

An Autonomous Online I-V Tracer for PV Monitoring Applications

**A Thesis Presented for the
Master of Science
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DEDICATION

*To my parents, Mark and Teresa Riley, and all of my family and friends for their love, support,
and encouragement.*

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ABSTRACT

With the unprecedented growth of photovoltaic technologies and their implementation in recent times, more precise methods of determining modules health, degradation, and performance are needed. Current monitoring efforts are helpful in determining these attributes but do not provide all of the information necessary to truly understand the health properties of the PV module in question. The current-voltage curve, or I-V curve, provides a level of insight into a PV module's health unparalleled by most monitoring efforts. However, the tools which measure the I-V curve exist in an undesirable form—PV must be disconnected from its load and connected to the tool in order to trace the I-V curve. This is undesirable due to the fact that it requires a trained technician to perform, as well as requiring some time to disconnect and reconnect the modules.

In this thesis, an I-V tracer which operates autonomously, with no need to be disconnected from its load, will be discussed. The current state of I-V tracers commercially available will be discussed and motivation will be provided for the online autonomous I-V tracer. Design of such an I-V tracer using the single-ended primary inductance converter (SEPIC) will be discussed, and simulation results of such a converter operating as an I-V tracer will be presented. Analysis techniques of the I-V curve are also presented.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION AND OVERVIEW	1
1.1 The I-V Curve	2
1.2 Irradiance and Temperature	4
1.3 Combining Cells in Series and Parallel	5
1.4 Metrics Available from I-V Curves	9
1.4.1 Slope Near Isc.....	9
1.4.2 Slope Near Voc.....	10
1.4.3 Analysis of the I-V Curve.....	11
1.5 Case for I-V Tracing as a Common Monitoring Method.....	13
1.5.1 Field I-V Tracers currently available.....	15
1.6 Case for Autonomous Tracer	16
1.7 Chapter Summary.....	17
CHAPTER 2 LITERATURE REVIEW	18
2.1 Introduction	18
2.2 Photovoltaic Cell Review	18
2.2.1 PV Cell Characteristics.....	19
2.3 Power Electronics.....	23
2.3.1 I-V Tracers.....	23
2.3.2 The SEPIC	28

2.4 State Space Representation	30
2.4.1 State Space Averaging.....	32
2.5 Chapter Summary.....	35
CHAPTER 3 MODELING AND CALCULATIONS.....	36
3.1.1 Mode 1 Operation.....	38
3.1.2 Mode 2 Operation.....	39
3.1.3 Mode 3 Operation.....	40
3.2 Small Signal Modeling.....	43
3.3 Component Sizing.....	46
3.3.1 Inductor L_1 and L_2 sizing	46
3.3.2 Capacitor C_P sizing	47
3.3.3 Input and Output Capacitor sizing.....	47
3.3.4 Inductor Design	48
3.4 Notch Analysis Technique	48
3.5 Chapter Summary.....	50
CHAPTER 4 RESULTS	52
4.1 Chapter Introduction	52
4.2 Input Voltage Control SEPIC.....	52
4.2.1 Step Test	53
4.2.2 Disturbance Test	55
4.3 I-V Trace With Simulated SEPIC	58

4.4 Notch Analysis Validation.....	62
4.6 Chapter Summary.....	77
CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS	78
5.1 Conclusions	78
5.2 Recommendations	79
LIST OF REFERENCES	81
APPENDIX.....	84
Code A.1: Matlab Code for Inductor Design	85
VITA.....	88

LIST OF FIGURES

Figure 1.1: Growth of PV [19].....	1
Figure 1.2: I-V Curve of Solar Cell	3
Figure 1.3: Effect of incident solar irradiation and temperature on PV's I-V curve [2].....	4
Figure 1.4: Parallel and Series combinations of PV Cells	6
Figure 1.5: Example topology with all cells illuminated (a) 3 cells illuminated (b) 3 cells illuminated with bypass diode (c)	6
Figure 1.6: Combined I-V curve of partially shaded module with (a) and without (b) bypass diode.....	8
Figure 1.7: I-V curve showing approximation for R_{sh} and R_s	9
Figure 1.8: The single diode model of a PV cell	10
Figure 1.9: All metrics available from an I-V trace.....	11
Figure 1.10: Topology of two strings with autonomous I-V tracers connected	16
Figure 2.1: Illustration of Photovoltaic Cell	19
Figure 2.2: Diode I-V Curve (a) Diode I-V Curve with Reverse Current Notation (b)	20
Figure 2.3: I-V Curve of Illuminated PV Cell	21
Figure 2.4: String of Series Cells with One Underperforming Cell	22

Figure 2.5: Eko Rack Mountable I-V Tracer [12]	24
Figure 2.6: MP-11 I-V Checker [13]	24
Figure 2.7: Available Solar Resource (a) Population Density (b) [14].....	26
Figure 2.8: Some Common Switching Converter Technologies with Buck and Boost Capabilities: SEPIC (a) Buck-Boost (b) Cuk (c) Zeta (d)	28
Figure 2.9: Illustration of SEPIC Topology and All 3 Switching States: SEPIC Topology (a) Mode 1 Operation (b) Mode 2 Operation (c) Mode 3 Operation (d).....	31
Figure 3.1: SEPIC Topology.....	36
Figure 3.2: Mode 1 of Operation of DCM SEPIC	38
Figure 3.3: Mode 2 Operation of DCM SEPIC	39
Figure 3.4: Mode 3 Operation of DCM SEPIC	40
Figure 3.4: Bode Plot of DCM SEPIC Operation from Analytical Results.....	44
Figure 3.5: Bode Plot from SABER AC Analysis.....	45
Figure 3.6: Definition of V_{OC1} and V_{OC2}	49
Figure 3.7: Definition of I_{SC1} and I_{SC2}	50
Figure 4.1: Control Loop of Proposed SEPIC	53
Figure 4.2: Step Test of SEPIC in CCM Input Voltage Response	54

Figure 4.3: Step Test SEPIC in DCM Input Voltage Response	55
Figure 4.4 Disturbance Test in CCM Input Voltage Response	56
Figure 4.5: Disturbance Test in DCM Input Voltage and Current Response	57
Figure 4.6 Voltage Reference Waveform	58
Figure 4.8: I-V Curve.....	60
Figure 4.9: P-V Curve.....	61
Figure 4.10: Topology of Simulated Module with 3 Bypass Diodes	63
Figure 4.11: Time Domain Plot of I-V Curve with 1 Cell Shaded.....	64
Figure 4.12: Data from Figure 4.11 Represented as I-V curve.....	65
Figure 4.13: P-V Curve from Figure 4.12.....	65
Figure 4.14: PV Module with 2 Mismatches	67
Figure 4.15: Time Domain I-V Curve with 2 Mismatches	68
Figure 4.16: Time Domain I-V Curve with 2 Mismatches.....	69
Figure 4.17: P-V Curve from Test in Figure 4.16.....	70
Figure 4.18: I-V Curve with 2 Cells Mismatched and Only 1 Bypass Diode	71
Figure 4.19: I-V Curve with 2 Mismatches and 6 Bypass Diodes.....	72
Figure 4.20: P-V Curve with 2 Mismatches and 6 Bypass Diodes.....	73

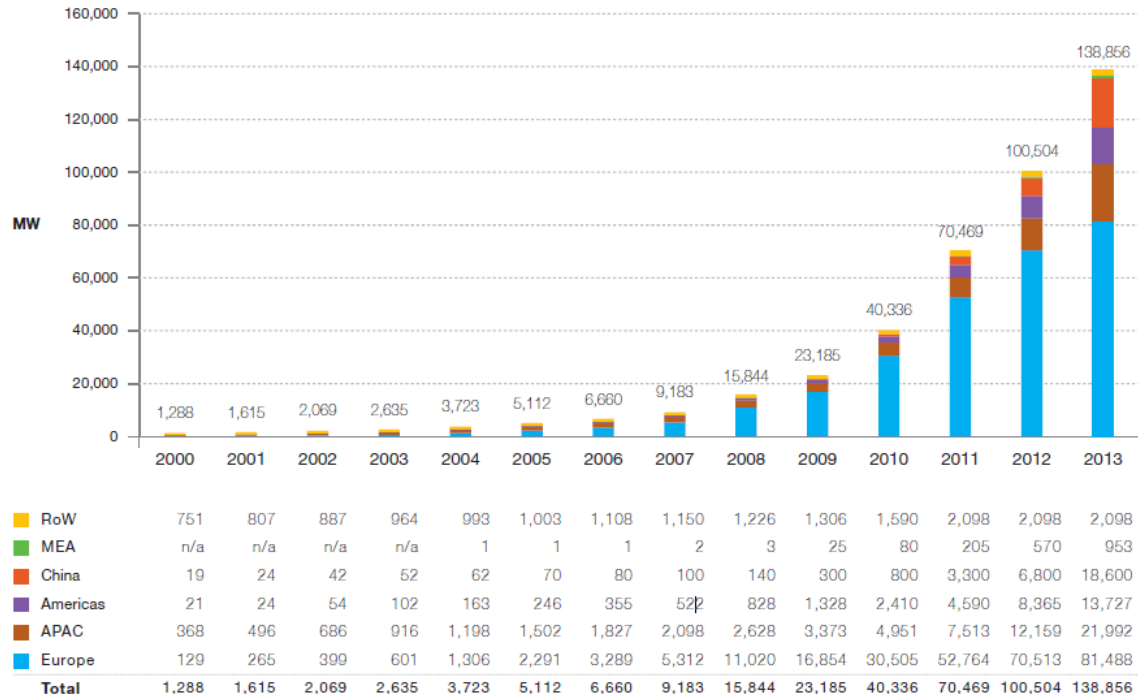
Figure 4.21: I-V Curve with 2 Mismatches and 12 Bypass Diodes.....	74
Figure 4.21: Module with 2 cells mismatched (a) Module with 10 cells in a string mismatched (b).....	75
Figure 4.23: 12 Diode Case I-V Curve (a) 12 Diode Case P-V Curve (b)	76

CHAPTER 1

INTRODUCTION AND OVERVIEW

Photovoltaic (PV) technologies are technologies by which electricity is generated from the energy in the sunlight near the earth's surface. PV is considered a renewable energy resource, due its fuel source, the sun, occurring naturally with no need to be 'refueled'. This is attractive for power generation, which typically relies on fossil fuels which are not in infinite supply.

PV technologies have grown at a rapid pace since the beginning of the new millennium. As the population becomes more energy and environmentally conscious, renewable energies which produce no greenhouse gases during generation are increasingly popular. This is illustrated in Figure 1.1.



RoW: Rest of the World. MEA: Middle East and Africa. APAC: Asia Pacific.
Methodology used for RoW data collection has changed in 2012.

Figure 1.1: Growth of PV [19]

With growth as drastic as is seen in Figure 1.1, it is necessary to fully understand the health of PV modules installed in-field. This thesis will discuss a monitoring device which will operate without the need for an on-site technician and provide useful information about PV health.

1.1 The I-V Curve

The current-voltage characteristics of a PV cell are often collectively referred to as the I-V curve. A PV cell is a p-n junction with traits similar to a diode. When illuminated, photons excite electrons in the PV cell, and a current is generated. This is known as the photovoltaic effect. The current density of a PV cell can be modeled by (1.1) below.

$$J_L = J_s - J_0 \left[\exp\left(\frac{e_0 V}{kT}\right) - 1 \right] \quad (1.1) [1]$$

J_L is the load current density of the PV cell, while J_s is the cell output current density and J_0 is the reverse saturation current density. The variable e_0 is the charge of one electron in coulombs, k is Boltzmann's constant, T is the temperature in kelvin, and V is the voltage across the cell. Using $J_L = J_s - J_0 \left[\exp\left(\frac{e_0 V}{kT}\right) - 1 \right]$ with arbitrary values for the variables, the current-voltage characteristics of a PV cell can be plotted. This plot is known as the I-V curve, and a great deal of information can be obtained from it.

For the purposes of analysis, the first quadrant of the I-V curve is typically all that is considered because the first quadrant is the only quadrant where a PV cell generates power. The I-V curve starts at the short-circuit condition, I_{sc} , where the voltage is zero. The current decreases slightly as the voltage is increased, until the curve nears the open-circuit condition where the current rapidly drops off. The curve ends at the open-circuit condition, V_{oc} , with the current at

zero. Both the short-circuit condition and open circuit condition result in zero power being generated by the PV cell. The I-V curve is plotted in Figure 1.2.

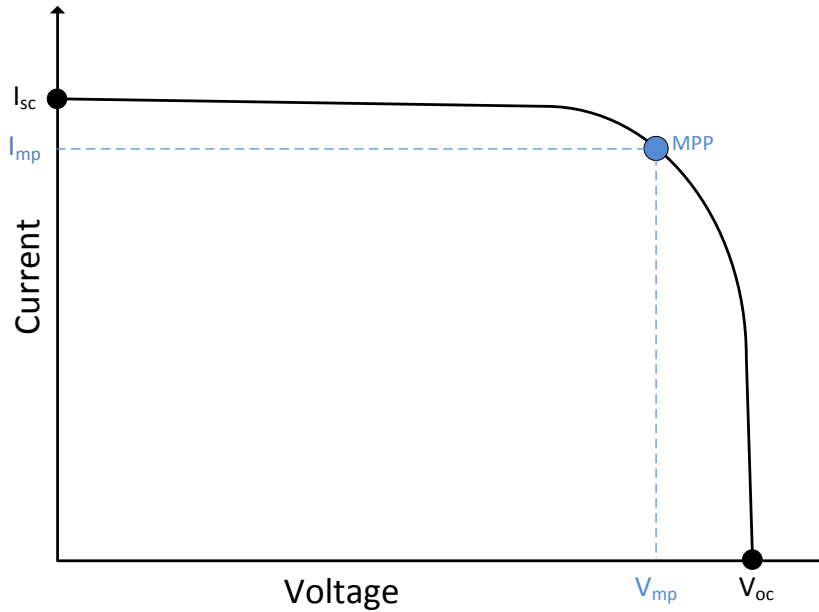


Figure 1.2: I-V Curve of Solar Cell

At some point on the I-V curve, the power of the cell is at its maximum. This point is known as the maximum power point (MPP), and solar cells are the most efficient at converting light energy into electrical energy at this point. In the case of inverters produced for solar energy applications, the inverter will have maximum-power-point tracking (MPPT) to ensure that the PV is operating at the MPP at all times. The voltage and current at these points is commonly referred to as I_{mp} and V_{mp} .

1.2 Irradiance and Temperature

The solar irradiance incident to a solar panel is the most important factor in amount of power a solar cell can generate. The amount of irradiation affects the short-circuit current drastically, while the open-circuit voltage remains relatively the same. The MPP tracks very closely with the irradiance incident to the module and can be estimated to be proportional to the irradiance.

CS6P-255P | I-V CURVES

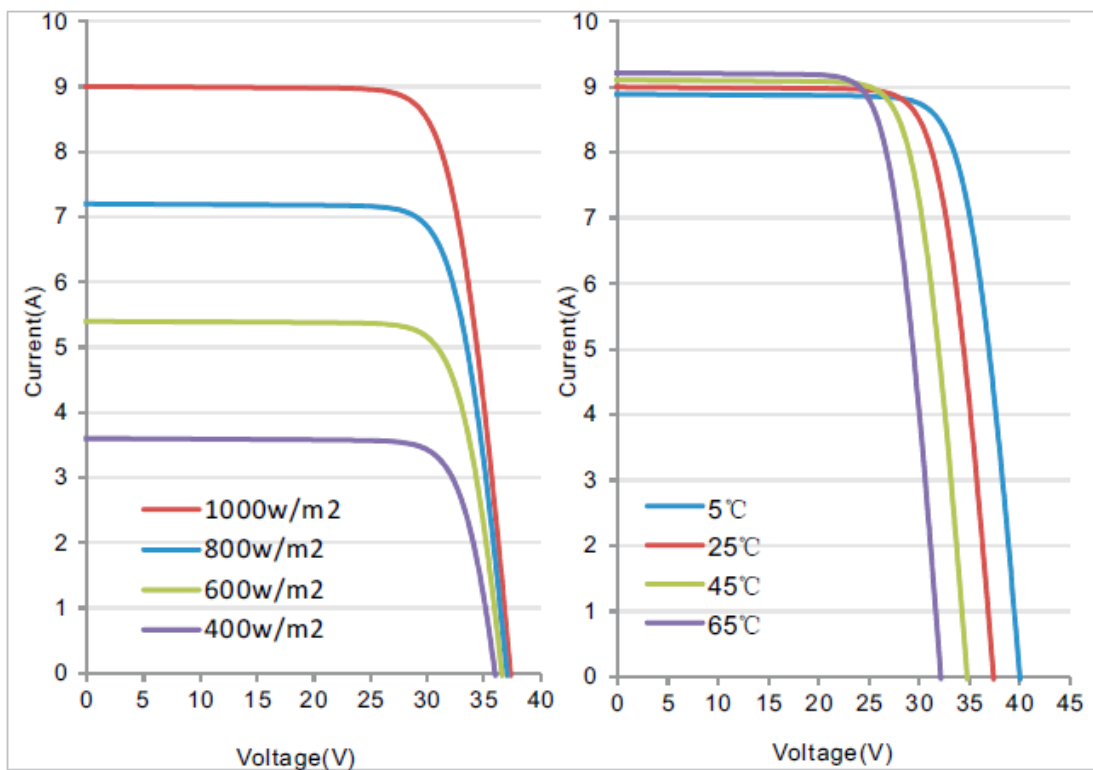


Figure 1.3: Effect of incident solar irradiance and temperature on PV's I-V curve [2]

Figure 1.3 illustrates sample I-V curves for the CS6P-255P solar module by Canadian Solar. As Figure 1.3 shows, increasing the irradiance changes the I-V curve by increasing the short-circuit current proportionally to the increase in irradiance. The open-circuit voltage also increases slightly as the irradiance increases.

Temperature has a non-negligible effect on the I-V curve and is of particular importance because solar modules are usually placed in areas that have a high ambient temperature during times of peak sunlight. As the temperature of a cell increases, the open circuit voltage decreases, the short-circuit current is raised by a small amount. Figure 1.3 shows the effect temperature has on the CS6P-255P solar module. For this particular module, for every degree C of temperature rise the open-circuit voltage falls by 0.34%, the MPP falls by 0.43%, and the short-circuit current raises by 0.065% [2].

1.3 Combining Cells in Series and Parallel

Solar cells used for electricity generation are usually connected in combinations of series and parallel to create a solar module. In the case of PV plants operating with centralized inverters, these modules are further connected in series and parallel combinations until a certain power level is obtained. Combining PV in series has the effect of extending the I-V curve further to the right (increasing voltage), while combinations added in parallel extend the curve vertically (increasing current). The combined total I-V curve of series and parallel combinations can be found by adding the individual I-V curves together.

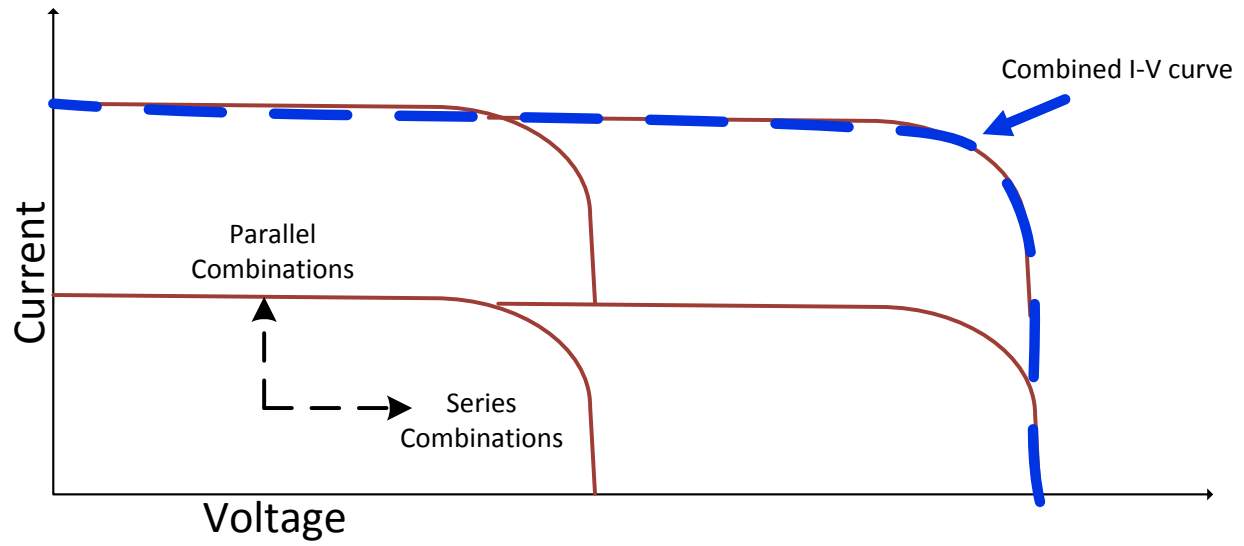


Figure 1.4: Parallel and Series combinations of PV Cells

Figure 1.4 illustrates the effect parallel and series combinations have on the I-V characteristics.

Consider a PV module that is made up of 4 PV cells with the topology shown in Figure 1.5.

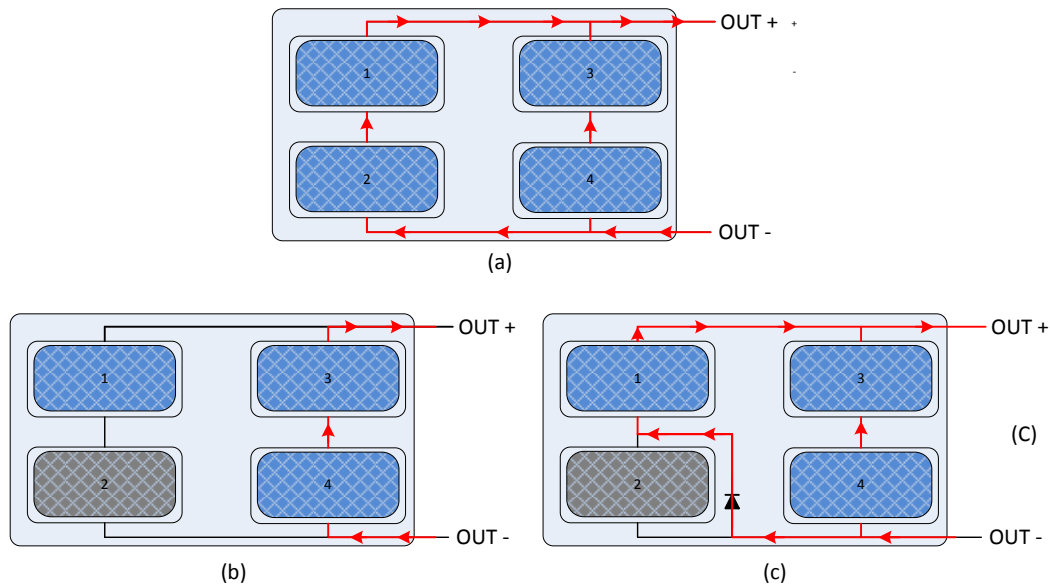


Figure 1.5: Example topology with all cells illuminated (a) 3 cells illuminated (b) 3 cells illuminated with bypass diode (c)

The 4 PV cells are arranged so that two are in series with each other, and those two are paralleled with the other two. Example (a) shows the current flow when all four cells are illuminated equally. Example (b) shows the current flow when three of the four cells are illuminated, and there is no bypass diode installed. Example (c) shows the current flow when three of the four cells are illuminated, and a bypass diode is installed.

If cell #2 is shaded completely, then its short circuit current goes down to zero. This limits cell #1's current to zero also, because it is in series with cell #2. This means the potential power from half the module is lost due to shading on one-quarter of the module. To remedy this, a diode can be paralleled with the cells so that the current of one cell does not limit the other. Looking at Figure 1.5, example (a) shows a scenario where all four cells are equally lit. As shown in the figure, current flows through each parallel leg and the I-V curve would combine the same way as Figure 1. illustrates. The bypass diode allows a path for the current to flow that does not exist in example (b). The combined I-V curve can be found by adding together the I-V curves of the cells which are active. In Figure 1. (b), cell #1 is illuminated but not active, so the I-V curve is unable to reach the second tier of current. The combined I-V curve for this scenario can be seen in Figure 1. (a). The combined I-V curve is unable to reach the second tier of parallel combinations, and is the same as if two cells in series were the only ones connected. To avoid this, a bypass diode can be paralleled with the unilluminated cell so that current from cell #1 has path. This scenario is illustrated in Figure 1. (c). The I-V curve is affected by including the third cell because it now has a current path. This is illustrated in Figure 1.6 (b). Including the third cell, but not the fourth cell, creates a notch in the I-V curve. This notch is a common characteristic of bypass diode activity characteristic of bypass diode activity.

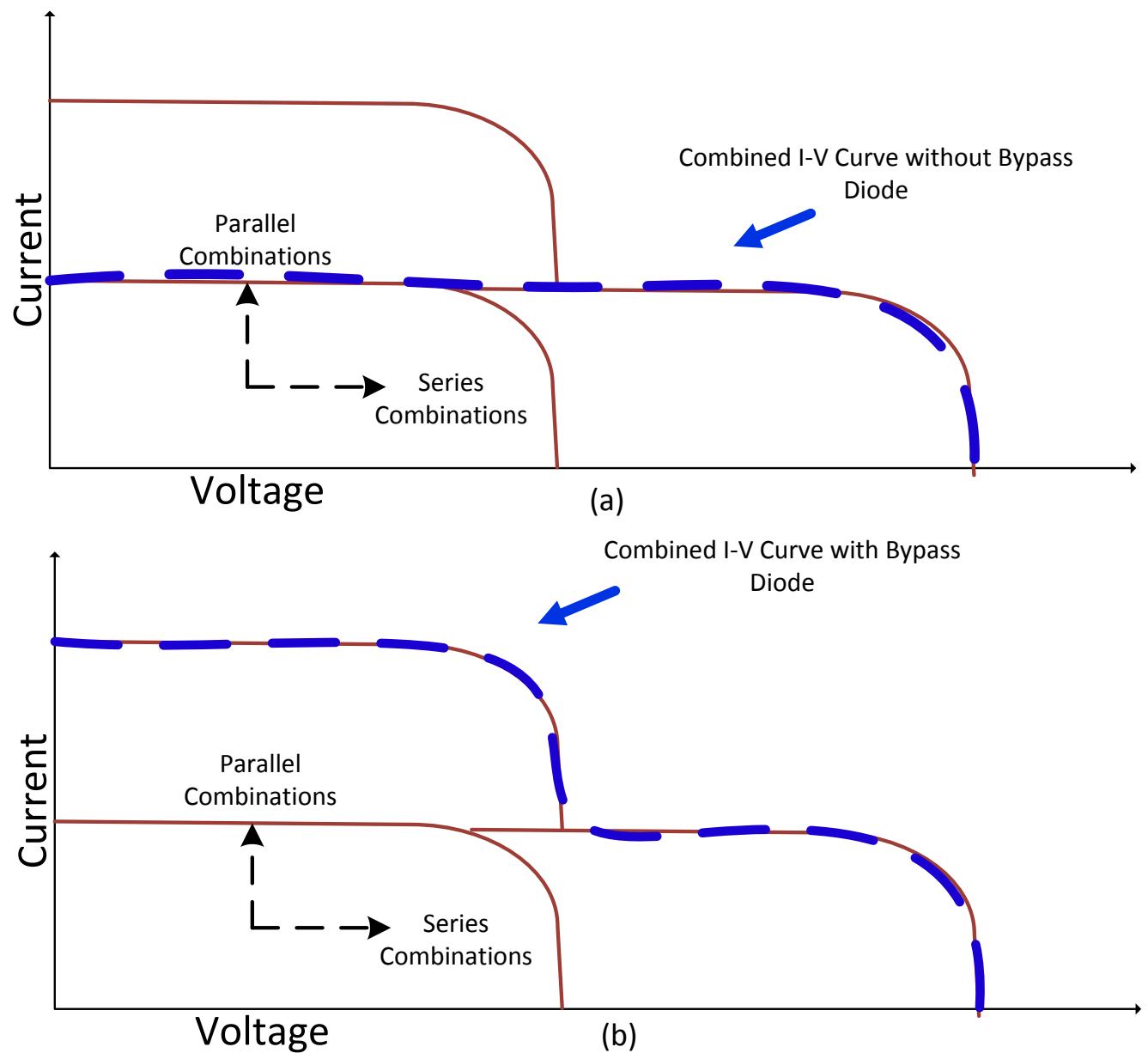


Figure 1.6: Combined I-V curve of partially shaded circuit with (a) and without (b) bypass diode

Bypass diode activity is indicative of some form mismatch among series connected cells. This mismatch may be due to partial shading, different degradation rates among cells, or non-uniform soiling.

1.4 Metrics Available from I-V Curves

1.4.1 Slope Near I_{sc}

There is other valuable information in the shape of the I-V curve. Examining the slope of the curve near I_{sc} reveals an approximation of the shunt resistance (R_{sh}). The shunt resistance represents the availability of parallel current paths, which are undesirable as they limit the current available from the output of a cell. In an ideal case this value would be infinitely high. Figure 1. illustrates the slope used to approximate the shunt resistance.

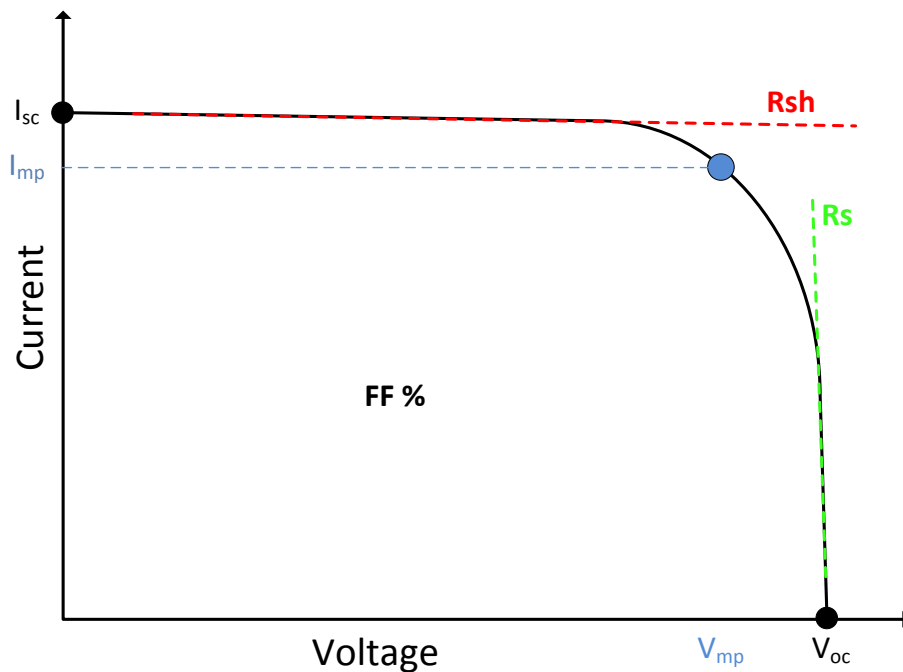


Figure 1.7: I-V curve showing approximation for R_{sh} and R_s

Physically damaged modules sometimes have lower-than-expected shunt resistances due to new current paths formed by the damage. This problem is sometimes self-correcting, as the current through the shunt path burns it out. Other times, a module may need to be replaced.

1.4.2 Slope Near V_{oc}

Similar to the shunt resistance, the series resistance (R_s) can be approximated by examining the slope of the I-V curve near the open-circuit voltage. The series resistance is representative of the resistive losses before energy leaves the panel. In an ideal cell it would be zero.

The series and shunt resistances are terms that come from a popular model of a PV cell, the single diode model [1]. This model is illustrated in Figure 1.8. In the single diode model, a PV cell is represented as current source in parallel with a diode, and two parasitic resistances.

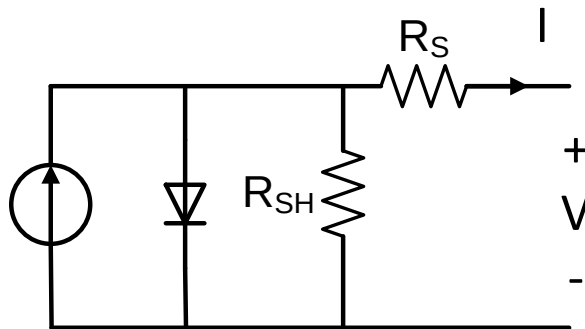


Figure 1.8: The single diode model of a PV cell

1.4.3 Analysis of the I-V Curve

The I-V curve offers data helpful in diagnosing a PV cell's health.

Figure 1. shows the metrics available from an I-V trace. Each of these metrics reveal unique information about the health of a cell and can be useful in diagnosing underperforming cells.

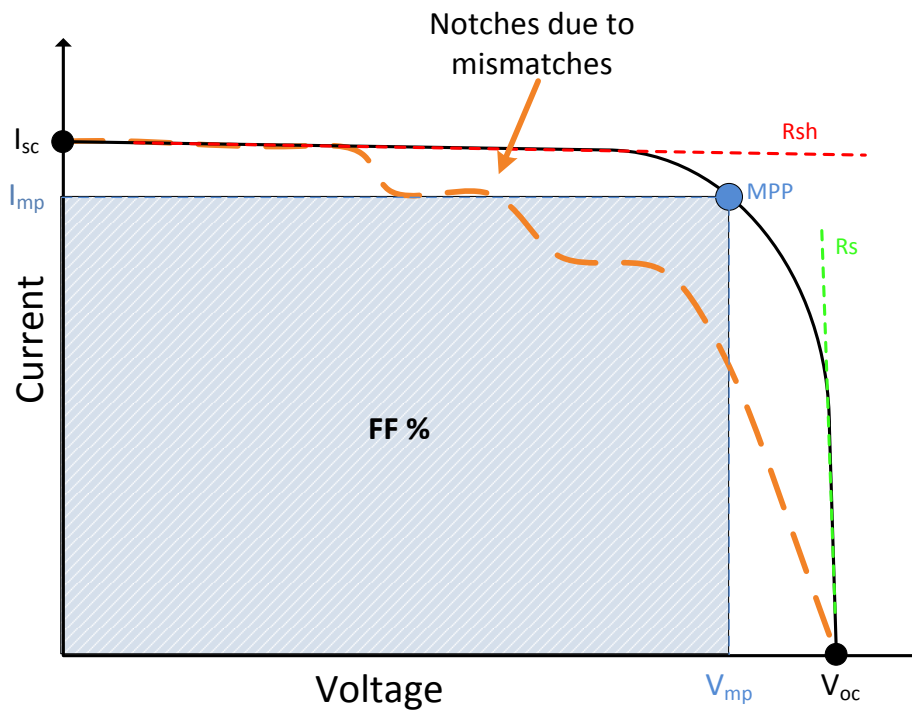


Figure 1.9: All metrics available from an I-V trace

I-V curves should be taken under controlled conditions, and should not be measured in low sunlight. Under high sunlight conditions with stable cell temperatures, each quantifiable part of the I-V curve tells its own story about PV health. Each of the metrics shown in Figure 1. and their usefulness in diagnosing health are explained below.

- **Shunt Resistance:** An R_{sh} value that is too small, approximated from the slope of the I-V curve near I_{sc} , is usually an indicator of shunt paths existing in a module. Shunt paths are electrical current paths in parallel with the output of the module, dissipating power loss as heat. They are also commonly identified by infrared imaging, as they can cause a significant temperature rise.
- **Series Resistance:** An R_s value that is too large, approximated from the slope of the I-V curve near V_{oc} , is generally indicative of a poor connection somewhere along the line that is creating excess resistance; it could also be caused by insufficiently sized wire. This value increasing over time can also be used as a metric to quantify panel degradation. Large R_s values reveal higher series losses.
- **Open-Circuit Voltage:** Lower than expected V_{oc} can also be an indicator of failures. It can mean the module's cell temperature is higher than expected, that a single module in the string is uniformly shaded, or indicate bypass diode activity (i.e. forward bias or short).
- **Short-Circuit Current:** Lower than expected I_{sc} usually indicates either uniform soiling across the PV string or uniform aging. It is a significant metric, along with the more commonly available I_{mp} and V_{mp} , to use for quantifying degradation on a string that otherwise has an ideal I-V curve.
- **Maximum Power Point:** Lower than expected **MPP** is usually the result of some other metric failing to meet expectations. A low MPP can be a result of a visibly deformed I-V curve (which may be because of notches or unwanted R_s and R_{sh} values). If the curve is the correct shape and the MPP is still too low, the I_{sc} or V_{oc} is likely too low also.

I-V curves can also reveal any deviations from an ideal or theoretical curve. Notches are indicative of bypass diode activity, which hints toward mismatch problems or shorted diodes. The fill factor is a parameter which, in conjunction with I_{sc} and V_{oc} , determines the maximum power from a solar cell. It is defined as the ratio of the maximum power from the solar cell to the product of I_{sc} and V_{oc} , or $(V_{mp} \times I_{mp}) / (V_{oc} \times I_{sc})$. Graphically, the fill factor is a measure of the "rectangularity" of the solar cell's I-V curve and is also the area of the largest rectangle which will fit in the I-V curve.

1.5 Case for I-V Tracing as a Common Monitoring Method

The value of data available from an I-V trace outweighs the value of data from traditional monitoring. Today, few metrics are readily available to determine solar PV plant performance degradation. PV system operators typically only track the lifecycle power and energy output of their systems, and occasionally they calculate additional metrics—such as performance relative to available sunlight (a.k.a. performance factor or performance ratio)—for plants with installed pyranometers or reference cells. Together, these metrics are moderately helpful in determining PV system health. However, they tend to be more useful in diagnosing larger failures and often overlook underperforming or failing PV modules. The extra metrics provided by I-V curve analysis offer added insight beyond that provided by typical monitoring systems gives PV plant owners a better understanding of how their PV plant is operating. The full I-V curve offers the potential to diagnose specific types of failures within the PV plant beyond general performance degradation. By quantitatively measuring PV health at a particular moment in time, string level I-V curves, for example, offer a useful snapshot of the extent to which degradation has occurred relative to the historic measurements and rate values of observed PV modules. Subsequent I-V

curves, taken periodically under similar temperature and irradiance conditions, can also reveal the rate of degradation. This offers a two-fold advantage in assessing string-level performance degradation issues that:

1. Occur quickly, perhaps as the result of mechanical breaking or electrical malfunction
2. Occur more slowly as part of the natural aging process of the modules.

In the first case, where a PV system has been damaged resulting in a noticeable change in the I-V curve, regular I-V curve measurements can reveal the damage and allow for timely repair. At the most basic level of monitoring, a PV plant operator will only know the plant's power/energy output. A misshapen I-V curve is a more conclusive indicator of damage than diminished power output.

In the case of aging modules, which experience no significant forms of damage, I-V curves can diagnose accelerated deterioration that is faster than their warranties allow. A string level I-V curve prior to implementation provides a baseline for future performance, while future I-V curves can indicate degradation rates.

A PV module warranty is typically based on the ability of the module to produce a percentage of its original power rating over a certain time period after purchase. For example, manufacturer warranties for modules are typically activated if the module performs at less than 90% of its nameplate rating before 10 years, and less than 80% before 25 years [2]. In the operation of a large PV system, a PV system operator may only have inverter-level data (per array), or perhaps string-level data at the inverter's operating point, with little information at the module level. While an I-V trace of a string may not be able to identify a specific module that is damaged or critically underperforming, misshapen I-V curves can indicate mismatch losses

which might identify existence of a damaged or underperforming module. This level of detail allows individual modules to be replaced per the warranty without waiting for the entire string to fall below the warranty's standards.

Separately, proactive diagnosis of failing modules has an added safety benefit in that replacing the failing module earlier may prevent a catastrophic failure which damages surrounding modules. As has been seen in the past, PV plants are not immune to electrical fires, and diagnosing a failing module earlier may help prevent similar events from occurring.

1.5.1 Field I-V Tracers currently available

There are several methods available to measure the I-V curve, most of which focus on using an electronic load to trace the curve. To this end, commercial I-V tracers are currently available for both laboratory and field applications. I-V tracers used in the field are available in power ratings ranging from less than 1 kW to tens of kilowatts, allowing for all levels of monitoring except for large (>100kW) arrays.

In-field I-V tracers are usually portable with a carrying case and battery. These manual devices require a complete disconnect of the string/module to measure the I-V curve and can be an expensive proposition: They have a substantial upfront purchase price (typically several thousand dollars) and also require a trained technician to take manual I-V traces on-site. This is not ideal, as many solar farms are in remote locations and the cost of sending a technician to take periodic I-V curves would be expensive and too costly for normal operations and maintenance (O&M) companies.

1.6 Case for Autonomous Tracer

For I-V tracing to become a regular part of O&M activities, it must be financially viable. Currently, no known PV O&M companies use I-V traces as part of regular monitoring activities. This is likely because of the high cost associated with the ‘manual’ aspect of currently available I-V tracers. An I-V tracer could be placed between a string of modules and the inverter, with a power electronics interface that traces the string once per day. This would remove the human element and associated labor costs. If implemented at the string level, the autonomous I-V tracer provides a detailed measure of system health, and historical data shows degradation rates. This data is useful for early detection of failures as well as a general measure of health for investment or warranty renegotiation purposes.

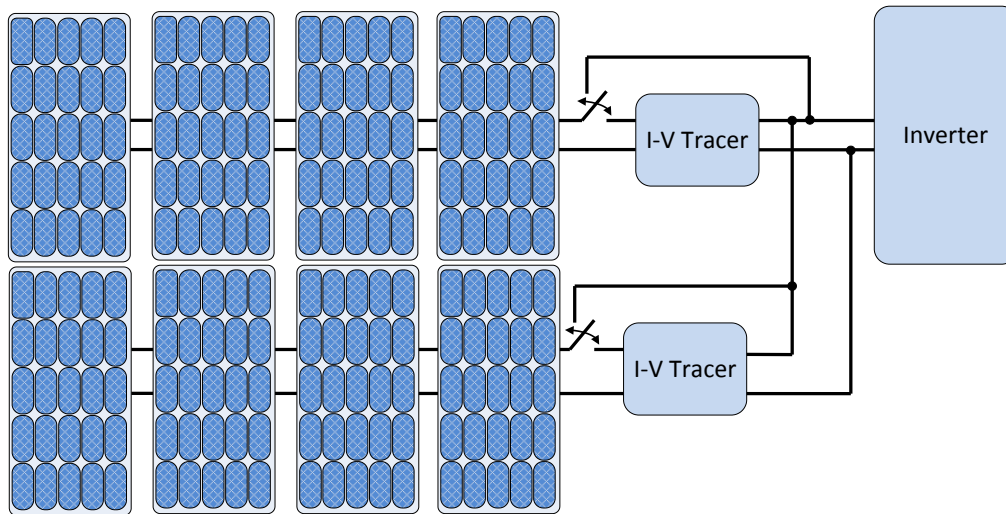


Figure 1.10: Topology of two strings with autonomous I-V tracers connected

In Figure 1., the I-V tracer will not be part of the PV generation circuit during normal operation. At regular intervals, and during instances of acceptable conditions (high and stable irradiance, stable module temperature), the I-V tracer will switch into the circuit. The voltage on the PV side of the I-V tracer is swept via a switching converter from open-circuit voltage to short-circuit current while the voltage on the inverter side is held constant. This means the I-V tracer, when part of the circuit, requires no external load.

1.7 Chapter Summary

In this thesis, a simulated model of a power electronics based converter for the purpose of obtaining PV I-V traces will be presented. This converter will be created using the SEPIC topology and will operate as an interface between the PV array and the inverter. In Chapter 2, the basics of photovoltaics will be discussed, as well as the current state of the market for commercial I-V tracers. Motivation will be shown for an autonomous I-V tracer to exist and the reasoning behind choosing a SEPIC topology will be revealed. Chapter 3 will focus on the modelling of the SEPIC converter, the sizing of passive components, and methodology of analyzing I-V curves. Chapter 4 will present the overall results of the converter's simulation and will demonstrate the converter's ability to diagnose a wide range of module mismatches. Chapter 5 will be a conclusion with recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This literature review will discuss photovoltaic cells, the way these cells generate electricity, and the current-voltage characteristics of PV cells. It will continue to discuss the current commercially available I-V tracers, and why the lack of autonomy for current I-V tracers is an issue. Reasoning behind choosing a SEPIC topology to trace the I-V curve will be shown, and an averaging technique helpful in modeling the SEPIC is reviewed.

2.2 Photovoltaic Cell Review

A photovoltaic cell is a p-n junction which experiences the photovoltaic effect. According to atomic theory, an atom is composed of a nucleus with protons and neutrons, with electrons in orbit. These electrons are positioned in ‘bands’ around the nucleus. Electrons fill the bands from inner to outer, so only the outermost band has the possibility of being unfilled. The outermost band of electrons is called the **valence band**. Insulators have relatively full valence bands, conductors have relatively empty valence bands, while semiconductors are somewhere in between. Sometimes, electrons in the valence band can become energetic enough that they jump into a different band, far from the nucleus of the atom. This band is called the **conduction band**. The energy it takes for an electron to move from the valence band to the conduction band is known as the **band gap energy**. In a PV cell, if a photon with sufficient energy strikes the cell, an electron will become dislodged from the valence band and move into the conduction band, where it can be used as electricity [1]. This is illustrated in Figure 2..

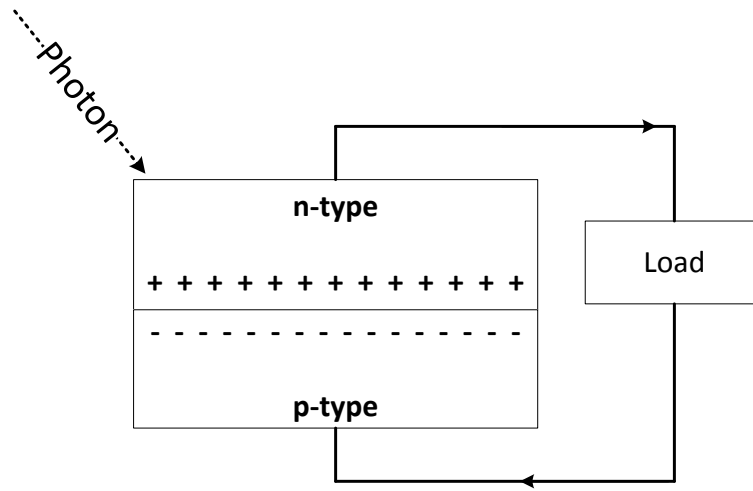


Figure 2.1: Illustration of Photovoltaic Cell

2.2.1 PV Cell Characteristics

If no photon strikes the PV cell, then the cell is simply a p-n junction which behaves like a diode.

A diode is a device that conducts when a positive voltage is applied from the anode to the cathode, and blocks current when a negative voltage that is not too large is applied. A diode has 3 regions of operation:

- **Forward Bias:** The conducting region of the diode
- **Reverse Bias:** The blocking region of the diode
- **Breakdown:** If a reverse voltage is too large the diode cannot block and becomes conductive

The I-V curve for a diode is illustrated in Figure 2.2 (a).

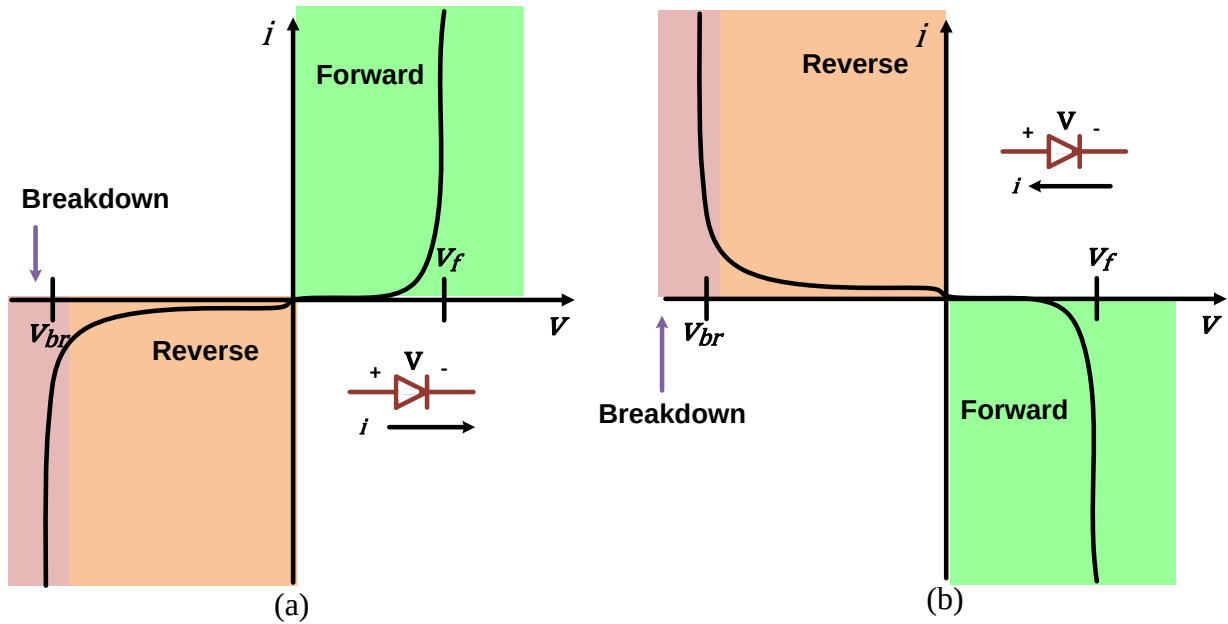


Figure 2.2: Diode I-V Curve (a) Diode I-V Curve with Reverse Current Notation (b)

In a PV cell, the current convention is opposite that of a diode. This is illustrated in Figure 2. (b) by flipping the curve about the x-axis and noting the current direction change. When light strikes the PV cell the I-V curve changes by shifting upward. For basic analysis the I-V curve of an illuminated cell can be assumed to be the unilluminated I-V curve shifted by the short circuit current [4]. A PV cell's I-V curve under illumination is illustrated in Figure 2. with the same current notation as Figure 2..2 (b).

The power generation capabilities of a PV cell are limited by the intensity of the solar energy incident to the cell. Solar energy comes from, as one might expect, the sun. The sun is a celestial body which radiates energy. At the outer edge of the atmosphere, the flux of solar energy incident on the surface and oriented normal to the sun's rays has a mean value of about

1350W/m² [1]. This value is attenuated due to the filtering properties of the earth's atmosphere. By the time the energy reaches the earth's surface, it can be assumed to be about 1000 W/m², though this is dependent on a large number of factors. The actual irradiance at any time is dependent on latitude, cloud cover, atmospheric properties, and angle of the sun. Nonetheless, 1000W/m² is defined as the default irradiance to use when testing PV cells under standard test conditions (STC).

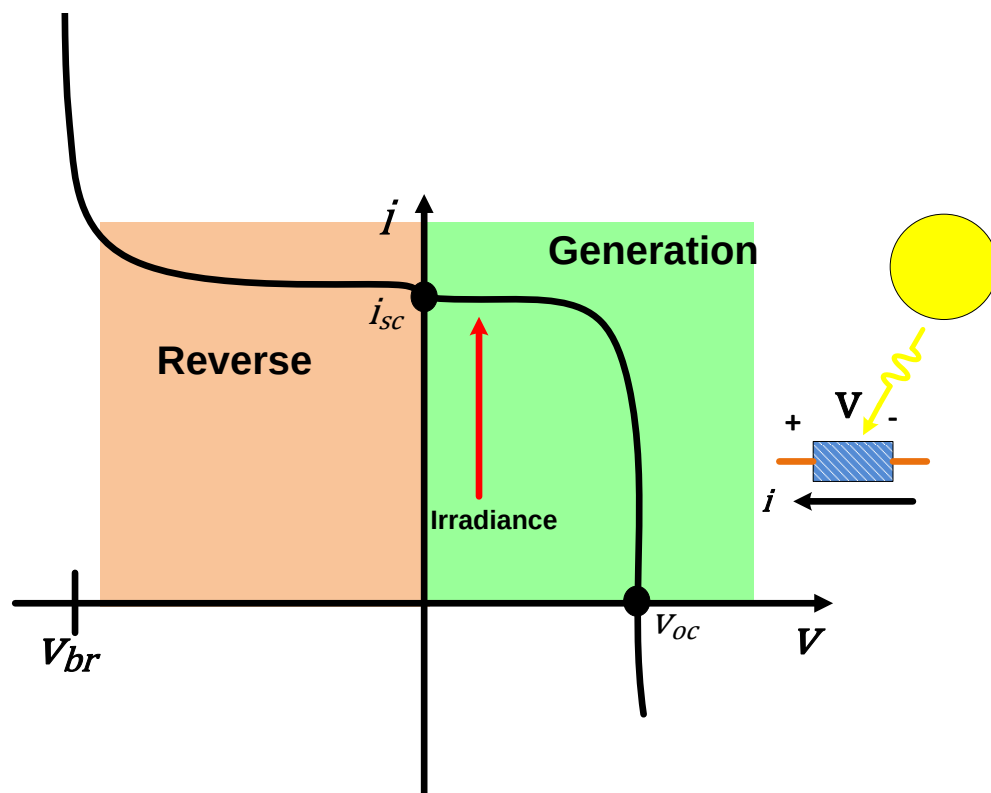


Figure 2.3: I-V Curve of Illuminated PV Cell

The first quadrant of the curve seen in Figure 2. is what is typically defined as the I-V curve for a PV cell. The other quadrants of the curve are often ignored because the PV cell is designed to operate only in the first quadrant, which is the only power generating quadrant.

The second quadrant of the I-V curve is useful for understanding some of the problems that can occur when combining PV cells in series. Recall from chapter 1 that when connected in series, the I-V curve is extended on the x (voltage) axis. This means that a current mismatch in series connected cells will limit the cells to the current of the worst cell. This is a weakest-link-in-the-chain scenario. Consider a string of cells in series with one shaded cell as illustrated in Figure 2..

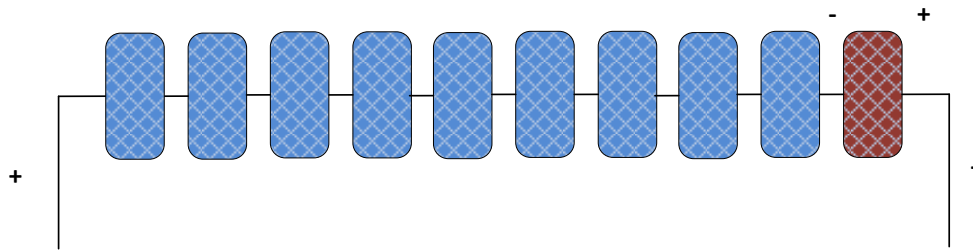


Figure 2.4: String of Series Cells with One Underperforming Cell

Under normal operation, this single shaded cell will limit the current of all the other 9 cells. If a large number of series connected ‘good’ cells reverse bias the shaded cell, the shaded cell’s operating point moves into the second quadrant of the I-V curve. This results in the single cell dissipating power instead of generating it. This dissipation of power becomes worst at the short circuit condition, when the bad cell blocks the entirety of the good cells’ voltage, dissipating a large amount of power. In the case of a normal cells, the reverse biased cell will dissipate up to 5 W, resulting in localized hot spots on the module [2]. These hot spots are easily identified by IR cameras as they cause large temperature spikes on the affected cells. These hot spots can cause cell or glass cracking, faster degradation, and melting of electrical paths within the module. A bypass diode on every cell would remedy this and help avoid cells becoming reverse biased, but would be economically unfeasible. In practice, most modules are just series

combined cells, meaning a 260 W module with 60 cells in series would need 60 bypass diodes to have one for every cell [2]. For the CS6P module from Canadian Solar, the module instead has 3 bypass diodes, one for every twenty cells. This provides a happy medium between excessive diodes and not enough diodes, though hot spot heating can still occur.

2.3 Power Electronics

2.3.1 I-V Tracers

The current of a PV panel can be said to be a function of its voltage, that is, for each voltage point between short-circuit current and open-circuit voltage there exists one current value. Because of this, anything that can vary the voltage as well as measure the current and voltage simultaneously can be used to capture the I-V characteristics. A popular I-V tracer manufacturer, DayStar, uses a capacitive load to measure the I-V curve [5]. The DayStar I-V tracer allows the PV to charge a large capacitor, measuring the voltage and current as the capacitor is charged from zero at the short-circuit condition to the open-circuit voltage. Other I-V tracers use resistive loads to vary the PV voltage and capture the curve. Lab-grade curve tracers with high accuracy typically used in research facilities use an electronic load [6]. These methods vary in sweep time, accuracy, and price, but all of them operate on the same basic principle of varying the voltage and capturing the voltage and current at the same time.

The purpose of these I-V tracers varies from device to device. For example, the MP-180, a lab-grade I-V tracer intended for PV use from Eko Instruments is shaped in a way to be rack mounted and fit in a laboratory space. It is clear from the design in Figure 2. that it is not intended to be mobile, or be used in-field.



Figure 2.5: Eko Rack Mountable I-V Tracer [12]

The curve tracer pictured above in Figure 2. is a 100W peak input power device, meaning it is too small to measure most PV modules' I-V curve. It can sense currents as low as 10 μA and voltages as low as 1 mV, and is intended characterization of single cells [12]. Compare this to a different I-V tracer also manufactured by Eko, the MP-11 I-V checker.



Figure 2.6: MP-11 I-V Checker [13]

The MP-11 I-V Checker shown in Figure 2.6 comes in a hard plastic case with a handle, a far-cry from the rack-mounted device shown in Figure 2.. This device is intended for in-field use, and its technical specs reflect this. The MP-11 can sense current as low as 10 mA, making it much less sensitive than the 10 μ A sensing MP-180. The MP-11's power level is much higher as well, allowing for measurements of strings of PV modules up to 18 kW and 1000VDC at the open circuit condition [13]. This device is intended for monitoring of large PV plants, and is more useful as a health measurement than a device characterization tool. This can be seen in the naming convention between the two devices. The lab-grade MP-180 is referred to as an I-V tracer, while the rugged MP-11 is known as an I-V checker.

For the purposes of health measurement of large-scale PV systems, the laboratory grade I-V tracers are not suitable. They are often not made to handle high power, and are too accurate to be cost effective.

There are many I-V tracers intended for in-field use. These I-V tracers vary in method of measurement, accuracy, and power ratings. Generally the accuracy of the I-V tracers intended for field use in PV generation is around 1% and the power ratings vary from ~5 kW to 50 kW.

The two largest environmental factors that affect the I-V curve are irradiance and temperature. Some field I-V tracers come equipped with temperature and irradiance measurement tools and use models to find the common parameters like I_{SC} , V_{OC} , and P_{MP} at standard test conditions. Recall from earlier that STC is defined as 1000 W/m², AM1.5, and 25°C cell temperature. This translation from measured to STC is helpful for comparing nameplate ratings as it is difficult to get 1000 W/m² and 25°C cell temperature in field environments.

Different commercial I-V tracers intended for field use vary slightly in price, accuracy, and portability, but remain largely the same in operation. To capture the I-V curve, the module, string, or strings of modules are connected to the I-V tracer's positive and negative terminals. This requires disconnecting the module, string, or strings from their generation circuit. If available, irradiance and temperature sensors are attached. The I-V curve is then captured, stored to a device or local computer, and the module, string, or strings are reconnected in their generation circuit. This is repeated for all the I-V curves of other strings or modules.

This method is not ideal for a PV plant owner who is interested in automating their monitoring system. In fact, some of the best locations for PV resources are in places with a very low population density, meaning O&M technicians are likely further away and need more time to dispatch a solution.

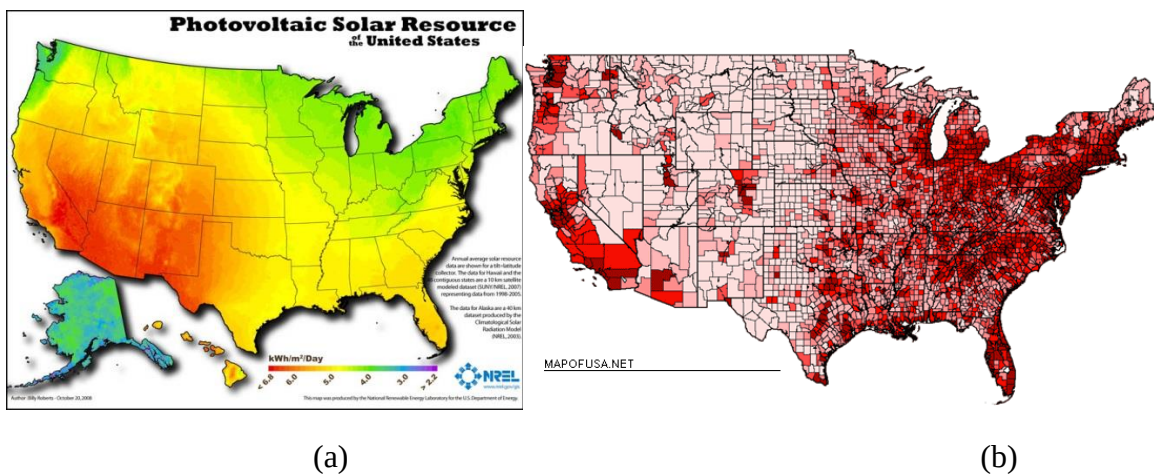


Figure 2.7: Available Solar Resource (a) Population Density (b) [14]

Figure 2 compares a map of PV resources to population density to illustrate this. On both maps, darker red indicates higher density.

I-V tracers have an excellent future in PV monitoring, and can be extremely useful in monitoring the health and degradation effects that a PV plant is undergoing. However, the manual method of acquiring the trace limits the frequency that I-V traces can be captured and studied. I-V curves have the potential to be very useful for monitoring degradation of PV modules relative to their rating, but only if periodic I-V curves are captured. An autonomous approach is needed.

DC-DC optimizers are power electronics converters which have the ability to hold a module or string of modules at its individual MPP, regardless of the condition of surrounding PV. With the use of these at the module level, mismatch effects are greatly reduced [7]. The DC-DC optimizers operate by varying the voltage on the PV input side to find the MPP, while maintaining the DC bus voltage going to the central inverter.

This same topology could be used as an I-V tracer for monitoring purposes. The PV side of the converter would sweep and capture the I-V curve while maintaining the DC voltage on the inverter side. The converter would need to be able to buck and boost the voltage as it covered the entirety of the I-V curve.

A switching converter would be best for this application. A Duran, Galan, Sidrach-de-Cardona have investigated different topologies' effectiveness at capturing I-V curves [10]. They found that converter topologies capable of replicating the entire I-V curve of a PV module were those that could buck or boost the voltage. These included the buck-boost converter, Zeta, Cuk, and SEPIC. These topologies are illustrated in Figure 2.8: Some Common Switching Converter Technologies below.

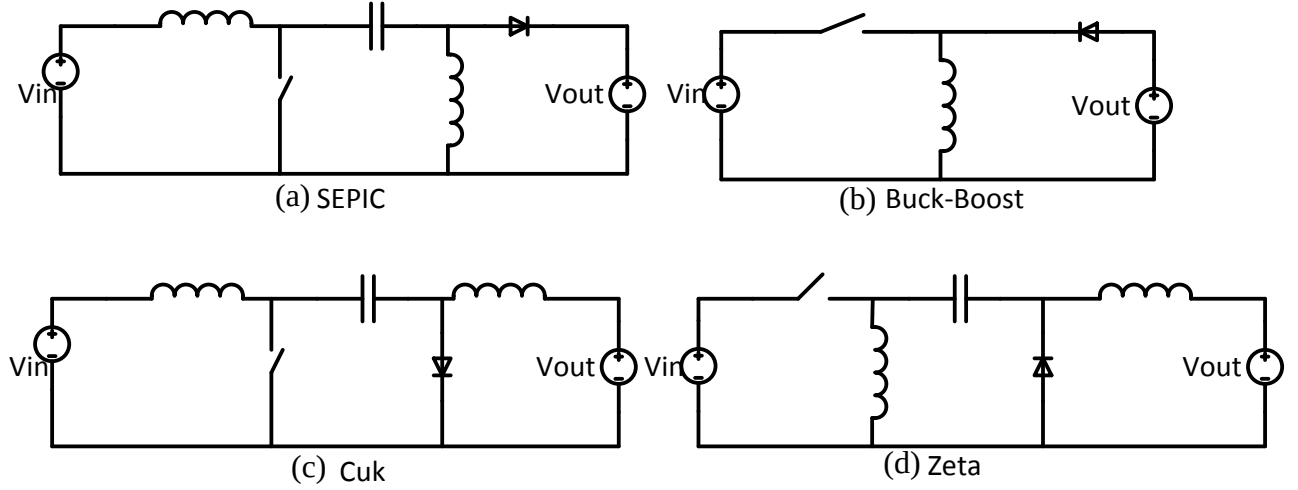


Figure 2.8: Some Common Switching Converter Technologies with Buck and Boost Capabilities: SEPIC (a) Buck-Boost (b) Cuk (c) Zeta (d)

The Buck-Boost converter and Zeta converter both place the switch in series with the input. This produces a discontinuous input current which can introduce significant noise problems when trying to capture the I-V curve. In [9], the SEPIC is offered as the best option for I-V tracing PV modules.

2.3.2 The SEPIC

The single-ended primary-inductance converter (SEPIC) converter is a non-inverting DC-DC converter capable of producing an output voltage less than, greater than, or equal to its output voltage. It is advantageous for I-V tracing due to its ability to buck and boost, its non-inverting input, and its continuous input current. The authors in [9] chose a load resistor with a value that would ensure the SEPIC converter remained in continuous conduction mode (CCM) for the entirety of the trace. It is helpful to keep the converter in CCM for analysis and control purposes, as the dynamics of the converter change when it enters discontinuous conduction mode (DCM). However, keeping I-V tracer in CCM is not possible with the autonomous topology. The

load side of the SEPIC converter in an autonomous I-V tracer is connected to the DC side of the inverter, and it can be assumed that near V_{OC} of the traced module the converter will enter discontinuous conduction mode (DCM). In CCM, the converter can be assumed to have two states, on and off. In the first state, on, the switch is turned on. The input voltage source charges the first inductor, and the second inductor takes energy from coupling capacitor C_p . The diode is not turned on. In the second state, off, the switch is turned off. The first inductor charges the coupling capacitor and provides current to the load. The second inductor also provides current to the load. In the DCM case, the current in L1 and L2 drop to a point where they fail to forward-bias the diode, and both the diode and switch are off. These three states are illustrated in Figure 2.9.

The first switching state occurs when the switch is driven on, and lasts until the switch is turned off. This switching period is defined as $d_1 T_s$, where d_1 is the ratio of time the switch is on compared to the switching period. The second switching state occurs when the switch is off, and the diode is on. This period is defined as $d_2 T_s$, where d_2 is the ratio of time that the diode is turned on. The final switching period occurs when the diode turns off and as defined as $d_3 T_s$, where $d_3 = 1 - d_2 - d_1$. The switching states can be seen in the inductor current in **Error!**

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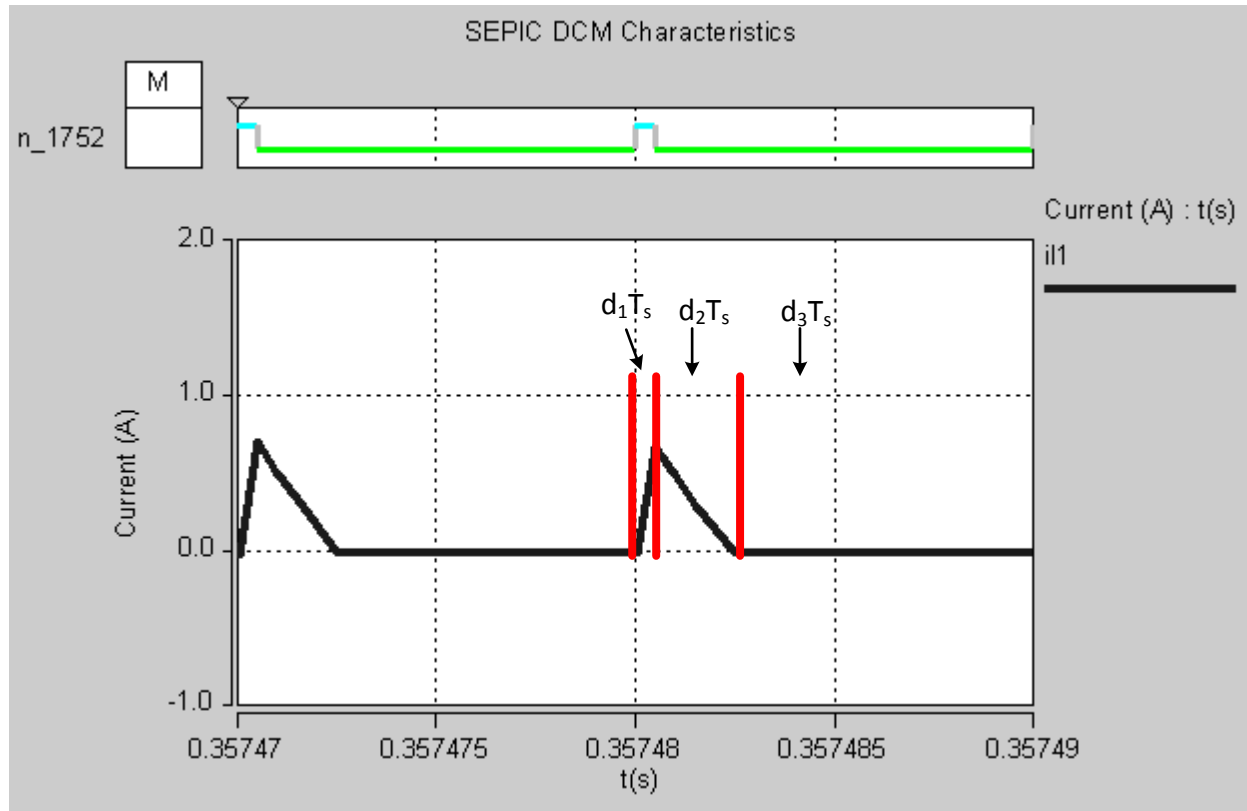


Figure 2.10: Inductor Current in all 3 Switching States

2.4 State Space Representation

The 3 different modes of operation seen in Figure 2.9 result in a non-linear switching converter. This is difficult to model with traditional circuit analysis techniques, but becomes simpler through the use of the state space averaging method.

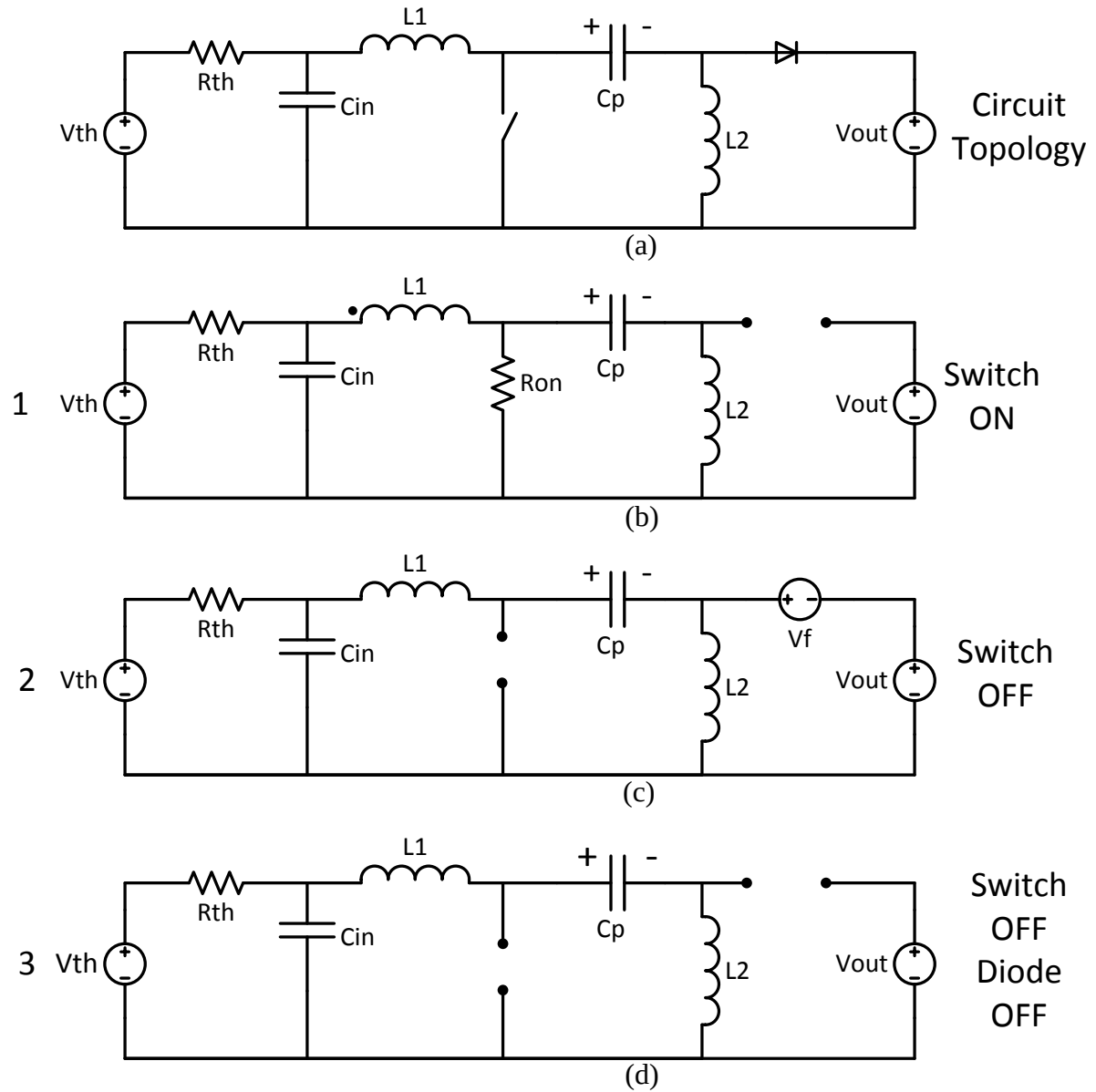


Figure 2.9: Illustration of SEPIC Topology and All 3 Switching States: SEPIC Topology (a) Mode 1 Operation (b) Mode 2 Operation (c) Mode 3 Operation (d)

The state space representation is a canonical form of describing a linear system. In state-space representation, derivatives of state variables are described as linear combinations of inputs and the state variables themselves. The state variables are typically properties of energy storage components. For switching converters, this usually means the state variables are inductor voltages and capacitor currents [15]. Inductor voltages are the time-domain derivative of their currents. Similarly, capacitor currents are the time-domain derivative of their voltages. The general form of state-space represented systems is seen below in (2.1).

$$\begin{aligned} \mathbf{K} \frac{dx(t)}{dt} &= \mathbf{A}x(t) + \mathbf{B}u(t) \\ y(t) &= \mathbf{C}x(t) + \mathbf{E}u(t) \end{aligned} \tag{2.1}$$

The variable $x(t)$ is a vector which contains all the state variables. $u(t)$ is a vector of input variables, and is independent to the system. The derivative of the state vector $\frac{dx(t)}{dt}$ is simply a vector the same size as the state vector whose individual components are equal to the derivatives of the corresponding components in the state vector. In power electronics, $\mathbf{K}$ is a matrix of values for capacitance, inductance, and mutual inductances. Matrices $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, and $\mathbf{E}$, are matrices full of constants of proportionality. The vector $y(t)$ is the output vector which can be any dependent signal in the switching converter, regardless of if it is an actual output [15].

2.4.1 State Space Averaging

In a switching converter, each switching state reduces the converter to a single linear circuit. In the case of a SEPIC converter operating in DCM there are switching states. Each of these states can be represented in state-space form individually [15]. The equations for these are shown below in (2.2)-(2.4).

For Time Interval 1: (d_1T_s)

$$\frac{dx}{dt} = A_1x + B_1u \quad (2.2)$$

$$y = C_1x + E_1u$$

For Time Interval 2: (d_2T_s)

$$\frac{dx}{dt} = A_2x + B_2u \quad (2.3)$$

$$y = C_2x + E_2u$$

For Time Interval 3: (d_3T_s)

$$\frac{dx}{dt} = A_3x + B_3u \quad (2.4)$$

$$y = C_3x + E_3u$$

During each the three time intervals, the converter is connected in a different configuration. Because of this, it is likely the variables A_1, B_1, C_1, E_1 , A_2, B_2, C_2, E_2 , and A_3, B_3, C_3, E_3 , are different from each other. The state vector x and the input vector u remain the same across all three time intervals.

Due to volt-second balance and charge balance properties of inductors and capacitors, these state space matrices can be averaged to find the **State Space Averaged Model**. At equilibrium, the discontinuous conduction mode circuit can be described as:

$$0 = AX + BU \quad (2.5)$$

$$Y = CX + EU \quad (2.6)$$

where the averaged matrices A, B, C , and E , are the averaged values of the same variables in equation 1-A through 1-C weighted by the duty cycle values.

$$A = D_1 A_1 + D_2 A_2 + D_3 A_3 \quad (2.7)$$

$$B = D_1 B_1 + D_2 B_2 + D_3 B_3 \quad (2.8)$$

$$C = D_1 C_1 + D_2 C_2 + D_3 C_3 \quad (2.9)$$

$$E = D_1 E_1 + D_2 E_2 + D_3 E_3 \quad (2.10)$$

The small signal model can be derived from the state space averaged model by perturbing and linearizing the state space average model about the equilibrium point seen in (2.5) and (2.6). To perturb and linearize the model the vectors X, U, Y, D_1, D_2 , and D_3 can be represented as combinations of DC terms and high frequency perturbations as shown in (2.11) – (2.16) [15].

$$\langle x(t) \rangle_{Ts} = X + \tilde{x}(t) \quad (2.11)$$

$$\langle u(t) \rangle_{Ts} = U + \tilde{u}(t) \quad (2.12)$$

$$\langle y(t) \rangle_{Ts} = Y + \tilde{y}(t) \quad (2.13)$$

$$\langle D_1(t) \rangle_{Ts} = D_1 + \tilde{d}_1(t) \quad (2.14)$$

$$\langle D_2(t) \rangle_{Ts} = D_2 + \tilde{d}_2(t) \quad (2.15)$$

$$\langle D_3(t) \rangle_{Ts} = D_3 - \tilde{d}_1(t) - \tilde{d}_2(t) \quad (2.16)$$

2.5 Chapter Summary

In this chapter the basic properties of PV panels and their I-V characteristics have been discussed. The current state of PV monitoring equipment for the purposes of characterizing PV I-V curves has been described, and sufficient motivation has been shown for an I-V tracer to exist which operates autonomously in-line with the inverter. Well-known power electronics topologies have been analyzed for the purpose of tracing the I-V characteristics of a PV module and the single-ended primary inductance converter (SEPIC) has been chosen as the optimal topology for an I-V tracer. Finally, the state space averaging technique, which will be used to understand the large and small signal characteristics of the converter has been discussed.

CHAPTER 3

MODELING AND CALCULATIONS

In this chapter, the modeling of the SEPIC Converter for online PV I-V tracing is shown as well as the process of sizing passive components. Additionally, an analysis technique for quantifiably understanding notches in the I-V is proposed.

3.1 Modeling of the SEPIC Converter in DCM

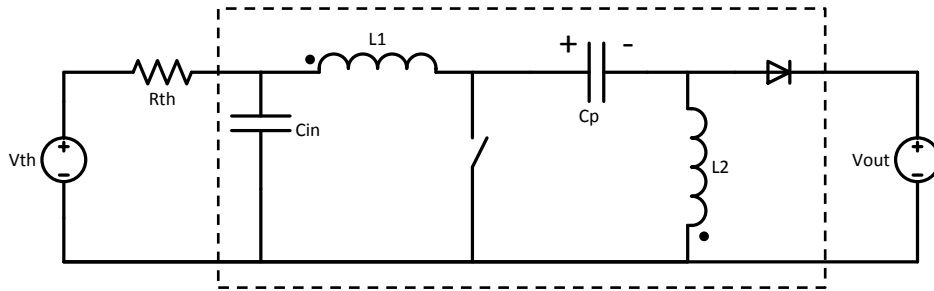


Figure 3.2: SEPIC Topology

For the topology seen in Figure 3.1, the SEPIC is noted by the components inside the dashed line. The PV module is represented by a Thevenin equivalent voltage and resistance, and the DC bus input to the inverter is modeled as an ideal voltage source [16].

As discussed in Chapter 2, it is important to model this circuit in the state-space form. Recalling from Chapter 2, the state-space representation is of the form shown in (3.1).

$$K\dot{x} = Ax + Bu \tag{3.1}$$

$$y = Cx + Eu$$

Also described in Chapter 2, the vector x contains the state variables, u contains the input variables, and y contains the output variables. For this particular application, there will only be one output variable, the voltage across capacitor C_{IN} . This is chosen as the output variable because the purpose of the converter is to control the PV module's voltage and trace the entirety of the curve. The state variables in this converter are chosen to be the inductor currents and capacitor voltages. The state variable vector X is defined below in (3.2).

$$X = \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{Cin} \\ V_{Cp} \end{bmatrix} \quad (3.2)$$

The input variables for this topology are chosen to be the Thevenin voltage source representing the PV module, the forward voltage drop across the diode, and the output voltage, which is the DC bus to the inverter. The input variable vector U is defined below in 3.3.

$$U = \begin{bmatrix} V_{th} \\ V_f \\ V_{out} \end{bmatrix} \quad (3.3)$$

Matrices K , C , and E are constant for all switching states and are defined in (3.4). K is a diagonal matrix containing the inductance and capacitance values for the state variables seen in (3.2). E is a vector of zeros because the output has been defined as one of the state variables. C is a vector of zeros except for the position which corresponds to the output variable, V_{Cin} .

$$C = [0 \quad 0 \quad 1 \quad 0], \quad E = [0 \quad 0 \quad 0], \quad K = \begin{bmatrix} L1 & 0 & 0 & 0 \\ 0 & L2 & 0 & 0 \\ 0 & 0 & C_{in} & 0 \\ 0 & 0 & 0 & C_p \end{bmatrix} \quad (3.4)$$

3.1.1 Mode 1 Operation

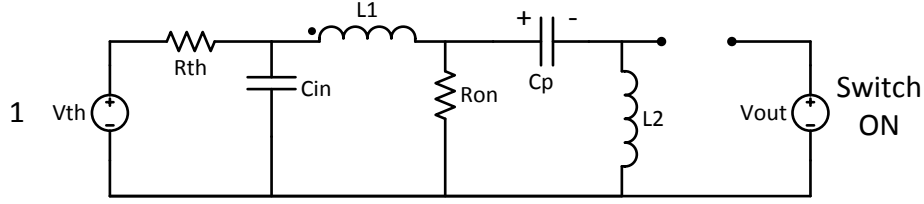


Figure 3.3: Mode 1 of Operation of DCM SEPIC

Variables A and B are unique to each of the three switching states seen in Figure 2.9. For mode 1 operation, when the switch is on and the diode is off (shown again in Figure 3.3), the state space form can be found by using nodal analysis to solve the equations for inductor voltages, and mesh analysis to solve the equations for capacitor currents. All of these equations are solved in terms of the state variables seen in (3.2). These equations are shown in (3.5).

$$V_{L1} = L_1 \frac{dI_{L1}}{dt} = V_{Cin} - R_{on}(I_{L1} + I_{L2})$$

$$V_{L2} = L_2 \frac{dI_{L1}}{dt} = V_{Cp} - R_{on}(I_{L1} + I_{L2}) \quad (3.5)$$

$$I_{Cin} = C_{in} \frac{dV_{Cin}}{dt} = \frac{V_{th}}{R_{th}} - \frac{V_{Cin}}{R_{th}} - I_{L1}$$

$$I_{Cp} = -I_{L2}$$

These variables can be written in matrix form to obtain a form which resembles 3.1. The matrix form of mode 1 operation of this topology is shown in (3.6).

$$\begin{bmatrix} L1 & 0 & 0 & 0 \\ 0 & L2 & 0 & 0 \\ 0 & 0 & C_{in} & 0 \\ 0 & 0 & 0 & C_p \end{bmatrix} \begin{bmatrix} \dot{I}_{L1} \\ \dot{I}_{L2} \\ \dot{V}_{Cin} \\ \dot{V}_{Cp} \end{bmatrix} = \begin{bmatrix} -R_{on} & -R_{on} & 1 & 0 \\ -R_{on} & -R_{on} & 0 & 1 \\ -1 & 0 & -\frac{1}{R_{th}} & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{Cin} \\ V_{Cp} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{R_{th}} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{th} \\ V_f \\ V_{out} \end{bmatrix} \quad (3.6)$$

$$V_{Cin} = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{Cin} \\ V_{Cp} \end{bmatrix} \quad (3.6)$$

3.1.2 Mode 2 Operation

In mode 2 operation of the DCM SEPIC, shown again in Figure 3.3, the switch is off, the diode is on and conducting with its power loss represented as the diode's forward voltage drop.

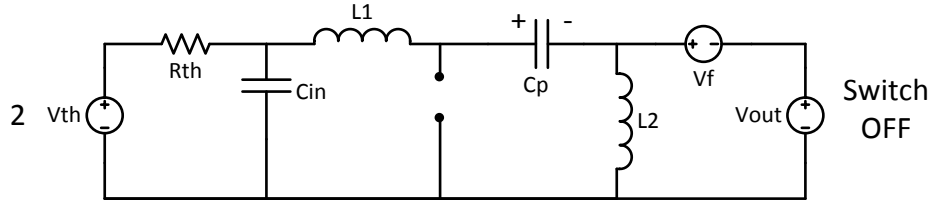


Figure 3.4: Mode 2 Operation of DCM SEPIC

The state space form for mode 2 operation is again found using nodal and mesh analysis to solve the circuit in terms of the state equations. This is shown in (3.7).

$$\begin{aligned} V_{L1} &= L1 \frac{dI_{L1}}{dt} = V_{Cin} - V_f - V_{out} - V_{Cp} \\ V_{L2} &= L2 \frac{dI_{L2}}{dt} = -V_f - V_{out} \\ I_{Cin} &= C_{in} \frac{dV_{Cin}}{dt} = \frac{V_{th}}{R_{th}} - \frac{V_{Cin}}{R_{th}} - I_{L1} \\ I_{Cp} &= I_{L1} \end{aligned} \quad (3.7)$$

Similar to the mode 1, these equations can be represented as matrices to better resemble (3.1).

The matrix form of (3.6) is shown in (3.8).

$$\begin{bmatrix} L1 & 0 & 0 & 0 \\ 0 & L2 & 0 & 0 \\ 0 & 0 & C_{in} & 0 \\ 0 & 0 & 0 & C_p \end{bmatrix} \begin{bmatrix} \dot{I}_{L1} \\ \dot{I}_{L2} \\ \dot{V}_{Cin} \\ \dot{V}_{Cp} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & -\frac{1}{R_{th}} & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{Cin} \\ V_{Cp} \end{bmatrix} + \begin{bmatrix} 0 & -1 & -1 \\ 0 & -1 & -1 \\ \frac{1}{R_{th}} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{th} \\ V_f \\ V_{out} \end{bmatrix} \quad (3.8)$$

$$V_{Cin} = [0 \quad 0 \quad 1 \quad 0] \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{Cin} \\ V_{Cp} \end{bmatrix}$$

3.1.3 Mode 3 Operation

Mode 3 is where the converter enters discontinuous conduction mode, and where both the switch and diode are no longer conducting. The topology of the circuit in this state is shown below in Figure 3.5.

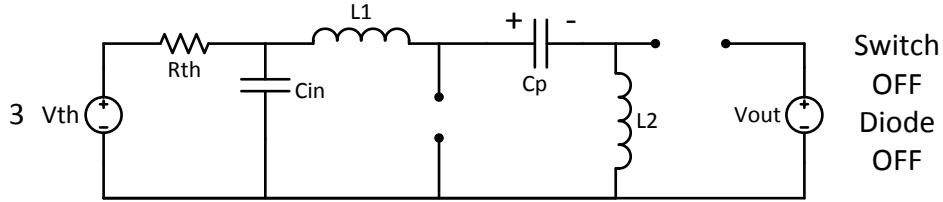


Figure 3.5: Mode 3 Operation of DCM SEPIC

Nodal and mesh analysis are again used to represent the circuit in terms of its state variables. The equations describing the circuit in this mode are shown in (3.9).

$$V_{L1} = L_1 \frac{dI_{L1}}{dt} = V_{Cin} - V_{Cp}$$

$$V_{L2} = L_2 \frac{dI_{L1}}{dt} = -V_{Cin} - V_{Cp} \quad (3.9)$$

$$I_{Cin} = C_{in} \frac{dV_{Cin}}{dt} = \frac{V_{th}}{R_{th}} - \frac{V_{Cin}}{R_{th}} - I_{L1}$$

$$I_{Cp} = I_{L1}$$

Similar to the other modes of operation, these four equations can be converted to matrix form to better resemble the state space form. Equation (3.9) represented in matrix form can be seen in (3.10).

$$\begin{bmatrix} L1 & 0 & 0 & 0 \\ 0 & L2 & 0 & 0 \\ 0 & 0 & C_{in} & 0 \\ 0 & 0 & 0 & Cp \end{bmatrix} \begin{bmatrix} \dot{I}_{L1} \\ \dot{I}_{L2} \\ \dot{V}_{Cin} \\ \dot{V}_{Cp} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & -1 & -1 \\ -1 & 0 & -\frac{1}{R_{th}} & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{Cin} \\ V_{Cp} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{R_{th}} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{th} \\ V_f \\ V_{out} \end{bmatrix} \quad (3.10)$$

$$V_{Cin} = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{Cin} \\ V_{Cp} \end{bmatrix}$$

Now that the circuit has been modeled in each of the three switching states, analysis can be completed using the state space averaging technique discussed in 2.4.1. Equations (3.6), (3.8), and (3.10) are enough to create the three state space equations shown in (2.2)-(2.4).

For the matrices shown in (2.2)-(2.4), each state space representation has different constant matrices A , B , C , and E . In the case of the SEPIC operating in DCM for PV I-V curve tracing, only the matrices A and B change during the three switching states. Dividing these three matrices

through by matrix K defined in (3.4) yields (3.11) and (3.12), which defines the three matrices for A and B each in the state space description.

$$\begin{aligned}
 A1 &= \begin{bmatrix} -\frac{R_{on}}{L1} & -\frac{R_{on}}{L1} & \frac{1}{L1} & 0 \\ -\frac{R_{on}}{L2} & -\frac{R_{on}}{L2} & 0 & \frac{1}{L2} \\ -\frac{1}{Cin} & 0 & -\frac{1}{CinR_{th}} & 0 \\ 0 & -\frac{1}{Cp} & 0 & 0 \end{bmatrix} & A2 &= \begin{bmatrix} 0 & 0 & \frac{1}{L1} & -\frac{1}{L1} \\ 0 & 0 & 0 & 0 \\ -\frac{1}{Cin} & 0 & -\frac{1}{R_{th}} & 0 \\ \frac{1}{Cp} & 0 & 0 & 0 \end{bmatrix} \\
 A3 &= \begin{bmatrix} 0 & 0 & \frac{1}{L1} & -\frac{1}{L1} \\ 0 & 0 & -\frac{1}{L2} & -\frac{1}{L2} \\ -\frac{1}{Cin} & 0 & -\frac{1}{CinR_{th}} & 0 \\ \frac{1}{Cp} & 0 & 0 & 0 \end{bmatrix} & & (3.11)
 \end{aligned}$$

$$\begin{aligned}
 B1 &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{CinR_{th}} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} & B2 &= \begin{bmatrix} 0 & -\frac{1}{L1} & -\frac{1}{L1} \\ 0 & -\frac{1}{L2} & -\frac{1}{L2} \\ \frac{1}{CinR_{th}} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} & B3 &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{CinR_{th}} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\
 & & & & (3.12)
 \end{aligned}$$

$$D1 = \frac{\text{Time in Mode 1}}{T_s} \quad D2 = \frac{\text{Time in Mode 2}}{T_s} \quad D3 = \frac{\text{Time in Mode 3}}{T_s} \quad (3.13)$$

The duty cycle variables are defined in (3.13) as the time spent in each switching state divided by the switching period. According to the state-space averaging technique discussed in 2.4.1, the state space description of the converter across all three switching states can be described by multiplying each of the mode of operations' variables with the corresponding duty cycle as shown in (3.14).

$$\dot{X} = (A1D1 + A2D2 + A3D3)X + (B1D1 + B2D2 + B3D3)U \quad (3.14)$$

The equation describing the output variable Y is the same across all switching states. This is due to the fact that the output variable is one of the state variables.

3.2 Small Signal Modeling

As discussed in 2.4.1, these variables can be described as combinations of their averaged terms and small signal perturbations. Using (2.11)-(2.15), (3.14) is amended to include the small and large signal portions. This is described by (3.15).

$$\dot{X} + \dot{\tilde{x}} = \left(A1(D1 + \tilde{d}1) + A2(D2 + \tilde{d}2) + A3(D3 - \tilde{d}1 - \tilde{d}2) \right) (X + \tilde{x}) + \left(B1(D1 + \tilde{d}1) + B2(D2 + \tilde{d}2) + B3(D3 - \tilde{d}1 - \tilde{d}2) \right) (U + \tilde{u}) \quad (3.15)$$

Expanding (3.15), and discarding the second order nonlinear terms as well as the large signal terms reveals the small signal representation of the circuit. This is described by (3.16).

$$s\tilde{x} = (A1D1 + A2D2 + A3D3)\tilde{x} + (B1D1 + B2D2 + B3D3)\tilde{u} + ((A1 - A3)X + (B1 - B3)U)\tilde{d}1 + ((A2 - A3)X + (B2 - B3)U)\tilde{d}2 \quad (3.16)$$

It is important at this point to redefine $\tilde{d}2$ in terms of $\tilde{d}1$. From [17], it is known that the average inductor current in inductor L_1 can be written as described in (3.16).

$$I_{L1} = \frac{1}{2} I_{L1pk} (D_1 + D_2) \quad (3.17)$$

The peak inductor 1 current I_{L1pk} can be replaced with the voltage across the input capacitor multiplied by the length of time spent in mode one operation and divided by the inductance. This is shown in (3.18).

$$I_{L1} = \frac{1}{2} I_{L1pk} (D_1 + D_2) = \frac{D_1 T_s (V_{Cin}) (D_1 + D_2)}{2L} \quad (3.18)$$

This allows $\tilde{d}2$ to be represented in terms of $\tilde{d}1$ and the system variables. Adding in AC perturbations and removing second order AC terms as well as DC terms, a description of $\tilde{d}2$ in terms of $\tilde{d}1$ is found. This is shown in (3.19).

$$\tilde{d}2 = \tilde{d}1 \left(\frac{\frac{2Lf_s I_{L1}}{D_1^2} - 1}{V_{Cin}} \right) \quad (3.19)$$

Substituting (3.19) into (3.16) reveals (3.20).

$$s\tilde{x} = (A1D1 + A2D2 + A3D3)\tilde{x} + (B1D1 + B2D2 + B3D3)\tilde{u} + ((A1 - A3)X + (B1 - B3)U)\tilde{d}1 + ((A2 - A3)X + (B2 - B3)U)\tilde{d}1 \left(\frac{\frac{2Lf_s I_{L1}}{D_1^2} - 1}{V_{Cin}} \right) \quad (3.20)$$

Using simulation results to determine the large signal characteristics of the converter, including the state variables and duty cycle values, MATLAB code is written to find the transfer function of the converter's duty cycle to input. Figure 3.4 shows the Bode plot of this transfer function.

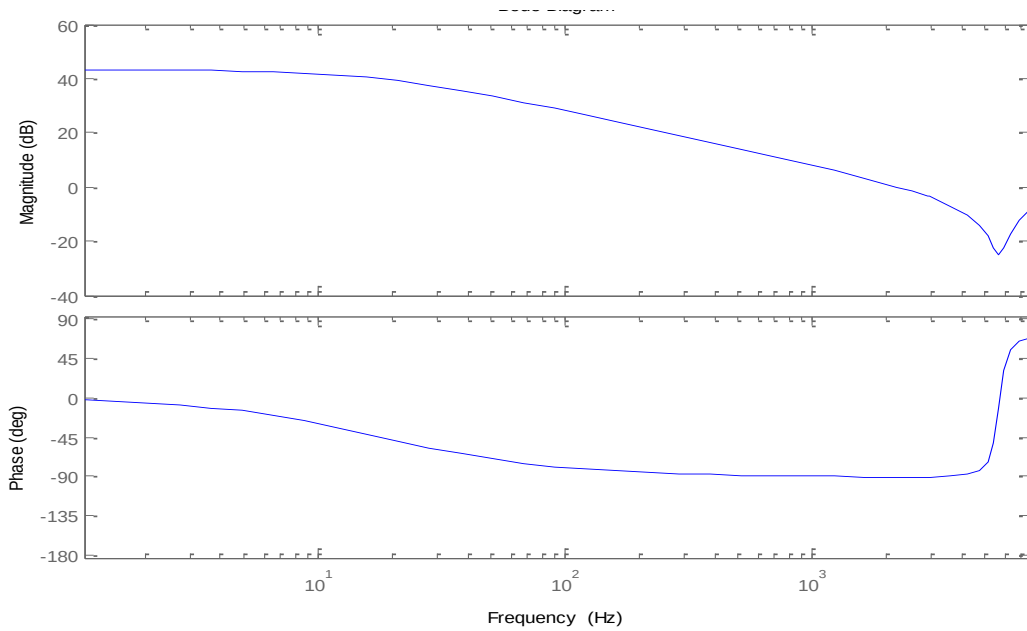


Figure 3.4: Bode Plot of DCM SEPIC Operation from Analytical Results

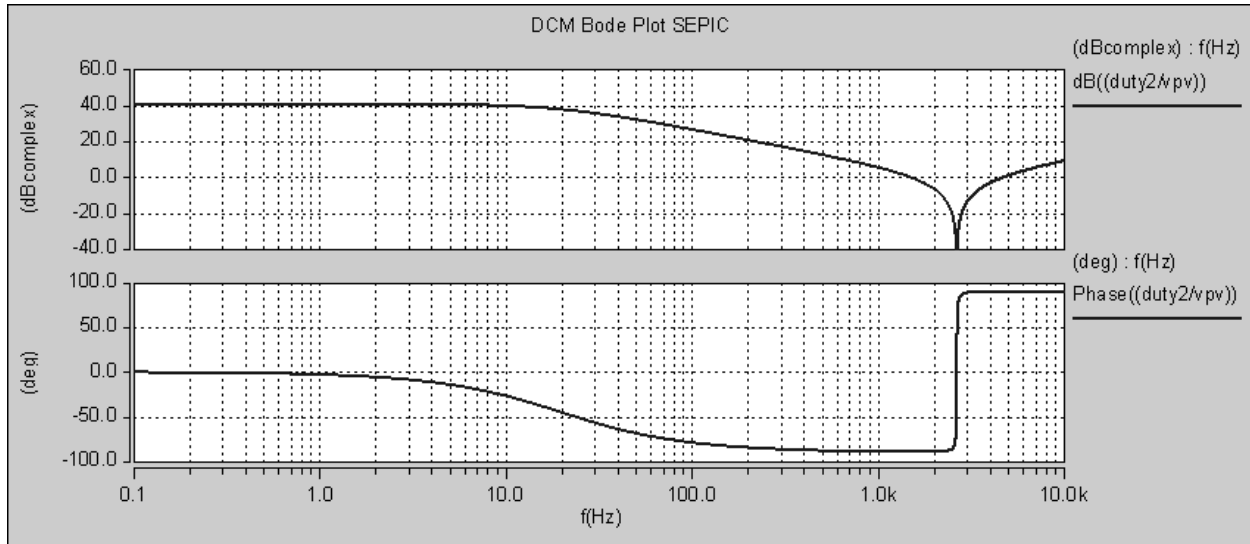


Figure 3.5: Bode Plot from SABER AC Analysis

Figure 3.5 is the bode plot of the simulated converter, and is used to check the analytical results. Comparing Figure 3.4 and Figure 3.5, the model is considered to be valid for frequencies less than 10 kHz, or one-tenth the switching frequency. The transfer function for the DCM duty cycle to input-voltage response has 4 LHP poles and 2 LHP zeros. The 2 LHP zeros are responsible for the 180 degree phase shift near 2 kHz.

Through the use of the SISOTOOL in MATLAB, a simple single-pole controller to control the switch duty cycle is designed with a control transfer function of $\frac{-8}{1-10s}$. This was chosen after tuning to find a reasonable step-response settling time and disturbance rejection ability using SISO tool. The DCM converter is difficult to control, and its low crossover frequency means its transient response is poor. For this reason, a reference voltage that allows the controller the time it needs to reach a DCM value is necessary. This will be further discussed in chapter 4.

3.3 Component Sizing

3.3.1 Inductor L_1 and L_2 sizing

It is known from [17] that the minimum inductance for inductor L_1 can be defined in terms of the desired minimum input current ripple. This is shown in (3.20). In the case of the autonomous I-V tracer for PV monitoring applications, the input current should be kept low because it greatly affects the accuracy of the trace. The input current, along with the input voltage, are the two most important variables in the circuit. This is due to the fact the purpose of the converter is to measure and report the PV voltage and current. For the module-sized converter in question, the input current ripple is limited to 2% of the maximum input current, 9 A. 2% is chosen to keep the inductor reasonably small while still retaining accuracy. Most I-V tracers on the market have 1% current accuracy ratings [7], but for health measurements 2% is considered accurate enough. This works out to be an input current ripple of less than 180 mA at any point during the converter's operation.

$$L_{1min} = \frac{V_{in(min)}D_{MAX}}{\Delta I_L f_{SW}} \quad (3.21)$$

The maximum duty cycle is 1 for this converter, in order to measure the short circuit condition. The minimum input voltage will drop to zero at this point, but to simplify calculations 1 V will be assumed to be the minimum, as this is close enough to the short circuit condition. The switching frequency has been chosen to be 100 kHz, so we can solve (3.21) as shown in (3.22).

$$L_{1min} = \frac{V_{in(min)}^{D_{MAX}}}{\Delta I_{L} f_{SW}} = \frac{1 \times 1}{0.18 \times 100,000} = 55.5 \mu H \quad (3.22)$$

The inductance must be greater than the value shown in (3.21). To be conservative, a value of $80 \mu H$ is chosen. For simplicity of design and due to the information in [17], the same value is chosen for inductor L_2 .

3.3.2 Capacitor C_P sizing

Due to the placement of C_P in the circuit, it is clear from Figure 3.1 that a large amount of current needs to flow through the capacitor during operation. Because of this, a ceramic capacitor must be used with low esr to reduce losses. Following the examples seen in [17], and finding a 35 V ripple across C_P acceptable, $1 \mu F$ is chosen.

3.3.3 Input and Output Capacitor sizing

The size of the input capacitor is important, because it is necessary to limit the input voltage ripple to 1% of the open circuit voltage. A voltage accuracy of 1% is most common in the I-V tracers reviewed in [7]. A high ripple means an inaccurate I-V tracer, so it is important not to undersize the input capacitor. Tuning of the capacitor size through simulation has found that $45 \mu F$ meets the voltage ripple requirement. The output capacitance is to be connected in parallel with the DC input to the inverter, which will likely mean the output capacitance of the SEPIC will be in parallel with the input capacitance of the inverter. For simplicity, this output capacitance is chosen to be the same as the input capacitance.

3.3.4 Inductor Design

Reference [18] provides excellent examples for inductor design of all kinds. Chapter 8 of [18] specifically provides examples of DC Inductor design using gapped cores, which is what will be used in this inductor design. Though chapter 4 provides only simulation results, the inductor design is important to understand the parasitic properties of the inductor for simulation. A PQ core is chosen due to its small size compared to other cores. The MATLAB code following the examples shown in Chapter 8 of [18] can be seen in the appendix. This analysis reveals a winding resistance of 12 m Ω .

3.4 Notch Analysis Technique

An important aspect of having an autonomous, online I-V tracer is the ability to analyze the I-V curve and draw some insight from characteristics of the curve. These characteristics and the conclusions that can be drawn from them are discussed extensively in chapter 1.4 of this thesis as well as in [3], [6], and [7]. Reference [3] mentions briefly that the vertical amplitude of a notch is equal to the reduced short-circuit current of the affected cells, and that the horizontal distance is related to the number of cells bypassed. However, this reference does not provide an equation describing this analysis. It is proposed that an relationship can be derived between the location of the notch in the current-voltage plane and the number of cells bypassed by the bypass diode activity. Similarly, it is proposed that relationship between the location of the notch and the degree to which the bypass cells are degraded/shaded can be derived.

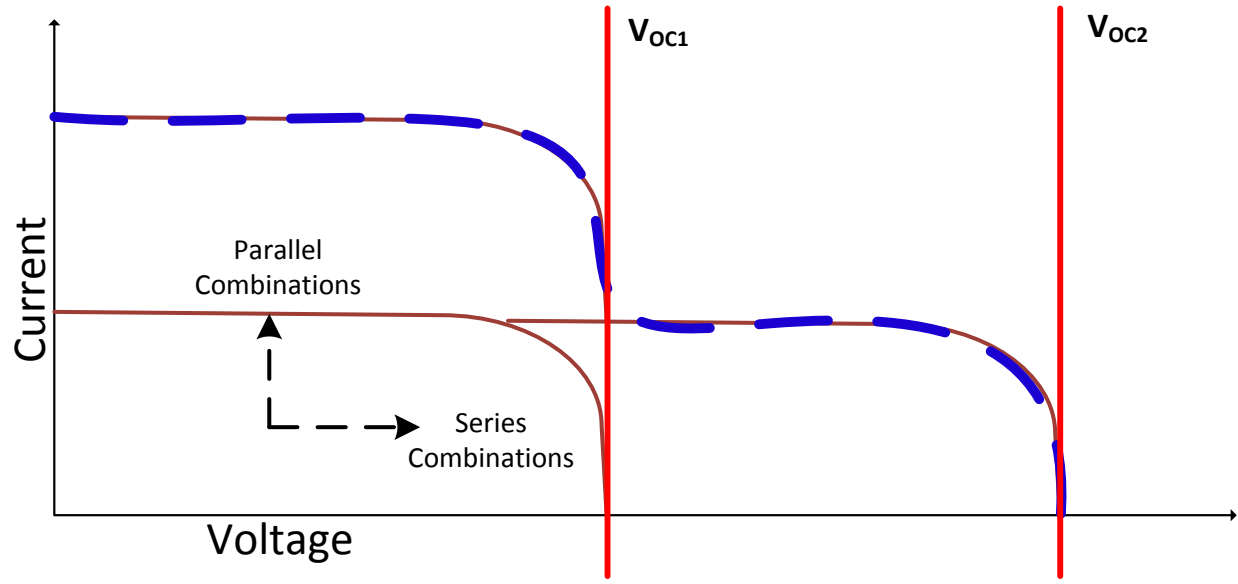


Figure 3.6: Definition of V_{OC1} and V_{OC2}

Figure 3.6 shows the theoretical module from Figure 1.6 (b) which experiences a notch. The two red lines on Figure 3.6 show the two values which determine the horizontal distance of a notch. According to [3], this is related to the number of cells affected. From the understanding of notches presented in chapter 1, it is proposed that the number of cells affected can be defined as shown in (3.23).

$$\frac{V_{OC2} - V_{OC1}}{V_{OC_cell}} = \text{Number Of Cells Affected} \quad (3.23)$$

Where V_{OC1} and V_{OC2} are the points on the I-V curve defined in Figure 3.6, and V_{OC_Cell} is the open circuit voltage for a single cell. This will be tested with simulation results in chapter 4.

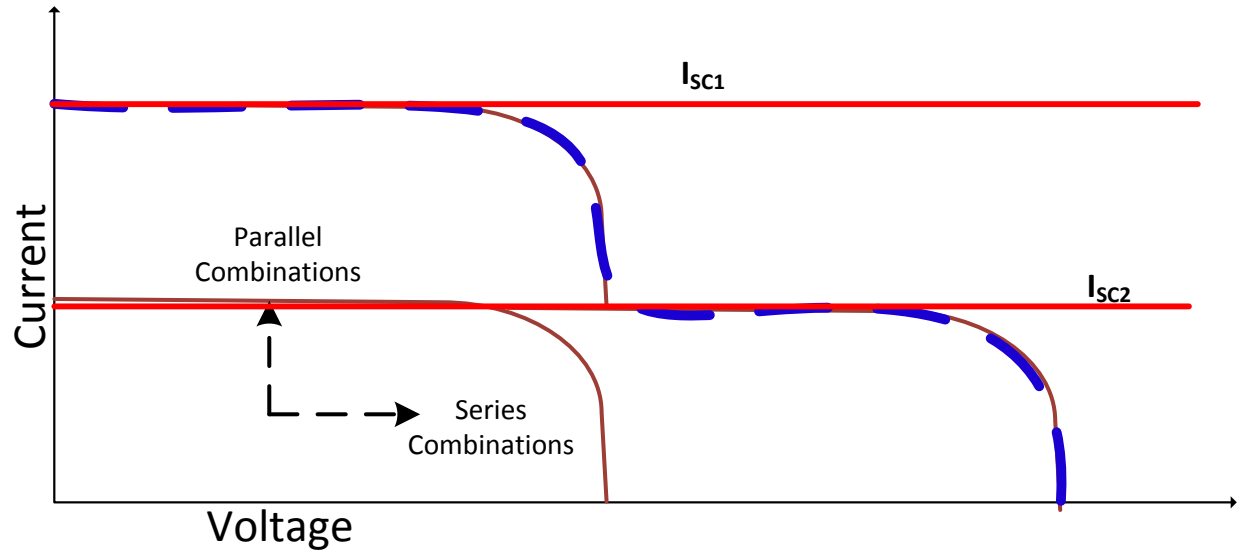


Figure 3.7: Definition of I_{SC1} and I_{SC2}

Figure 3.7 shows the same theoretical module as Figure 3.6. The two red lines in Figure 3.7 show the vertical amplitude difference mentioned in [3] which relates to the difference in short circuit current. The expression in (3.24) allows this difference to be quantified as a number describing how badly the mismatched cells are affected relative to the good cells. This will be tested with simulation in chapter 4.

$$\frac{I_{SC2}}{I_{SC1}} \times 100 = \% \text{ Affected} \quad (3.24)$$

3.5 Chapter Summary

In this chapter, the small-signal model for the SEPIC converter was found, and the duty-cycle to input-voltage small-signal Bode plots shown. Through the use of SISOTOOL in MATLAB, a controller is designed with reasonable dynamic response characteristics. The sizing of passive

components is also described, and components are sized to ensure current ripple less than 2% of I_{SC} and voltage ripple less than 1% of V_{OC} , which is competitive with current I-V tracers commercially available. Finally, an analysis technique for notches found in I-V curves is proposed, and will be tested in the following chapter.

CHAPTER 4 RESULTS

4.1 Chapter Introduction

In this chapter, simulation results of the SEPIC converter acting as a I-V tracer will be shown. The chapter will begin with traditional power electronics tests, which involve showing that the converter can reject disturbances and reach the desired input voltage relatively quickly. Following this, the SEPIC as an I-V tracer results will be shown in different scenarios which validate the analysis techniques discussed in Chapter 1. Finally, tests will be conducted to validate the notch analysis technique proposed in Chapter 3.4.

4.2 Input Voltage Control SEPIC

Small signal analysis of the converter was completed in Chapter 3.2. From the analysis done in 3.2 and help from SISOTOOL in MATLAB to design the compensator function, a control loop with a PI controller is designed. The MATLAB tool was used to analyze the small signal characteristics at several operating points in DCM and CCM. The compensator is a PI controller which was chosen to allow the converter to respond to a step test in CCM with no overshoot and a settling time of less than 10 ms. The control loop measures the input voltage, compares it to the reference voltage, and compensates the difference to create the duty cycle. The duty cycle is then compared to a sawtooth waveform at the switching frequency. This creates the PWM signal to turn on and off the switch.

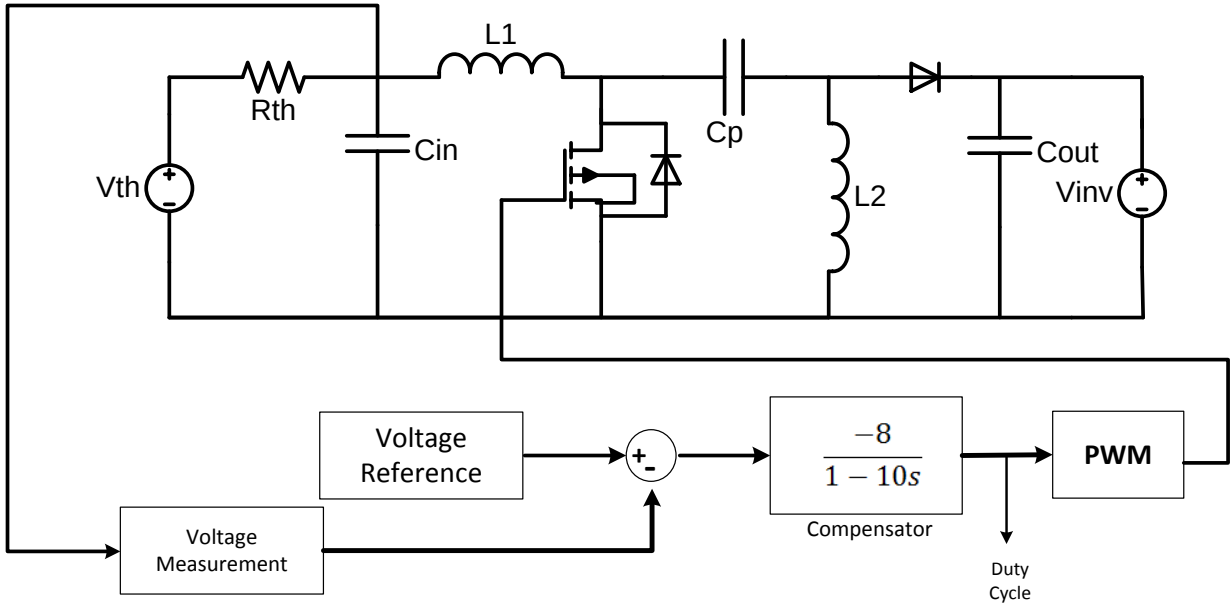


Figure 4.1: Control Loop of Proposed SEPIC

4.2.1 Step Test

To test this control loop, the circuit is simulated in SABER. For the test, SABER's PV model is used as the input, with characteristics similar to the CS6P-250P module seen in [2]. The inverter DC bus is modeled as a voltage source which is set to 30 VDC. The voltage reference starts at 20 V and steps up to 30 V at 0.25 seconds into the simulation. In normal operation, the converter will be used to sweep, so this kind of test is not entirely relevant. However, it is indicative of the controller's general performance. The input reference voltage values are chosen to ensure the converter stays in CCM for the entirety of the test.

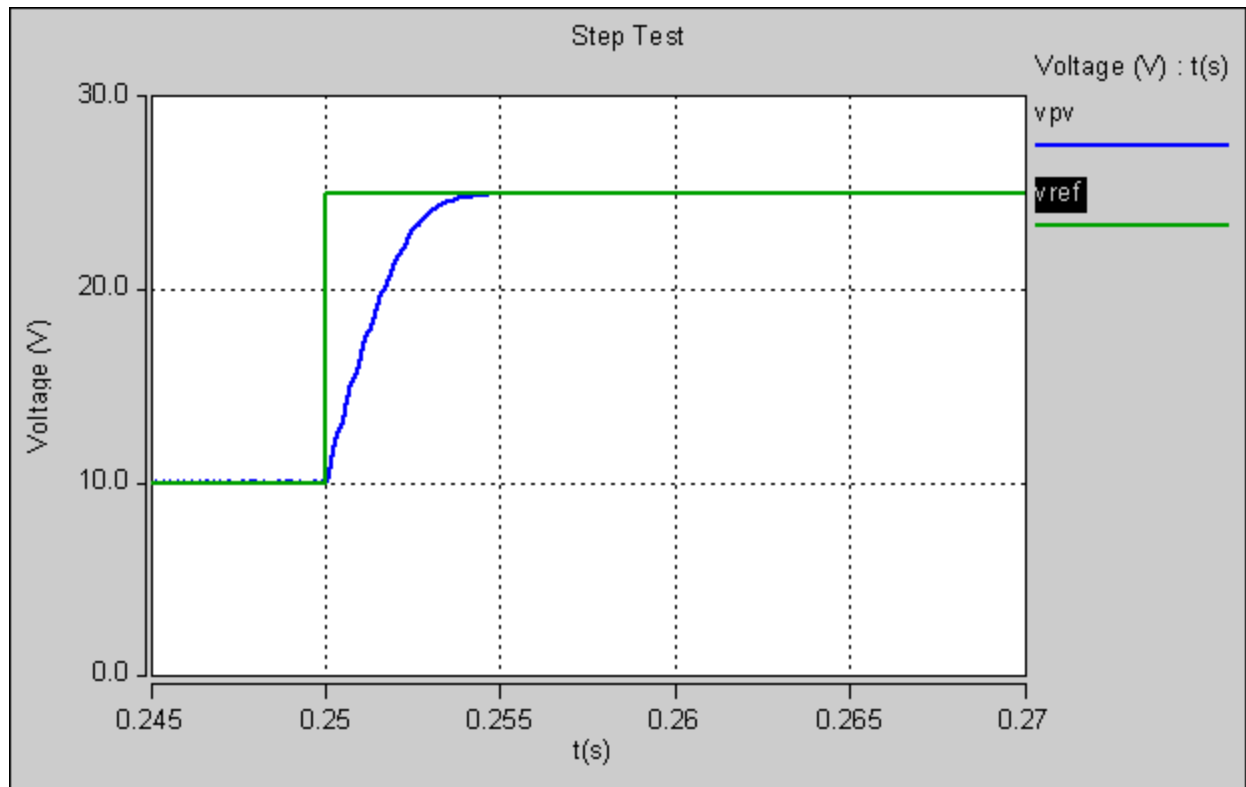


Figure 4.2: Step Test of SEPIC in CCM Input Voltage Response

The test results are shown in Figure 4.2. In the test, the converter takes less than 10 ms to settle upon the new value, with no overshoot. green line is reference voltage, and the blue line is the input voltage from the PV module.

In DCM the controller is not as fast, but is still adequate. A DCM step test is performed to illustrate this.. In the DCM step test, the reference voltage starts at 25 volts and steps up to 37.5 volts at 0.25 seconds. The V_{OC} of the simulated module is 37.5 volts, so this brings the duty cycle down to zero and forces the converter into discontinuous conduction mode.

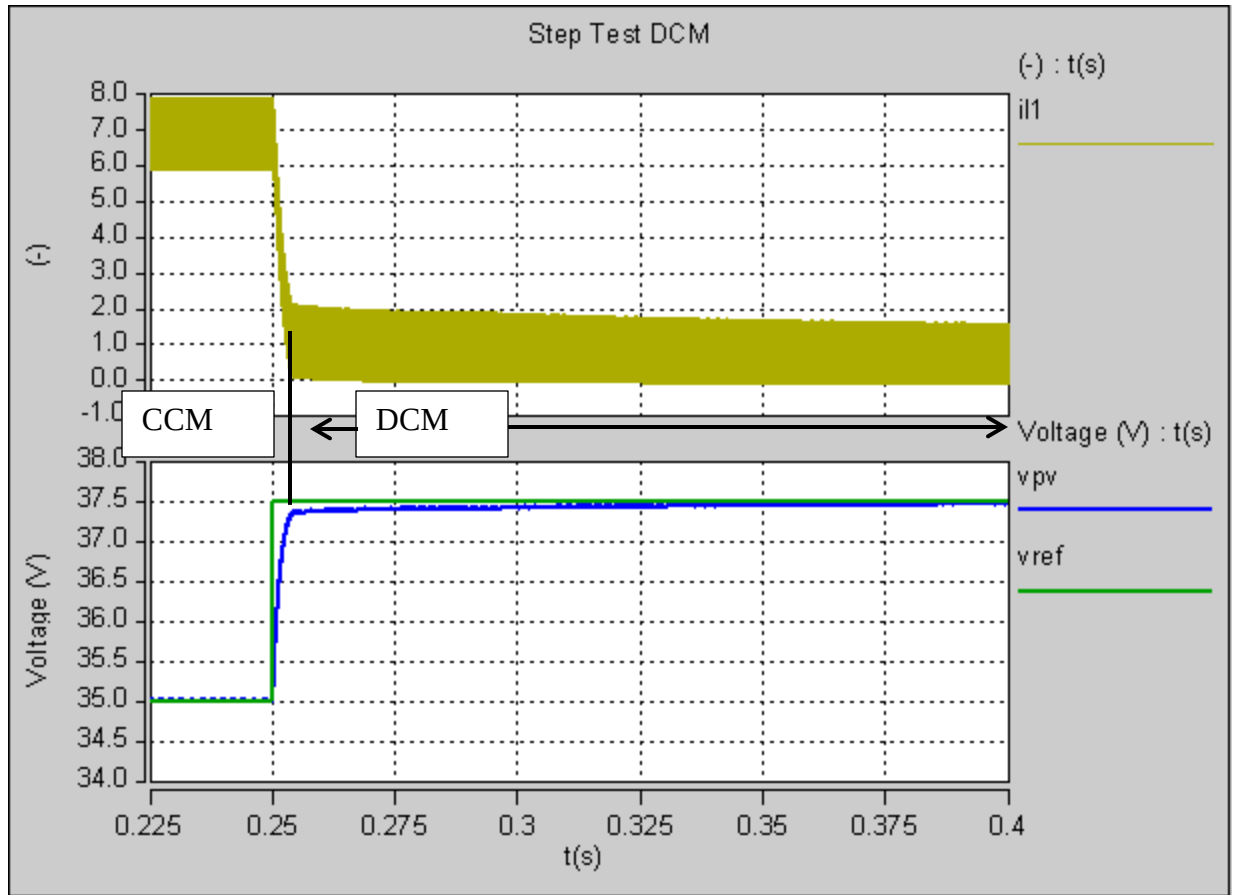


Figure 4.3: Step Test SEPIC in DCM Input Voltage Response

Figure 4.3 shows the results of the DCM step test. As can be seen in Figure 4.3, the controller is slower to reach its new reference voltage when operating in DCM. Because of this, the I-V tracer will hold the reference voltage at the open-circuit voltage for an adequate time to ensure the converter reaches open circuit.

4.2.2 Disturbance Test

Next, a disturbance test is performed. For the disturbance, the voltage at the output of the SEPIC is stepped up, similar to the tests performed in Figures 4.2 and 4.3. At 0.25 seconds, the

voltage at the output of the converter is stepped up from 10 V to 30 V. For the entirety of the test, the reference input voltage is held at 15 V. The results of this test are shown in Figure 4.4.

In Figure 4.4 it can be seen that step in output voltage affects the input voltage, but the controller quickly returns the input voltage to the reference. The reference voltage chosen, 15 V, places the converter in CCM for the entirety of the test. The controller performs better in CCM in the step test than in DCM, and this is true in the disturbance test too.

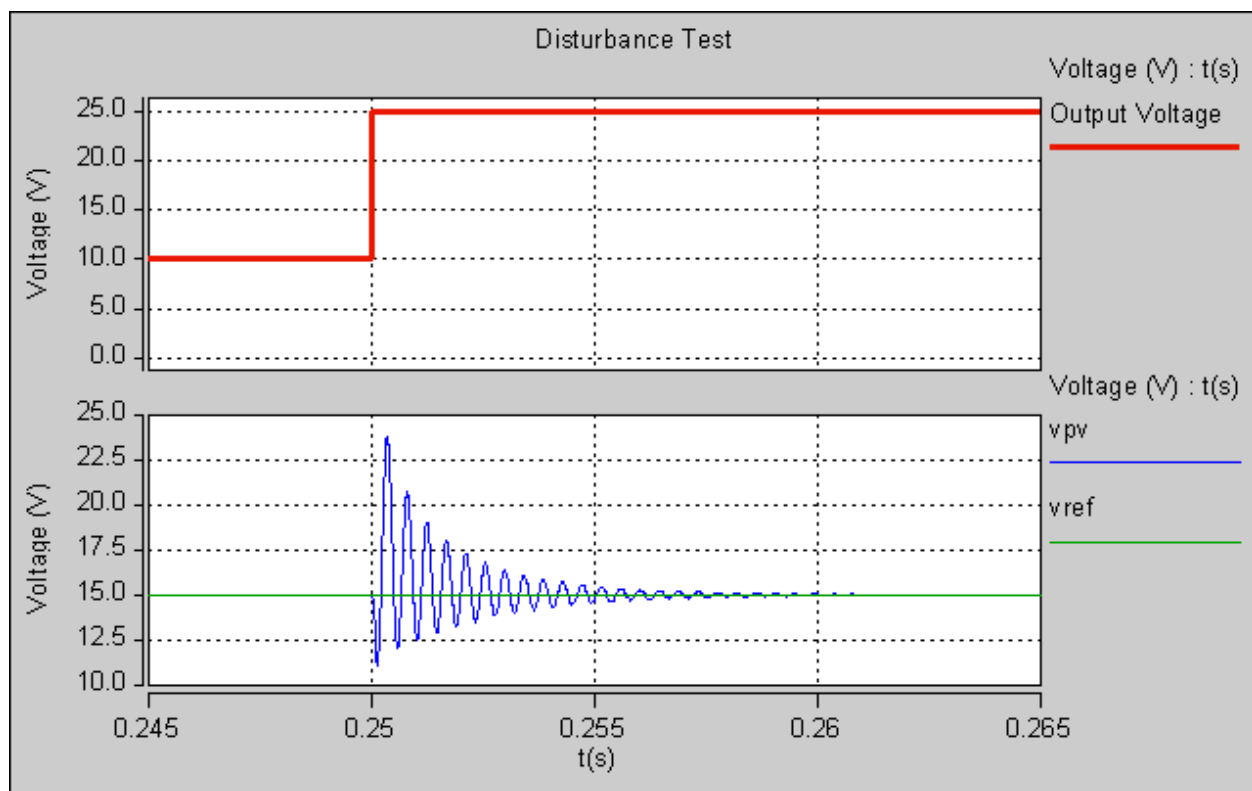


Figure 4.4 Disturbance Test in CCM Input Voltage Response

Next, the same test is conducted, but the reference voltage is set to 36.5 volts—a volt away from the model’s open-circuit voltage. When the output voltage disturbance occurs, the converter is forced into DCM and recovers slowly until the converter enters CCM, where it then recovers much faster. This test is shown in Figure 4.5. In addition to showing the voltage response, the current response is shown as well. In Figure 4.5, the current response in an opposite manner to the voltage. This is due to the fact that in a PV module the voltage is a function of current, so if the voltage experiences a spike the current will too. This is true in the other step tests shown in Figures 4.2-4.4.

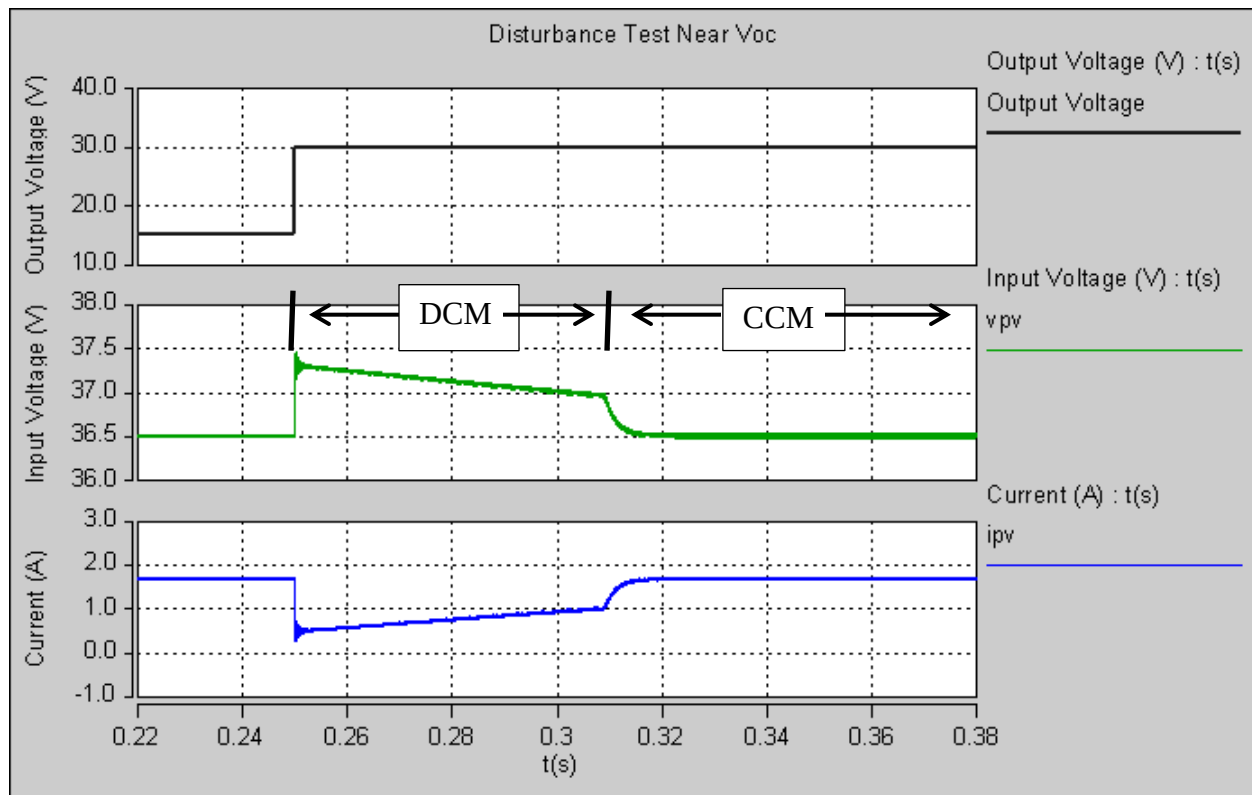


Figure 4.5: Disturbance Test in DCM Input Voltage and Current Response

4.3 I-V Trace With Simulated SEPIC

The controller is unable to quickly bring the voltage back to its reference as it did in Figure 4.4 due to the converter's DCM operation. Near $t = 0.31$ s the converter leaves DCM and quickly converges to the correct input voltage. This provides further motivation to ensure the I-V trace holds on the open-circuit voltage long enough to guarantee a valid measurement can be taken, as the converter will always enter DCM near V_{OC} . From this knowledge, a reference voltage waveform is constructed. The reference waveform is shown in Figure 4.6.

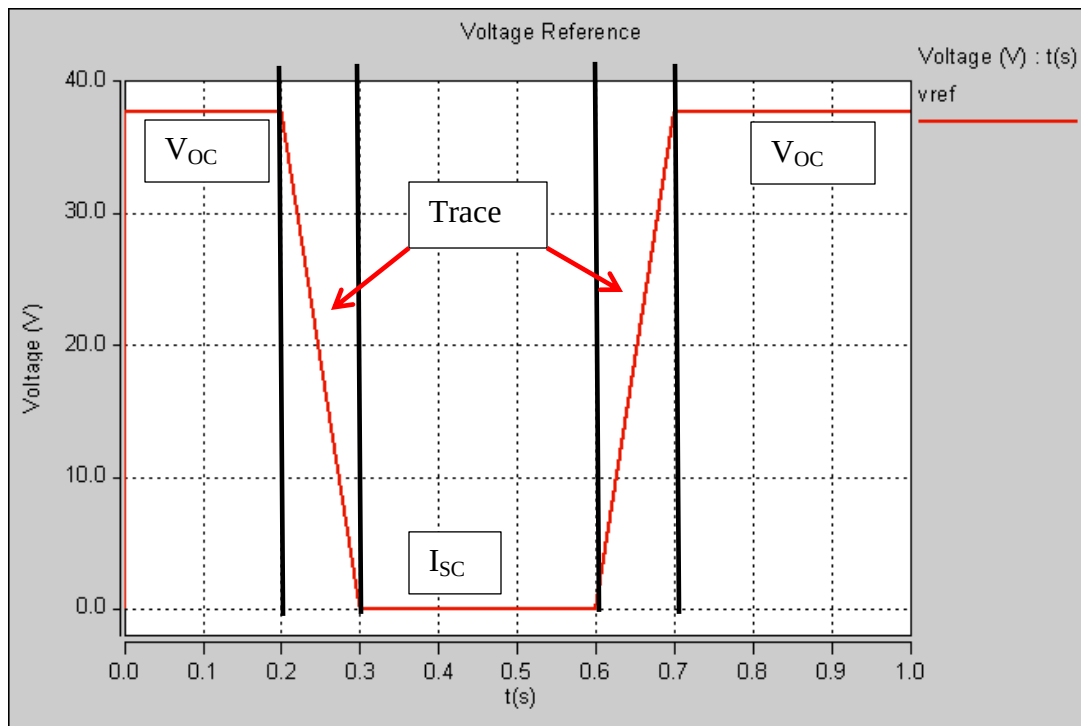


Figure 4.6 Voltage Reference Waveform

The I-V trace lasts 1 second and covers the I-V curve twice, holding at the open-circuit voltage and short-circuit current to ensure both values are reached. Recall from Chapter 1 that the Online

Autonomous I-V Tracer will not be connected to the panel at all times. The I-V tracer will be switched in to measure the curve, and then switched out to reconnect the PV module to the inverter. The reference starts at V_{OC} because this is the operating point of the PV module when the converter is switched in. The converter then traces the curve by moving the reference voltage from V_{OC} to I_{SC} , where it holds at I_{SC} for 300 ms to ensure a true I_{SC} is reached. The converter then traces the curve towards V_{OC} again and ends on V_{OC} so that the switching device can switch the PV module back into the inverter at zero current.

The results of the simulated I-V trace are shown in Figure 4.7.

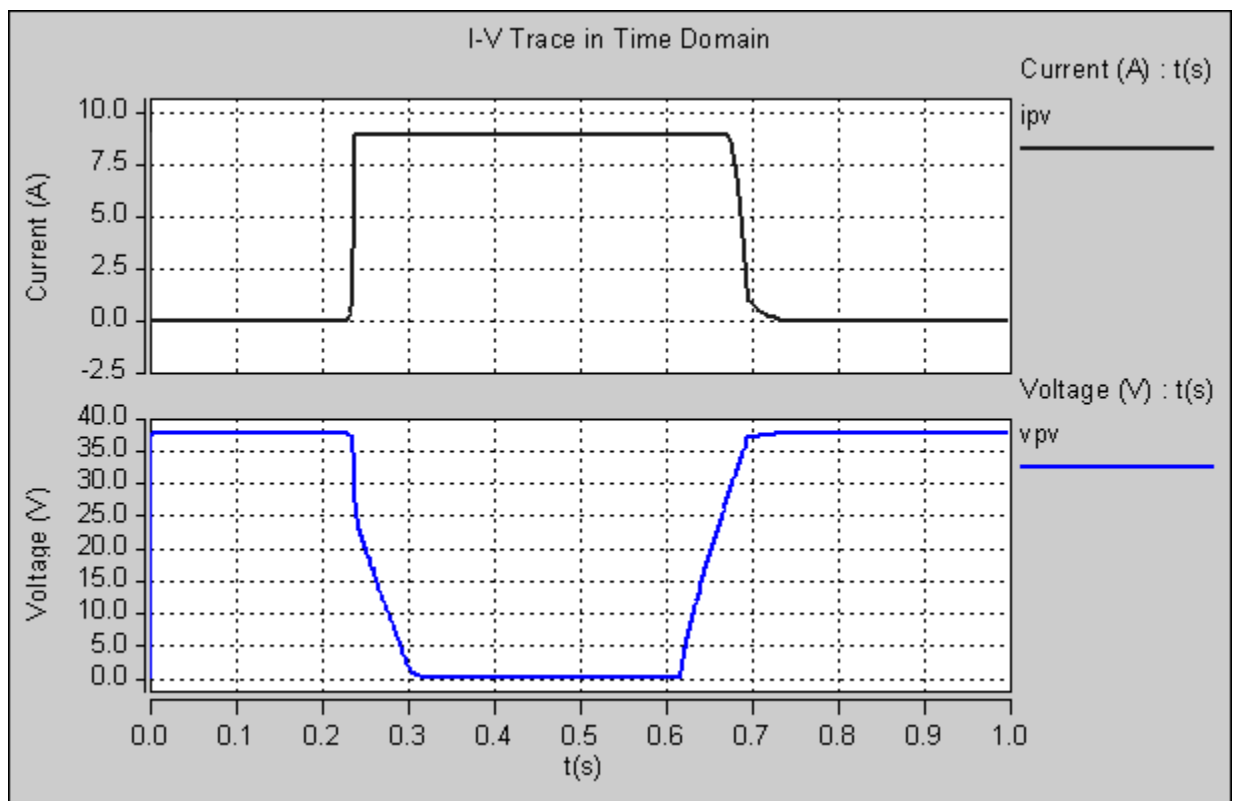


Figure 4.7: Time Domain Simulated I-V Trace

In Figure 4.7 it is seen that the converter has difficulty moving from V_{OC} in DCM to CCM operation. From Figure 4.6 the voltage reference begins to decrease from V_{OC} at 0.2 seconds. However, as shown in Figure 4.7, the converter does not begin to move from V_{OC} until about 30 ms later. This may affect the required bandwidth for the sensing device used to measure the I-V curve. However, the converter has an easier time approaching V_{OC} than it does moving away from V_{OC} , so the I-V characteristics near V_{OC} can be obtained on the second trace. This is evident by the behavior of the voltage waveform near 0.7 seconds.

The current-voltage characteristics shown in the time domain in Figure 4.7 are shown in Figure 4.8 with current on the Y axis and voltage on the X axis. This is the convention for viewing the I-V characteristics as discussed in Chapter 1.

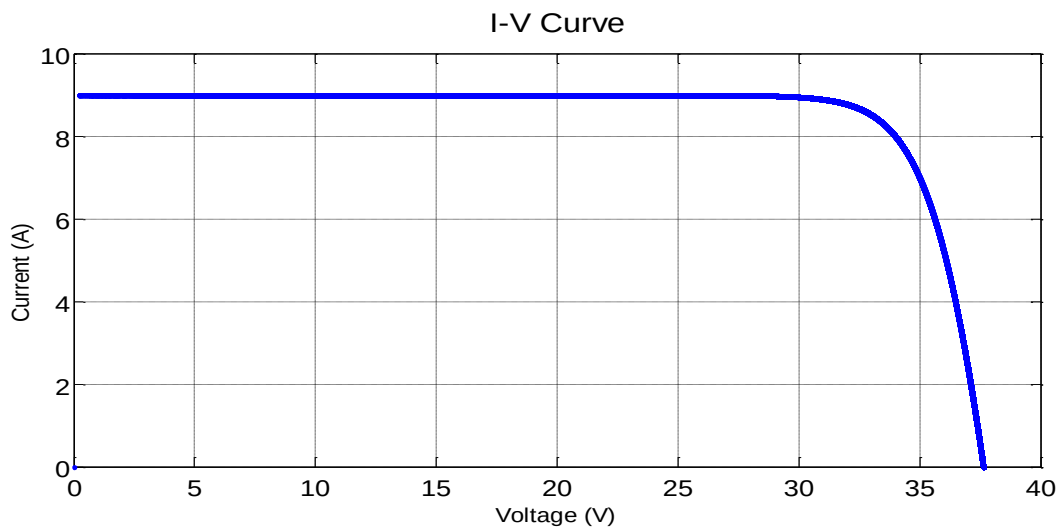


Figure 4.8: I-V Curve

The power can be calculated at each current-voltage pair revealing the maximum power point.

For the simulated module under STC, the MPP is 252 W.

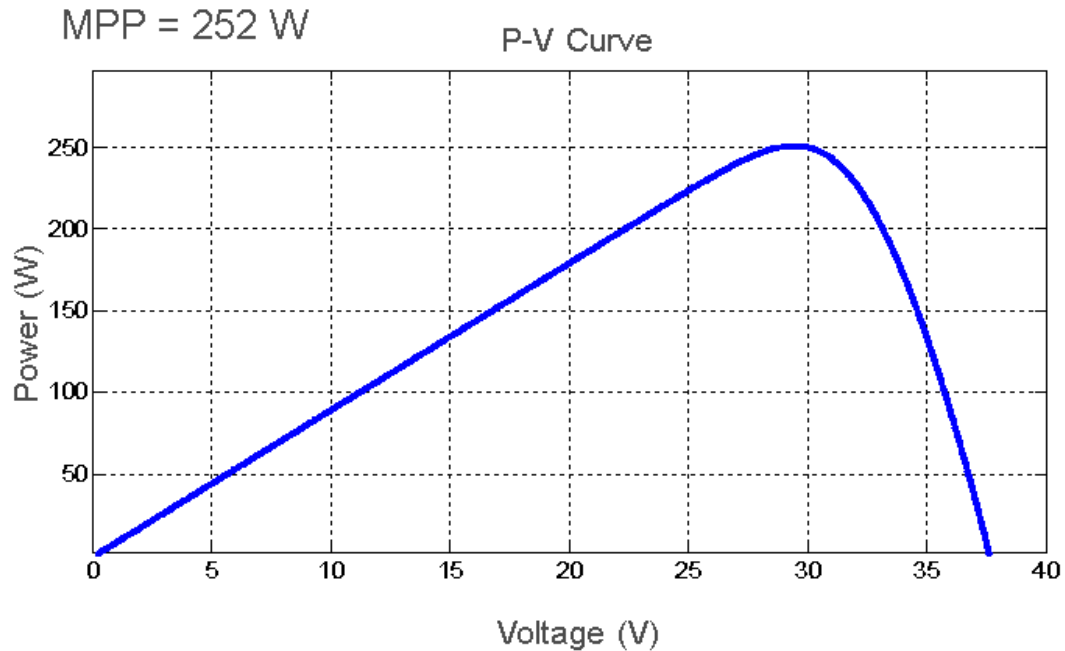


Figure 4.9: P-V Curve

The P-V curve is also shown in Figure 4.9, revealing the MPP to occur around 30 V.

The SABER model of the PV Module used in the simulation has the following characteristics:

- V_{OC} : 37.5 V
- I_{SC} : 9 A
- R_{SH} : 5 k Ω
- R_S : 100 m Ω

Working backwards from the I-V curve seen in Figure 4.8, it is possible to use the analysis techniques in chapter 1 to calculate these parameters. These calculated parameters can then be compared to the known values to validate the analysis of the I-V curve. Recall from Chapter 1 checking V_{OC} and I_{SC} is easy to do with the I-V curve, as V_{OC} is the point where the current is zero, and I_{SC} is the point where the voltage is zero. An approximation of the shunt resistance can

be found by checking the slope near I_{SC} , and an approximation of the series resistance can be found by checking the slope near V_{OC} .

The measured characteristics are:

- Measured V_{OC} : 37.6 V | 99.6% accurate
- Measured I_{SC} : 9 A | 100% accurate
- Measured R_{SH} : 5.01 k Ω | 99.8% accurate
- Measured R_S : 250 m Ω | 40% accurate

All values are very close to known values except the series resistance. The series resistance value is polluted due to the resistances of other components in the converter (inductor, switch). It is not recommended to use the slope of the curve as a precise tool to model the resistances seen in the single diode model of a PV cell. However, this does not mean the slopes are useless for analysis. These slopes are still indicative of the series resistance and shunt resistance, but are more useful as historical data. This means the slopes may not be accurate to determine actual parameters of the cell, but can be compared to previous slopes taken at earlier dates to determine rates of degradation. I_{SC} and V_{OC} should be the same as the nameplate ratings – assuming the curve was taken at STC.

4.4 Notch Analysis Validation

Beyond the parameters discussed above, the I-V curve is also very useful for identifying bypass diode activity. Recall from chapter 1 that bypass diode activity is identifiable from notches in the I-V curve. To test the SEPIC I-V tracer's ability to show notches, a 60 cell module is simulated with 1 cell shaded. In the test, 1 cell receives 10% sunlight, or 100 W/m², while the rest receive full sunlight at 1000 W/m². The module has 3 bypass diodes, which is the same as

the module in [2]. This means 20 cells will be bypassed if 1 is mismatched. Figure 4.10 illustrates the topology of the simulated module.

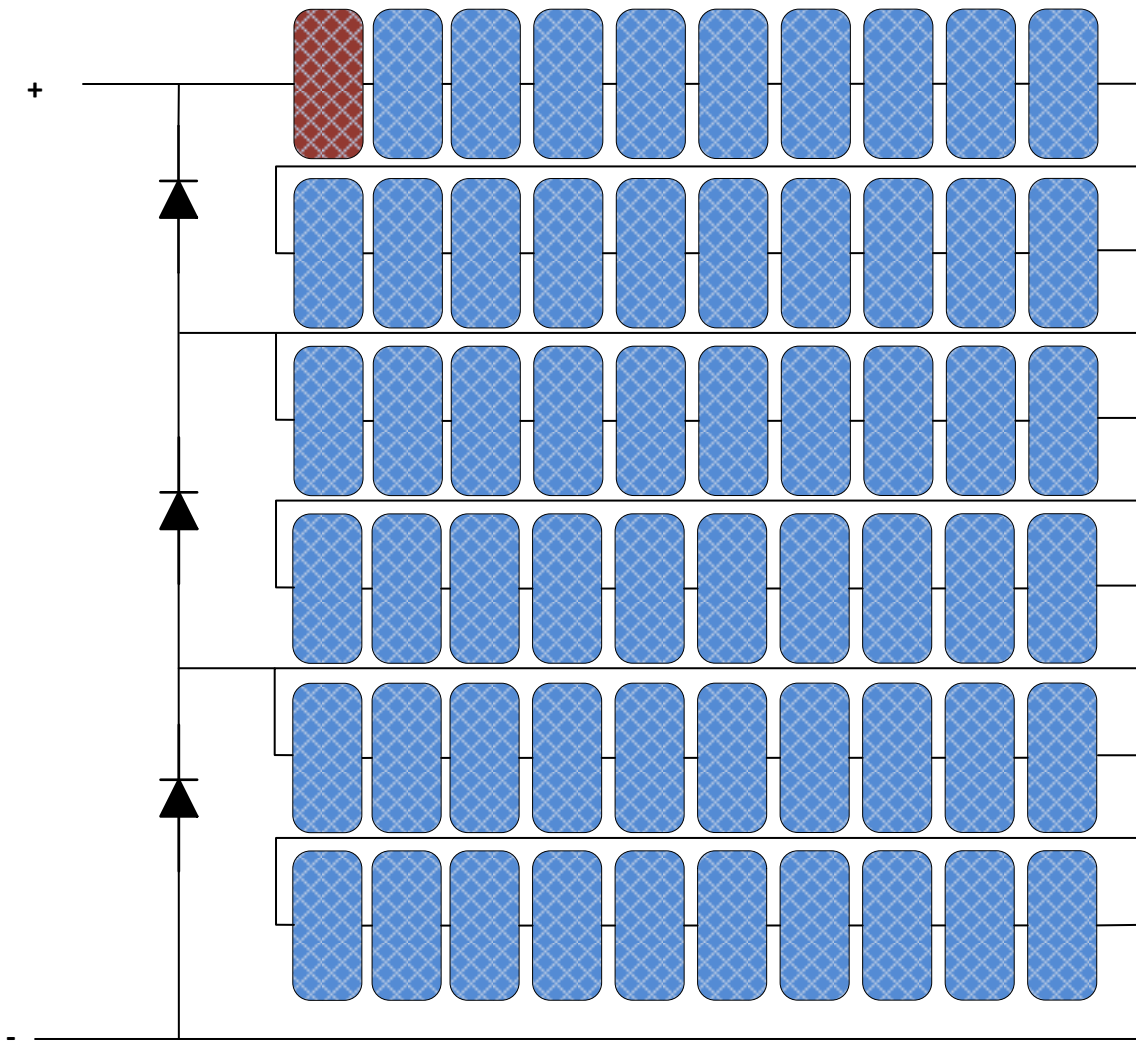


Figure 4.10: Topology of Simulated Module with 3 Bypass Diodes

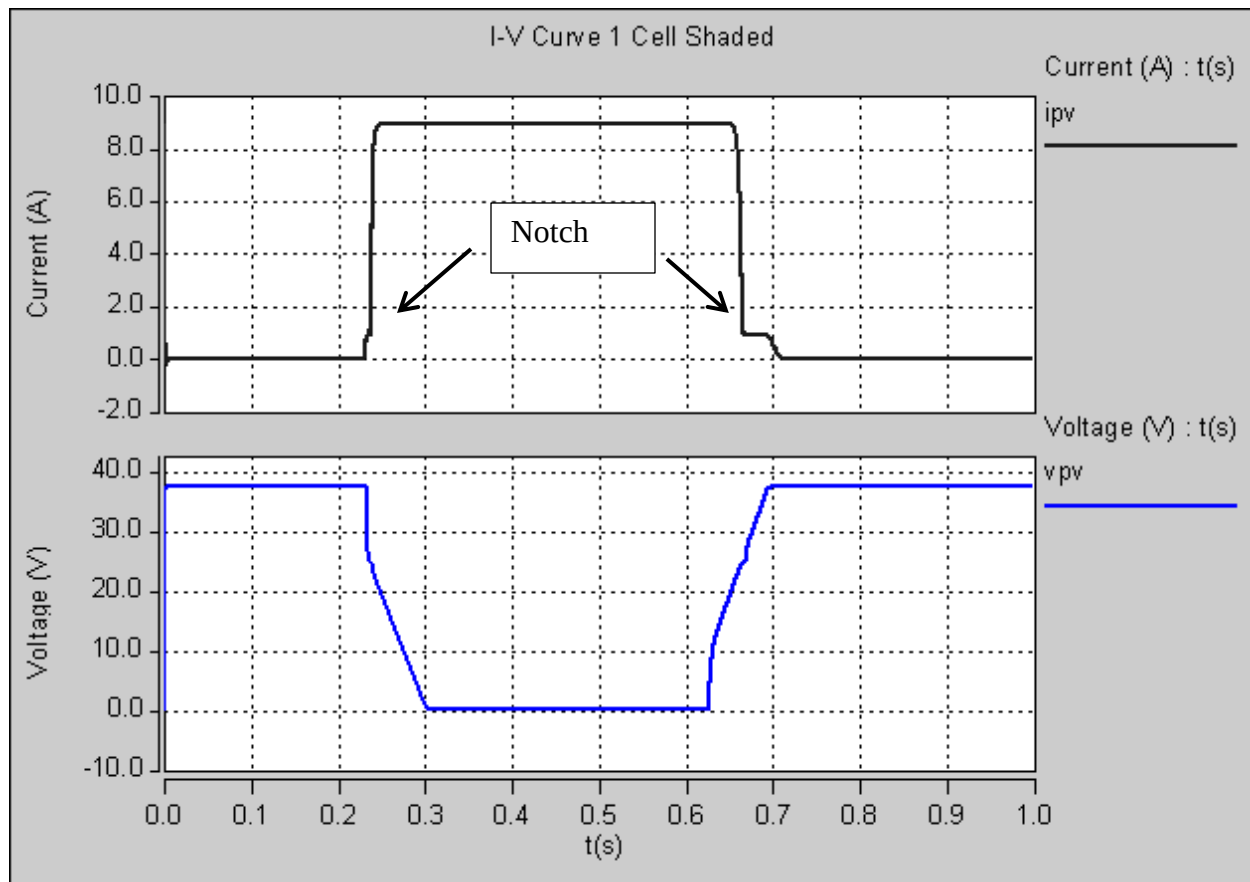


Figure 4.11: Time Domain Plot of I-V Curve with 1 Cell Shaded

Figure 4.11 shows the simulation results of the module shown in Figure 4.10. In Figure 4.11 it is clear that there is something different about the current-voltage characteristics compared to Figure 4.7. However, it is difficult to understand the affect shading has on the I-V curve in this form. The data seen in Figure 4.11 should be represented in the conventional method for viewing I-V curves, with voltage and current plotted against each other. The notch, which is more obvious in the I-V plane, occurs near $t = 0.25$ s and $t = 0.65$ s.

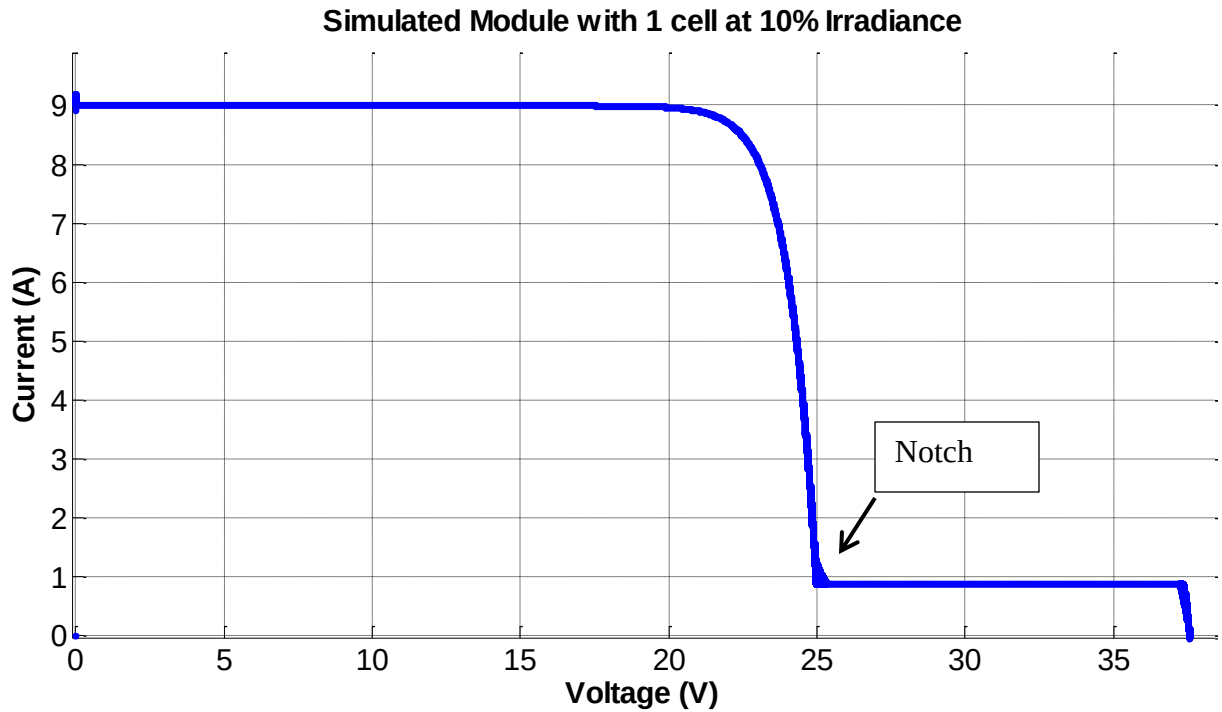


Figure 4.12: Data from Figure 4.11 Represented as I-V curve

Figure 4.12 shows the data in the I-V plane, revealing the notch. Figure 4.13 shows the data in the P-V plane, revealing the MPP.

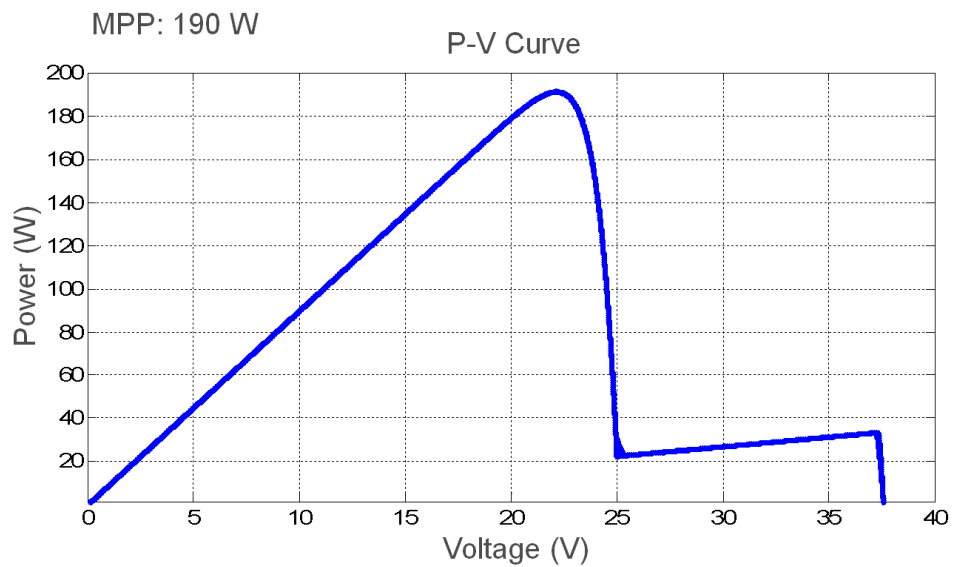


Figure 4.13: P-V Curve from Figure 4.12

In Figure 4.12 the effect of the partial shading is clearer than in Figure 4.11. The notch effect is seen plainly, resulting in two ‘knees’ of the I-V curve. One knee is located near 25 V, and the other near the true open-circuit voltage near 38 V.

Using this simulation, the analysis techniques proposed in 3.4 can be validated. First, using (3.22) the number of cells affected by the mismatch can be calculated. This is seen in (4.1).

$$\frac{V_{OC2}-V_{OC1}}{V_{OC_cell}} = \frac{37.5-25}{0.625} = 20 \quad (4.1)$$

From (4.1) the number of cells affected is 20. This is consistent with the understanding of the simulated module, as there is one bypass diode for every 20 cells (see Figure 4.10). Due to the bypass diode activity, it is not possible to discern how many cells of the 20 are affected. One cell and 20 uniformly shaded cells appear the same when analyzing I-V curves.

Next, the expression in (3.23) to determine the amount the affected cells were shaded/mismatched is validated. This is seen in (4.2).

$$\% \text{ Affected} = \frac{I_{SC2}}{I_{SC1}} \times 100 = \frac{0.9}{9} \times 100 = 10\% \quad (4.2)$$

Equation (4.2) reveals that the affected cells were shaded 10% relative to the unshaded cells. This is consistent with the simulation parameters, as one cell received 100 W/m² irradiance while the rest received 1000 W/m².

Next, a test is performed on the same module in Figure 4.10 with two mismatches. The first mismatch occurs with one cell receiving 10% irradiance. In a different bypass diode circuit, a different cell receives 50% irradiance, creating the second mismatch.

This is illustrated in Figure 4.14. The dark red cell is the cell receiving 10% irradiance, and the light red cell is receiving 50%.

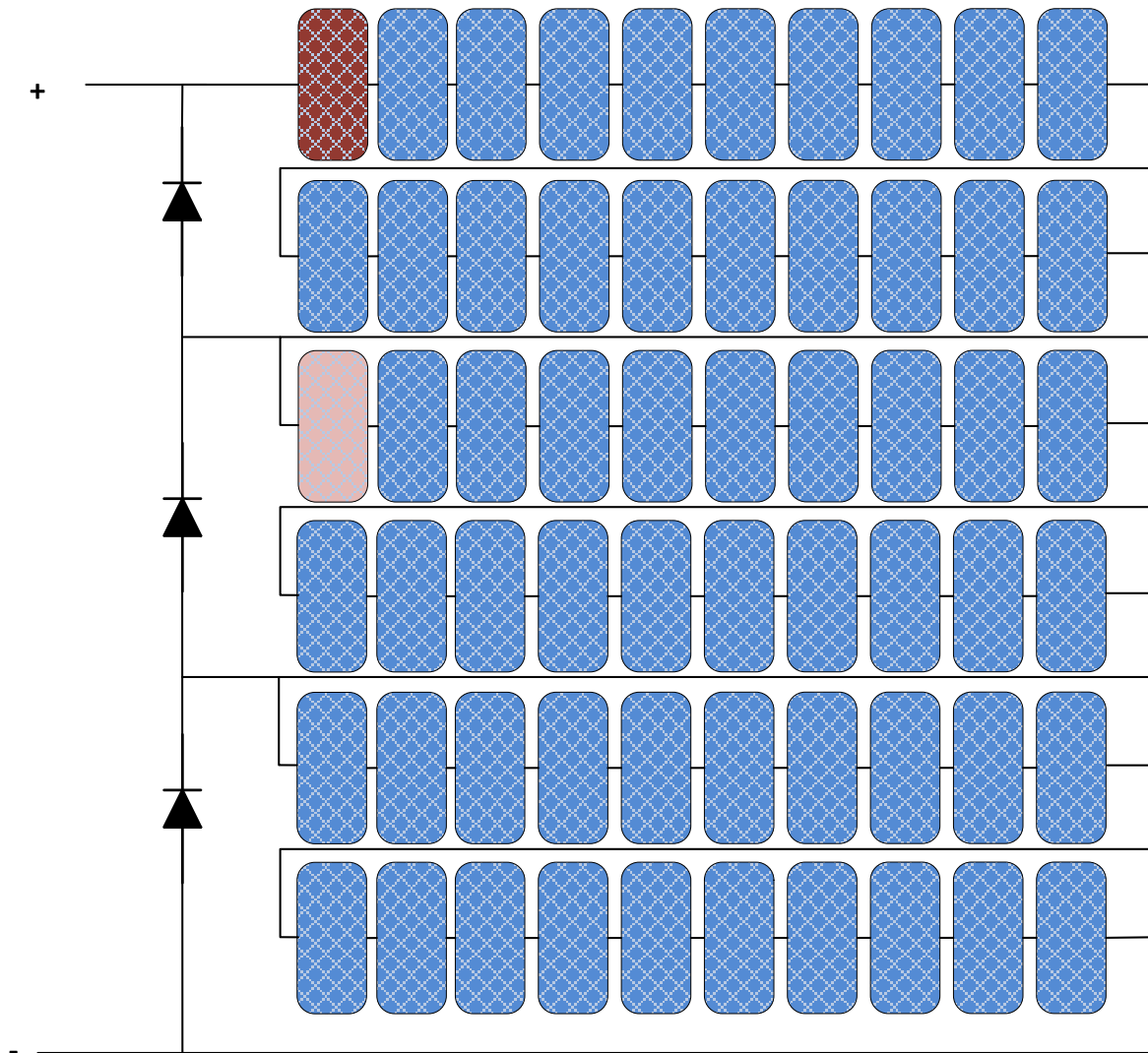


Figure 4.14: PV Module with 2 Mismatches

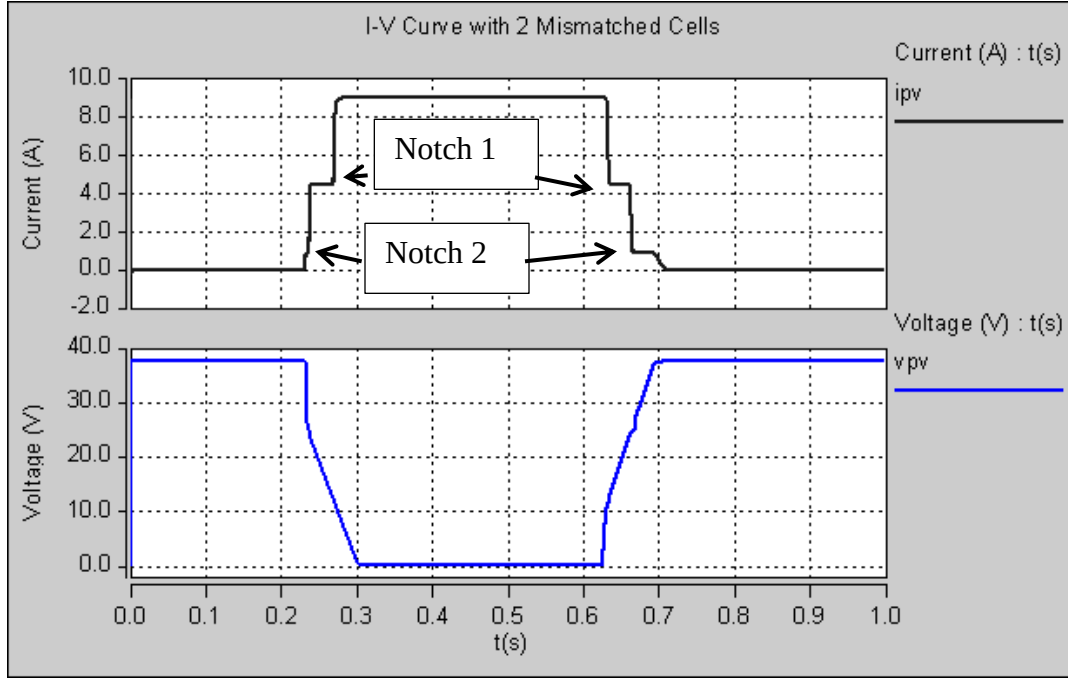


Figure 4.15: Time Domain I-V Curve with 2 Mismatches

Figure 4.15 shows the time-domain results of the test on the topology in Figure 4.14. In Figure 4.16 the data from Figure 4.15 is plotted in the I-V plane to more clearly show the notch characteristics. It is clear in the I-V plane that there are two bypass diodes activating, creating two notches at $\frac{V_{OC}}{3}$ and $\frac{2V_{OC}}{3}$. The same analysis technique used in (4.1) and (4.2) can be used on each notch to further validate the analysis technique. First, the number of cells bypassed due to each notch is calculated.

$$Notch1 \text{ Cells Bypassed} = \frac{V_{OC2} - V_{OC1}}{V_{OC_cell}} = \frac{25 - 12.5}{0.625} = 20 \quad (4.3)$$

$$Notch2 \text{ Cells Bypassed} = \frac{V_{OC3} - V_{OC2}}{V_{OC_cell}} = \frac{37.5 - 25}{0.625} = 20 \quad (4.4)$$

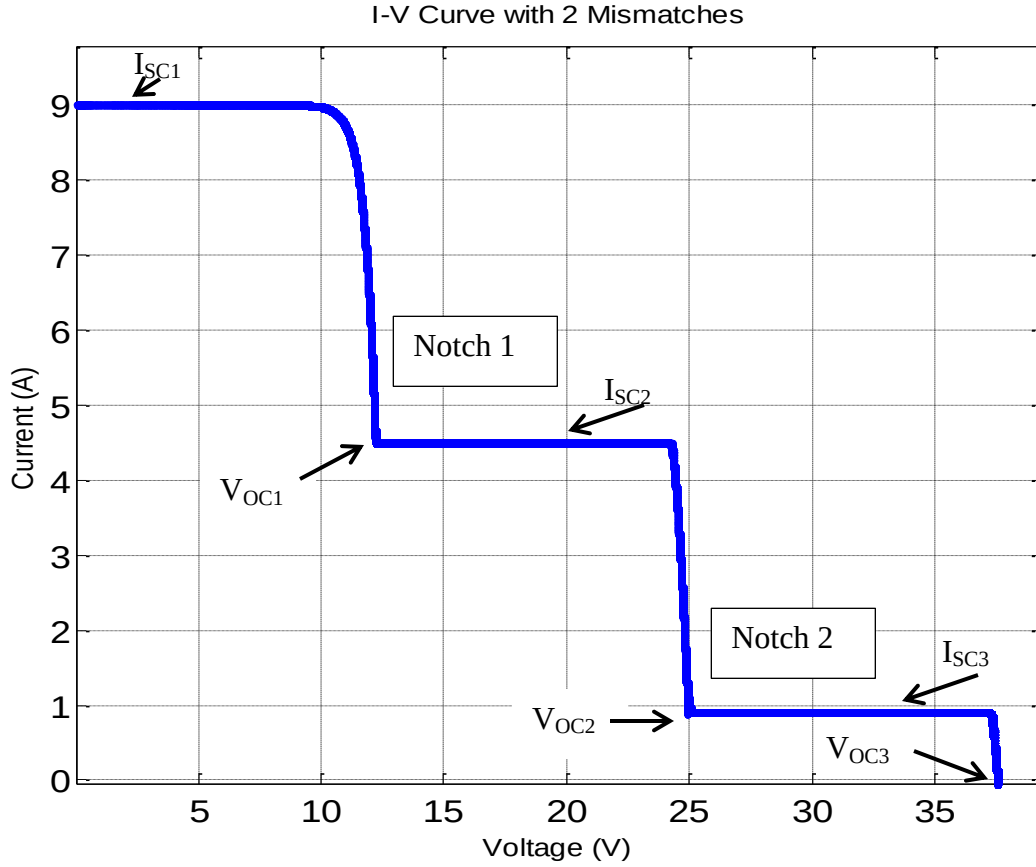


Figure 4.16: Time Domain I-V Curve with 2 Mismatches

Figure 4.16 shows the data from Figure 4.15 in the I-V plane with labels for the notch analysis variables. Next, the amount of mismatch is calculated.

$$\text{Notch 1 \% Affected} = \frac{I_{SC2}}{I_{SC1}} \times 100 = \frac{4.5}{9} \times 100 = 50\% \quad (4.5)$$

$$\text{Notch 2 \% Affected} = \frac{I_{SC3}}{I_{SC1}} \times 100 = \frac{0.9}{9} \times 100 = 10\% \quad (4.6)$$

According to (4.3)-(4.6), the first notch causes 20 cells to be bypassed due to 50% performance. Additionally, the second notch also causes 20 cells to be bypassed due to 10% performance. This

is consistent with the topology seen in 4.14 as well as the known irradiances used in the simulation. The P-V curve for this test is shown in Figure 4.17

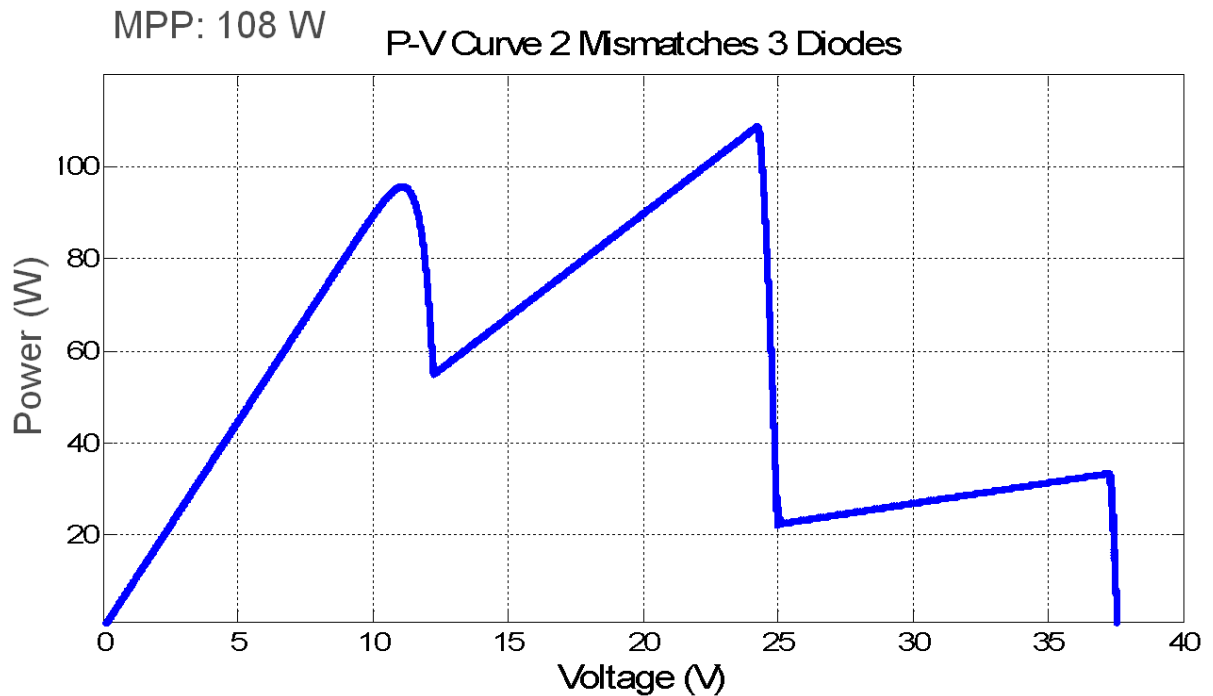


Figure 4.17: P-V Curve from Test in Figure 4.16

The P-V curve has 3 local maximums. This could be a potential problem in inverters which use the perturb and observe (P&O) MPPT method. In the P&O method, the input voltage is perturbed and the power is calculated. If the power is less than it was before the perturbation, the converter assumes the previous point is the maximum power point. This only works for local maximums, and may miss the overall maximum.

If there is only one bypass diode, the cell performing at 10% would limit the entire module to its short-circuit current. The test from Figure 4.16 is repeated with only one bypass diode, and the results are shown in Figure 4.18. These are the same results as if there was no bypass diode.

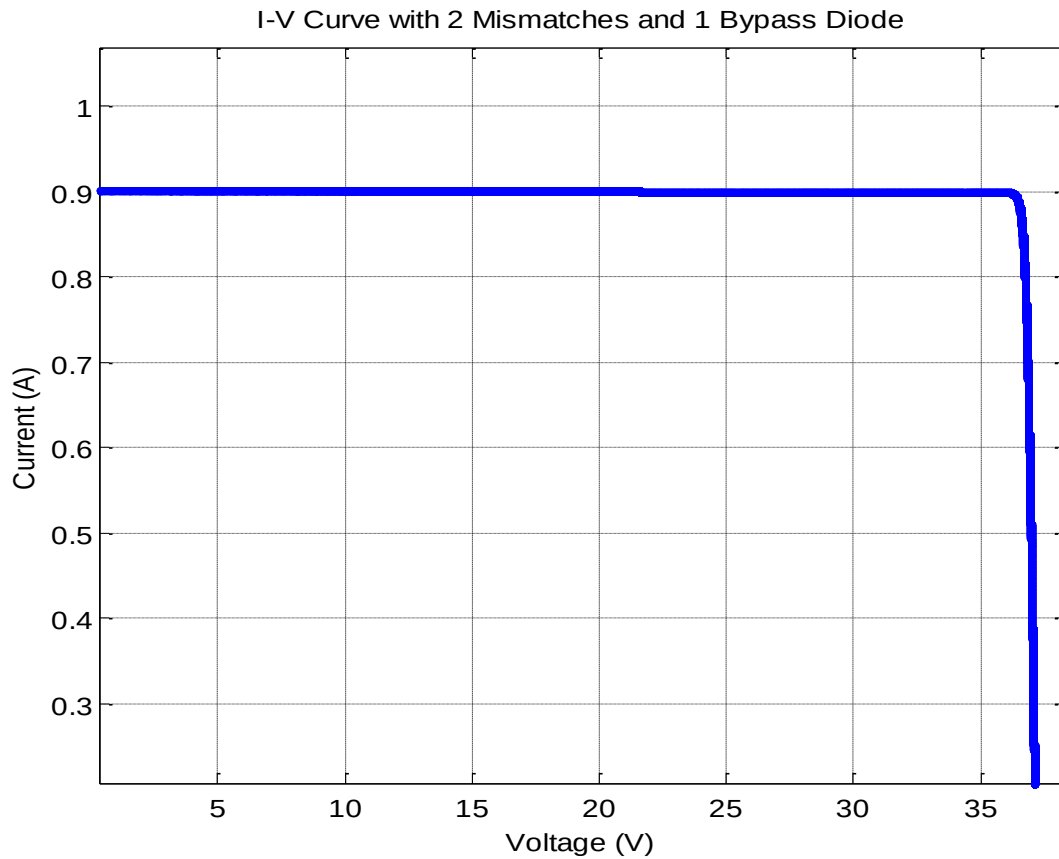


Figure 4.18: I-V Curve with 2 Cells Mismatched and Only 1 Bypass Diode

From Figure 4.18 it is clear that having only 1 bypass diode causes the I-V curve to be limited by the single worst cell.

Increasing the number of bypass diodes shortens the voltage difference between the notches. In Figure 4.19, the same test is carried out as Figure 4.16, except the module topology is changed to have 6 bypass diodes instead of 3 or 1.

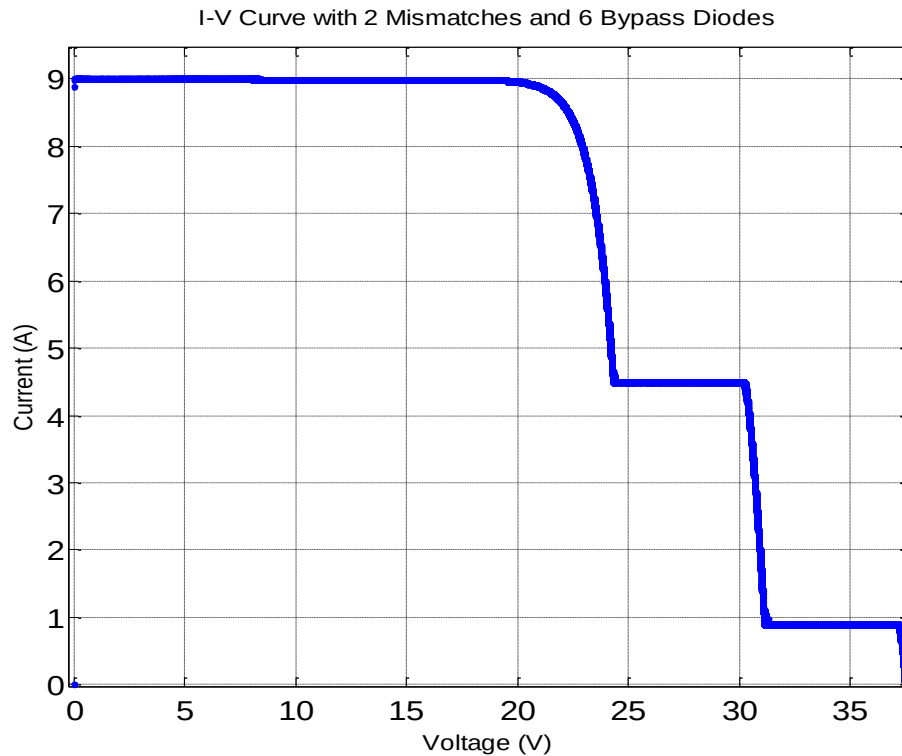


Figure 4.19: I-V Curve with 2 Mismatches and 6 Bypass Diodes

In Figure 4.19, the difference in voltage between notches is half the size as is seen in Figure 4.16. This is due to the module having twice the number of bypass diodes. The first knee of the curve is also extended farther along the voltage axis. This results in the MPP rising from the 3 diode case.

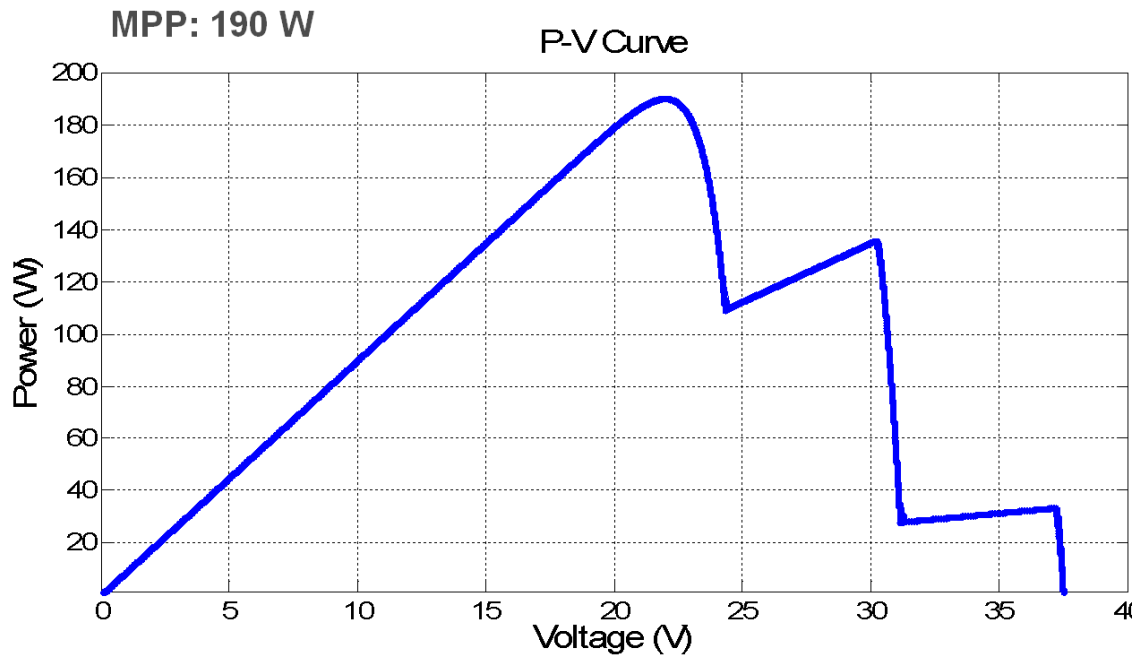


Figure 4.20: P-V Curve with 2 Mismatches and 6 Bypass Diodes

Figure 4.20 shows the P-V curve, and the MPP rises to 190 W from 108 W by doubling the number of bypass diodes.

If the number of bypass diodes is doubled again to 12, then the distance between notches closes even further. The test is repeated with 12 bypass diodes instead of 6. Most modules have between 3 and 8 bypass diodes, depending on the number of cells, so it is unlikely that a module would exist with 12 bypass diodes.

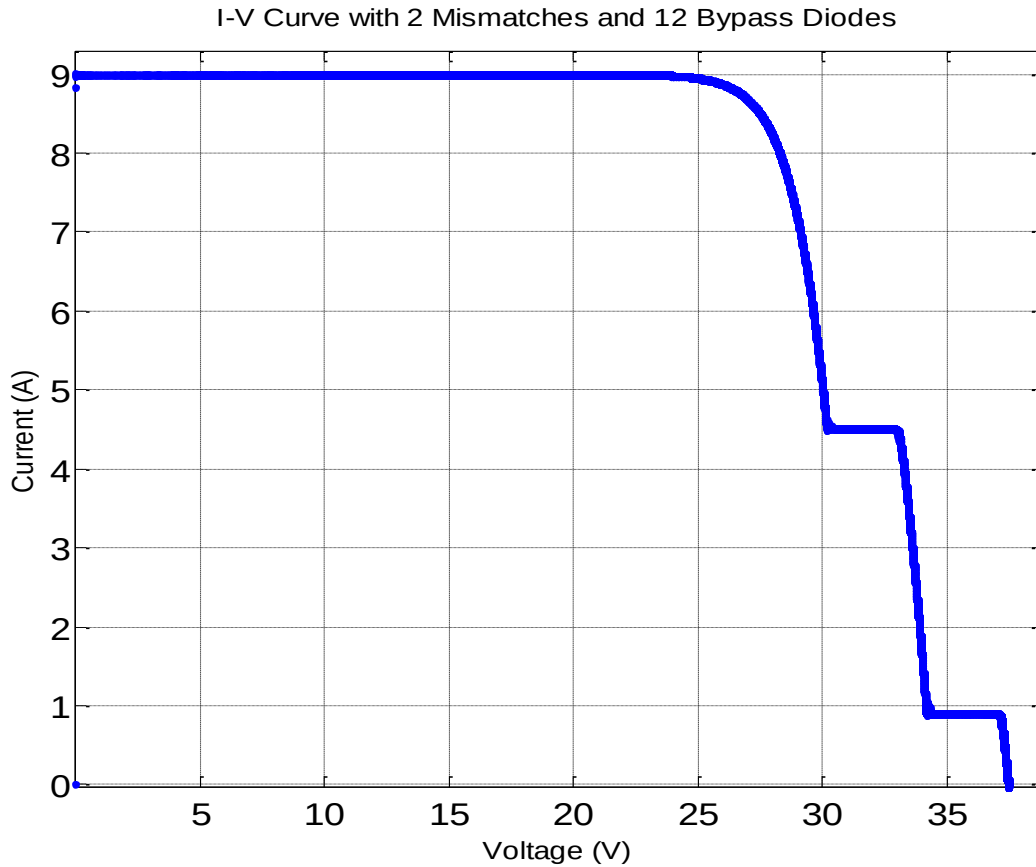


Figure 4.21: I-V Curve with 2 Mismatches and 12 Bypass Diodes

These test results show the proposed SEPIC's ability to trace the I-V curve of a module, and its use in detecting bypass diode activity. With the I-V curve, the amount a mismatched string is underperforming can be calculated, and the number of cells affected can also be found. However, there is a drawback to notch analysis. A single cell underperforming and an entire string of cells with the same bypass diode underperforming will appear the same on the I-V curve. The test performed in Figure 4.21 had two cells underperforming from different strings. One cell performed at 10%, and the other at 50%, while the rest of the module performed at 100%. The topology from the test in Figure 4.21 had 12 bypass diodes for 60 cells, which means there is one bypass diode for every 5 cells. Figure 4.23 shows the same test, but all 5 cells from one string are

performing at 50%, and all 5 cells from a different string are performing at 10%. Figure 4.22 (a) shows the topology of the test in Figure 4.21 and Figure 4.22 (b) shows the topology of the test to be shown in Figure 2.23 (a).

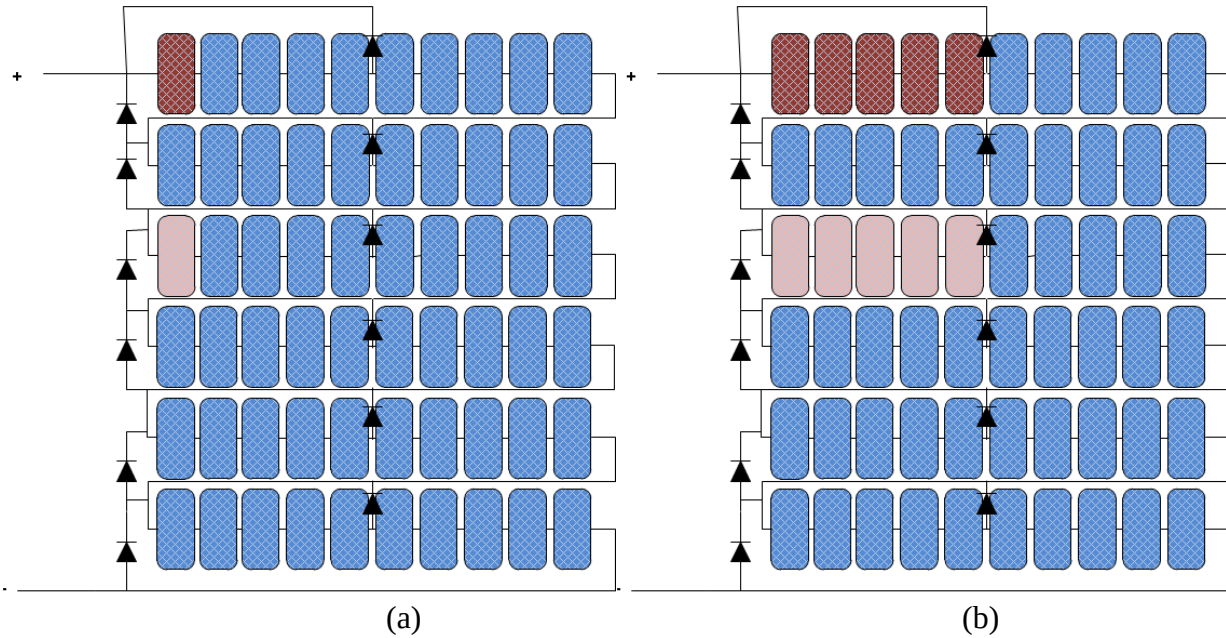
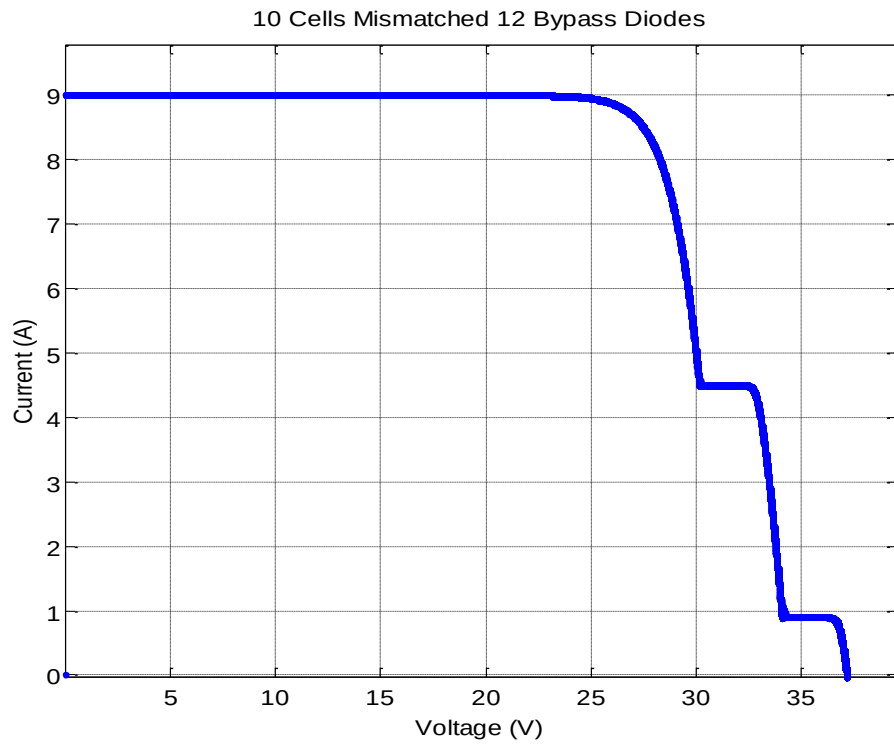


Figure 4.21: Module with 2 cells mismatched (a) Module with 10 cells in a string mismatched (b)

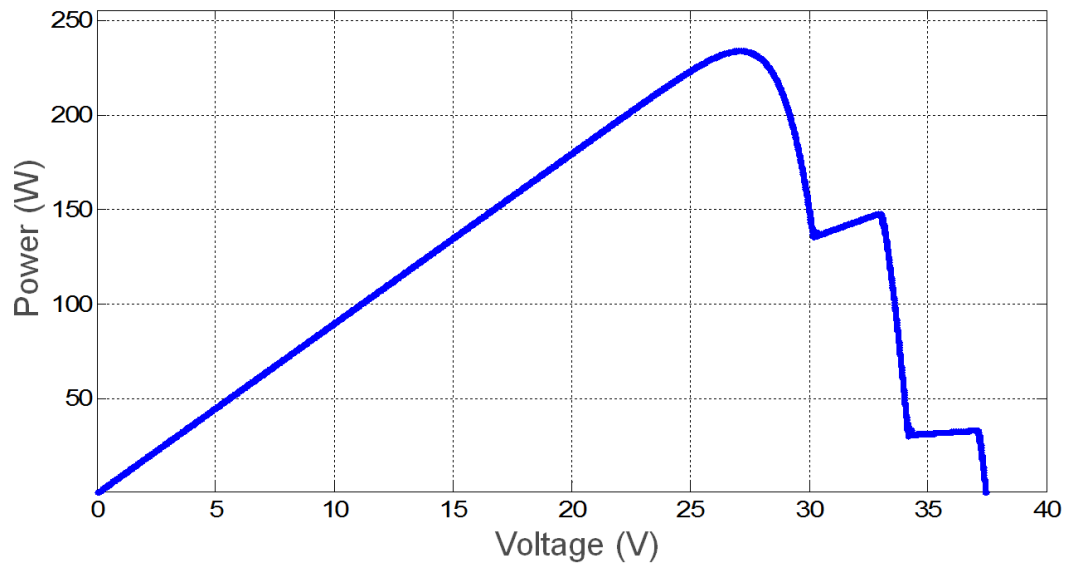
Comparing Figure 2.23 (a) to Figure 2.21, it is clear that the I-V curve appears the same in both plots. This proves that mismatches below the bypass diode string level cannot be detected with I-V traces. The P-V curve is shown in Figure 4.23 (b). It reveals that doubling the number of diodes from 6 to 12 increases the MPP from 190 W to 234 W. Notch analysis, paired with the knowledge of how many bypass diodes a module has, can be used to calculate the number of cells bypassed, how many bypass diodes are activating, and how badly mismatched strings within the module are. It is a powerful analysis tool only available from the I-V curve.



(a)

MPP: 234 W

P-V Curve



(b)

Figure 4.23: 12 Diode Case I-V Curve (a) 12 Diode Case P-V Curve (b)

4.6 Chapter Summary

In this chapter, the SEPIC as an I-V tracer simulation results were presented. The control loop was described, and simulations showing the control loop's ability to reject disturbances and move to a new operating point in both CCM and DCM were shown. Next, a full I-V trace was simulated with the SEPIC, and its results in the time domain and the I-V domain presented. More results from simulations of the proposed converter were shown to illustrate the depth of information I-V curves can provide. The mismatch analysis techniques proposed in 3.4 are validated using simulation results of a mismatched module and analysis of simulation results in the I-V domain. Finally, more results from simulations of the proposed converter were shown to illustrate the depth of information I-V curves can provide.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

As PV generation continues to grow in the US and abroad, more robust and informative monitoring equipment is necessary. I-V curves offer the most information about a PV module, but current I-V tracers require a trained technician to operate and measure the curve. An autonomously operating I-V tracer would be the best option to fully monitor a PV module. By using a SEPIC DC/DC converter topology, an I-V tracer with continuous input current which operates in-line with the inverter can be built. The SEPIC must operate in DCM near V_{OC} , which makes control difficult. However, a reference voltage waveform which allows the converter extra time to reach its operating point in DCM solves this problem.

The SEPIC in DCM was modeled and compensator was designed with reasonable dynamic characteristics. It is understood that near V_{OC} the converter operates in DCM where the controller has a worse transient response. Thus a voltage reference waveform was constructed which allows the converter enough time to reach V_{OC} even in DCM. The converter has been simulated in SABER simulation tool, and its ability to take the I-V curve has been shown.

Additionally, several tests were conducted to validate the notch analysis proposed in chapter 3. During these tests, the proposed SEPIC was used to trace the varying I-V curves. Tests were conducted with multiple mismatches under several different bypass diode cases. A drawback of notch analysis was shown, where mismatches within a single bypass diode string cannot be found.

5.2 Recommendations

While simulation is useful for design and experimentation, to be completed a SEPIC with the component values and control scheme seen in this thesis should be built and tested to confirm the results shown here. The converter shown in this thesis was built to be able to trace a single module. This is useful, but the next step must be to design and build a converter which operates at a string-of-modules level. This converter would have a similar current rating and a voltage rating above 600 VDC. It is at this level that the I-V tracer would be most useful in a PV generation plant.

Additional research on the operation of the input-voltage controlled SEPIC operating in DCM to obtain a better control compensator would be valuable for this project as well. Currently the controller works in DCM, but is too slow. The step response of the converter in DCM converges in about 100 ms, while the CCM case converges in 5 ms. A DCM controller for the SEPIC that can converge in 10 ms with no overshoot would improve the converter.

It is also worth noting it may be possible to adjust the DC boost converter which is commonly the first stage of a PV inverter, or the inverter itself to measure the I-V curve. The SEPIC presented in this thesis is intended as a retrofit for existing systems, but an inverter with the I-V tracer functionality internally would be a cheaper and more robust option, as there would be no need for a bypass relay.

Additionally, it may be helpful to use the I-V tracer to find the true MPP of an array and communicate this to the inverter. This would avoid the inverter becoming stuck on a local maximum as seen in Figure 4.17. This would be easiest to communicate if the I-V tracer were

part of the front-end of an inverter, but may be possible with the retrofitted I-V tracer discussed in this thesis.

Lastly, an algorithm for detecting I-V curves should be developed. Such an algorithm would scan the I-V curve for anomalies, and report if any of the curves indicated a problem. This would remove the need to view each I-V curve to inspect them individually for mismatches or degradation.

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APPENDIX

Code A.1: Matlab Code for Inductor Design

```
% Inductor Design for I-V tracer

%From Chapter 8 McLyman

%% Step 1
L = 80E-6;
Idc = 8.1; %taken from simulation
Iac = 2.52 ; %Peak-Peak worst case ripple
f = 100E3; %switching frequency
%% Step 2
Ipk = Idc + Iac/2;

%% Step 3
Energy = (L*Ipk^2)/2

%% Step 4
Bm = 0.22; %initial guess from chapter 8 McLyman
Ku = 0.5; %initial guess window utilization factor
J = 248; %Current density, A/cm^2

ApCalc = ((2*Energy*10^4)/(Bm*Ku*J)) %in cm^4

%% Step 5
%choose RM-14 TDK (specs from McLyman
% Ap = 2.779; %in cm^4
% MPL = 6.9; %in cm
% CoreWeight = 70; %grams
% MLT = 7.2; %cm
% Ac = 1.88; %cm^2 Effective Area
% Wa = 1.561; %cm^2 Window Area
% Kg = 0.2755; %cm^5 equation 8-17 in McLyman
% At = 62.8; %cm^2 surface area
% P = 2500; %from McLyman for Ferrite
% Al = 2869; %mh/1k
% G = 2.11; %cm

%%choose PQ 35/35 FerroxCube

Ap = 2.8880; %in cm^4
MPL = 8.61; %in cm
CoreWeight = 73; %grams
MLT = 7.5; %cm
Ac = 1.90; %cm^2 Effective Area
Wa = 1.52; %cm^2 Window Area
Kg = Wa*(Ac^2)*Ku/MLT; %cm^5 equation 8-17 in McLyman
At = 60.7; %cm^2 surface area, taken from McLyman table for TDK PQ35/35
P = 2100; %from datasheet for 3C91
Al = 6000; %mh/1k
G = 1.44; %cm

%% Step 6
```

```

Irms = sqrt(Idc^2 + Iac^2) %RMS Current

%% Step 7
AwbCalc = Irms/J %bare wire area

%% Step 8
%Choose AWG 12 Awb = 0.03308

Awb = 0.03308; %uninsulated, cm^2
Resistance = 65.6; %micro-Ohm/cm
Aw = 0.03564; %insulated, cm^2

%% Step 9
WaEff = Wa * 0.75; %cm^2

%% Step 10
N = 1.76*0.6/Aw

%% Step 11
lg = (0.4*pi*(N^2)*Ac*(10^-8)/L)-MPL/P %air gap in cm

%% Step 12
%air gap in mils
lgMil = 0.120*lg

%% Step 13
F = 1 + (lg/sqrt(Ac))*log(2*G/lg) %Fringe Factor

%% Step 14
Nn = sqrt(lg*L/(0.4*pi*Ac*F*(10^-8))) %New Number of turns

%% Step 15
RL = MLT*Nn*Resistance*(10^-6) %Resistance

%% Step 16
Pcu = (Irms^2)*RL %Copper Losses

%% Step 17

%skip, what is Po?

%% Step 18
Bac = 0.4*pi*Nn*F*(Iac/2)*(10^-4)/(lg+MPL/P) %Ac flux density, Tesla

%% Step 19
%milliwatts/gram of magnetic material

%values below from chapter 2 McLyman

k = 4.316E-5;
m = 1.64;
n = 2.68;

```

```

mwg = k*(f^m)*(Bac^n);

%% Step 20
%Core Loss

Pfe = mwg*CoreWeight*(10^-3) %watts

%% Step 21
% Total Loss
Psum = Pfe + Pcu %watts

%% Step 22
Psi = Psum/At %Watt density W/cm^2

%% Step 23
Tr = 450*Psi^0.826 %Temperature rise in degrees C

%% Step 24
Bpk = 0.4*pi*Nn*F*(Idc+Iac/2)*(10^-4)/(lg+MPL/P)

%% Step 25
%effective permeability
ue = P/(1 + (lg/MPL)*P)

%% Step 26
Ku2 = Nn*Awb/Wa

```

VITA

Cameron Riley was born in Knoxville, Tennessee. He graduated from the University of Tennessee, Knoxville, in May 2012 Magna Cum Laude with a Bachelor's of Science degree in Electrical Engineering. Furthering his education, he attended graduate school at the University of Tennessee, Knoxville, where he graduated in December 2014 with a Master of Science Degree in Electrical Engineering with a concentration in Power Electronics. Throughout graduate school and most of undergraduate school, he worked at the Electric Power Research Institute, whose resources he used to complete the research for his thesis. He plans to pursue a career in a power engineering field with a hope to do more work in renewable technologies.