a PV system. Therefore, individual modules in a large PV array and their interactions can be well studied. Specifically, power generation of individual modules, power losses on wirings and fault currents can be well predicted in our simulation. Based on the developed simulation model, two PV benchmark systems with different technologies and various scales have been established in simulations. Furthermore, small-scale experimental PV benchmark systems are developed in real test conditions for proof of model accuracy.

**Objective 2 (in Chapter 3)**

Simulate and analyze typical faults of PV arrays under different fault locations. Explain approaches of fault analysis and examine the effects of the MPPT on the fault current. Carry out the fault experiments under real test conditions.

Chapter 3 of the thesis studies the modeling and simulation of a variety of faults in the 5.25kW PV simulation system, especially ground faults, line-line faults, and mismatch faults. The fundamental approaches of fault analysis in PV array are introduced and discussed. The effect on fault currents from the MPPT of the inverter is discussed in fault analysis, which has not been seen in the literature. Fault experiments are carried out in
the small-scale experimental PV benchmark system under real test conditions to verify simulation results.

**Objective 3 (in Chapter 4)**

*Study unique faults to PV arrays under varying irradiance conditions, such as faults in “low irradiance” conditions and fault evolutions during “night-to-day transition”.*

*Explain the new challenges to existing protection approaches that these environmental conditions create.*

Chapter 4 of this thesis studies two types of unique faults in PV arrays that cannot be found in any other conventional power sources. (1) One is a fault that occurs in a PV array under low irradiance, which may have small fault current so that it may not be detected with conventional protection schemes. The reason is that after the fault, the MPPT of the inverter will adjust the array output power and consequently reduce the fault current. As a result, this fault may be hidden in this PV array forever, even after irradiance increases or during night-to-day transition. (2) The second unique fault is that a fault in the PV array evolves during “night-to-day” transition. Specifically, the fault happens in the PV array at night when there is no solar irradiance. During sunrise, the irradiance on the PV array increases slowly, as does the PV array voltage. As long as the PV array voltage reaches the minimum start voltage of inverter, the PV inverter and its MPPT start to work (commonly by using the Perturb and Observe algorithm [20-21]). Consequently, instead of causing large overcurrent, the faulted PV array during night-to-day transition might lead to smaller fault current. Thus, it may be difficult to clear with conventional protection devices. These two types of unique faults in PV arrays may subsequently lead to unexpected safety hazards, reduced system efficiency and reduced reliability. Therefore, special considerations should be taken into the fault analysis.
2. Modeling and Simulation of PV Modules

2.1 Introduction

As Fig. 2.1 shows, a solar cell exhibits a non-linear output characteristic in three quadrants of its I-V curve. The solar cell generates power in the 1st quadrant, but dissipates power as a load in the 2nd and 4th quadrants of its I-V curve. In the 1st quadrant, the solar cell’s I-V curve varies with solar irradiance and ambient temperature.

![I-V curve of a solar cell](image)

The PV module usually is composed of a number of solar cells with identical characteristics. Similarly, a number of PV modules are used to build a PV array. Ideally, a PV array would have a similar non-linear I-V curve as shown in Fig 2.1. However, in real working conditions, since PV modules may work at different irradiance, ambient temperature and even under fault conditions, the I-V curve of a PV array will be completely different, and the interconnection of PV modules becomes difficult to predict. These complexities bring challenges to existing simulation approaches of PV arrays.

Several models for PV modules/arrays have been studied in the literature [23-27]. However, these models are either too simple to be accurate enough for power losses...
estimation [25] or are not applicable for interconnection studies of PV modules in a large PV array [23-24, 26]. A numerical simulation of a PV array adopts the Newton-Raphson method to solve the electrical solutions for every electrical component in PV array [28]. But sometimes this method has convergence problems under PV fault scenarios because the configuration of PV array is greatly changed due to faults. A circuit-level PV array model is built in SPICE for power electronics simulation in [27], but this paper does not discuss the interconnection among PV modules under normal or fault scenarios.

This thesis proposes a new simulation model for PV modules that is applicable in both normal and fault working conditions. The proposed simulation model presents the following features over previous works [23-28]:

- The model can be simulated in any circuit simulation package (such as PSpice) and is even simple enough to be accurately simulated in MATLAB/Simulink;
- Taking the solar irradiance level and PV module temperature as inputs, the simulation model has accurate steady-state performance verified by the manufacturer’s data;
- The PV model is versatile enough to modify and simulate the output performance of the most of modules in solar market;
- The PV model is modular and scalable to build PV arrays with various configurations, which is especially useful for studies of PV modules interconnection under normal and fault scenarios;
- The proposed PV model is capable to predict PV array performance under fault scenarios, such as ground faults, line-line faults, and mismatch faults.
2.2 Modeling and simulation of PV modules

2.2.1 Models for solar cells

Because of the non-linear I-V characteristics of solar cells, it is not appropriate to simply model them as a constant voltage source or a constant current source. The one-diode model and the double-diode model are most commonly used to describe the electrical behaviors of solar cells [26-27]. The equivalent circuits for the one-diode model and the double-diode model are shown in Fig. 2.2(a) and Fig. 2.2(b).

![Equivalent circuits for (a) the one-diode model, (b) the double-diode model](image)

For the one-diode model in Fig. 2.2(a), the solar cell current equation is

\[
I = I_L - I_S \left[ \exp \left( \frac{V + IR_{c,s}}{AKT} \right) - 1 \right] - \frac{V + IR_{c,s}}{R_{c,sh}}
\]

(2.1)

where

\[
\begin{align*}
I &= \text{solar cell current (A)} \\
V &= \text{solar cell voltage (V)} \\
I_L &= \text{light-generated current (A)} \\
I_D &= \text{diode current (A)} \\
I_{sh} &= \text{shunt resistance current (A)} \\
I_S &= \text{saturation current of the diode (A)}
\end{align*}
\]
\[ R_{c,s} = \text{solar cell series resistance (ohms)} \]
\[ R_{c,sh} = \text{solar cell shunt resistance (ohms)} \]
\[ q = \text{electron charge} = 1.6 \times 10^{-19} \text{ C} \]
\[ k = \text{Boltzmann’s constant} = 1.38 \times 10^{-23} \text{ J/K} \]
\[ A = \text{diode ideal factor} \quad (1 \leq A \leq 2) \]
\[ T = \text{ambient temperature (K)} \]

For the double-diode model, the solar cell current equation is:

\[
I = I_L - I_{S1} \left[ \exp \left( \frac{V + IR_{c,s}}{kT} \cdot q \right) - 1 \right] - I_{S2} \left[ \exp \left( \frac{V + IR_{c,s}}{2kT} \cdot q \right) - 1 \right] - \frac{V + IR_{c,s}}{R_{c,sh}} \tag{2.2}
\]

where

\[ I_{S1} = \text{saturation current for diode1 (A)} \]
\[ I_{S2} = \text{saturation current for diode2 (A)} \]
\[ I_{D1} = \text{diode1 current (A)} \]
\[ I_{D2} = \text{diode2 current (A)} \]

This thesis adopts the one-diode model for solar cells in simulation, because the one-diode model has several advantages over the double-diode model:

- The one-diode model is accurate enough for steady-state and fault analysis for PV modules in system level;
- Numerical method for one-diode model converges faster than the one of the double-diode model in simulation environment;
- Detailed parameters of one-diode model are available for the most PV modules in market [29].
2.2.2 Modeling algorithm

To model a PV array, it is unrealistic to simulate every solar cell in the array. Moreover, PV manufacturers usually only provide end users with complete and environmentally protected modules rather than solar cells in bulk. In addition, in real working conditions, solar cells packaged in the same module usually have almost the same irradiance conditions. For these reasons, we can simply assume that all the solar cells in each PV module have identical characteristics and working conditions. Thus, a PV module can be viewed as a basic unit consisting of identical solar cells. Therefore, modeling and simulation of PV modules become key steps for PV system normal and fault analysis.

The simulation model for PV modules is developed as follows. According to the one-diode model of PV modules in Fig. 2.3.(a), by using voltage $V_{pv}$ as an input parameter, the modeling algorithm solves (2.1) iteratively to find the mathematical solution for $(I_L - I_D)$, and feed the solution to a controlled current source in Fig. 2.3.(b).

![Figure 2.3](image)

(a) (b)

Figure 2.3 The one-diode model for a PV module (a) equivalent circuits, (b) numerical model

Developed from the one-diode model, the model for a PV module is written as [29]:

$$I_L - I_D = \frac{V_{pv} - I_{sh} R_{sh}}{R_s + R_{sh}}$$
\[ I_{pv} = I_L - I_S \left[ \exp \left( \frac{V_{pv} + I_{pv}R_s}{AkT \cdot N_S} \cdot q \right) - 1 \right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \]  

(2.3)

where

\[ N_s = \text{the number of solar cells in series for a PV module} \]
\[ I_{pv} = \text{PV module current} \]
\[ V_{pv} = \text{PV module voltage} \]
\[ R_s = \text{PV module series resistance} \]
\[ R_{sh} = \text{PV module shunt resistance} \]

Depending on solar irradiance and ambient temperature, the light generated current \( I_L \) is described as [29]:

\[ I_L = G / G_0 \cdot \left[ I_{L0} + C_T (T - T_0) \right] \]  

(2.4)

where

\[ G = \text{solar irradiance (W/m}^2\text{)} \]
\[ G_0 = \text{reference solar irradiance (W/m}^2\text{)} \]
\[ I_{L0} = \text{reference light generated current (A)} \]
\[ T_0 = \text{reference temperature (K)} \]
\[ C_T = \text{temperature coefficient of the light generated current (A/K)} \]

Varying with the temperature, the saturation current \( I_S \) of the diode is [29-30]:

\[ I_S = I_{S0} \cdot \left( \frac{T}{T_0} \right)^3 \cdot \exp \left[ \frac{q \cdot E_g}{Ak} \cdot \left( \frac{1}{T_0} - \frac{1}{T} \right) \right] \]  

(2.5)

The temperature dependence of band gap energy \( E_g \) for Si can be expressed as:
\[ E_g = 1.170 - \frac{4.73 \times 10^{-4} T^2}{T + 636} \text{ eV} \]  

(2.6)

where [30]

\[ \begin{align*} 
E_g & = \text{Band gap energy of the material (eV)} \\
\text{Electron volts (eV)} & = 1.6 \times 10^{-19} \text{ J} 
\end{align*} \]

Depending on the semiconductor material used for PV modules, \( E_g \) may have different values. Usually \( E_g \) is approximate 1.12 eV for crystalline silicon, 1.03 eV for Copper Indium Diselenide (CIS), 1.7 eV for amorphous silicon and 1.5 eV for Cadmium Telluride (CdTe) under room temperature [29].

### 2.2.3 Simulation in MATLAB/Simulink

The proposed numerical model (shown in Fig. 2.3(b)) can be simulated in any circuit simulation package (such as PSpice), and it is even simple enough to be accurately simulated in MATLAB/Simulink. This thesis adopts MATLAB/Simulink as the simulation environment, since it has SimPowerSystems toolbox which can offer an open and flexible interface to model numerical, electrical and control systems.

As an illustration, Fig. 2.4 shows the numerical model for PV modules. The “Numerical Solution” subsystem has three inputs: irradiance, temperature and PV module’s terminal voltage \( V_{pv} \). Fig. 2.5 shows the model for PV modules in MATLAB/Simulink, where a subsystem in Simulink is used as the “Numerical Solution” block. The other components are: voltage measurement block, controlled current source, and series RLC branch.
In order to initialize the simulation, all the constant parameters for PV modules are set in *InitFcn* of *Callbacks* in *Model Properties* menu of Simulink. Function blocks for the numerical solution ($I_{L-ID}$) can be modified by selecting *Look Under Mask* of the *Numerical Solution* menu of the subsystem, as shown in Fig. 2.6. In this subsystem, an *Algebraic Constraint* function block plays a critical role in looking for the numerical solution. The block constrains input signal $I_L - (I_{pv} + I_D + I_{sh}) = 0$ and outputs the diode voltage $V_D$, which affects the input through feedback path and necessarily constrains input at zero.

The primary parameters for PV modules, such as $I_{sc}$, $I_{so}$, $V_{oc}$, $C_T$ and $A$, can be set as constants in the input windows for the model, shown in Fig. 2.7 That means the MATLAB/Simulink model can be universal and applicable to any PV modules in solar
market, making the model as a powerful toolbox for research and design of PV systems.

Figure 2.6  “Numerical solution“ subsystem in MATLAB/Simulink

Figure 2.7  Primary input parameters for PV model in MATLAB/Simulink

2.3  Validating the model for PV modules

To validate the PV model in MATLAB/Simulink, two commercial PV modules in market with different technologies are simulated and compared with the manufacturer’s
datasheet. One is SHARP NT-175UC1 module made of mono-crystalline silicon; the other one is PowerFilm R-7 module made of amorphous silicon.

2.3.1 Mono-crystalline silicon modules

A top view of the SHARP NT-175UC1 module is shown in Fig. 2.8. The main parameters for this mono-crystalline silicon module are listed in Table 2.1. The main parameters are from the manufacturer’s datasheet and the others are created by PVsyst, a software for study of photovoltaic system [29]. The PV module has 72 solar cells connected in series, with each solar cell generating approximately 0.5V. There are 6 columns of solar cells in portrait orientation of module. For hot-spot prevention, one bypass diode is connected to every two adjacent columns of cells. In total, there are three bypass diodes located in the module’s junction box.

![Figure 2.8](image)
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power</td>
<td>$P_{mp}$</td>
<td>175</td>
<td>W</td>
</tr>
<tr>
<td>Cell configuration (in series)</td>
<td>$N_S$</td>
<td>72</td>
<td>-</td>
</tr>
<tr>
<td>Open Circuit Voltage</td>
<td>$V_{oc}$</td>
<td>44.4</td>
<td>V</td>
</tr>
<tr>
<td>Maximum Power Voltage</td>
<td>$V_{mp}$</td>
<td>35.4</td>
<td>V</td>
</tr>
<tr>
<td>Short Circuit Current</td>
<td>$I_{sc}$</td>
<td>5.40</td>
<td>A</td>
</tr>
<tr>
<td>Maximum Power Current</td>
<td>$I_{mp}$</td>
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<td>A</td>
</tr>
<tr>
<td>Series fuse rating</td>
<td>$I_{fus}$</td>
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<td>Series resistance</td>
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<td>Ohm</td>
</tr>
<tr>
<td>Shunt resistance</td>
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<td>Ohm</td>
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<td>Saturation current of solar cell diode</td>
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<td>nA</td>
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<tr>
<td>Ideality factor</td>
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<td>-</td>
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<tr>
<td>Temperature Coefficient of $I_L$</td>
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<td>(mA/°C)</td>
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<tr>
<td>Number of bypass diodes per module</td>
<td>$N_b$</td>
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<td>-</td>
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<tr>
<td>Bypass diode forward voltage</td>
<td>$V_F$</td>
<td>0.7</td>
<td>V</td>
</tr>
</tbody>
</table>

Table 2.1 Parameters at STC for SHARP NT-175UC1 PV module [29, 31]

The comparison between simulation results and the manufacturer’s datasheet for crystalline silicon module are shown in Fig. 2.9. It is shown that under three different irradiance levels at temperature 25°C and air mass (AM) 1.5, the simulation model is closely matched with most of the manufacturer’s data along the points of the I-V curve. Especially at standard test conditions (STC) under 1000W/m², the model is coincident with the manufacturer’s data: The model is accurate enough to predict the performance of PV modules under normal and fault scenarios.
2.3.2 Amorphous silicon modules

A picture of PowerFilm R7 rollable module is shown in Fig. 2.10. This module is lightweight, portable, water-proof, and easily integrated to provide charging power for small appliances. It produces 7.5W of power at an operating voltage of 15.4 volts under STC. The main model parameters for R7 module are from the manufacturer’s datasheet, and the others are also created by PVsyst using curve fitting method [29]. The simulation parameters for R7 module are listed in Table 2.2. Since the number of solar cells in series is not available by the manufacturer’s datasheet, we assume that there are 24 solar cells in series in one PV module.
Figure 2.10  Picture of PowerFilm R7 PV module (a) open module, (b)bundled module [32]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>Cell configuration (# of cells in series)</td>
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<td>-</td>
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<tr>
<td>Open Circuit Voltage</td>
<td>$V_{oc}$</td>
<td>21.4</td>
<td>V</td>
</tr>
<tr>
<td>Maximum Power Voltage</td>
<td>$V_{mp}$</td>
<td>15.8</td>
<td>V</td>
</tr>
<tr>
<td>Short Circuit Current</td>
<td>$I_{sc}$</td>
<td>0.58</td>
<td>A</td>
</tr>
<tr>
<td>Maximum Power Current</td>
<td>$I_{mp}$</td>
<td>0.48</td>
<td>A</td>
</tr>
<tr>
<td>Series fuse rating</td>
<td>$I_{fuse}$</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>Series resistance</td>
<td>$R_s$</td>
<td>6</td>
<td>Ohm</td>
</tr>
<tr>
<td>Shunt resistance</td>
<td>$R_{sh}$</td>
<td>450</td>
<td>Ohm</td>
</tr>
<tr>
<td>Saturation current of solar cell diode</td>
<td>$I_S$</td>
<td>45</td>
<td>nA</td>
</tr>
<tr>
<td>Ideality factor</td>
<td>$A$</td>
<td>2.13</td>
<td>-</td>
</tr>
<tr>
<td>Temperature Coefficient of $I_L$</td>
<td>$C_T$</td>
<td>0.1</td>
<td>(mA/°C)</td>
</tr>
<tr>
<td>Number of bypass diodes per module</td>
<td>$N_b$</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Bypass diode forward voltage</td>
<td>$V_F$</td>
<td>0.5</td>
<td>V</td>
</tr>
</tbody>
</table>

Table 2.2  Parameters at STC for PowerFilm R7 PV module
The comparison between simulation results and the manufacturer’s datasheet verifies the validity of the simulation model very well.

![I-V curves of simulation model and the manufacturer’s datasheet for PowerFilm module](image)

**Figure 2.11** I-V curves of simulation model and the manufacturer’s datasheet for PowerFilm module

### 2.4 PV benchmark systems

In this research, two benchmark PV systems are built using simulation models for crystalline silicon and amorphous silicon respectively. In addition, the amorphous silicon PV system is implemented in real working conditions for verification. Table 2.3 summarizes main parameters of two benchmark systems.

<table>
<thead>
<tr>
<th>Type of PV modules</th>
<th>Configuration (series × parallel)</th>
<th>System nominal power ( (P_{mp,sys}) )</th>
<th>System nominal voltage ( (V_{mp,sys}) )</th>
<th>System nominal current ( (I_{mp,sys}) )</th>
<th>PV modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline silicon</td>
<td>6 × 5</td>
<td>5.25 kW</td>
<td>212.4 V</td>
<td>24.75 A</td>
<td>175W by SHARP</td>
</tr>
<tr>
<td>Amorphous silicon</td>
<td>2× 6</td>
<td>90 W</td>
<td>31.6 V</td>
<td>2.4 A</td>
<td>7.5W by PowerFilm</td>
</tr>
</tbody>
</table>

Table 2.3 Summary of two benchmark PV systems
2.4.1 Mono-crystalline silicon PV system

For a more comprehensive understanding of typical residential/commercial PV systems, a PV benchmark system (see Fig. 2.12) is simulated for mono-crystalline silicon modules in MATLAB/Simulink. The grid-connected PV system contains 5 parallel PV strings. Each string has 6 mono-crystalline silicon PV modules in series. Detailed parameters for module have been given in Table 2.1. For hot spot prevention, three bypass diodes (not shown in the diagram) are added in parallel with every module. According to the US NEC requirement, the system negative conductor and module frames (not shown in the diagram) are required to be solidly grounded [12]. Under normal working conditions, two switches in the GFPD are all closed. In simulations, it is assumed that the MPPT of the inverter ranges from 80V to 240V.

![Schematic diagram of PV system of crystalline silicon modules](image)

Figure 2.12 Schematic diagram of PV system of crystalline silicon modules

Simulations of PV system

The PV system is built in MATLAB/Simulink using the simulation model introduced in Chapter 2.3. In simulations, each PV model represents a PV module, which is modular and scalable. The model is input-independent with each other so that they may have their own temperature and irradiance conditions. To build a PV array, PV modules usually are put in certain series and/or parallel configurations. More importantly, their overall system
performance greatly depends on individual interconnected modules. The corresponding I-V curve for entire the PV array and each PV module under normal working conditions at STC are shown in Fig. 2.13.

![I-V curves of crystalline silicon PV array and PV module at STC](image)

Figure 2.13  I-V curves of crystalline silicon PV array and PV module at STC

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PV module</strong></td>
<td><strong>Type</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Detailed parameters</strong></td>
</tr>
<tr>
<td>SHARP NT-175UC1</td>
<td>At STC: ( V_{oc} = 44.4 \text{V} ), ( I_{sc} = 5.4 \text{A} ), ( V_{mpp} = 35.4 \text{V} ), ( I_{mpp} = 4.95 \text{A} ), ( P_{mpp} = 175 \text{W} )</td>
</tr>
<tr>
<td>(mono-crystalline</td>
<td></td>
</tr>
<tr>
<td>silicon)</td>
<td></td>
</tr>
<tr>
<td><strong>Entire PV array</strong></td>
<td>6 × 5 configuration</td>
</tr>
<tr>
<td></td>
<td>At STC: ( P_{sys} = 5.25 \text{kW} ), ( V_{sys} = 212.4 \text{V} ), ( I_{sys} = 24.75 \text{A} )</td>
</tr>
<tr>
<td><strong>Grid-connected</strong></td>
<td>Inverter for 5.25 kW</td>
</tr>
<tr>
<td>inverter</td>
<td>The MPPT of the inverter ranges: 80V ~ 240V</td>
</tr>
<tr>
<td></td>
<td>Min. start voltage=180V</td>
</tr>
</tbody>
</table>

Table 2.4  Parameters of main components in the 5.25kW mono-crystalline silicon PV system

2.4.2  Amorphous silicon PV system

The second PV benchmark system made of amorphous silicon modules is simulated in MATLAB/Simulink using our developed PV model. Also, the PV system is built and tested under real test conditions for experimental verifications. Fig. 2.14 illustrates this
grid-connected PV system containing 12 modules in a series-parallel configuration (for illustration purposes only). For instance, two modules are connected in series to create a string. Then 6 strings are all connected in parallel to build an array. For hot-spot prevention, one bypass diode is added in parallel with every module. Although this PV system is relatively small-scale, it consists of all typical components for a grid-connected system, such as PV modules, a grid-connected inverter, overcurrent devices for each string, a GFPD, proper system groundings, and connection wirings. In simulations and experiments, the MPPT of the inverter ranges from 22V to 40V.

Figure 2.14  Schematic diagram of PV system of amorphous silicon modules

Simulations of the amorphous silicon PV system

The PV system demonstrated here is built in MATLAB/Simulink using the simulation model created in Chapter 2.3. The PV simulation models are able to have different I-V curves which are especially useful for fault studies. To simulate the same PV system, 12 PV modules are assembled in the configuration of two modules in series as a PV string, and 6 strings in parallel. The corresponding I-V curves for entire PV array and each PV module under normal working conditions at STC are shown in Fig. 2.15.
Experimental set up of PV systems

The same PV system is set up for experimental verifications on the roof of Dana research building at Northeastern University (see Fig. 2.16). The parameters of PV modules and the inverter are given in Table 2.4. The inverter by Enphase and its maximum power point tracker (MPPT) are used to harvest the maximum power from array, and feed the power to the utility grid.

Figure 2.16  Picture of amorphous silicon PV system set up on Dana building at Northeastern University, Boston
### Equipment Parameters

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Parameters</th>
<th>Detailed parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module</td>
<td>Power Film R7 (amorphous silicon)</td>
<td>At STC: $V_{oc}=21.4\text{V}$, $I_{sc}=0.58\text{A}$, $V_{mp}=15.8\text{V}$, $I_{mpp}=0.48\text{A}$, $P_{mpp}=7.5\text{W}$</td>
</tr>
<tr>
<td>Entire PV array</td>
<td>2× 6 configuration</td>
<td>At STC: $P_{sys}=90\text{ W}$, $V_{sys}=31\text{ V}$, $I_{sys}=2.9\text{ A}$</td>
</tr>
<tr>
<td>Grid-connected inverter</td>
<td>Enphase microinverter M190</td>
<td>Max. output power 190W, min. start voltage: 28V; MPPT voltage range: 22 ~ 40V</td>
</tr>
</tbody>
</table>

Table 2.5  Parameters of PV modules and the inverter in the amorphous silicon PV system

### 2.5 Conclusions

The numerical modeling for PV modules based on the one-diode model has been described in this chapter. The modeling algorithm is implemented successfully in MATLAB/Simulink and converges fast and accurately enough to be used for large PV array simulations. The simulation model has accurate steady-state performance compared with the manufacturer’s datasheet.

Two PV benchmark systems with different solar-cell technologies and various power scales have been built in MATLAB/Simulink using the developed PV models. Their output performances under normal working conditions can be accurately predicted in simulation environment. Furthermore, one of the benchmark systems, the amorphous silicon PV system is also set up in Northeastern University to further validate the simulation conclusions. Based on the developed benchmark systems, fault scenarios in the PV array will be studied in the following chapters.
3. Typical Faults in PV Arrays

3.1 Introduction

A PV array usually has multiple parallel PV strings, and each string has a number of modules in series. Every module, string, and whole array, whether in normal or fault condition, has its own I-V characteristics and unique maximum power point (MPP). When PV modules are connected together, their total I-V curve is determined by the interactions among them. For this reason, PV modules perform together like a chain that it is only as strong as the weakest link. For a PV array’s performance, the weakest link is the poorest performing module or string under normal conditions [33]. This is also true for the PV array under fault scenarios.

Faults in PV arrays damage the PV modules and cables, as well as lead to electrical shock hazards and fire risk. For example, two fire hazards caused by ground faults and line-line faults, respectively, in PV arrays have been demonstrated in case studies of a large PV power plant in California, US [18]. Furthermore, faults in PV arrays may cause a large amount of energy loss. For instance, in UK domestic PV systems, the annual energy loss due to faults in PV systems is estimated to be up to 18.9% [34]. Therefore, fault analysis for a PV array is an important task for system efficiency and reliability analysis.

Based on the developed simulation model in Chapter 2, this chapter studies the simulation and experiments of various types of faults in PV arrays under high irradiance level, including the effects of the MPPT algorithm. Fundamental approaches of fault analysis are summarized based on I-V characteristic analysis, electric circuit analysis, numerical calculations, and understanding of MPPT algorithms.
There are some special considerations and assumptions in our research. It is considered that PV array is the only source of fault current. In other words, it is assumed that there is no overcurrent or overvoltage from any utility inverter, battery, lightning strikes or external sources. This consideration is appropriate because most grid-connected inverters of 10kW or less cannot backfeed current into PV array faults from utility grid [35]. Also, for simplicity, this research only studies the faults in PV arrays with zero impedance.

According to fault current behaviors, the faults in power systems (including PV systems) often have three states: pre-fault steady state, transients, and post-fault steady state (see Fig. 3.1). However, this thesis does not take into account the transient state in fault analysis because the fault current settling time is negligible (e.g. short-circuit fault is less than 0.1ms for a 175W crystalline silicon PV module), and the transients do not have effects on conventional protection devices. Therefore, this thesis only focuses on pre-fault steady state (called normal conditions) and post-fault steady-state (called fault conditions).

![Figure 3.1 Three states of fault evolutions in power systems](image)

Several analysis approaches of faults in PV systems have been proposed in the literature [17, 19, 34, 36-40]. The study [36] firstly summarizes the principal causes of failure in terrestrial PV modules, but it does not give any detailed fault current analysis. The I-V
characteristic analysis of a PV array under typical faults is first studied in the literature [37]. However, it only demonstrates the overall performance of the faulted array without showing any interconnection studies of PV modules or strings. Similarly in [38-39], only power vs. voltage (P-V) characteristics is simulated for a few types of faults in a PV array without giving any fault current estimation. The paper [17] focuses on selection of overcurrent protection devices in PV arrays, such as fuses, based on maximum possible fault current. But it does not show any detailed fault current analysis under different environmental or electrical conditions. An investigation of ground fault protection devices for PV systems [19] focuses on the ground-fault issues on the AC side of PV systems. But unfortunately it does not show any fault current on the DC side. A long-term performance data of PV systems has been collected and categorized in varied types of faults [34]. However, it only focuses on the annual energy losses due to the faults rather than detailed fault scenarios analysis.

In addition, maximum power point tracking (MPPT) have been studied for reliability issues in PV systems in the literature [40]. It only discusses the MPPT reliability of a PV array under partial shading rather than faults in the array. In fact, the MPPT algorithm of the PV inverter has a great impact on the fault scenarios in PV arrays. However, none of previous studies have mentioned that properly.

Specifically, this chapter of the thesis presents the following research contributions over previous works:

- Using the simulation model developed in Chapter 2, the thesis simulates a variety of typical faults in PV arrays and gives complete fault current analysis. The simulation model has advantages over previous works since it can accurate predict the interconnections among PV modules. The simulation results show that the instantaneous fault currents vary greatly with fault locations in the PV array;
• The effects of the MPPT of the inverter on fault currents are firstly introduced and explained. During the fault, as long as the MPPT is still working, the MPPT helps the PV array work at maximum power point and therefore, clips the fault current in the PV array to a small value. This feature of the MPPT may result in hidden fault currents within a PV array and bring new challenges to existing conventional protection devices;

• Experiments of typical faults have been carried out in a small-scale grid-connected PV system under real test conditions for proof of concepts. The summarized fault characteristics, the MPPT effects and subsequent new challenges to PV systems are explained and experimentally verified.

In summary, Chapter 3 of the thesis describes three of the most common types of faults that occur in PV systems: ground faults, line-line faults, and mismatch faults. Chapter 3 utilizes three steps in analyzing PV faults. The first step is to summarize the fundamental fault analysis approaches based on I-V characteristics analysis, KCL analysis, and conservation of power analysis. The second step is to simulate typical faults in the crystalline silicon benchmark PV system (installed power 5.25kW) built by the simulation model developed in Chapter 2. The third step is to carry out the fault experiments in a small-scaled PV system (installed power is 90W) for proof of concept verification.

3.2 Approaches of fault analysis

At first, this thesis gives three fundamental approaches of fault analysis in a PV array in more detail. To illustrate these approaches, this thesis introduces a typical PV system with series-parallel configuration shown in Fig. 3.2. The PV system contains \( n \) parallel PV strings, with the PV string cables connected in separate positive and negative buses. According to NEC requirements, the negative bus is intentionally grounded [12]. Each
string has $m$ PV modules in series. The equipment grounding is not shown in Fig. 3.2. This PV array is working under normal conditions and each string is generating current $I_1$, $I_2$... $I_n$. If the PV strings are all electrically identical and have the same environmental working condition, then $I_1=I_2=...=I_n=I$. The total current going into the inverter is $I_{pos}=n \times I$. Under normal working conditions, two switches in the GFPD are both closed, and the ground fault current $I_g$ in GFPD is zero. As a result, the current coming out of the inverter $I_{neg}$ should be equal to $I_{pos}$ ($I_{pos}=I_{neg}$).

![Figure 3.2 A schematic diagram of a grid-connected PV system with $m \times n$ modules](image)

If there is a fault occurring in the PV array in Fig 3.2, the configuration of the PV array will be changed accordingly. Then the schematic diagram of the faulted PV array can be modified as the combination of two groups of PV strings (see Fig. 3.3). There are currents $I_{f1}$ flowing out and $I_{f2}$ flowing into the faulted part of the array. Meanwhile, there are currents $I_{n1}$ flowing out and $I_{n2}$ flowing into the normal part of array, where $I_{n1}=I_{n2}$.

If the fault is a non-ground fault, the ground-fault current will be zero ($I_g=I_{f1}-I_{f2}=0$). On the other hand, if the fault is a ground fault, the ground-fault point will create a ground fault path, since there is already a system ground point at the negative conductors. As a
result, the ground-fault current \( I_g = I_{f1} - I_{f2} \) might not be zero. If \( I_g \) is high enough (i.e. \( >0.5A \)), \( I_g \) might trip the GFPD and the faulty circuitry will be isolated. The two linked switches in the GFPD will both be subsequently open. Therefore, the whole PV array and the inverter usually will be shut down.

![Modified schematic diagram of a PV system under fault](image)

According to the distinct features of a PV array, this research proposes fundamental approaches of fault analysis, which can be applied under a variety of fault scenarios. The basic approaches of fault analysis include I-V characteristics analysis, Kirchhoff's Current Law (KCL) analysis, and conservation of power analysis.

### 3.2.1 I-V characteristics analysis

The I-V characteristic describes the behaviors of PV arrays, and it is a basic tool for normal and fault analysis. In a faulted PV array with series-parallel configuration, the normal part and faulted part share the same operation voltage. According to the given I-V characteristics for PV arrays and array operation voltage, it is possible to derive the working points of normal and faulted parts of the array.
Generally, faults on PV arrays will cause voltage changes and unbalanced currents among PV strings. Sometimes, unbalanced currents may backfeed into the faulted string to cause damages to the PV modules or interconnecting conductors [12]. For example, the I-V characteristics of the previous faulted array (see Fig. 3.3) are plotted in Fig. 3.4 for illustration purposes only. Fig 3.4 shows that I-V curves for the entire array, the normal part of the array, and the faulted part of array substantially differ. The faulted part and the normal part of the array must work at the same voltage, since they are in parallel with each other. But they do not have the same MPP anymore. For example, at operation voltage $V_{op}$ on the I-V curve in Fig. 3.4, the operation points of the normal part, the entire array, and the faulted part can be found at points A, B and C, respectively. It is also noticed that the normal part will still have positive current even under fault, but the faulted part of the array will have negative current (backfed current), which may damage PV modules and cables.

The main reason for fault current is that the I-V curve of the faulted string changes to a lower open-circuit voltage ($V_{oc}$). However, the operating voltage of the array does not change immediately after the fault, since the MPPT in the inverter responds relatively slow compared to the fault. Therefore, the MPPT is keeping the system voltage relatively constant immediately after the fault. As a result, the faulted string must work in the 4th quadrant of its I-V curve as a load, instead of in the 1st quadrant as a source (see Fig. 3.4). If the fault happens on a clear day, it is likely that the backfed current becomes sufficiently high and the overcurrent protection devices (OCPD) in series with the faulted PV string will be tripped. However, if the fault occurs on a cloudy day or at night, it is likely that the backfed current is not high enough to trigger the OCPD.
3.2.2 KCL analysis

Kirchhoff’s Current Law (KCL) requires that at any node (or junction) in an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node, where a node is any spot where two or more wires are joined. From this point of view, for PV systems, a ground-fault point, positive/negative bus bar, or even the inverter can be viewed as a node (or junction).

Applying KCL analysis on a ground-fault PV system previously shown in Fig 3.3, the current relations must comply with:

- At ground-fault point: $I_{f_2} - (I_{f_1} + I_g) = 0$
- At positive bus bar: $(I_{f_1} + I_{n1}) - I_{pos} = 0$
- At negative bus bar: $I_{neg} - (I_{f_2} + I_{n2}) = 0$
- At inverter: $I_{in} = I_{out}$ and $I_{in} = I_{pos}$
- At GPFD: $I_{out} + I_g - I_{neg} = 0$

Figure 3.4  I-V characteristics of array under fault on a clear day
3.2.3 Conservation of power analysis

The law of conservation of power can be applied in PV arrays. Specifically in PV arrays, the power generation must be equal to the sum of load power and any power losses, which can be described in (3.1):

\[ P_G = P_{load} + P_{loss} + P_{fault} \]  

(3.1)

where \( P_G \) is the power generated by PV array; \( P_{load} \) is the power feeding to the inverter; \( P_{loss} \) is the power losses among PV array, which is mainly caused by the resistance of wiring cables [41]; \( P_{fault} \) is a special load which represents the power dissipated in the faulted part of the array under fault working conditions.

The power conservation of PV systems can be derived from the I-V characteristics of the array under fault in Fig. 3.4. Since \( I_{pos} = I_{n1} + I_{f1} \) at the operation voltage \( V_{op} \), it is concluded that \( I_{pos} \cdot V_{op} = (I_{n1} + I_{f1}) \cdot V_{op} \), which is equivalent to \( P_G = P_{load} + P_{fault} \), where \( P_{loss} \) is so small that can be neglected. The power diagram is illustrated in Fig. 3.5.

Figure 3.5   Conservation of power in a PV array under fault
3.3 Ground faults in a PV array under STC

A ground fault is an accidental electrical short circuit involving ground and one or more normally designated current-carrying conductors. The magnitude of ground-fault current depends on fault location, fault impedance, and geographical factors. If a ground fault is not cleared by proper fault protection, the fault connection might begin to generate and sustain a DC arc, which may become a fire hazard. Typical ground faults are usually caused by the following reasons [35, 42]:

- Incidental short circuit between normal conductor and ground, i.e. a cable in a module junction box contacting a grounded conductor incidentally;
- Insulation failure of cables, i.e. an animal chewing through cable insulation and causing a ground fault;
- Ground faults with PV modules, i.e. a solar cell short circuiting to grounded module frames due to deteriorating encapsulation of a PV module, impact damage, or water corrosion.

3.3.1 Simulation results of ground faults under STC

Ground faults are simulated in the crystalline-silicon benchmark system \((P_{mp}=5.25\,\text{kW}, V_{mp}=212.4\,\text{V}, I_{mp}=24.75\,\text{A})\) under STC. In simulations, the ground faults are solid faults that occur immediately. To fully understand the evolution of fault currents, the GFPD is not taken into consideration so that the fault can evolve without interruption. Two types of ground faults with zero impedance at different locations have been studied and their fault currents are predicted.

3.3.1.1 Lower ground fault

As shown in Fig. 3.6, a lower ground fault with zero fault impedance occurs between the last two modules at PV String #1. The instantaneous fault often creates voltage changes
and unbalanced currents between the faulted string and other normal strings.

Figure 3.6  Schematic diagram of a lower ground fault under STC

Simulation results

The simulation results have been summarized in Table 3.1.

<table>
<thead>
<tr>
<th>Lower ground fault</th>
<th>Fault current ($I_{\text{fault}}$)</th>
<th>Top String #1 current ($I_{1a}$) at fault</th>
<th>Array operation point</th>
<th>System efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>When fault occurs</td>
<td>3.92 A (0.726$I_{sc}$)</td>
<td>1.5 A (0.28$I_{sc}$)</td>
<td>213.6V, 21.4A, 4.57 kW</td>
<td>87%</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>1.4 A (0.26$I_{sc}$)</td>
<td>3.95A (0.73$I_{sc}$)</td>
<td>195.6V, 24.9A, 4.87 kW (new MPP)</td>
<td>92.8%</td>
</tr>
</tbody>
</table>

Table 3.1  Simulation results of a lower ground fault under STC

When the ground fault occurs at $t=2$s, the ground-fault current $I_{\text{fault}}$ has the maximum magnitude 3.92A (0.726$I_{sc}$). After that, the MPPT detects the sudden change of output power and begins to reduce $I_{\text{fault}}$ to 1.4A (0.26$I_{sc}$). Meanwhile, the faulted string current $I_{1a}$ is increased from 1.5A (0.28$I_{sc}$) to 3.95A (0.73$I_{sc}$) by the MPPT. In this lower ground fault case, there is no backfed current into the faulted string. The ground-fault current is larger than 0.5A so that it could be tripped by the GFPD (not included in simulation).
The simulated fault current ($I_{\text{fault}}$) evolution is given in Fig. 3.7. The simulated top String #1 current ($I_{1a}$) is plotted in Fig. 3.8. The output voltage ($V_{\text{sys}}$), current ($I_{\text{sys}}$) and power ($P_{\text{sys}}$) of the entire PV array are illustrated in Fig. 3.9.

![Figure 3.7 Simulated fault current ($I_{\text{fault}}$) of a lower ground fault under STC](image1)

![Figure 3.8 Simulated top String #1 current ($I_{1a}$) of a lower ground fault under STC](image2)
Figure 3.9  Simulated results of entire PV array under a lower ground fault under STC

**I-V characteristics analysis**

The I-V characteristics analysis in Fig. 3.10 is helpful for fault analysis in PV array.

- After the fault occurs at $t=2s$, the PV array operates at point “B” at fault from pre-fault MPP “A”;
- Meanwhile, the faulted String #1 operates at points from pre-fault MPP “D” to the operation point at fault “E” instantaneously;
- The MPPT will detect the sudden drop of output power and begin to optimize the output power of array. The MPPT will decrease array voltage ($V_{sys}$) in order to optimize the total output of array. As a result, the PV array’s operation point is moving from “B” to “C” gradually;
- With the help of the MPPT, the operation point of the faulted string is changed from “E” to “F”. However, the faulted string cannot work at its real MPP “G” anymore since it is mismatched with the other strings due to the fault.
• During the lower ground fault, the faulted PV String #1 always has the positive string current and works as a power source in the 1st quadrant of the I-V curve;

• The current equation $I_{1b} = I_{1a} + I_{\text{fault}}$ complies with KCL at the ground fault point.

![I-V characteristics of PV array under a lower ground fault](image)

**Figure 3.10  I-V characteristics of PV array under a lower ground fault**

### 3.3.1.2 Upper ground fault

As shown in Fig. 3.11, an upper ground fault with zero fault impedance occurs between the 2nd and the 3rd two modules at PV String #1 under STC. This upper ground fault will cause large backfed current and very high ground-fault current.
Simulation results

The simulation results have been summarized in Table 3.2.

<table>
<thead>
<tr>
<th>Upper ground fault</th>
<th>Fault current ($I_{\text{fault}}$)</th>
<th>Top String #1 current ($I_{1a}$) at fault</th>
<th>Array operation point</th>
<th>System efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>When fault occurs</td>
<td>27.22A (5.04$I_{\text{sc}}$)</td>
<td>-21.75A (-4.03$I_{\text{sc}}$)</td>
<td>116.4V, 0A, 0W</td>
<td>0%</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>2.1A (0.4$I_{\text{sc}}$)</td>
<td>3.24A (0.6$I_{\text{sc}}$)</td>
<td>80.4V, 25.05A, 2kW</td>
<td>38.1%</td>
</tr>
</tbody>
</table>

Table 3.2   Simulation results of a upper ground fault under STC

After the ground fault occurs at $t=2s$, the ground-fault current $I_{\text{fault}}$ reaches the maximum magnitude 27.22A ($5.04I_{\text{sc}}$). At the same time, the String #1 has a large amount of backfed current -21.75A (-4.03$I_{\text{sc}}$) from other normal strings. In this case, the ground-fault current is larger than 0.5A and can be tripped by the GFPD (not included in simulation). If the ground fault is cleared by the GFPD, the negative current-carrying conductor of the array is not grounded anymore so that the fault path is disconnected. The positive conductor is instantaneously open as well by the coupled switches in the GFPD.
If the fault is not cleared properly, the simulated fault current ($I_{\text{fault}}$) will evolve without interruption (see Fig. 3.12). The simulated top String #1 current ($I_{1a}$) is plotted in Fig. 3.13. The output voltage ($V_{\text{sys}}$), current ($I_{\text{sys}}$) and power ($P_{\text{sys}}$) of the entire PV array are illustrated in Fig. 3.14.

![Figure 3.12 Simulated fault current ($I_{\text{fault}}$) of a upper ground fault](image1)

![Figure 3.13 Simulated top String #1 current ($I_{1a}$) of a upper ground fault](image2)
I-V characteristics analysis

The I-V characteristics analysis in Fig. 3.15 can be used to derive the working points for the PV array during the fault.

- Before fault occurs, the PV array operates at its optimum point “A”;
- When the fault occurs at $t=2s$, the operating point of the array drops to “B” instantaneously. At the same time, the output current and power are both zero, since all the normal strings are backfeeding current into the faulted string (String #1);
- Meanwhile, the faulted String #1 operates instantaneously at point “E” under fault from pre-fault MPP “D”. It is noticed that the faulted String #1 has a large backfed current from other strings that may damage modules and cables;
- The MPPT will detect the sudden drop of output power and begin to optimize the
output power of the array. The MPPT will decrease array voltage \( V_{sys} \) in order to reduce the reverse current and power losses in the faulted string. As a result, the PV array’s operation point is moving from “\( B \)” to “\( C \)” gradually;

- With the help of the MPPT, the operation point of the faulted string is changed from “\( E \)” to “\( F \)” with positive current. However, the faulted string cannot work at its real MPP “\( G \)” anymore, since it is mismatched with the other strings due to the fault;

- At the beginning of the upper ground fault, the faulted PV String #1 has the large reverse string current and works as a load in the 4\(^{th}\) quadrant of the I-V characteristics. If the fault evolves without interruption, the MPPT can help the faulted PV array operate at new MPP, then the faulted string can generate power again;

- The current equation \( I_{1b} = I_{1a} + I_{\text{fault}} \) complies with KCL at the ground fault point.

![I-V characteristics of PV array under a upper ground fault](image-url)

**Figure 3.15** I-V characteristics of PV array under a upper ground fault
3.3.2 Summary of ground faults

Solid ground faults with zero fault impedance are simulated in 5.25kW benchmark PV systems. The specific simulation results of ground faults are summarized in Table 3.3.

<table>
<thead>
<tr>
<th>Simulation at STC</th>
<th>Type of systems</th>
<th>Type of ground faults</th>
<th>Maximum fault current $I_{\text{fault}}$ (A)</th>
<th>Worst faulted top String #1 current $I_{\text{fault1}}$</th>
<th>Fault effects on the faulted string</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.25kW crystalline silicon PV system</td>
<td>Lower</td>
<td>3.92 A (0.73$I_{\text{sc}}$)</td>
<td>1.5 A (0.28$I_{\text{sc}}$)</td>
<td>No backfed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td>27.21 A (5.04$I_{\text{sc}}$)</td>
<td>-21.74 A (-4.03$I_{\text{sc}}$)</td>
<td>Large backfed current</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3 Simulation results of upper ground faults under STC

In summary, based on the previous simulation results, ground faults in PV arrays have the following features:

- Ground-fault current ($I_{\text{fault}}$) varies with different locations of faults in PV arrays. When the ground fault is “higher” in the faulted string, the larger the voltage difference between faulty and normal strings becomes, and therefore, the larger $I_g$ becomes;

- Faulted string current (i.e. top String #1: $I_{1a}$) also depends on ground fault locations. If a lower ground fault occurs, the faulted string current may still be positive. However, in an upper ground fault, there may be a large backfed current into the faulted string;

- If ground-fault current exceeds the GFPD’s pickup current (0.5A), depending on specific time-current characteristics of the GFPD, the GFPD may trip the ground fault and disconnect the faulty circuitry;

- If the fault can evolve without interruption, the MPPT of the inverter can reduce the fault effects on a PV array by reducing the array’s operating point towards to the new maximum power point;
During the post-fault steady state, ground faults usually involve reduced array voltage ($V_{sys}$), but have much small reduction in array current ($I_{sys}$).

3.4 Line-line faults in a PV array under STC

A line-line fault is an accidental low-resistance connection established between two points of different potential in an electric network or system. For PV systems, a line-line fault is usually defined as a short-circuit fault among PV modules or array cables with different potential. In this research, it is assumed that line-line faults do not involve any ground points. Otherwise, a line-line fault with any ground points can be categorized as a ground fault.

Similar to ground faults, the magnitude of line-line fault current also depends on types of faults and environmental factors. The main causes for a line-line fault may be as follows [42]:

- Incidental short circuit between current carrying conductors, i.e. a nail driven through unprotected wirings;
- Insulation failure of cables, i.e. an animal chewing through cable insulation and causing a line fault;
- Line-line faults within the DC junction box, i.e. mechanical damage, water ingress and corrosion.

3.4.1 Simulation results of line-line faults under STC

Line-line faults are simulated in the 5.25kW crystalline-silicon benchmark system under STC. In simulations, the line-line faults are solid faults that occur immediately. It is assumed that the fault impedance is zero. To fully understand the evolution of fault currents, the overcurrent protection devices are not taken into consideration so that the fault is not cleared in the simulation. Two types of line-line faults at different locations
named the small voltage difference fault and the large voltage difference fault have been studied and their fault currents are predicted.

### 3.4.1.1 Line-line fault with small voltage difference

In Fig. 3.16, there is a short-circuit fault between fault point $F1$ at String #1 and fault point $F2$ at String #2. That is to say that there is a line-line fault with one-module level difference between String #1 and String #2. Similar to ground faults, line-line faults will also cause voltage difference between the faulted and the normal parts of the array, which lead to unbalanced currents among PV array. But unlike ground faults, line-line faults do not involve any grounding points, so that the current from system grounding point to negative conductor is always zero ($I_g=0$).

![Schematic diagram of a line-line fault with small voltage difference](image)

Figure 3.16  Schematic diagram of a line-line fault with small voltage difference

After the line-line fault in String #1 and String #2, the schematic diagram of the PV array can be divided into two parts, the faulted part and the normal part of the PV array, as illustrated in Fig. 3.17. Each part of the array can be seen as a node in the circuit analysis. The line-line fault is inside the faulted part, and there is no other closed path outside the array. Therefore, by using KCL analysis, the currents flowing into each part must be
equal to currents flowing out from each one. Therefore, the currents for each part of the array can be derived as:

- Current of faulted part of array \((I_F)\): \[ I_F = I_{1a} + I_{2a} = I_{1b} + I_{2b} \]

- Current of normal part of array \((I_N)\): \[ I_N = I_{3a} + I_{4a} + I_{5a} = I_{3b} + I_{4b} + I_{5b} \]

![Diagram of a line-line fault](image)

**Figure 3.17**  Modified schematic diagram of a line-line fault

The simulation results are summarized in Table 3.5 and plotted in Fig. 3.18 – Fig. 3.21.

**Simulation results**

<table>
<thead>
<tr>
<th>Line-line fault with small voltage difference</th>
<th>Fault current ((I_{fault}))</th>
<th>Top string #1 current ((I_{1a})) at fault</th>
<th>Top string #2 current ((I_{3a})) at fault</th>
<th>Array operation point</th>
<th>System efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>When fault occurs</td>
<td>3.5A ((0.65I_{sc}))</td>
<td>1.75A ((0.32I_{sc}))</td>
<td>5.33A ((0.99I_{sc}))</td>
<td>214V, 21.9A, 4.73kW</td>
<td>89.3%</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>1.5A ((0.28I_{sc}))</td>
<td>3.7A ((0.69I_{sc}))</td>
<td>5.33A ((0.99I_{sc}))</td>
<td>198.5V, 24.7A, 5kW</td>
<td>93.6%</td>
</tr>
</tbody>
</table>

Table 3.4  Simulation results of a line-line fault with small voltage difference

After the line-line fault occurs, the fault current \(I_{fault}\) has reached its maximum magnitude
(4A) and decreases to around 1.5A (0.28\(I_{sc}\)) with the help of the MPPT. Meanwhile, the faulted String #1’s top current reaches its minimum 1.75A (0.32\(I_{sc}\)) first, and then increases to 3.7A (0.69\(I_{sc}\)) by the MPPT. In this case, there is no backfed current into the faulted string, and no overcurrent is larger than the fuse rated current 5.4A (1.56\(I_{sc}\)). Therefore, the line-line fault with small-voltage difference cannot trip conventional protection devices. As a result, this line-line fault might be hidden in the PV array forever and cause reduced system reliability and efficiency.

Figure 3.18  Simulated fault current (\(I_{fault}\)) of a line-line fault with small voltage difference

Figure 3.19  Simulated top current of String #1 (\(I_{1a}\)) in a line-line fault with small voltage difference
Figure 3.20  Simulated top current of String #2 ($I_{2a}$) in a line-line fault with small voltage difference

Figure 3.21  Simulated results of entire PV array under a line-line fault with small voltage difference

**I-V characteristics analysis**

The I-V curve analysis in Fig. 3.22 is helpful for fault analysis in the PV array.
• After the fault, the PV array operates at point “B” from pre-fault MPP “A”;  
• Meanwhile, the fault current $I_{fault}$ reaches $3.6A (0.67I_{sc})$ instantaneously;  
• The MPPT will detect the sudden drop of output power and begin to optimize the output power of the array. The MPPT will decrease the array voltage ($V_{sys}$) in order to optimize the total output of the array. As a result, the PV array’s operation point moves from “B” to “C” gradually;  
• With the help of the MPPT, $I_{fault}$ is decreased from “D” to “E” along with the fault current curve;  
• The current equation $I_{fault} = I_{1b} - I_{1a} = I_{2a} - I_{2b}$ complies with KCL at the fault point.

Figure 3.22  I-V characteristics of PV array under a line-line fault with small voltage difference

3.4.1.2 Line-line fault with large voltage difference

In Fig. 3.23, there is a short-circuit fault between fault point $F1$ at String #1 and fault point $F2$ at String #2. That is to say that there is a line-line fault with two-module level difference between String #1 and String #2. This line-line fault will also cause large
voltage difference between the faulted and the normal parts of the array, and lead to unbalanced current among the PV array.

![Schematic diagram of a line-line fault with large voltage difference](image)

**Figure 3.23  Schematic diagram of a line-line fault with large voltage difference**

The simulation results are summarized in Table 3.5 and plotted in Fig. 3.24 – Fig. 3.27.

**Simulation results**

<table>
<thead>
<tr>
<th>Line-line fault with large voltage difference</th>
<th>Fault current ($I_{\text{fault}}$)</th>
<th>Top String #1 current ($I_{1a}$) at fault</th>
<th>Top String #2 current ($I_{2a}$) at fault</th>
<th>Array operation point</th>
<th>System efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>When fault occurs</td>
<td>18.42A ($3.4I_{sc}$)</td>
<td>-13A (-2.4$I_{sc}$)</td>
<td>5.35A (0.99$I_{sc}$)</td>
<td>213.4V, 7.25A, 1.55kW</td>
<td>29.5%</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>1.9A ($0.35I_{sc}$)</td>
<td>3.3A ($0.61I_{sc}$)</td>
<td>5.354A (0.99$I_{sc}$)</td>
<td>161.7V, 24.7A, 4kW</td>
<td>76.2%</td>
</tr>
</tbody>
</table>

Table 3.5  Simulation results of a line-line fault with large voltage difference

After the line-line fault occurs, the fault current $I_{\text{fault}}$ has reached its maximum magnitude (19.8A) and decreases to around 2A with the help of the MPPT. Meanwhile, the faulted String #1’s top current reaches its negative minimum 13A (-2.4$I_{sc}$) first, and then
increases to 3.3A (0.61$I_{sc}$) by the MPPT. In this case, there is a large backfed current into the faulted String #1 which will melt the fuse protections (rated no less than 1.56$I_{sc}$). Therefore, the line-line fault with large voltage difference under STC will be cleared by conventional protection devices properly.

Figure 3.24  Simulated fault current of a line-line fault with large voltage difference

Figure 3.25  Simulated top current of String #1 ($I_{ta}$) in a line-line fault with large voltage difference
Figure 3.26  Simulated top current of String #2 ($I_{2a}$) in a line-line fault with large voltage difference

Figure 3.27  Simulated results of entire PV array under a line-line fault with large voltage difference

**I-V characteristics analysis**

The I-V characteristics analysis in Fig. 3.28 is helpful for fault analysis in PV array.
• After the fault, PV array’s operation point suddenly drop to point “B” from pre-fault MPP “A”;  
• Meanwhile, the fault becomes 18.42A (3.4\(I_{sc}\)) fault current \(I_{fault}\) instantaneously;  
• The MPPT will detect the sudden drop of output power and begin to optimize the output power of array. The MPPT will decrease the array voltage \(V_{sys}\) in order to optimize the total output power of the array. As a result, the PV array’s operating point is moving from “B” to “C” gradually;  
• With the help of the MPPT, \(I_{fault}\) is decreased to 1.9A (0.35\(I_{sc}\)) at “E” along with the fault current curve;  
• The current equation \(I_{fault} = I_{1b} - I_{1a} = I_{2a} - I_{2b}\) complies with KCL at the fault point.

![Figure 3.28 I-V characteristics of PV array under a line-line fault with large voltage difference](image)

**3.4.2 Summary of line-line faults**

Line-line faults with zero fault impedance are simulated in 5.25kW benchmark PV systems. The specific simulation results are summarized in Table 3.6.
In summary, based on previous simulation results, line-line (LL) faults in PV arrays have the following features:

- LL-fault current \( I_{\text{fault}} \) varies with types of faults in the PV array. The fault with larger voltage difference between two fault points will lead to larger fault current;

- LL faults with small voltage difference (i.e. one-module voltage difference) might not cause any backfed current into the faulted string, so that this LL fault might be hidden in PV array and become a potential hazard for system efficiency and reliability. Therefore, LL faults with small voltage difference might bring challenges to existing protection devices;

- LL faults with large voltage difference (i.e. voltage difference larger than one module) will lead to large backfed current into the faulted string and large fault current in the fault path;

- If LL fault backfed current exceeds the rated current of overcurrent protection (i.e. fuses rated no less than \( 1.56I_{\text{sc}} \) according to the US NEC requirements [12]), depending on specific time-current characteristics of the fuse, the fault might be cleared and the faulty circuitry will be disconnected;

- Similar to ground faults, in line-line faults, as long as the inverter is still working, the MPPT of the inverter can reduce the fault effects on the PV array by changing the array’s operating point to move towards total array’s maximum power point;
If the fault can evolve without interruption, LL faults usually involve reduced array voltage ($V_{sys}$), but have much small reduction in array current ($I_{sys}$).

### 3.5 Mismatch faults in a PV array

Mismatches in PV modules occur when the electrical parameters of one module are significantly changed from those of the remaining modules. Also, mismatch faults are caused by interconnection of solar cells or modules which experience different environmental conditions (i.e. irradiance or temperature) from one another. Compared with ground faults and line-line faults, mismatch faults are the most common type of fault among PV arrays. Mismatch faults may lead to irreversible damage on PV modules and large power loss. However, they are difficult to detect using conventional protection devices, since they generally do not lead to large fault currents.

Mismatch losses may lead to serious problems in PV modules and arrays because the operating condition of the entire PV module under worst case conditions is determined by the PV module with the poorest performance. The impact and power losses due to mismatch are closely related to:

- The operating point (i.e. array voltage $V_{sys}$) of the PV module;
- The PV array configuration;
- The variation of parameters of the various PV modules.

Mismatch faults can be categorized into two groups, permanent and temporary. Their causes are listed below.

1. Temporary mismatches: partial shading and/or non-uniform temperature on a PV
array [43-44];

(2) Permanent mismatches: open-circuit faults in PV strings or modules, aging/degradation problems, hot spots due to bypass diode failure, and/or defective PV modules [45].

The first group is temporary mismatches, such as non-uniform shading on a PV array installation. Non-uniform shading by passing clouds is very common in large centralized PV arrays [44], which has a disproportionate impact on system efficiency and may lead to local heating problems (called hot spots). To prevent hot-spot damage, every PV module of a PV array usually will be equipped with several bypass diodes to bypass the extra current that the module cannot afford.

The second group is permanent mismatches, which will cause more severe irreversible damage on PV arrays and do harm to system efficiency and reliability. In this thesis, two types of permanent mismatches are studied and discussed based on the 5.25kW crystalline-silicon benchmark system. They are open-circuit faults and degradation faults.

3.5.1 Open-circuit fault in a PV array

An open-circuit fault is an accidental disconnection at a normal current-carrying conductor. For example, there is an open-circuit fault at point “F” on the String #1 of a PV array (see Fig. 3.29). This fault might occur on cracking PV cells/modules, or between module interconnections, typically in bus wiring or junction box. These faults might be caused by:

- Cyclic thermal stress;
- Hail or wind loading;
- Damage during processing and assembly.
It is assumed that the open-circuit fault occurring instantaneous in String #1 under STC. The simulation results are summarized in Table 3.7 and plotted in Fig. 3.30 and Fig. 3.31. It is noticed that the open-circuit fault will not generate any large fault current. Since one of 5 strings is disconnected at the fault, a large amount of power (nearly 20% of rated power) will lost. In Table 3.7, it is also noticed that the operation voltages at fault and post-fault happen to be almost identical (~213.4V). Consequently, the faulted PV array reaches its optimum immediately after the fault.

**Simulation results**

<table>
<thead>
<tr>
<th>Open-circuit fault</th>
<th>Fault current ($I_{fault}$)</th>
<th>Top string#1 current ($I_{1a}$) at fault</th>
<th>Array operation point</th>
<th>System efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>When fault occurs</td>
<td>0</td>
<td>0</td>
<td>213.4V, 19.94A, 4.26kW</td>
<td>80%</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>0</td>
<td>0</td>
<td>213.6V, 19.95A, 4.26kW</td>
<td>80%</td>
</tr>
</tbody>
</table>

Table 3.7 Simulation results of an open-circuit fault at STC
Figure 3.30  Simulated faulted string current $I_{fa}$ under an open-circuit fault

Figure 3.31  Simulated results of entire PV array under an open-circuit fault

**I-V characteristics analysis**

The I-V curve analysis in Fig. 3.32 gives more detailed information about the open-circuit fault in PV array. There are two MPPs: pre-fault and post-fault.
### Summary

- Before the fault occurs, the PV array is working normally at its rated MPP “A”. After the open-circuit fault occurs at $t=5s$, the current of String #1 ($I_{1a}$) drops to zero immediately since String #1 is disconnected due to the fault. As a result, the PV array has 4 strings left operating, and its operation point suddenly drops to point “B” from pre-fault MPP “A”. Moreover, the point “B” happens to be the MPP of the post-fault array;

- With the help of the MPPT of the inverter, the rest of PV strings will work at its post-fault optimum at 80% of total rated power. Unlike ground faults or line-line faults, open-circuit faults in PV arrays will not generate any overcurrent. Instead, the open-circuit fault will lead to increased power loss;

- Open-circuit faults usually involve with reduced array current ($I_{sys}$) but have almost the same array voltage ($V_{sys}$) as the normal PV array voltage.

#### 3.5.2 Degradation faults within PV modules

Although PV modules are reliable power sources, studies in [45] indicate that degradation problems on PV modules are common in PV array over a long-run field exposure. The
PV modules can fail or degrade in a number of ways, such as:

- Optical degradation caused by long-time exposure to ultraviolet;
- Cell degradation, such as increasing series resistance ($R_s$), decreasing shunt resistance ($R_{sh}$), and decreasing short-circuit current ($I_{sc}$);
- Front surface soiling i.e. a dirt spot adheres to module surfaces.

A degradation fault on the PV array is simulated in the 5.25kW crystalline-silicon benchmark system under STC. In Fig. 3.33, the second module in String #1 is deteriorated due to solar cell aging problems, resulting in degraded parameters in the one-diode model (see Table 3.8). The simulation results are summarized in Table 3.9 and plotted in Fig. 3.34 and Fig. 3.35.

![Figure 3.33 Schematic diagram of a degradation fault in PV array](image)

<table>
<thead>
<tr>
<th>Parameters for the one-diode model</th>
<th>Normal</th>
<th>Degraded parameter</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series resistor $R_s$</td>
<td>0.452 ohms</td>
<td>4.452 ohms</td>
<td>Larger series resistance</td>
</tr>
<tr>
<td>Shunt resistor $R_{sh}$</td>
<td>450 ohms</td>
<td>150 ohms</td>
<td>Smaller shunt resistance</td>
</tr>
<tr>
<td>Short-circuit current $I_{sc}$ at STC</td>
<td>$I_{sc}$=5.4A</td>
<td>$0.5I_{sc}$=2.7A</td>
<td>Smaller $I_{sc}$</td>
</tr>
</tbody>
</table>

Table 3.8 Degraded parameters of a PV module in simulation
Simulation results

<table>
<thead>
<tr>
<th>Working conditions</th>
<th>Faulted string#1 current ($I_{sc}$)</th>
<th>Other normal PV strings</th>
<th>Array operation point</th>
<th>System efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal working</td>
<td>$4.91A$ ($0.91I_{sc}$)</td>
<td>$4.91A$ ($0.91I_{sc}$)</td>
<td>$213.9V$, $24.5A$, $5.25kW$</td>
<td>100%</td>
</tr>
<tr>
<td>Degradation problems</td>
<td>$3.64A$ ($0.67I_{sc}$)</td>
<td>$4.92$ ($0.91I_{sc}$)</td>
<td>$213V$, $22.6A$, $4.81kW$</td>
<td>91%</td>
</tr>
</tbody>
</table>

Table 3.9 Simulation results of a degradation fault at STC

Figure 3.34 Simulated currents of a degradation fault in the PV array

Figure 3.35 Simulated results of the entire PV array under a degradation fault
**I-V characteristics analysis**

According to the I-V characteristics in Fig. 3.36, it is noticed that the degraded PV array has a much smaller fill factor ($FF = \frac{P_{mp}}{I_{sc} \cdot V_{oc}}$) and reduced MPP.

**Summary**

- The degradation problems will not generate any large fault current but may cause large power loss (depending on specific degradation conditions). Even though there is only one module degraded in String #1, the whole String #1 output current is greatly reduced to 52% of other normal strings in the simulation;
- The degraded module has detrimental effects on other modules in the array. In the simulation, there is only one PV module out of 30 modules degraded, which means 96.67% of PV modules are normal, but the overall output efficiency is only around 91%;
- Degradation faults usually involve reduced array current ($I_{sys}$) but have almost the same array voltage ($V_{sys}$) as the normal PV array voltage.
3.6 Experimental verification in real working conditions

Based on the small-scale benchmark PV systems that this research developed, a ground fault, a line-line fault and mismatch faults have been carried out for experimental verification. The experiments are implemented on the roof of Dana research building at Northeastern University in Boston. Photograph of the outdoor experiments are shown in Fig. 3.37(a) and Fig. 3.37(b). Component parameters have previously been presented in Table 2.5 in Chapter 2. To better understand the fault scenarios, overcurrent protection devices and the GFPD are not used in experiment so that the fault current will evolve without interruption.

![Photograph of the outdoor experiments on Dana building at Northeastern University, Boston](image)

(a)  (b)

Figure 3.37  Photograph of the outdoor experiments on Dana building at Northeastern University, Boston

3.6.1 Experiments of a ground fault

One ground fault in String #1 has been carried out in experiments under high irradiance level, as shown in Fig. 3.38. A circuit breaker is used to create the ground fault between the middle of String #1 and the ground. The array voltage \( V_{sys} \), array current \( I_{sys} \), and ground fault current \( I_{fault} \) are captured by Tektronix oscilloscope in Fig. 3.39 and Fig. 3.40. In the ground fault, the ground fault current \( I_{fault} \) equals to the current going
through the GFPD ($I_g$). Therefore, $I_{\text{fault}} = I_g$. The fault scenarios of a ground fault in the PV array are summarized in the Table 3.10.

Figure 3.38  Schematic diagram of PV system under a ground fault

Figure 3.39  Experimental results: $V_{sys}$ and $I_{sys}$ at a ground fault without interruption
Figure 3.40  Experimental results: $V_{sys}$ and $I_{fault}$ at a ground fault without interruption

**Experimental results**

| Ground fault       | Fault current ($I_{fault}$) | Top String #1 current ($I_{1a}$) at fault | Array operation point | System efficiency%
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-fault steady state</td>
<td>N/A</td>
<td>0.3A (0.52$I_{sc}$)</td>
<td>28V, 1.8A, 50.4W</td>
<td>56%</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>0.6A (1.03$I_{sc}$)</td>
<td>-0.1A (-0.17$I_{sc}$)</td>
<td>20V, 1.5A, 30W</td>
<td>33%</td>
</tr>
</tbody>
</table>

Table 3.10  Experimental results of a ground fault in the PV array

**Summary**

- During the fault: The array current ($I_{sys}$) drops to zero immediately since all normal string currents are backfeeding into the faulted String #1. As a result, the faulted array is operating at open-circuit conditions;

- The currents at ground-fault point always comply with KCL: $I_{1b} - I_{1a} = I_g$, where $I_{1a}$ represents top current of String #1, $I_{1b}$ represents bottom current of String #1. If $I_{1a}$ is negative, it means that the current is the backfed current from other normal strings. At the ground fault, the bottom module of String #1 is short-circuited by two ground
points, so that \( I_{lb} = I_{sc} = -0.5 \text{A} \) under specific environmental conditions;

- If the ground fault protection device GFPD is equipped, the ground fault current (\( I_{\text{fault}} \)) will go through the GFPD. The fault may be detected and cleared according to the GFPD’s protection characteristics, since \( I_{\text{fault}} \) is larger than the rated current of the GFPD (i.e. 0.5A) during the fault;

- After the fault, the fault evolves without interruption and the inverter is still working. The MPPT of the inverter will detect the sudden drop of output power and begin to optimize the output power of the array. The MPPT will decrease the array voltage (\( V_{\text{sys}} \)) in order to optimize the total output power of the array. As a result, the system will eventually operate around a new MPP. During this process, \( V_{\text{sys}} \) reduces (28V → 20V, 29% decreases), and \( I_{\text{sys}} \) changes a little less (1.8A → 1.5A, 16.7% decreases);

- The conclusion is that ground fault simulation results in Chapter 3.3 are verified by the experimental results: Ground fault current (\( I_{\text{fault}} \)) reaches its maximum at the fault. \( I_{\text{fault}} \) usually is larger than the rated current of the GFPD (i.e. 0.5A) so that the ground fault might be cleared. If the ground fault is not interrupted properly, the MPPT of the inverter will reduce the array voltage (\( V_{\text{sys}} \)) as well as \( I_{\text{fault}} \). After that, the system will operate at a lower \( V_{\text{sys}} \) but less reduced \( I_{\text{sys}} \).

### 3.6.2 Experiments of a line-line fault

A line-line fault in String #1 has been created in experiments in real working conditions, as shown in Fig. 3.41. String #1 only has one module left after the fault. Array voltage (\( V_{\text{sys}} \)), array current (\( I_{\text{sys}} \)), and ground fault current (\( I_{g} \)) during the fault are plotted in Fig. 3.42 to Fig. 3.44. The fault scenarios of a line-line fault in the PV array are summarized in the Table 3.11.

Fig. 3.42 shows experimental results of a line-line fault occurring in daytime under real
test conditions with high irradiance conditions (~800W/m²). Before $t=T_1$, each PV string is operating normally with string current 0.35A (0.6\text{I}_{sc})$. At $t=T_1$, the fault occurs instantaneously. After some switching transients during $T_1<t<T_2$, the fault current ($I_{\text{fault}}$) reaches its negative peak -1.41A (-2.43\text{I}_{sc}) immediately, and remains for $T_2<t<T_3$, which might be sufficient high to melt the fuse protection. From $T_3<t<T_4$, the MPPT responds and begins to optimize the operation points of array. After $t=T_4$, the PV system is working at reduced power output steady state. Finally, $I_{\text{fault}}$ is reduced to -0.35A (-0.6\text{I}_{sc}) by the MPPT of the inverter.

Figure 3.41  Schematic diagram of PV system under a line-line fault

Figure 3.42  Experimental results: $V_{sys}$ and $I_{1a}$ at a line-line fault without interruption
Experimental results: $I_{sys}$ and $I_{1a}$ during a line-line fault and normal conditions

![Graph showing $I_{sys}$ and $I_{1a}$ time vs. current]({})

Experimental results: $V_{sys}$ during a line-line fault and normal conditions

![Graph showing $V_{sys}$ time vs. voltage]({})

**Experimental results**

<table>
<thead>
<tr>
<th>Line-line fault</th>
<th>Backfed current (when $I_{1a} &lt; 0$, $I_{back}=I_{1a}$)</th>
<th>Top String #1 current ($I_{1a}$) at fault</th>
<th>Array operation point</th>
<th>System efficiency(=\dfrac{\text{Actual output power}}{\text{Nominal output power at STC}}) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-fault steady state</td>
<td>0</td>
<td>0.32A (0.55$I_{sc}$)</td>
<td>30V, 1.75A, 52.5W</td>
<td>58.3%</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>-0.12A (-0.2$I_{sc}$)</td>
<td>-0.12A (-0.2$I_{sc}$)</td>
<td>23V, 1.6A, 36.8W</td>
<td>41%</td>
</tr>
</tbody>
</table>

Table 3.11  Experimental results of a line-line fault in the PV array
Summary

- During the line-line fault experiments on a clear day, the backfed current into the faulted string \( I_{\text{back}} = I_{1a} \) has negative minimum \(-1.41A(-2.43I_{sc})\), which may melt the series fuse protection devices (rated at \( 1.56I_{sc} \));

- After the fault, the fault evolves without interruption and the inverter is still working. The MPPT of the inverter will detect the sudden drop of output power and begin to optimize the output power of the array. The MPPT will decrease the array voltage \( V_{sys} \) in order to optimize the total output power of the array. As a result, the system will eventually operate around a new MPP. During this process, \( V_{sys} \) reduces a lot (\( 30V \rightarrow 23V, 23\% \) decreases), and \( I_{sys} \) also changes (\( 1.75A \rightarrow 1.6A, 8.6\% \) decreases);

- If the overcurrent protection devices (i.e. fuses) are equipped at String #1, the backfed fault current \( I_{\text{back}} \) will go through the fuse. The fault may be cleared according to the fuse’s protection characteristics, since \( I_{\text{back}} \) is larger than the rated current of the fuse (no less than \( 1.56I_{sc} \) according to the US NEC [12]) during the fault;

- There are no additional grounding points in the line-line fault path, so that \( I_{g} = 0 \) and the ground fault protection device (GFPD) does not trigger for this type of fault;

- The conclusion is that line-line fault simulation results in Chapter 3.4 are verified by the experimental results: backfed current \( I_{\text{back}} \) reaches its maximum magnitude at the fault. If \( I_{\text{back}} \) is larger than the rated current of the OCPD (i.e. fuses rated no less than \( 1.56I_{sc} \) according to the US NEC [12]), the line-line fault might be cleared. If the line-line fault is not interrupted properly, the MPPT of the inverter will reduce the array voltage \( V_{sys} \) as well as \( I_{\text{fault}} \). After that, the system will operate at a lower \( V_{sys} \) but less reduced \( I_{sys} \).
3.6.3 Experiments of mismatch faults

In the experiments, two types of permanent mismatches are studied and discussed based on the 90W amorphous-silicon benchmark system in real working conditions. Two types of mismatch faults are open-circuit faults and degradation faults.

3.6.3.1 Experiments of an open-circuit fault

An open-circuit fault in String #1 has been created in experiments under high irradiance level, as shown in Fig. 3.45. Array voltage \( V_{\text{sys}} \), array current \( I_{\text{sys}} \), and top String #1 current \( I_{1a} \) during the fault are plotted in Fig. 3.46 and Fig. 3.47, and summarized in Table 3.12.

---

![Schematic diagram of PV system under an open-circuit fault](image)

**Figure 3.45**  Schematic diagram of PV system under an open-circuit fault

![Experimental results: \( I_{\text{sys}} \) and \( I_{1a} \) during an open-circuit fault and normal conditions](image)

**Figure 3.46**  Experimental results: \( I_{\text{sys}} \) and \( I_{1a} \) during an open-circuit fault and normal conditions
Experimental results

<table>
<thead>
<tr>
<th>Open-circuit fault</th>
<th>Fault current</th>
<th>Top String #1 current ($I_{fa}$) at fault</th>
<th>Array operation point</th>
<th>System efficiency=%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-fault steady state</td>
<td>0</td>
<td>0.32A ($0.55I_{sc}$)</td>
<td>30V, 1.75A, 52.5W</td>
<td>58.3%</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>0</td>
<td>0</td>
<td>30V, 1.45A, 43.5W</td>
<td>48.3%</td>
</tr>
</tbody>
</table>

Table 3.12  Experimental results of an open-circuit fault in the PV array

Summary

- During the open-circuit fault experiments on a clear day, there is no backfed current or overcurrent into the faulted string;

- During the open-circuit fault: String #1 is disconnected during the fault so that $I_{fa}=0$ immediately after the open-circuit fault. The faulted system will operate around a new optimum power point controlled by the MPPT of the inverter. Therefore $I_{sys} = \sum_{i=2}^{6} I_i$ is ~1.5A instead of $I_{sys}=1.8A$ at normal condition. Array voltage $V_{sys}$ almost remains the same (~30V) as expected in the simulation;
- There are no additional grounding points in the line-line fault path, so that \( I_g = 0 \) and the ground fault protection device (GFPD) does not trigger for this type of fault;

- The conclusion is that open-circuit fault simulation results in Chapter 3.5.1 are verified by the experimental results: The open-circuit fault in PV arrays does not involve overcurrent but cause power losses depending on specific fault scenarios. The MPPT of the inverter may help the array work around its new MPP with almost the same \( V_{sys} \) but reduced \( I_{sys} \).

3.6.3.2 Experiments of a degradation fault

A degradation fault in String #1 has been created in experiments, as shown in Fig. 3.48. To create a degradation fault, a variable resistor is inserted in the middle of String #1 to increase the series resistor of the 1\(^\text{st} \) module. The variable resistor will be increased from 0 ohms to 100 ohms gradually to represent the slow degradation process. Array voltage (\( V_{sys} \)), array current (\( I_{sys} \)), and String #1 current (\( I_{1a} \)) during the fault are plotted in Fig. 3.48 and Fig. 3.49. The experimental results are summarized in Table 3.13.

![Figure 3.48  Schematic diagram of PV system under a degradation fault](image-url)
Experimental results

Table 3.13  Experimental results of a degradation fault in the PV array

<table>
<thead>
<tr>
<th>Degradation fault</th>
<th>Degradation series resistor in String #1</th>
<th>Top String #1 current ($I_{1a}$) at fault</th>
<th>Array operation point</th>
<th>System efficiency = Actual output power / Nominal output power at STC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-fault steady state</td>
<td>0 ohms</td>
<td>0.36A (0.62$I_{sc}$)</td>
<td>27V, 1.84A, 50W</td>
<td>55.6%</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>100 ohms</td>
<td>0.11A (0.19$I_{sc}$)</td>
<td>26V, 1.59A, 41W</td>
<td>46%</td>
</tr>
</tbody>
</table>
Summary

- During the degradation-fault experiments on a clear day, there is not any backfed current or overcurrent into the faulted string. The series resistor of the 1st module in String #1 increases gradually from 0 ohms to 100 ohms at 10 ohms step size. At each step, the MPPT of the inverter responds fast enough to make the array operate at its optimum output power point. Meanwhile, faulted String #1 current ($I_{fa}$) is reduced at each step of series resistor degradation. As a result, the array current ($I_{sys}$) is reduced as well;

- During the degradation fault: the array voltage ($V_{sys}$=−26V) keeps almost the same as normal PV array voltage (~27V), which is predicted by simulation results in Chapter 3.5.2;

- There are no additional grounding points in the line-line fault path, so that $I_g$=0 and the ground fault protection device (GFPD) does not work for this fault;

- The conclusion is that degradation fault simulation results in Chapter 3.5.2 are verified by the experimental results: The degradation fault in PV arrays does not involve overcurrent but cause power losses depending on specific fault scenarios. The MPPT of the inverter may help the array work around its new MPP with almost the same $V_{sys}$ but reduced $I_{sys}$.

3.7 Conclusions

This research gives comprehensive analysis of PV arrays under typical fault conditions that may lead to unexpected fire hazards and personnel safety issues [14]. A summary of the research contributions for the achievement of Objective 2 is as follows:

- Chapter 3 of the thesis focuses on simulations and experiments of a variety of
PV-array faults, especially ground faults, line-line faults, and mismatch faults. These typical faults are simulated using 5.25kW mono-crystalline silicon PV benchmark system under STC. Their fault output characteristics are summarized and experimentally verified by a 90W amorphous silicon PV system in real working conditions;

- Based on simulation and experimental results, it is noticed that instantaneous fault currents vary with types of faults. (1) Ground faults and line-line faults usually may cause large fault currents and significant power loss. Fault currents in PV array may be large enough to cause irreversible damages on PV modules or wiring connections and even fire hazards on the fault path. Generally ground faults and line-line faults will have an impact on the entire PV array. (2) On the other hand, mismatch faults may only have some power loss rather than large fault currents. Depending on the specific case, mismatch faults are more likely to have impact on individual PV module/string instead of “dragging down” the whole array;

- In practice, the ground fault protection devices (GFPD) and overcurrent protection devices (OCPD) will be equipped with PV arrays to prevent the damage from large fault currents. But they function differently. (1) In a system-grounded PV system, the ground fault current will go through the GFPD, which normally has a small fault trip level (generally around 0.5A) [19]. Thus, according to its protection characteristics, GFPD may trip any ground fault current larger than 0.5A. (2) In a system-grounded PV system, the line-line fault may cause large backfed current into the faulted string and its series OCPD. In the US NEC [12], OCPD is rated no less than \(1.56I_{sc}\), where \(I_{sc}\) is the short-circuit current of individual PV module. If the backfed current is larger than \(1.56I_{sc}\), the OCPD may work properly according to its protection characteristics. (3) In summary, in the system-grounded PV system in the US, if there is a ground fault, GFPD is supposed to be the only device to trip the fault. In the case of line-line faults, OCPD is supposed to isolate the faults because
no extra ground points involved and GFPD will not work;

- Simulation results and experimental verification show that the post-fault steady state characteristics of PV arrays depending on types of faults, if the fault is not properly disconnected. (1) During ground fault or line-line fault, if the fault is not interrupted properly, the PV array may have significant post-fault voltage ($V_{sys}$) drops. However, the post-fault current ($I_{sys}$) does not change much. (2) During open-circuit fault or degradation fault (increased series resistance), post-fault voltage ($V_{sys}$) remains the same, but post-fault current ($I_{sys}$) may drop significantly. This fault information could be helpful for fault location and identification in PV arrays;

- The research results demonstrate that the line-line fault with small voltage difference may not generate large fault current. Therefore, it may not be cleared and could bring new challenges to existing conventional protection approaches;

- The effect of the MPPT on fault current in PV systems is discussed in simulation and experiments, which has not previously appeared in the literature. If the fault in the PV array is not properly interrupted when the fault occurs, the MPPT may cause the PV array to operate at lower power. This may reduce the fault on the PV array to a value below the tripping value of the OCPD. Therefore, the fault may be hidden in the PV array by MPPT and bring new challenges to existing conventional protection devices. The effect of the MPPT is further explained in Chapter 4.
4. **Unique Faults in PV Arrays**

4.1 **Introduction**

Fault detection and protection in solar photovoltaic (PV) arrays are important tasks for improving PV system efficiency and reliability. Faults in PV arrays not only damage the PV modules and cables, but also lead to electrical shock hazards and fire risk. For instance, two fire hazards caused by ground faults and line-line faults, respectively, in PV arrays have been demonstrated in case studies of a large PV power plant in California, US [18]. Furthermore, faults in PV arrays may cause large amount of energy loss. For example, in UK domestic PV systems, the annual energy loss due to faults in PV systems is estimated to be up to 18.9% [34]. To achieve proper overcurrent fault detection and protection, conventional approaches usually add circuit breakers or fuses in series with PV components [17-19, 35]. But these overcurrent protection devices (OCPD) are designed to protect PV modules and connection cables from damage caused by maximum possible fault currents in PV arrays. For instance, the OCPDs, such as fuses, are rated no less than $1.56I_{sc}$ according to the US NEC [12]. In other words, these protection devices are able to clear faults and isolate faulty circuits only if they carry sufficiently large faulty current under high irradiance level [17-19]. However, in many cases, such as faults in PV arrays at cloudy or overcast weather conditions, or even at night, the faults may not cause significant overcurrent. Additionally, the maximum power point tracker (MPPT) of the PV inverter may make fault detection and protection more complicated.

Unlike faults occurring in high irradiance [17-19, 35] or normal PV systems under changing irradiance during a day [46], Chapter 4 of the thesis primarily discusses two specific types of line-line faults under different meteorological conditions. One is a fault that occurs under “low irradiance” condition. The other is a fault that evolves under...
varying irradiance condition (called “night-to-day” transition). They are unique types of faults to PV systems that have not been studied in the literature.

- The first fault considered is a line-line fault that occurs in a grid-connected PV array under low irradiance level. As we have shown in Chapter 2 of this thesis, PV modules have limited output current, which is roughly proportional to irradiance level. If a fault occurs in the PV array on a cloudy day, the fault current may be consequentially small and commonly may not melt fuse protections. After the fault, the inverter and its MPPT (commonly by using Perturb and Observe (P&O) algorithm [20-21]) might still work and help the PV array to operate at its lower power nominal optimum conditions. As a result, the fault current will be greatly reduced and limited to a small value by the MPPT. After that, no matter how irradiance changes, the MPPT can maintain the fault current to a low value that cannot melt fuse protection. This leads to an unsafe condition in the PV array that has not been reported in the literature before;

- The second fault is a line-line fault evolution in a grid-connected PV array during “night-to-day” transition. Specifically, a “night-to-day” transition fault occurs in the PV array at night when there is no solar irradiance. During sunrise, the irradiance on the PV array increases slowly, as does the PV array voltage. As long as the PV array voltage reaches the minimum start voltage of the inverter, the PV inverter and its MPPT start to work. Then the PV system begins to feed energy to the utility grid. However, the MPPT responds quicker than the slow irradiance changes. As a result, the faulted PV system is forced by the MPPT to operate at a low optimum output point after the inverter’s startup. Consequently, instead of causing large overcurrent, the faulted PV array during night-to-day transition might lead to a smaller fault current, which is difficult to clear with conventional protection devices.
On the other hand, if the same fault occurred in daytime under high irradiance, the MPPT would have responded too slow to prevent the fault current protection device (fuse, or circuit breaker) to trigger. Thus, the same fault in daylight operating condition would have been cleared.

In summary, the results in this chapter describe how previously unreported low irradiance fault and night-to-day transition fault bring challenges to PV systems as follows:

- System reliability: Conventional fault detection might not detect or clear the unique faults to PV arrays, since there is not a large fault current. Because of this, the fault may remain undetected and cause DC arcs, which might lead to unexpected fire hazards and personnel safety issues on the fault path [47-49];

- System efficiency: Unlike normal operating conditions, the faulted PV array has a substantially different current vs. voltage (I-V) curve and reduced maximum power point (MPP). The PV system may still function after the unique faults, but the output power will be greatly reduced.

4.2 Overview of a line-line fault in the PV array

In the research, a line-line fault with large voltage difference has been created in the 5.25kW simulation benchmark PV system. In the schematic diagram shown in Fig. 4.1, there is a short-circuit fault between fault point \( F1 \) at String #1 and fault point \( F2 \) at String #2. The parameters for the simulated PV system are given in Table 4.1. When the fault occurs in high irradiance on a clear day, our research results in Chapter 3 demonstrate that the fault will lead to enough large backfed current to melt the OCPD (fuses) protections. However, the same fault will behave distinctively under low irradiance and changing irradiance level.
In simulations, real irradiance data with one-minute resolution is used as input for the 5.25 kW benchmark PV system. The irradiance data during a cloudy day is sampled each minute in Eugene Oregon [50] (see Fig. 4.2). It is noticed that the irradiance data is varying greatly during a daytime with the maximum irradiance 1000W/m² and the minimum irradiance 200W/m². The irradiance with such a large variation is good to test the fault characteristics of the PV system and the MPPT responses of the inverter.
In the research, some assumptions are made for these two types of unique faults in PV systems as follows.

- Two types of faults are using the same pattern of solar irradiance shown in Fig. 4.2. For simplicity, it is assumed that the PV array’s working temperature is constant at 25°C;

- Fault occurs in daytime: The MPPT responds relatively slow compared to the fault. Therefore, the MPPT is keeping the system voltage relatively constant immediately after the fault. As a result, the faulted PV array may not work at its optimum output point at the moment of fault. The backfed current or fault current may occur during this time. However, after the fault, as long as the MPPT is still working, the MPPT will take a while to help the faulted PV array work back to its nominal MPP eventually;

- Fault occurs at night: It is assumed that the fault occurs with zero solar irradiance at night. Therefore, there is no light-generated current or any fault currents among the PV array;
- Also, it is considered that PV array is the only source of fault current and fault impedance on fault path is zero.

### 4.3 The line-line fault in the PV array under low irradiance

In the research, the line-line fault occurs in the PV array when the irradiance reaches 300W/m² during sunrise. The I-V curves and P-V curves of the PV array have been simulated in Fig. 4.3, Fig. 4.4 and Fig. 4.5.

#### I-V curve analysis

Before the fault, the PV array is operating normally at its optimum working point \( MPP1 \). At the fault, I-V curve of the faulted array changes to a lower open-circuit voltage \( V_{oc\_array} \), where \( V_{oc\_array} \) is lower than voltage of \( MPP1 \) \( (V_{mpp1}) \). Thus, the PV array cannot maintain the operating voltage at \( V_{mpp1} \) anymore. Instead of dropping vertically to \( X_1 \), the operating point of the faulted array moves at its open-circuit condition at \( X_2 \) with voltage \( V_{oc\_array} \). In the meantime, the operating point of String #1 and String #2 moves to \( Y_2 \) at the same voltage \( V_{oc\_array} \) as \( X_2 \). As a result, the faulted String #1 and String #2 must work at the voltage \( V_{oc\_array} \) in the 4\(^{th}\) quadrant of its I-V curve as a load, instead of in the 1\(^{st}\) quadrant as a source (see Fig. 4.3). Therefore, since the faulted PV array is at open-circuit condition, the output power drops to zero immediately.

After the fault, the MPPT of the inverter identifies the sudden drop of the array’s output power and begins to look for a new MPP. The MPPT reduces the array voltage as well as \( I_{back} \) and \( I_{fault} \), in order to minimize the power consumed by the faulted string. Eventually, the faulted array oscillates along with its I-V curve to a new optimum working point \( (MPP2) \). As a result, \( I_{fault} \) is decreased to a much smaller value and there is no \( I_{back} \) into the faulted strings.
Figure 4.3  The I-V curve analysis of PV array under a line-line fault at low irradiance

**P-V curve analysis**

The corresponding P-V curves of the normal and the faulted PV arrays are shown in Fig. 4.4. When the fault occurs, the PV array is operating at $MPP_1$. After the instantaneous line-line fault, the operating point of the array drops vertically to $F$ immediately. It can be seen that the output power of array is therefore greatly reduced. Detecting sudden drop of the array’s output power, the MPPT is going to change the operation of array from $F$ to $MPP_2$, which is a new MPP for the faulted array.

After the array reaches $MPP_2$, the operating point of the array will vary with the changing irradiance, as shown in Fig. 4.5. The MPPT operates fast enough to help the faulted PV array working around its MPP under varying irradiance level. Therefore, the operating point of the array will be moving around the MPPs of each P-V curve depending on specific irradiance level.
4.3.1 Simulation results

The irradiance data on a cloudy day has been shown in Fig. 4.2. The fault occurs at 8AM when the irradiance is relatively low (~300W/m²). The simulation results have been summarized in Table 4.2. Detailed simulation results are shown in Fig. 4.6 – Fig. 4.9.
<table>
<thead>
<tr>
<th>Low irradiance fault</th>
<th>Irradiance level W/m²</th>
<th>Fault current ($I_{faul}$)</th>
<th>Top String #1 current ($I_{ta}$) at fault</th>
<th>Cleared by OCPD (rated at $1.56I_{sc}$)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>When fault occurs</td>
<td>300</td>
<td>7.84A (1.45$I_{sc}$)</td>
<td>-6.27A (-1.16$I_{sc}$)</td>
<td>No</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>Varying between 0 ~1038</td>
<td>0 ~ 4.82A (0.9$I_{sc}$)</td>
<td>-0.72A (-0.13$I_{sc}$) ~ 4.28A (0.9$I_{sc}$)</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 4.2  Simulation results of a line-line fault at low irradiance

![Figure 4.6](image1.png)  Simulated fault current of a line-line fault under low irradiance

![Figure 4.7](image2.png)  Simulated top current of String#1 ($I_{ta}$) of a line-line fault under low irradiance
The conclusions from these “low irradiance” fault simulations are as follows:

- When the line-line fault occurs under low irradiance, the array’s output current \( (I_{sys}) \) is significantly reduced to zero, since almost all of the normal strings’ current are...
backfeeding into the faulted string. Therefore, the array’s output power ($P_{sys}$) drops to zero immediately at the fault. However, since the irradiance is low (~300W/m$^2$), the backfed current into String #1 ($I_{back}$) is not large enough to melt the OCPD fuses. Therefore, the OCPD fuses (usually rated no less than $1.56I_{sc}$) cannot clear the fault;

- The MPPT in the inverter identifies the sudden drop of the array’s output power and begins to look for a new MPP of the array. As a result, the MPPT reduces the array’s voltage ($V_{sys}$) as well as $I_{back}$ to increase the $P_{sys}$;

- When the array reaches its MPP, $I_{back}$ and $I_{fault}$ are reduced greatly to a much smaller value. After that, following the varying irradiance, the faulted array is working around its MPP with the help of the MPPT. Notice that $I_{back}$ never reaches a high enough value to blow a fuse, and therefore, the fault remains undetected;

- During fault evolution under low irradiance, the array’s voltage ($V_{sys}$) does not change much with varying irradiance. Instead, the array’s current ($I_{sys}$) and output power ($P_{sys}$) are roughly proportional to the irradiance level.

4.4 The line-line fault in the PV array during night-to-day transition

In the research, the second unique PV fault is the same line-line fault (with large voltage difference) occurs in the PV array at night with no solar irradiance. The same irradiance data on a cloudy day (see Fig. 4.2) has been used as input in simulations of fault evolution during night-to-day transition.

P-V curve analysis

The simulated P-V curves of the faulted PV array under during night-to-day transition are shown in Fig. 4.10. Under the irradiance level lower than 160W/m$^2$, the MPPT of the inverter has not started to work, because the array voltage is not as high as the minimum start voltage of the inverter ($V_{min}$=180V). Therefore the array is at open-circuit conditions
with zero output power. The operation point on the P-V curve is moved from \( A \) to \( B \) along with voltage axis. After the inverter starts at \( B \), the MPPT of the inverter helps the operation point move from \( B \) to \( C \), which is the MPP at irradiance of 180W/m\(^2\). As time evolves and irradiance varies, the array operates between MPP \( C \) to MPP \( D \), where \( D \) is the MPP at 1000W/m\(^2\).

![Figure 4.10 The P-V curve analysis of the faulted PV array under different irradiance](image)

4.4.1 Simulation results

The simulation results have been summarized in Table 4.3. Detailed simulation results are shown in Fig. 4.11 – Fig. 4.14.

| Night-to-day fault | Irradiance level W/m\(^2\) | Fault current \( (I_{fault}) \) | Top String #1 current \( (I_{in}) \) at fault | Cleared by OCPD (rated at 1.56\( I_{sc} \))?
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>When fault occurs ( (t&lt;T_1) )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>When inverter starts ( (t=T_2) )</td>
<td>160</td>
<td>3.79A ( (0.7I_{sc}) )</td>
<td>-3A ( (-0.56I_{sc}) )</td>
<td>No</td>
</tr>
<tr>
<td>After inverter starts ( (T_2&lt;t&lt;T_3) )</td>
<td>Varying between 0 ~ 1038</td>
<td>0 ~ 4.65A ( (0.86I_{sc}) )</td>
<td>-0.52A ( (-0.1I_{sc}) ) ~ 4.27A ( (0.79I_{sc}) )</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 4.3 Simulation results of the line-line fault during night-to-day transition
Figure 4.11  Simulated fault current of a line-line fault during night-to-day transition

Figure 4.12  Simulated top current of String #1 ($I_{ta}$) of a line-line fault during night-to-day transition
If the same line-line fault (shown in Chapter 4.3) occurs at night with no solar irradiance, the fault evolves during night-to-day transition and behaves distinctively. The conclusions from these “night-to-day transition” fault simulations are as follows:

- Since the fault occurs under no irradiance, there is no backfed current ($I_{back}$) or fault
current ($I_{fault}$) to trigger the OCPD with the faulted string. Therefore, the fault is not interrupted so that it can evolve in the PV array during night-to-day transition;

- During sunrise with irradiance increasing, short-circuit current ($I_{sc}$) and open-circuit voltage ($V_{oc}$) of the faulted PV array are increasing as well. Before $V_{oc}$ reaches the min. start voltage of the inverter ($V_{min}$) ($t<T_1$), the inverter has not started to work yet, so that the PV array is still at open-circuit condition with zero total output current. But the PV strings are mismatched since the two strings are already faulted. Hence, the currents of other normal strings have no path to flow but backfeed together into the most faulted string (String #1). This negative reverse current is the backfed current ($I_{back}$) whose magnitude is also increasing with irradiance before $V_{oc}$ reaches $V_{min}$;

- When $V_{sys}$ reaches $V_{min}$ of the inverter ($t=T_2$), $I_{back}$ may reach its negative peak. It is shown that $I_{back}$ is dependent on $V_{min}$. For instance, $V_{min}$ is chosen as 180V in the simulation and $I_{back}$ has negative peak -3A (-0.56$I_{sc}$), which cannot melt the OCPD (rated at 1.56$I_{sc}$). It is also noticed that higher $V_{min}$ of the inverter will lead to larger magnitude of $I_{back}$;

- Meanwhile, the MPPT of the inverter starts to help the PV array work at its nominal MPP and minimizes $I_{back}$ as well as $I_{fault}$ under varying irradiance. During $T_2<t<T_3$, notice that $I_{back}$ never reaches a high enough value to blow a fuse, and therefore, the fault remains undetected during night-to-day transition;

- Notice that $I_{Ja}$ oscillates and sometimes goes to negative after the MPPT begins to work. The reason is that sometimes sudden changes of solar irradiance could mislead the MPPT (P&O algorithm) and the array’s operating point as well. But the MPPT is robust enough to identify and correct mistakes quickly;

- During fault evolution during night-to-day transition, the array’s voltage ($V_{sys}$) does not change much with varying irradiance. Instead, the array’s current ($I_{sys}$) and output power ($P_{sys}$) are roughly proportional to the irradiance level.
4.5 Experimental verification

The experiments of “low irradiance” fault and “night-to-day transition” fault have been carried out in the small-scale experimental PV benchmark system under real test condition. The benchmark PV system is a typical grid-connected PV system containing 12 modules in a series-parallel configuration (see Fig. 4.15). Under normal working conditions, the PV array can work normally around its present MPP at daytime, since the irradiance is usually high enough to start the inverter and its MPPT in the PV system. In the meantime, every parallel string is generating string current ($I_1$...$I_6$) at the same operation voltage ($V_{sys}$). The string currents sum up at positive bus bar as system current ($I_{sys}$) and flow into the inverter.

As shown in Fig. 4.15, there is a line-line fault in String #1. As a result, String #1 only has one module operating under the fault. This mismatch due to the fault in the PV array may disturb the normal operation of the array and generate the backfed current ($I_{back}$) among them.

![Figure 4.15 Schematic diagram of PV system under a line-line fault](image-url)
4.5.1 Experimental set-up

A small-scale lab test PV system has been established to verify our previous simulation results. Fig. 4.16 illustrates the PV system by 2×6 modules in series-parallel configuration, which has the same schematic diagram as the PV array in Fig. 4.15. The PV modules are made of amorphous silicon by PowerFilm Inc. The detailed parameters for PV modules and inverter in PV system have been given in Table 2.4 in Chapter 2. As in simulations, the overcurrent protection is not used in experiments so that the fault current will evolve without interruption.

Figure 4.16 Picture of PV system experimental set-up at Northeastern University, Boston

In order to understand the difficulties of PV system protection for night-to-day faults, it is helpful to understand and compare with faults that may occur during daytime/high irradiance conditions. If the fault happens on a clear day, it is likely that the fault current becomes sufficiently high and overcurrent protection fuses in series with the faulted PV string will be blown. In Chapter 3.6.2 of this thesis, the experimental results of line-line fault under high irradiance have shown that the backfed current \( I_{\text{back}} \) can reach -1.41A (-2.43\( I_{\text{sc}} \)). Conventional fault protection devices (i.e. fuses rated no less than 1.56\( I_{\text{sc}} \)) may easily handle these types of faults. However, the same fault will lead to different \( I_{\text{back}} \) under low irradiance and night-to-day transition.
4.5.2 Experimental results of the line-line fault under low irradiance

The PV array voltage ($V_{sys}$) and top current of String #1 ($I_{1a}$) are captured by the oscilloscope shown in Fig. 4.17. Before $t=T_1$, the 1st string is working normally and generating positive current 0.3A ($0.52I_{sc}$). After the fault occurs at $t=T_1$, there are some transients on the array voltage $V_{sys}$ and $I_{back}$. Then the negative backfed current ($I_{back}$) into the faulted string (String #1) reaches its maximum magnitude 0.8A ($1.38I_{sc}$). This fault current is not high enough to melt the fuses in series with String #1, because fuses rated current ($I_n$) are usually required to be no less than $1.56I_{sc}$ to protect the PV modules and conductors [12]. At $t=T_1$, the MPPT of the inverter identifies the sudden drop of the array’s output power and begins to look for a new MPP. During $T_1<t<T_2$, the MPPT reduces the array voltage $V_{sys}$ as well as $I_{back}$, in order to minimize the power consumed by the faulted string. As a result, $I_{back}$ oscillates and decreases over time rather than a constant value. After $t=T_2$, $I_{back}$ is decreased to a much smaller value $-0.2A$ ($-0.34I_{sc}$), when the array oscillates around a new optimum working point. It is noticed that after $t=T_2$, as long as the MPPT works fast as irradiance changes, $I_{back}$ is still clipped between $0 \sim -0.34I_{sc}$ by the MPPT. Also, $V_{sys}$ is greatly reduced by the MPPT. Therefore, the fault cannot be cleared by fuses at that day.

Figure 4.17 Experimental results of a line-line fault under low irradiance
The experimental results of the line-line fault under low irradiance (~400W/m²) are summarized in Table 4.4.

<table>
<thead>
<tr>
<th>Low irradiance fault</th>
<th>Irradiance level W/m²</th>
<th>Backfed current into String #1 ($I_{back}$)</th>
<th>Cleared by OCPD (rated at $1.56I_{sc}$)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>When fault occurs</td>
<td>400</td>
<td>-0.8A (-1.38$I_{sc}$)</td>
<td>No</td>
</tr>
<tr>
<td>Post-fault steady state</td>
<td>Varying between 400~830</td>
<td>-0.1A (-0.17$I_{sc}$)</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 4.4  Simulation results of the line-line fault under low irradiance

The conclusions from the “low irradiance” fault are as follows:

- Line-line faults in the PV array under low irradiance might be undetectable with conventional overcurrent protection devices;

- With the help of the MPPT, the faulted PV array might operate at a lower power output (forever) without ever triggering protection devices.

4.5.3 Experimental results of the line-line fault during night-to-day transition

The same fault (shown in Fig. 4.15) is carried out for fault evolution during night-to-day transition. The corresponding irradiance level is slowly changing from 0 to ~830W/m².

During “night-to-day” fault transition, the P-V curves of the PV array are shown in Fig. 4.18. Under the irradiance level lower than 383W/m², the MPPT of the inverter has not started to work, because the array voltage is not as high as the minimum start voltage ($V_{min}$) of the inverter. Therefore the array is at open-circuit conditions with zero output power. The operation point on the P-V curve is moved from $A$ to $B$ along with voltage...
axis. After the inverter starts at $B$, the MPPT of the inverter helps the operation point move from $B$ to $C$, which is the MPP at irradiance of $383\text{W/m}^2$. As time evolves and irradiance increases, the array transitions from MPP $C$ to MPP $E$, where $E$ is the MPP under irradiance $800\text{W/m}^2$.

![Figure 4.18 P-V curves of the faulted PV array with increasing irradiance during night-to-day transition.](image)

Similar to our simulation results, the magnitude of the reverse fault current ($I_{\text{fault}}$) is increasing with irradiance during $T_1<t<T_2$. At $t=T_2$, $I_{\text{fault}}$ has negative peak $-1.3I_{sc}$ (-0.75A) when array voltage reaches the minimum start voltage of inverter (28V). After that, $I_{\text{fault}}$ is clipped between $-0.34I_{sc}$~0 (-0.2A~0A) by the MPPT of the inverter. Therefore, $I_{\text{fault}}$ during night-to-day transition is greatly reduced and will not be high enough to blow the fuse protection (rated at $1.56I_{sc}$).
Figure 4.19  Experiments: the faulted PV array voltage \((V_{sys})\) during night-to-day transition

Figure 4.20  Experiments: the faulted PV array current \((I_{sys})\) and String #1 top current \((I_{1a})\) during night to day transition
Also, during sunset – the “day-to-night” transition, our research results show that the fault current is still so small that cannot melt the fuses, which means this fault could be hidden in the PV array and remain undetected. Fig. 4.22 and Fig. 4.23 illustrate the voltage and currents in PV array during day-to-night transition fault experiments. The output power of the PV array is plotted in Fig. 4.24.

During day-to-night transition, the irradiance on the PV array is reducing slowly, so does the array’s voltage. When the PV array voltage cannot sustain the inverter’s minimum working voltage, the inverter shuts down and the MPPT stops. Meanwhile, the PV array becomes open-circuit with zero output power. As a result, the currents of normal PV strings have no path to flow but backfeed together into the faulted string. Therefore, the magnitude of $I_{\text{back}}$ increases to 0.17A ($0.29I_{sc}$) at the time of the inverter’s shut down. However, because the irradiance is quite low, $I_{\text{back}}$ never reaches a high enough value to blow a fuse (usually rated at $1.56I_{sc}$). As time evolves and irradiance decreases to zero, $I_{\text{back}}$ becomes zero as well.
Figure 4.22  Experiments: the faulted PV array current ($V_{sys}$) during day-to-night transition

Figure 4.23  Experiments: the faulted PV array current ($I_{sys}$) and String #1 top current ($I_{1a}$) during day-to-night transition
The experimental results of the line-line fault during night-to-day transition are summarized in Table 4.5.

<table>
<thead>
<tr>
<th>Night-to-day fault</th>
<th>Irradiance level W/m²</th>
<th>Backfed current into String #1 ($I_{back}$)</th>
<th>Cleared by OCPD (rated at $1.56I_{sc}$)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>When fault occurs ($t&lt;T_1$)</td>
<td>0</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>When inverter starts ($t=T_2$)</td>
<td>383</td>
<td>-0.75A (-1.3$I_{sc}$)</td>
<td>No</td>
</tr>
<tr>
<td>After inverter starts ($T_2&lt;t&lt;T_3$)</td>
<td>Varying between 400 ~830</td>
<td>0 ~ -0.2A (-0.34$I_{sc}$)</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 4.5 Simulation results of the line-line fault during night-to-day transition

The conclusions from the “night-to-day” fault evolution are as follows:

- Line-line faults in the PV array might be undetectable with conventional overcurrent protection devices;
- Depending on fault location and $V_{min}$ of the inverter, the backfed current into the faulted string ($I_{back}$) reaches its negative peak when the inverter starts up. However, the negative peak is not high enough to blow a fuse;
• After the fault, the faulted PV array might operate at a lower power output (forever) with the help of the MPPT without ever triggering protection devices;

• During the “day-to-night” transition at sunset, the irradiance and PV array voltage decrease. When the array’s voltage become smaller than the inverters’ minimum working voltage, the inverter shuts down. Then $I_{\text{back}}$ reaches its negative peak but never blows a fuse.

• Therefore, the fault at night might be hidden in the PV array during both “night-to-day” and “day-to-night” transitions.

4.5.4 Summary of experiment results

The summary of experimental results is given in Table 4.6. According to National Electrical Code (NEC) [12], overcurrent protection devices (OCPD), such as fuses, are required to be sized no less than $1.56I_{sc}$ to protect the PV modules and conductors. In daytime fault experiments, the maximum magnitude of $I_{\text{back}}$ is $2.43I_{sc}$ (shown in Fig. 3.42 in Chapter 3) which is large enough to melt a fuse properly designed for PV protection. But under low irradiance, the maximum magnitude of is only 0.8A ($1.38I_{sc}$). During night-to-day transition experiments, in fact, at the time of the inverter’s startup, the magnitude of the $I_{\text{back}}$ reaches its maximum magnitude ($1.3I_{sc}$), which is not large enough to blow the fuse. After that, the magnitude of $I_{\text{back}}$ is reduced immediately and clipped between 0–0.34$I_{sc}$ by the MPPT. During sunset, when the inverter and its MPPT stop to work, $I_{\text{back}}$ drops to -0.29$I_{sc}$ (-0.17A) but never triggers the fuses.
<table>
<thead>
<tr>
<th>Irradiance condition of the line-line fault</th>
<th>Maximum backfed current</th>
<th>Melt the OCPD (fuses)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>High irradiance</td>
<td>-1.41A (-2.43I_{sc})</td>
<td>Yes</td>
</tr>
<tr>
<td>Low irradiance</td>
<td>-0.8A (-1.38I_{sc})</td>
<td>No</td>
</tr>
<tr>
<td>Night-to-day transition</td>
<td>-0.75A (-1.3I_{sc})</td>
<td>No</td>
</tr>
<tr>
<td>Day-to-night transition</td>
<td>-0.17A (-0.29I_{sc})</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 4.6 Summary of experimental results

4.6 Conclusions

Chapter 4 of this thesis presents evolution and implication of faults in PV array under “low irradiance” and during “night-to-day transition”. These two faults are unique to PV arrays that cannot be found in other power sources. The unique faults in PV have been simulated in a 5.25kW PV benchmark system. For experimental verification, the faults are carried out in a 90W small-scale PV benchmark system under real test conditions. Our research results demonstrate that fault current in PV arrays not only depends on fault locations, but also greatly relied on irradiance level on the PV array. It is noticed that even the same fault in the PV array may cause distinctive fault current under “high irradiance”, “low irradiance” or “night-to-day transition”.

Under high irradiance, the fault currents usually are large enough to melt the OCPD (fuses) so that the fault can be easily cleared and isolated. However, when fault occurs under “low irradiance” or “night-to-day transition”, due to the current-limiting nature of PV array, the fault current may not be large enough to blow the fuse.

Furthermore, under “low irradiance” and during “night-to-day transition”, the MPPT in
the inverter plays an important role on fault current. By reducing array’s voltage \((V_{sys})\), the MPPT of the inverter forces the remaining PV modules to operate sub-optimally at lower power. As a result, the fault current will be greatly reduced so that it becomes difficult to clear by OCPD (fuses).

(1) “Low irradiance” fault

Before the fault occurs, the PV array and the MPPT in the inverter are working normally under low irradiance level. When the fault occurs, the fault current may not be high enough to blow the fuse. As a result, the fault may still exist in the PV array without interruption. After the fault, the MPPT of the inverter identifies the sudden drop of the array’s output power and begins to look for a new MPP. As time evolves, the MPPT of the inverter will make the fault current even much smaller. After that, no matter how irradiance changes, the MPPT can help the faulted array work around its MPP and keep the fault current undetectable by fuses;

(2) Fault during “night-to-day transition”

- During sunrise

When fault occurs at night, the fault current is zero since there is no solar irradiance on the PV array. The grid-connected PV inverter has not started to work yet so that the PV array is at open-circuit conditions with zero output power. During sunrise, short-circuit current and open-circuit voltage of each string are increasing as well. But the PV strings are mismatched since some of them are already faulted with significantly changed I-V characteristics. Hence, the currents of normal strings have no path to flow but backfeed together into the faulted string. This negative reverse current is the backfed current \((I_{back})\), whose magnitude is also increasing during sunrise. When the PV array voltage reaches the minimum start voltage of the inverter \((V_{min})\), \(I_{back}\) reaches its negative peak.
Meanwhile, the MPPT of the inverter starts to help the PV array work at its nominal MPP and minimizes $I_{\text{back}}$ to a much smaller value. Notice that $I_{\text{back}}$ never reaches a high enough value to blow a fuse.

- **During sunset**

During sunset, the irradiance on the PV array and the array’s voltage are reducing slow. When the PV array voltage cannot sustain the inverter’s minimum working voltage, the inverter shuts down and the MPPT stops. Meanwhile, the PV array becomes open-circuit with zero output power. As a result, the currents of normal PV strings have not path to flow but backfeed together into the faulted string. Therefore, the $I_{\text{back}}$ increases to its negative peak -0.17A (-0.29$I_{\text{sc}}$) at the time of the inverter’s shut down. However, $I_{\text{back}}$ never reaches a high enough value to blow a fuse (usually rated at 1.56$I_{\text{sc}}$). As time evolves and irradiance decreases to zero, $I_{\text{back}}$ becomes zero as well.

Notice that during these two unique faults, $I_{\text{back}}$ never reaches a high enough value to blow a fuse, and therefore, the fault remains undetected. Furthermore, fault in “low irradiance” conditions during daytime, which is very common in real PV systems, might have the same issue as the “night-to-day” transition fault. In other words, the fault in “low irradiance” may not be cleared by OCPD during “night-to-day” and “day-to-night” transitions as well. As we have shown in this thesis, these types of faults pose immense difficulties to either protect against or detect. None of these results had previously been noticed in the literature before.

Although the unique faults in PV arrays do not involve large fault current, it may cause potential fire hazard in the fault path and significant output power losses [18, 34]. Additionally, the point of fault along the fault path may have large contact resistance that may lead to overheating or arcing problems [47-49]. Therefore, the fault current of
night-to-day transition can stay small enough so that it does not melt a fuse, but still large enough to cause arcing or fire hazards. Besides, due to the undetectable fault, a large amount of power is lost in the PV array. For example, in the simple test-setup in this paper, the experimental results show that power loss is approximate 28.3% of output power for the PV array.
5. Conclusion and Future Work

5.1 Conclusion

With emerging technologies and increasing financial incentives, world solar photovoltaic (PV) industry is scaling-up at a rapid growth rate in recently years [1]. However, PV systems may have faults or failures during the process of design, installation and operation [51], more than 20% of which are occurring on PV arrays. Therefore, fault analysis in solar PV array becomes a more important task for PV system efficiency and reliability improvement. However, unlike conventional power generation sources (e.g. generators and batteries), PV arrays are unique and have their distinctive characteristics under normal and fault conditions.

For fault detection and protection in PV arrays, conventional approaches usually add OCPD (circuit breakers or fuses) in series with PV components. These protection devices are able to clear faults and isolate faulty circuits only if they carry the large faulty current [17-19]. For example, the nominal current of series fuses with PV modules is rated at 1.56 times the short circuit current ($I_{sc}$) of PV modules according to NEC [12]. However, because of the non-linear current-voltage (I-V) characteristics and the current-limiting nature of PV arrays, sometimes fault currents may not be high enough to trigger the OCPD.

In addition, faults in the PV may become more complicated caused by varying environmental conditions, different fault locations, mismatches among PV modules and even the MPPT of the inverters. This requires special consideration into fault analysis in PV arrays.
Conclusion of Chapter 2

In order to fully understand fault scenarios in PV systems, Chapter 2 of this thesis proposes an accurate simulation model that is able to predict a PV array’s performance under both normal and fault conditions. Chapter 2 develops the modeling and simulation of PV modules by using the widely used one-diode model. The modeling algorithm is implemented successfully in MATLAB/Simulink and converges fast and accurately enough to be used for large PV array simulations. The simulation model is able to take the solar irradiance level and PV module temperature as inputs, and predict accurate steady-state performance compared with the manufacturer’s datasheet. Furthermore, the model is flexible enough to simulate solar PV arrays with different scales, with or without bypass diodes and diverse technologies. Unlike previous works in the literature [23-28], our PV simulation model is modular and scalable to build PV arrays with various configurations, which is especially useful for studies of PV modules interconnection under normal and fault scenarios.

In Chapter 2, two PV benchmark systems with different solar-cell technologies and various power scales have been built in MATLAB/Simulink using the developed PV simulation models. Their output performances under normal working conditions can be accurately predicted in simulation environment. Furthermore, one of the benchmark systems, the amorphous silicon PV system is also set up in experiments for further investigation. Based on the developed benchmark systems, fault scenarios in PV will be studied in the following chapters.

Conclusion of Chapter 3

Based on the developed PV benchmark systems, Chapter 3 simulates and analyzes the PV array performance under typical fault conditions, especially ground faults, line-line faults
and mismatch faults. The PV benchmark system has noticeable advantages over previous works [23-28] since it can accurately predict the interconnections among the mismatched PV modules under fault. Based on the simulation results, the fundamental approaches of fault analysis in PV array are introduced in detail. I-V characteristics analysis, KCL analysis and power conservation analysis are basic fault analysis approaches. Our simulation results show that the instantaneous fault currents vary greatly with fault locations in the PV array, which may bring new challenges to conventional overcurrent protection devices (OCPD, such as fuses). For instance, under high irradiance, the research found that the line-line fault with small voltage difference may not cause large enough overcurrent to trigger fuses. Therefore, this fault will become undetected and may be hidden in the PV array forever.

Furthermore, the effect on fault currents from the MPPT of the inverter is discussed in fault analysis, which has not been seen in the literature. If the fault in the PV array is not properly interrupted, as long as the MPPT is still working, the MPPT helps the PV array operate at lower power. Therefore, the MPPT reduces the fault current in the PV array to a much smaller value. The fault may be hidden and brings new challenges to PV systems, such as fire hazards, reduced system efficiency, damages on PV components.

For proof of simulation results, experiments of typical faults have been carried out in a small-scale grid-connected PV system under real test conditions. The summarized fault characteristics, the MPPT effects and subsequent new challenges to PV systems are verified by experimental results.

**Conclusion of Chapter 4**
Unlike faults occurring in high irradiance [17-19, 35] or normal PV systems under
changing irradiance during a day [46], Chapter 4 of the thesis primarily discusses two specific types of line-line faults under different meteorological conditions – “low irradiance” condition and varying irradiance condition (called “night-to-day” transition). They are unique types of faults to PV systems that have not been studied in the literature.

The first fault is a line-line fault that occurs in a grid-connected PV array under low irradiance level. If a fault occurs in the PV array on a cloudy day, the fault current may be consequently small and commonly may not melt fuse protections. After the fault, the inverter and its MPPT (commonly by using Perturb and Observe (P&O) algorithm [20-21]) might still work and help the PV array operating at nominal optimum conditions. As a result, the fault current will be greatly reduced and limited to a small value by the MPPT. After that, no matter how the irradiance changes, the MPPT may keep the fault current relative small that might not melt fuse protections anymore. This leads to an unsafe condition in the PV array that has not been reported before;

The second fault is a line-line fault evolution in a grid-connected PV array during “night-to-day” transition. Specifically, a “night-to-day” transition fault occurs in the PV array at night when there is no solar irradiance. During sunrise, the irradiance on the PV array increases slowly, as does the PV array voltage. As long as the PV array voltage reaches the minimum start voltage of the inverter, the PV inverter and its MPPT start to work. Then the PV system begins to feed the maximum energy to the utility grid. As a result, the faulted PV system is forced by the MPPT to operate at a low optimum output point. Also, the fault current is significantly reduced by the MPPT. After the inverter starts, no matter how irradiance changes, the fault current never reaches a high value to blow a fuse, and therefore, the fault remains undetected. In sum, instead of causing large overcurrent, the faulted PV array during night-to-day transition might lead to a smaller fault current, which is difficult to clear with conventional protection devices.
Similarly, the fault during “day-to-night” transition cannot cause a large current as well. During sunset, the irradiance on the PV array and the array’s voltage are decreasing slow. When the PV array voltage cannot maintain the inverter’s minimum working voltage, the inverter shuts down and its MPPT stops. Meanwhile, the PV array becomes open-circuit with zero output power. As a result, the currents of normal PV strings have not path to flow but backfeed together into the faulted string. Therefore, the fault current increases to its negative peak but it never reaches a high value to blow a fuse (usually rated at $1.56I_{sc}$). As time evolves and irradiance decreases to zero, the fault current becomes zero as well.

On the other hand, if the same fault occurred in daytime under high irradiance, the MPPT would have responded too slow to prevent the fault current protection device (fuse, or circuit breaker) to trigger. Thus, the same fault in daylight operating condition would have been cleared.

### 5.2 Future work: Development of fault detection and protection in PV arrays

The conventional overcurrent protection of PV arrays rely upon a circuit protection device (i.e. a fuse or a circuit breaker) to interrupt the fault current automatically. However, the current-limiting nature of PV arrays makes conventional protection devices difficult to apply properly. Our research has demonstrated that line-line faults in PV array may bring new protection issues. For instance, a line-line fault of small voltage difference may not cause high enough current to blow a fuse, even the fault occurs under high irradiance. Furthermore, a line-line fault under low irradiance may not be cleared by
fuses correctly. Also, this “low irradiance” fault may evolve during “night-to-day” transition and remains undetected even during sunrise and sunset. Therefore, the faults might be hidden in PV array and become a potential hazard to PV system efficiency and reliability. However, theses faults with small fault current cannot be cleared by OCPDs.

A new approach of fault detection and protection for large PV arrays would be an extension of our research. Fault detection and protection algorithms should be specially developed for newly emerging PV technologies, perhaps with real-time operation. The existing OCPD may not clear faults with small fault current. Therefore, small fault current protection devices are needed for PV systems. This would help large PV arrays to increase output efficiency, enhance system reliability, and reduce the maintenance cost.

In addition, improved fault identification and location for large-scale PV arrays would be another extension of the research. One disadvantage of centralized large PV arrays is that it is quite difficult to identify the type of the fault automatically and locate the fault accurately. Sometimes it is difficult to locate the fault correctly in a large PV plant by existing PV monitoring systems or by maintenance engineers. One reason for this is that PV modules impact on each other’s performance when they are electrically connected. Furthermore, the MPPT of the centralized inverter will reduce the fault impacts and make fault identification and location more difficult. In addition, different fault impedance, unpredictable geographical condition, and degradation problem could bring more unexpected issues into fault identification and location. Limited research has been performed on this topic for PV systems.
References

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