Solar Generation’s Impact on Fault Current

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Abstract

California is paving the road for other states with the capacity of solar installations for residential and commercial entities. The added capacity of solar generation to the state's electric grid has an impact on power flow and fault currents. This project looks at the impact of solar installations on fault currents. Feeders with added residential rooftop solar and larger commercial solar installations may impact the system differently than a large, utility-sized solar installation. This project looks at the impact of both cases on the magnitude of fault current during many different fault types and locations that can occur within a utility system.

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Chapter 1

Introduction

This project fulfills California Polytechnic State University's requirements for a Senior Project specific to obtain a bachelor's degree in Electrical Engineering. Renewable resources have exploded in technology and usability in the last 10 years. This project looks at solar generation's effect on the electric grid in terms of fault magnitude.

Distribution networks were designed and used in the past as a radial system [1]. Radial systems are simple and low cost and the cost of distributed generation was not economical. The falling prices and increased efficiency of distributed generation systems, specifically solar, combined with the increasing costs to produce and distribute power has made it more economical for utilities to make use of distributed generation [2]. The installation of distributed generation impacts the magnitude of the fault current of a circuit. A fault on a circuit causes massive amounts of power flow in a very short window of time which can have destructive affects [4]. Utilities must keep the magnitude of fault current down as much as possible. With distributed generation, more sources exist that contribute current to a fault [3].

This project looks at how distributed generation affects the magnitude of fault currents in two different situations. The first with solar generation in the form of rooftop and commercial solar installations spread throughout a feeder. In this case, 500 kVA of solar capacity was added and then the fault study conducted. Then, an additional 500 kVA, for a total of 1 MVA, was added to the same circuit and the study repeated. The second case is a 10 MVA solar system installed near the substation. In this case, two different scenarios were looked at. The first with 500 kVA inverters, and the second with 1 MVA inverters.

Milsoft Utility Solution’s WindMil software was used for this project because of my previous experience with it doing load-flow analysis and coordination studies. Turlock Irrigation District (TID) provided feeder models in WindMil with all of the required data. TID also provided information about solar inverters that had been installed on their system.

Chapter 2

Customer Needs, Requirements & Specifications

2.1 Customer Needs

This project was conducted for Turlock Irrigation District (TID). With the rise in solar installations throughout the electric grid, some impacts are not as well explored. TID was interested in knowing the effects of many solar installations throughout a feeder as well as the impacts a large solar system would have.

2.2 Requirements and Specifications

The electric grid is a complex interconnected system. Changes in the grid miles away, impacts the grid in multiple places. This is the driving thought determining the requirements and specifications. This project utilizes a computer model of a real-world feeder to look at various fault conditions. The requirements and specifications for this project narrow down the location of the simulated faults and the information gathered. Table 2.1 lists the full requirements and specifications.

Table 2.1: Requirements and Specifications

Marketing Requirements	**Engineering Specifications**	**Justification**
1	The model must utilize real-world circuits.	Using a real-world circuit ensures accuracy and remains unbiased.
1	Computer model must have the capability to calculate load flows, voltage drop, and fault current.	Computers are able to compute complex algorithms used in model.
2	The model must utilize existing inverter sizes and specifications.	Ensures accuracy.
3, 4, 5	Solar installations capacity must not	Increased generation in a circuit leads

<table>
<tr><td></td><td>produce a fault current above the rated safety values of feeder electrical equipment.</td><td>to higher fault currents. Adequately rated electrical equipment prevents larger and more costly failures.</td></tr>
<tr><td>3, 4, 5</td><td>Compare fault currents without generation and with generation.</td><td>This specification helps to quantify the impact of generation on the feeder(s).</td></tr>
<tr><td colspan="3">Marketing Requirements
1. A computer model of a feeder from a substation must be implemented.
2. A computer model of the solar inverters must be implemented.
3. Determine residential solar installations effect on fault current.
4. Determine commercial solar installations effect on fault current.
5. Determine utility-scale solar installations effect on fault current.</td></tr>
</table>

Table 2.2 lists the projects expected deliverables deadlines. A more detailed timeline is given in Appendix C in the form of a Gantt Chart.

Table 2.2: Project Deliverables

Delivery Date	**Deliverable Description**
November 2, 2015	ABET Sr. Project Analysis
December 11, 2015	Computer model chosen
January 15, 2016	Design Review
January 15, 2016	Data for computer model acquired
March 4, 2016	EE 461 report
June 1, 2016	EE 462 demo and first report
June 10, 2016	EE 462 Final Report

Chapter 3

Modeling an Inverter

3.1 Constant Voltage Source vs. Constant Current Source

In calculating fault currents, a constant voltage source is used for the substation. Then, using the impedances between the fault and the source, the magnitude of the fault current can be determined. In this way, the only thing that determines the magnitude of the fault, is the impedance between the fault and source. For example, for a three-phase fault, the simplified circuit is shown in Figure 3.1.

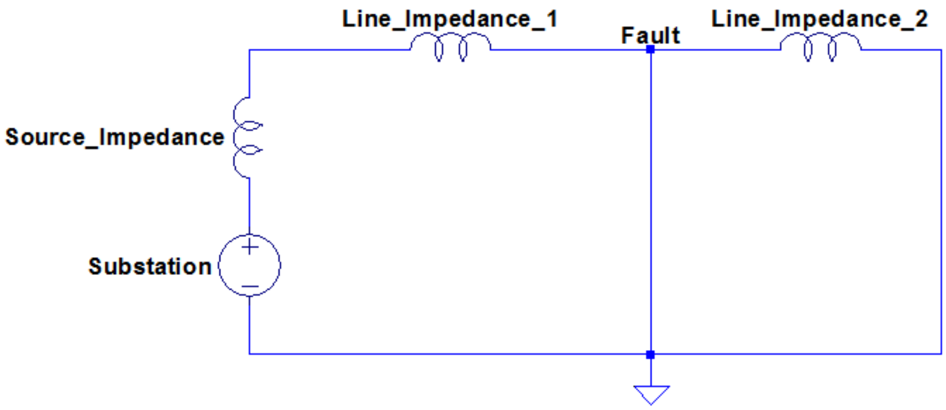


Figure 3.1: Three-Phase Fault Equivalent Circuit

In this case, the magnitude of the fault is mostly dependent on how close to the source the fault location is. If a fault occurs further from the source, the impedance between the source and fault is greater which results in a lower fault current.

The best way to model a solar inverter is to use the model of a solar panel which is a constant current source [6]. Using this model will produce a different magnitude of fault current than if a voltage source was used. For example, by inserting a solar generation plant between the substation and fault location of our previous case, the equivalent circuits shown in Figure 3.2 will be obtained for a constant voltage source and a constant current source.

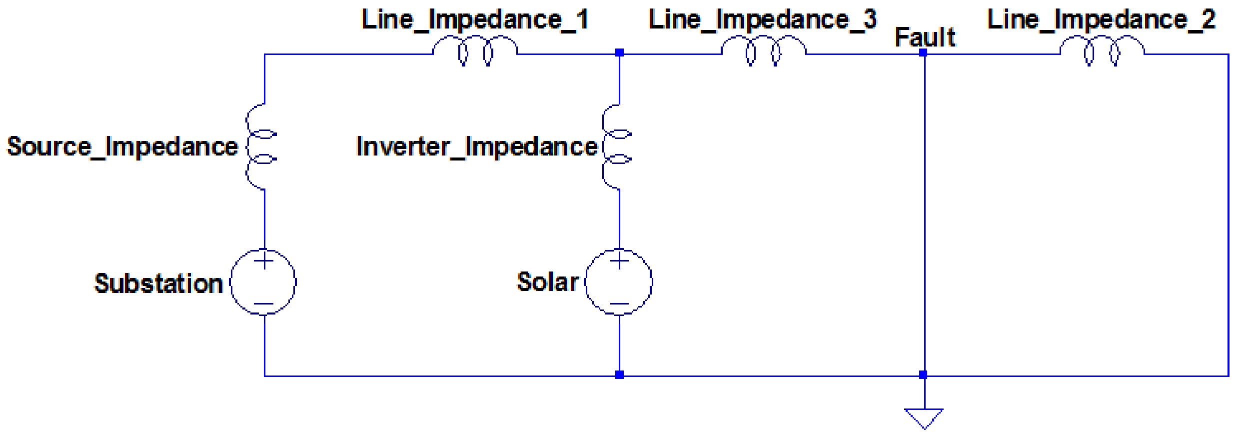


Figure 3.2a: Solar Plant as a Voltage Source

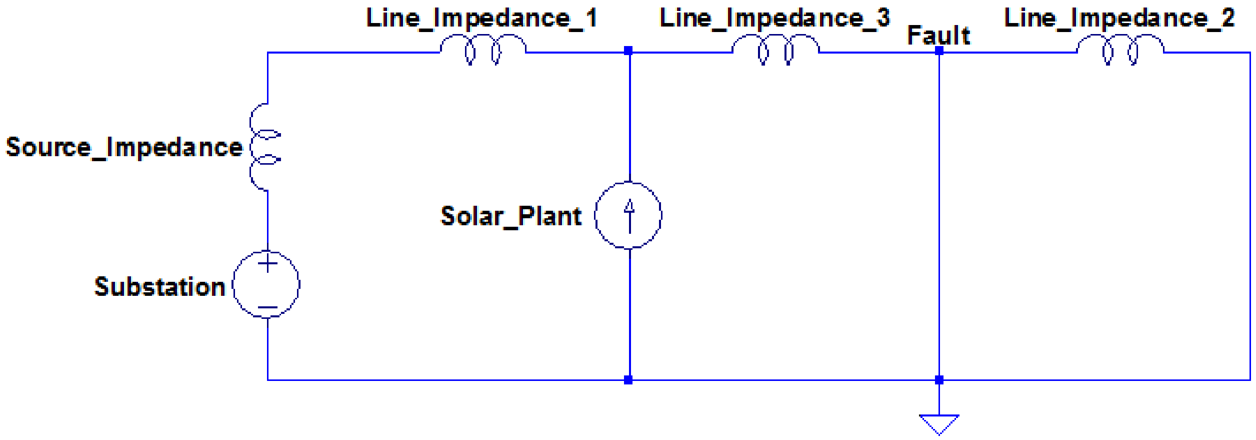


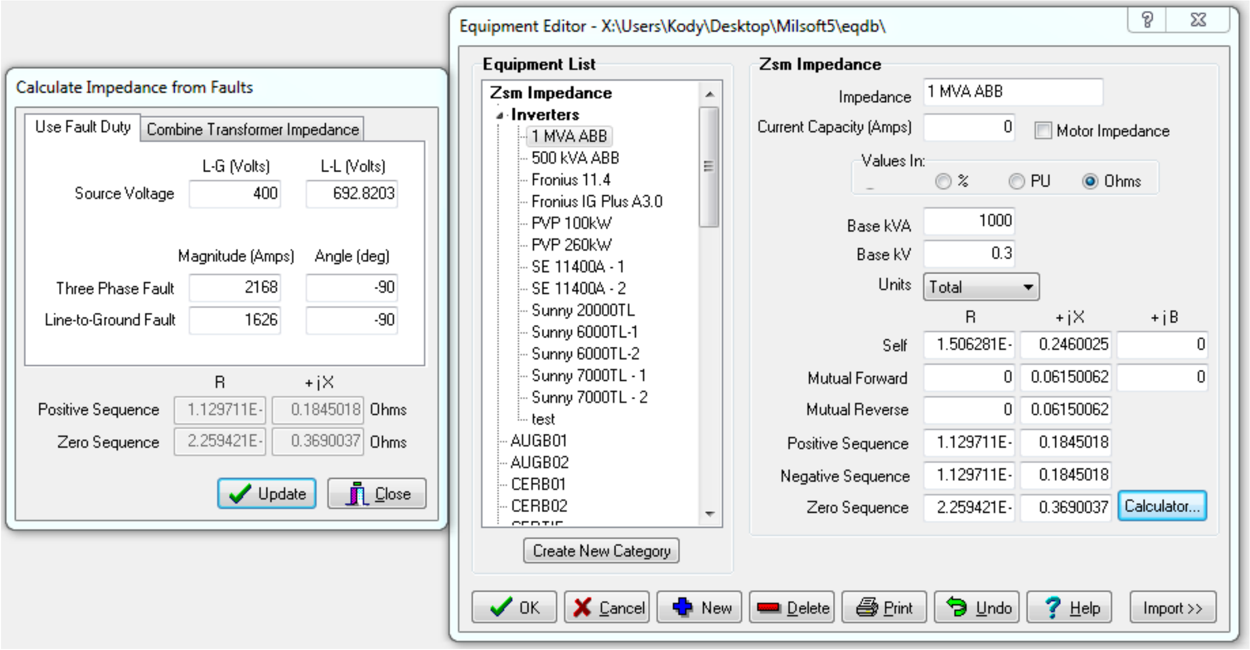
Figure 3.2b: Solar Plant as a Current Source

As can be seen from inspection, changing the fault location will change the line impedance values but will not affect the solar plants contribution to the fault. Unfortunately, Milsoft does not have the option to model the inverter as a constant current source. A constant voltage source was used and the error that this inflicts on each study will be addressed in each section.

3.2 Magnitude of Fault Current

To model an inverter in Milsoft, the inverter impedance was needed. Solar inverters have a maximum current output at full load conditions. The maximum magnitude of the fault current will not exceed 1.5 times the maximum current output [7]. In fact, most solar inverters will only output 1.2 times the maximum rated output [8]. To be conservative and leave room for error, 1.5 will be used. The value contributed from each inverter can then be calculated and is shown in Appendix D.

In Milsoft, the magnitude of the fault current was input for each type of inverter. Milsoft calculates the positive, negative, and zero sequence values of the inverter based on the input fault magnitudes for a three phase fault and a line-to-ground fault.



	L-G (Volts)	L-L (Volts)
Source Voltage	400	692.8203

	Magnitude (Amps)	Angle (deg)
Three Phase Fault	2168	-90
Line-to-Ground Fault	1626	-90

	R	+jX	
Positive Sequence	1.129711E-	0.1845018	Ohms
Zero Sequence	2.259421E-	0.3690037	Ohms

Zsm Impedance

Impedance: 1 MVA ABB
Current Capacity (Amps): 0
☐ Motor Impedance
Values In: ○ % ○ PU ● Ohms
Base kVA: 1000
Base kV: 0.3
Units: Total

	R	+jX	+jB
Self	1.506281E-	0.2460025	0
Mutual Forward	0	0.06150062	0
Mutual Reverse	0	0.06150062	
Positive Sequence	1.129711E-	0.1845018	
Negative Sequence	1.129711E-	0.1845018	
Zero Sequence	2.259421E-	0.3690037	

Figure 3.3: Milsoft Inverter Model

Shown in Figure 3.3 is a screenshot of the inverter settings for a 1 MVA ABB inverter. A fault magnitude of 1.5 times the maximum AC rated output or 2168 A is input. Milsoft calculates the positive sequence impedance value from this. Solar inverters during a fault, do not contribute any zero or negative sequence currents [9]. Because of this, changing the line-to-ground fault input in Milsoft does not affect the magnitude of the fault current calculation for any of the fault types. Therefore, it does not matter what the zero or negative sequence impedance values are for calculating the fault magnitude at another point in the feeder. Milsoft will only use the positive sequence value.

An example for calculating the magnitude of fault current contributed by a single inverter is as follows:

For the PVP 100 kVA inverter:

AC maximum current = 120 A

120 A x 1.5 = 180 A at 480 V

Transformer ratio: 12,470 V / 480 V = 26

180 A / 26 = 6.9 A

For an inverter designed to deliver up to 100 kVA, during a fault it will only contribute at most 6.9 A at the 12 kV level. The inverter is modeled to deliver 1.5 times the AC maximum current at the rated voltage. Milsoft does the above calculation to determine the fault contribution of an inverter. It also factors in other complex factors such as line reactances, distance, etc.

3.3 Type of Inverters Used

TID provided a list of inverters that have been installed on their system. Several were randomly selected for use in this project. A complete list of the inverters and their fault contribution can be found in Appendix D.

Chapter 4

Modeling Results

4.1 Small-Scale Solar Model Overview

Commercial and residential solar installations have become more popular on a utilities electric grid. To look at the impacts of installed solar plants on the grid, 500 kVA of solar capacity was modeled on a single feeder. Then on the same feeder, 500 kVA was added for a total of 1 MVA installed solar capacity. The installed solar plants were distributed throughout the circuit.

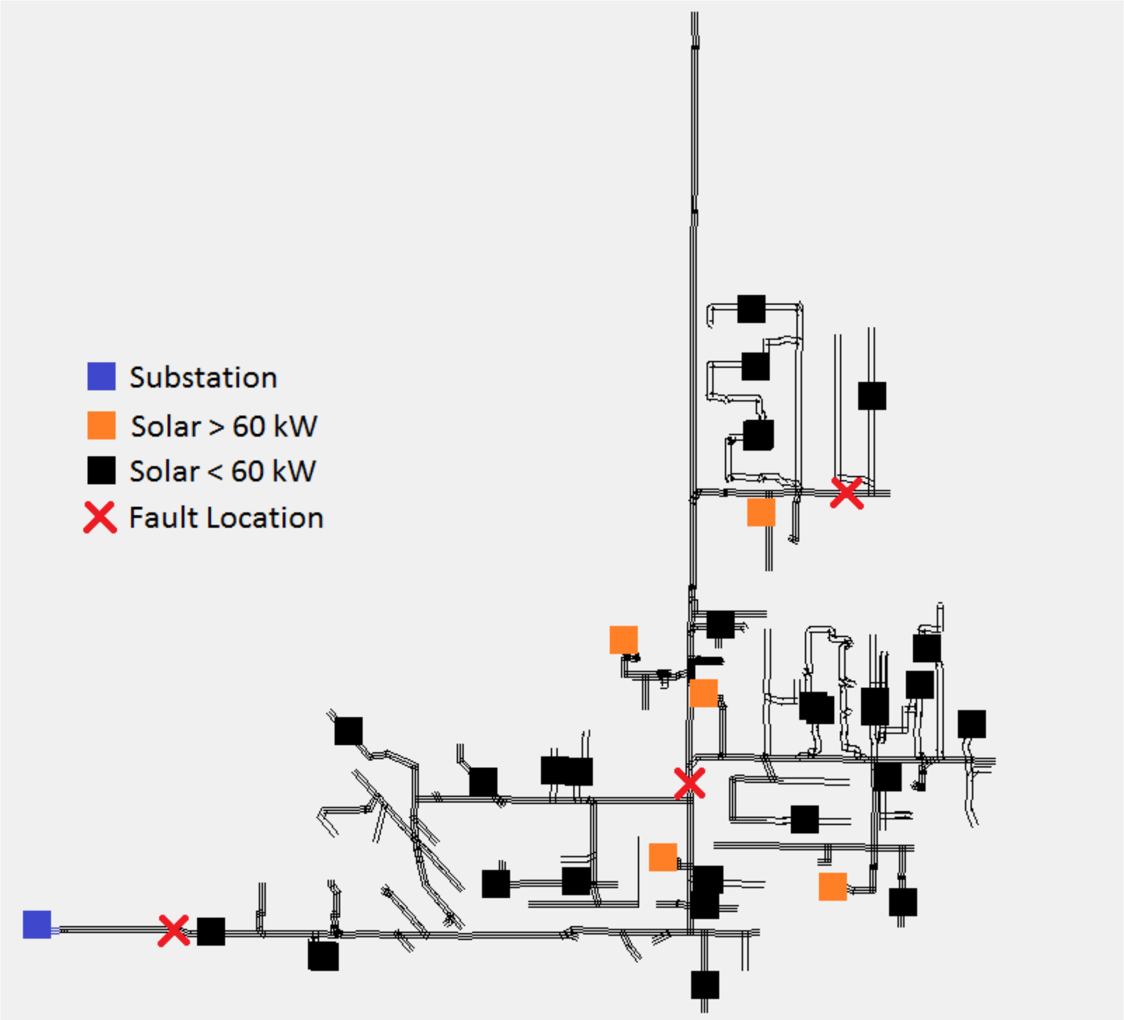


Figure 4.1: Feeder with 1 MW Installed Solar

Shown in Figure 4.1 is a high level view of the feeder with 1 MVA solar capacity installed. Visible in the picture is the solar plants locations and the fault locations. For a detailed list of inverters used, refer to Appendix D. For each case (500 kVA installed solar capacity, 1 MVA installed solar capacity), the fault flow tool in Milsoft was ran for three-phase faults, single line-to-ground faults on each phase, double line-to-ground faults, and line-to-line faults.

Table 4.1: Fault Locations with Respect to Substation

Fault Location	Distance From Substation
1	0.2 miles
2	1.2 miles
3	1.9 miles

Three fault locations were looked at for each case. The fault locations were chosen based on their distance from the feeder. The first fault location is very near the substation while the second location is about a mile downstream of the substation and close to the center of the feeder. The third location is at the end of the feeder and nearly 2 miles away from the substation.

4.2 Fault Current without Installed Solar Capacity

Using the model sent by TID, the fault currents at all three locations were calculated. The results are shown in Table 4.2. Since every fault location is on a three-phase line, the fault magnitude will be identical witgfh respect to its fault type.

Table 4.2: Fault Magnitudes without Installed Solar Capacity (Amps)

Location	LG	LLG	LL	LLL
1	11133	11953	10654	12302
2	4912	5884	5453	6296
3	3474	4291	4014	4635

4.3 Fault Current with 500 kW Installed Solar Capacity

With the added solar generators, the fault current analysis was run again. The fault current was calculated for each fault type and for each phase.

Table 4.3a: 500 kVA -- LL and LLL Fault Magnitudes (Amps)

Fault Type	**AB**		**BC**		**CA**		**LLL**		
Inverter Contribution	**A**	**B**	**B**	**C**	**C**	**A**	**A**	**B**	**C**
Fault Location 1	36	22	35	24	38	24	35	33	36
Fault Location 2	37	22	36	23	38	25	35	34	36
Fault Location 3	30	16	29	16	31	17	27	25	27

Table 4.3b: 500 kVA -- LG and LLG Fault Magnitudes (Amps)

Fault Type	**LG**			**ABG**		**BCG**		**CAG**	
Inverter Contribution	**AG**	**BB**	**CG**	**A**	**B**	**B**	**C**	**C**	**A**
Fault Location 1	24	23	24	34	25	34	26	26	37
Fault Location 2	21	21	23	36	24	35	26	37	26
Fault Location 3	15	14	16	27	20	27	20	27	20

Shown in Table 4.3a and Table 4.3b is the contribution of fault current from all the installed inverters during a fault. The fault current contributed by the source is in Table 4.2 for each respective case. The values shown in Table 4.3a and Table 4.3b were calculated from the model results by subtracting the current contributed by the source from the total current supplied to the fault. Compared to the magnitude of fault current contributed by the source, the inverters do not have a large impact. With fault current magnitudes not even in the triple digits, the inverters do not change the overall fault current by more than 1%.

4.4 Fault Current with 1 MW Installed Solar Capacity

With an additional 500 kW of installed solar capacity, the fault currents were again calculated. As expected, the additional generation did not have much of an impact.

Table 4.4a: 1 MVA -- LL and LLL Fault Magnitudes (Amps)

Fault Type	**AB**		**BC**		**CA**		**LLL**		
Inverter Contribution	**A**	**B**	**B**	**C**	**C**	**A**	**A**	**B**	**C**
Fault Location 1	69	46	67	42	65	45	66	64	62
Fault Location 2	57	36	58	35	56	34	52	54	52
Fault Location 3	59	35	58	32	56	33	54	54	51

Table 4.4b: 1 MVA -- LG and LLG Fault Magnitudes (Amps)

Fault Type	**LG**			**ABG**		**BCG**		**CAG**	
Inverter Contribution	**AG**	**BB**	**CG**	**A**	**B**	**B**	**C**	**C**	**A**
Fault Location 1	45	44	42	67	50	65	47	63	49
Fault Location 2	42	41	39	68	49	65	45	63	48
Fault Location 3	31	30	28	54	41	52	38	50	39

Since the magnitude of fault currents contributed by the inverters is small relative to the source, the error due to the inverter model being a constant voltage source instead of a constant current source does not have an impact.

4.5 Utility-Scale 10 MVA Solar Model Overview

To analyze the effects of a much larger sized solar installation, a 10 MVA system was added to the same feeder analyzed previously. All other solar inverters were removed so it was just the 10 MVA system. Because of the different designs available for use in the system, two different cases were studied. In the first case, the inverters used were 500 kVA. This required the use of 20 inverters to reach 10 MVA. In the second case, 1 MVA inverters were used with a total of 10 inverters. In each case, 10 – 1 MVA transformers were used. The inverters and transformers were connected to the 12 kV system just downline of Fault Location 1 in Figure 4.1.

4.6 Fault Current with 10 MVA System

The same fault locations and type of fault as studied in the previous sections was looked at here. The generation in the feeder is balanced on all three phases so the fault currents per phase will all be equal.

Table 4.5a: 500 kVA Inverters Total Fault Contribution (Amps)

	Fault Contribution			
Fault Type	**LLL**	**LL**	**LLG**	**LG**
Fault Location 1	1201	1043	1062	802
Fault Location 2	756	683	695	610
Fault Location 3	679	632	640	592

Table 4.5b: 1 MVA Inverters Total Fault Contribution (Amps)

	Fault Contribution			
Fault Type	**LLL**	**LL**	**LLG**	**LG**
Fault Location 1	1200	1041	1061	801
Fault Location 2	755	682	694	609
Fault Location 3	678	631	639	591

Shown in Table 4.5a is the magnitude of the fault contribution of the 20 – 500 kVA inverters. In Table 4.5b is the magnitude of the fault contribution of the 10 – 1 MVA inverters. Both types of inverters were from the same manufacturer. As a check, to determine if the model gives a reasonable solution the following is shown:

The fault magnitude of the 500 kVA inverter is 1,448 A at 519 V. These values can be seen in list form for all inverters in Appendix D.

$$12{,}470\text{ V} / 519\text{ V} = 24.0\text{ V} / \text{V}$$

$$1{,}448\text{ A} / 24 = 60.3\text{ A}$$

$$60.3\text{ A} \times 20\text{ inverters} = 1206\text{ A}$$

The fault magnitude of the 1 MVA inverter is 2,168 A at 692 V.

12,470 V / 692 V = 18.0 V / V

2,168 A / 18.0 = 120.4 A

120.4 A x 10 inverters = 1204 A

Therefore, the fault magnitudes of both types of inverters should be similar, which is what is seen.

The impact of the 10 MVA system effects the grid much greater than the smaller, distributed solar systems.

Table 4.6: Percent Increase in Fault Current Magnitude with 10 MVA System

Location	LG	LLG	LL	LLL
Fault Location 1	10.79 %	8.73 %	9.97 %	6.52 %
Fault Location 2	15.39 %	11.61 %	12.75 %	9.69 %
Fault Location 3	19.55 %	14.73 %	15.94 %	12.77 %

Shown in Table 4.6 is the percent increase of the fault current magnitude compared to the fault current with no solar plants installed on the system. It is clear from these percentages that the impact from the 10 MVA system is significant. At fault location 3, the difference results in an almost 20% increase in fault magnitude for a line-to-ground fault! It should be noted that the further away from the substation the fault occurs, the greater the impact on the fault magnitude. This is because the solar generation acts more as a constant current source rather than a constant voltage source.

Chapter 5

Conclusions

Solar installation’s effect on the electric grid depends on a couple things. The size of the installation is most important. Even when the capacity of solar reached 1 MW, the effect on the electric grid was barely even noticeable. However, a utility-sized installation may have a larger impact. The 10 MVA system modeled in this project had a significant impact. The installation contributed fault current that ranged from 600 A up to 1200 A. Comparing this current to the current contributed by the source during a fault gave a percent increase ranging from 6% up to 20% depending on the fault type and the fault location.

It is important to still note that the model used in Milsoft for the solar inverters was a constant voltage source associated with an impedance. This would cause a different effect than if the inverters were modeled with a constant current source. The closer the fault is to the modeled inverters, the less effect this will have. This may cause larger contribution to the fault current magnitude than modeled here for locations further from the solar installation. However, remember that the impedance of the inverters was calculated with 1.5 times the maximum rated output current rather than 1.2 multiples which will make up for some of that difference.

This project showed the importance of knowing the impacts of generation that is being tied to the grid. Analyzing the effects of a solar installation should be done on a case-by-case basis as no case is the same. The size of the installation as well as the equipment used will have an impact on how the feeder will behave during a fault.

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Appendix A

Senior Project Analysis

Functional Requirements

California paves the road for other states with the capacity of solar installations for residential and commercial entities. The magnitude of added capacity to the state's electric grid due to solar has an impact on power flow and fault currents. This project looks at the impact of solar installations to fault currents and load flows. The addition of so many power sources affects the fault current potential at various points along the grid.

Additionally, this project looks at the larger scale of power flow in the grid. With solar systems, both utility and consumer owned, now installed at various points along distribution feeders, power flows no longer in one directional. This project looks at the present protection schemes commonly in use today and whether they are adequate for continued use in a non-radial system.

Primary Constraints

A significant challenge with this project was choosing the correct circuits to analyze and modeling the circuits. The ideal situation uses actual circuits that exist in the field and have distributed generation. This goal was accomplished by speaking with Turlock Irrigation District and obtaining permission to utilize their circuit models. The next issue determined which circuits to model and study. Since in the field, infinite possibilities and set-ups exists, several circuits were chosen that had varying set-ups. For example, one circuit chosen had small distributed generation balanced throughout the circuit while another circuit studied had several large distributed generation throughout.

One limiting factor for this project was the model. The model used for the circuits was only as accurate as the data that was used to describe the circuit elements. The most accurate information about the circuit elements were obtained in order to most accurately build the model.

Economic

With every project attempted or completed, economic impacts occur. These impacts can be felt all the way from the manufacturing to the end user or even to a third party. Since this project contains only a computer simulations and data analysis there are no manufacturing impacts. The main economic impacts of this project applies to financial and natural capital. The main subject of this project is the impact of distributed generation on distribution circuits. Distributed generation mainly consists of solar or wind power. The more solar generation, the less utilities must rely on non-renewable energy sources to generate power. Determining how the influx of solar generation impacts the electric grid is a key component for future planning of the grid. This is a financial and natural capital economic impact. Investors have spent large sums of money on renewable energy and solar is the leading driver of this. This also, is a financial impact. Some human economic impacts as a result of this project are also felt. The electric grid must begin adapting to the changes occurring to it. This leads to more work for linemen and more money spent on wages and equipment.

Costs and benefits accrued throughout the duration of the project. Since the bulk of the project analyzed several computer models and simulations, the only costs for the project included labor and software. The software used was provided through California Polytechnic State University so there no financial charge occurred. Benefits occurred after project completion when the full analysis completed.

As mentioned earlier, since the project as based on computer modeling and simulation, the inputs to the experiment is the data for the model. The data for the model was obtained from data sheets for the electrical equipment used and billing information provided by Turlock Irrigation District. The total cost of the project included labor provided free of charge.

If Manufactured on a Commercial Basis

The data and information gathered from the study was shared with Turlock Irrigation District in response to them allowing the project to utilize their circuit models. Because of this, no part of this project was sold.

Environmental

Manufacturing for this project was defined as the time it takes to build and set-up the computer model. The environmental impacts of this are the power used by the computers to build the model. An indirect impact, energy, was used by the makers of the computer software. Overall, however, this project had a positive impact on the environment. The project looked at the impact of solar generation in which the results help make the grid safer and more adaptable. Through this project, the grid becomes more durable and more efficient which saves power, money, and resources directly by the power saved and by the equipment saved.

Manufacturability

Since the nature of this project is analysis of individual circuits using a computer model, there is no manufacturing involved.

Sustainability

The techniques developed from the completed project may be applied to other circuits and models. This is all done by use of computer modeling. Because of this the only environmental impact uses power to run the computers. This does not have a significant impact on the environment. Some challenges do arise when maintaining the project. The electric grid constantly changes even day-to-day. Keeping a large system modeled and up to date to constantly do analysis takes too much time. This project hopefully gives rise to techniques that can be applied to other circuits in terms of protection and sustainability so written standards help analyze the different types of circuits and models.

Ethical

It can be difficult to pin down a good definition of ethics. For this section ethics will be defined as a set of moral principles or values. To examine the ethics encompassed in this project, the IEEE Code of Ethics will be used with Ethical Principlism.

Looking at the IEEE Code of Ethics (CoE) reveals this project has some ethical implications relevant to the IEEE CoE and specifically numbers 3, 5, 6, and 7. The third code refers to honesty and being realistic in claims or estimates. This is specific to this project by one must be honest and not attempt to adjust the model or data in order to gain a desired output. With computer simulations, variables changed to affect the output of the system can skew results. In order for this project to adhere to the IEEE CoE this must be avoided. The fifth IEEE CoE refers to understanding the advantages and disadvantages of technology. In relation to this project, it must be kept clear that the main component is a computer model, not an exact representation. Trusting the model to be more than it is, can lead to fault analysis and conclusions.

At the beginning of the project, before the project plans had even been written, I did not have the technical skills to complete the project. Only by studying the material, guided by professionals who had specific experience, and referencing reliable sources have I gained the appropriate technical knowledge to complete this project. That said, one must ensure they have the technical skill and knowledge to use and apply the results of this project. This is the exact implications of IEEE CoE point 6. One must only take on tasks that he has qualified training or experience in. Knowing this it is also important to accept criticism. This is point 7 of IEEE CoE. If someone qualified takes issue with part of the project, their concerns should be adequately addressed.

This project can also be looked at in terms of Ethical Principlism. Ethical Principlism can be broken down into four different categories: autonomy which refers to freedom, non-maleficence, beneficence, and justice. Freedom in this case relates to the project by giving someone the freedom to analyze the computer models and do the project. Non-maleficence refers to the project not having bad qualities. As mentioned in the environmental section, the disadvantages of this project are the time it takes to complete and the energy spent. Beneficence refers to the amount of good that the project will accomplish. The goal of this project is to learn about the effect of distributed generation which the results help the grid become safer and more reliable. Therefore, this aspect fulfills the beneficence part of Ethical Principlism.

Health and Safety

One of the main goals of this project analyzed distributed generations effect on fault current and how that impacts power protection. Power protection protects the electric grid from dangerous situations and to cut power when the grid malfunctions. Therefore the project must be properly conducted and great care taken to avoid inaccuracies which lead to flawed conclusions. Overall, the project had a positive impact on safety since it looked at better protecting the electric grid and the equipment that is a part of the grid. This leads to fewer faults causing unsuspected results and accidents.

Social and Political

This project had many direct and indirect stakeholders involved. Some direct stakeholders are utilities and electric equipment manufacturers. Utilities are direct stakeholders because the project studied their product and way of delivering power. This project positively benefits utilities by making the grid safer, more efficient, and more understood. Electric equipment manufacturers are direct stakeholders since the equipment they sell to utilities must have a high enough safety rating of fault current. An indirect stakeholder is the solar companies and customers of the utilities. Solar companies are indirect stakeholders because changes in design of the panels or inverters may decrease the magnitude of fault current. Customers of the utilities are indirect stakeholders since having a safe and reliable grid benefits them as they have reliable power.

Development

In order to successfully complete this project, techniques for calculating fault current and modeling electrical systems were learned. Circuit modeling was something I had done several times during internships but did not require such an accurate model. Learning and deciding which factors to include or not include made an impact on the project. The other technique used during this project was the calculation of fault current. I had a general idea of how to calculate fault current before the project started but a higher level of understanding was required to complete the project.

Appendix B

Functional Decomposition

B.1 Level 0 Block Diagram

Figure B.1 shows a level 0 block diagram. The computer model takes conductor, transformer, load data, inverter impedances, and other relevant feeder information. The model calculates fault currents at any point in the circuit.

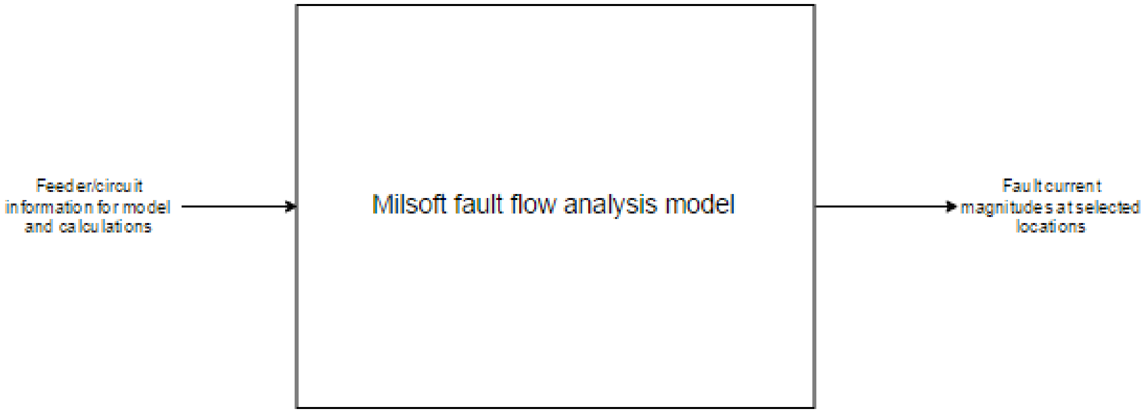

Figure B.1: Level 0 Block Diagram

Table B.1 shows a more detailed summary of the level 0 block diagram and summarizes the functionality of the system.

Table B.1: Level 0: Inputs, Outputs, and Functionality

Inputs:	Feeder/circuit information: • Conductor data: type, length, impedance, UG or OH • Transformer data: kVA, phase, impedance • Inverter data: impedance, fault current supplied
Outputs:	Fault currents at selected locations: • Near substation • Halfway down feeder • End of feeder
Functionality:	Solar generations effect on fault current and protection schemes.

B.2 Level 1 Block Diagram

A level 1 block diagram is shown in Figure B.2. This diagram shows 4 models contained inside the main block.

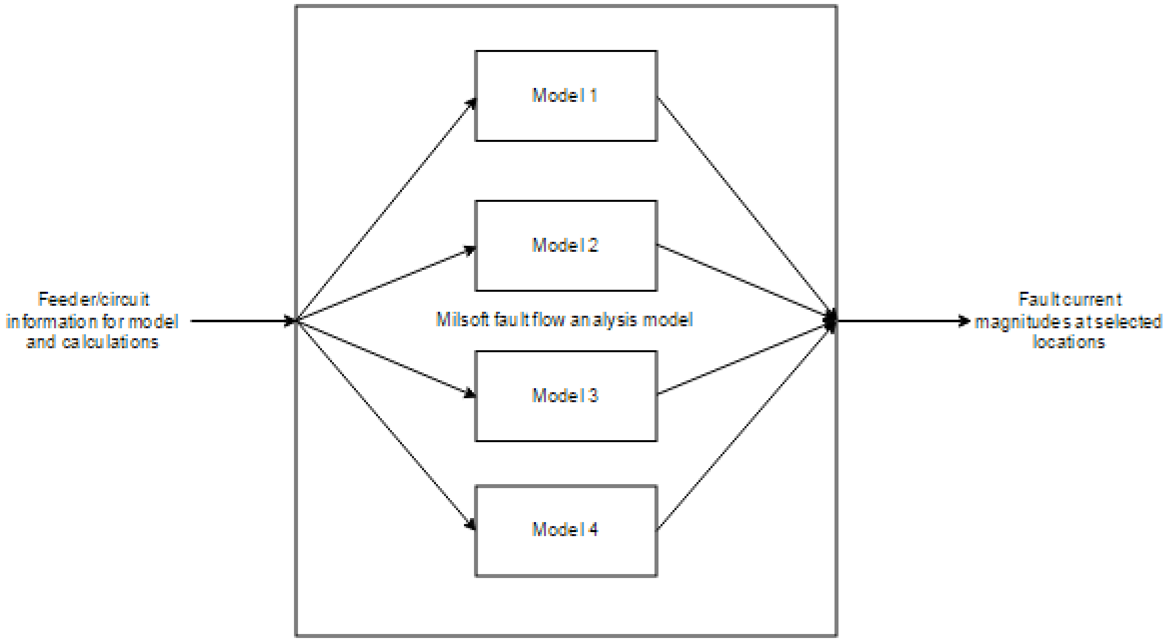

Figure B.2: Level 1 Block Diagram

The difference between the models is the amount and location of solar plants modeled. In the first model, 500 kW of solar is distributed throughout the feeder. The second model has 1 MW distributed throughout the feeder. Models 3 and 4 consist of a 10 MVA solar system installed near the substation. Model 3 has 500 kVA inverters and Model 4 has 1 MVA inverters. Shown in Table B.2 is a summary of the inputs, outputs, and functionality.

Table B.2: Level 1: Inputs, Outputs, and Functionality

Model Number	Inputs	Outputs	Functionality
1	500 kVA total of solar installations	Fault Current Magnitude	Solar generations effect on fault current and protection schemes.
2	1 MVA total of solar installations		
3	10 MVA solar system with 500 kVA inverters		
4	10 MVA solar system with 1 MVA inverters		

Appendix C

Project Planning

Gantt Chart

Displayed in Figure C.1 is a Gantt chart that lists the major project tasks. The gap in the center of the chart is the time between quarters for Cal Poly. The chart begins at December 28 but that task started in early October. The tasks proceeding it until the gap involved the set-up of a computer model. Once the model was complete, the first six weeks of the final quarter was allotted for analysis. The report was also written during this time.

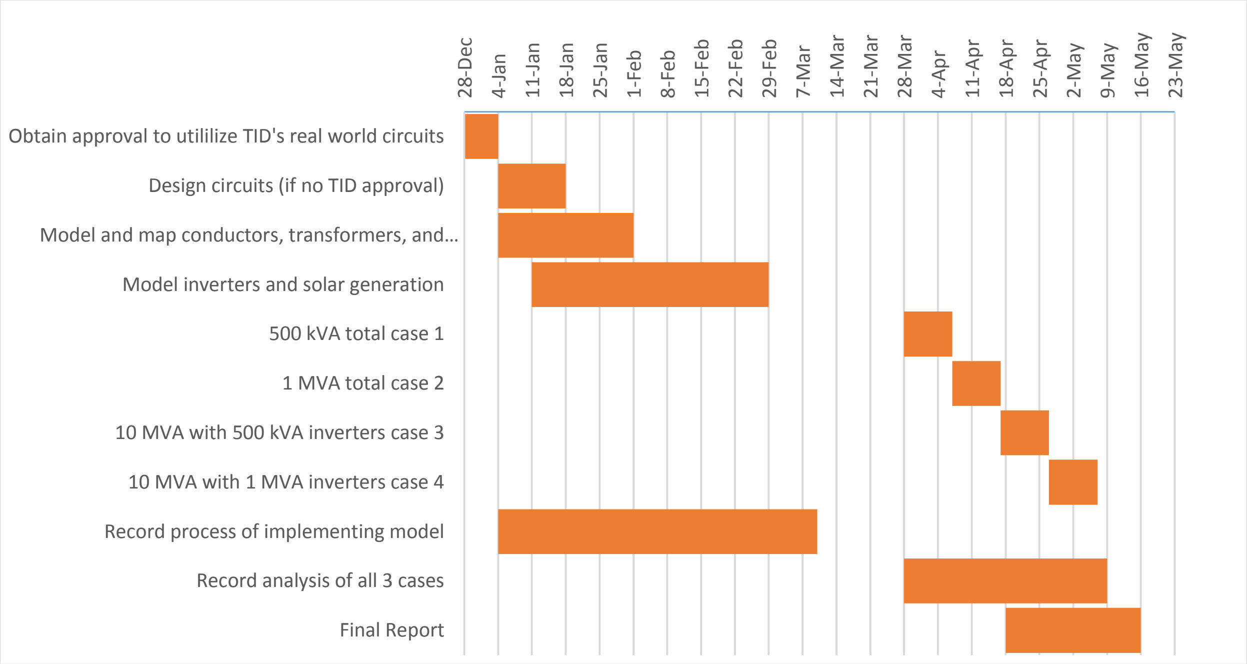

Figure C.1: Gantt Chart Project Timeline

Cost Estimates

Since this project involves computer simulations and analysis, the only cost required for this project is labor. The project makes use of free software programs through Cal Poly or student versions offered from software companies. The table shown in Table C.1 is of cost estimates for this project. The calculated cost was found by using the following equation:

$$Cost = \frac{Cost_{Pessimistic} + 4Cost_{Most\ Likely} + Cost_{Optimistic}}{6}$$

Table C.1: Cost Estimates

Item/part	Pessimistic Cost	Most Likely Cost	Optimistic Cost	Calculated Cost
Labor ($125.00 an hour)	$15,625.00 (125 Hours)	$18,750.00 (150 Hours)	$21,875.00 (175 Hours)	$18,750.00
WindMil	Free	Free	Free	Free

Appendix D

Solar Inverters

Inverters Used

Several inverters were provided by TID to be used in this project. Shown in Table D.1 and Table D.2 is the inverters used in this project. All values were obtained from the manufacturer’s datasheets.

Table D.1: Single Phase Inverters

Inverter	Power Rating (kW)	Nominal Voltage (V)	Maximum Current (A)	Fault Current (A)
Fronius IG Plus A 3.0-240	3	240	13	19
Sunny Boy 6000TL-240	6	240	25	38
Sunny Boy 7000TL-240	7	240	32	48
SE 11400-240	11.4	240	48	71
Fronius IG Plus 11.4-240	11.4	240	48	71

Table D.2: Three-Phase Inverters

Inverter	Power Rating (kW)	Nominal Voltage (V)	Maximum Current (A)	Fault Current (A)
Sunny 20000TL-US-480	20	480	24	36
PVP 100 kW	100	480	120	180
PVP 260 kW	260	480	316	474
PVS800-57-0500kW	500	300	965	1448
PVS800-57-1000kW	1000	400	1445	2168