Westplan Solar PV Penetration Study

Final Report

Roseville Electric Utility

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1. Executive Summary

The Westplan Solar PV Penetration Study focuses on potential voltage issues that may occur as the penetration of distributed PV generation on the distribution system increases. The study results indicate that prolonged voltage issues in the steady-state condition due to increasing PV penetration are not likely to occur so long as the system remains intact. The results do indicate, however, that temporary high voltages can occur as a result of rapid fluctuation in PV starting as low as 40%. Although a 40% PV penetration does not cause voltage issues on all feeders or under all system conditions, the majority of the feeders experience high voltage issues in the range of 40 to 50% PV penetration for the worst-case one-minute PV increase.

This study is based on the best available data and incorporates a number of necessary assumptions. The potential PV scenarios considered are reasonable given the limited knowledge of actual future system conditions, but these are not exhaustive. The SynerGEE model dataset is the most comprehensive and up-to-date model of the Westplan system and is validated against available measured data. However the steady-state SynerGEE model does have limitations. The SynerGEE model does not include system or PV inverter dynamics and may underestimate the effects of rapid changes in PV generation on the system. Converting the distribution system model to a dynamic model format (such as PSLF) to conduct detailed dynamic and stability analyses will result a more accurate understanding of system impacts caused by dynamic PV events.

2. Introduction

This report details a set of steady-state load flow analyses performed on the Westplan substation for Roseville Electric to identify potential voltage issues on the Westplan feeders due to increasing distributed solar PV generation. PV generation is largely a function of incident solar irradiance and can fluctuate widely from minute to minute as clouds move across the sky. As PV generation varies, so does the net demand at the substation transformer. Since the on-load tap changer (LTC) is not designed to regulate the feeder or bus voltages within the short timescales of PV variability, voltage issues may occur at various locations on the feeder that can be attributed to PV generation. As the amount of PV generation increases on a distribution feeder so does the risk of voltage issues. Voltage issues that can occur include voltage flicker, device malfunction in the case of low voltages, and device failure in the case of high voltages. Voltage issues may be temporary (i.e. relieved after the LTC responds) and may be prolonged if voltages exceed the voltage tolerance of a device (e.g. a fuse or distribution transformer).

The analyses are performed using the SynerGEE Electric dataset of Westplan system (hereafter called the "Westplan model") provided by Roseville Electric. The Westplan model is an unbalanced, steady-state power flow model that includes eight 12 kV distribution feeders served by two 60/12kV transformers in

the Westplan substation, as shown in the single line diagram in Figure 2.1. The Westplan Buses 1 & 2 are ideal voltage sources with source impedances that represent the equivalent 60 kV source at the high side of each substation transformer.

The amount of existing PV generation installed in Westplan is considered; and potential future PV generation is distributed throughout the dataset to simulate future system conditions. The total amount of potential PV distributed throughout a feeder is increased until voltage issues begin to occur on the feeder, or until the total amount of PV equals the peak demand measured in 2012 for the feeder, whichever comes first.

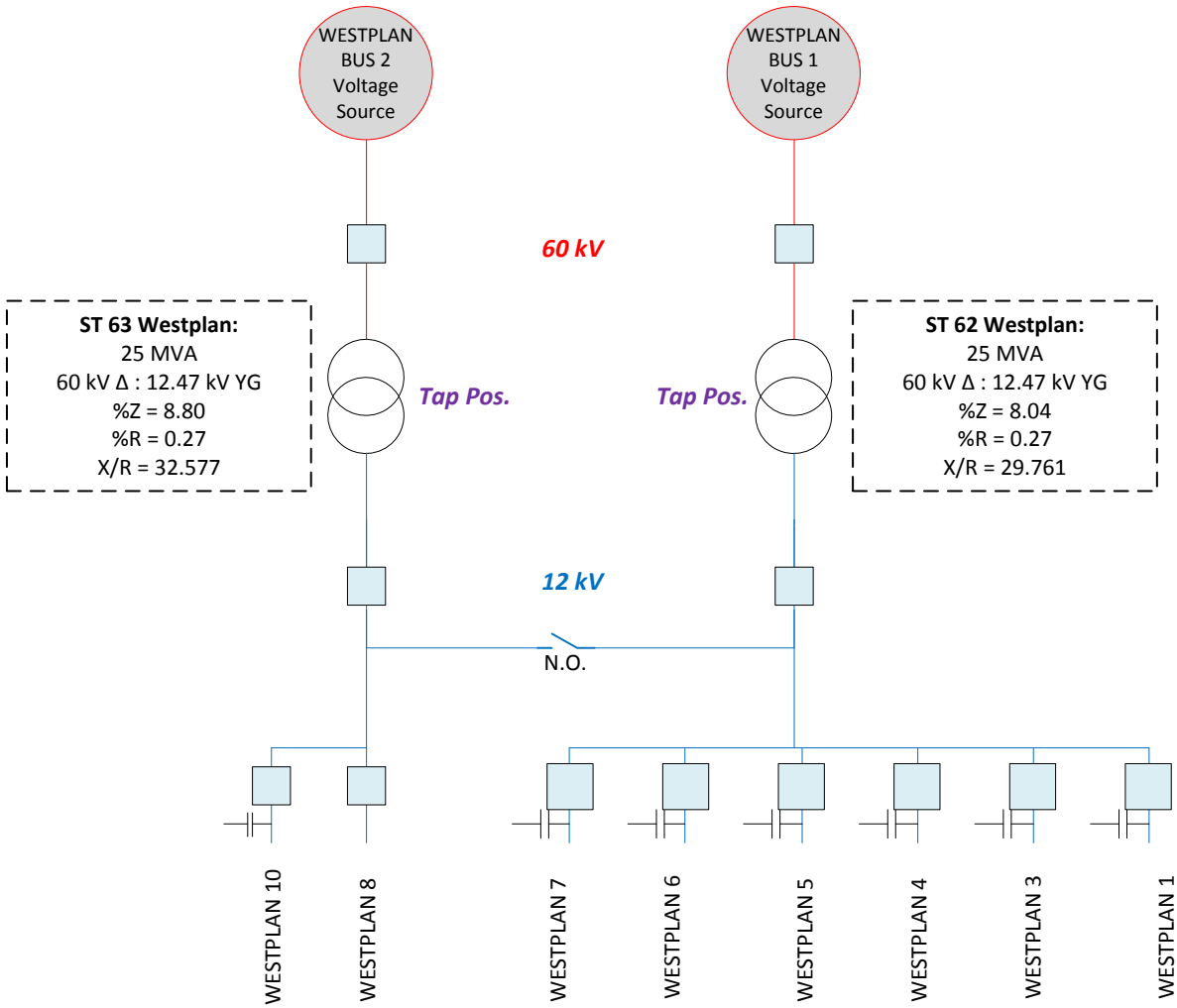

Figure 2.1: Westplan Substation Oneline Diagram, Microsoft Visio

3. Data Summary

DNV KEMA received the following data from Roseville to perform the Westplan Solar PV Penetration study as part of the CPUC CSI RDD Solicitation 3 Hi-PV penetration study:

- Model Dataset
  - *WestPlan_1_8_13.mdb*
- Warehouse Dataset
  - *Roseville Equipment V7.mdb*
- SCADA Demand Data
  - *Wplan SCADA Data - Peak.xlsx*
  - *Westplan_Data_5_30_13.xlsx*
- Customer Voltage Data Measured in the Field
  - *Westplan_Boomerang_Voltage_5_30_13.csv*
- Existing PV Generator Records
  - *pv.xlsx*
- Weather Data
  - *Irradiance_Temp_May_30_2013.xlsx*

3.1 Model and Warehouse Datasets

The base case Westplan model and warehouse datasets are provided by engineers at Roseville Electric ("Roseville"). The model dataset is built from geographical and electrical data stored in the utility's GIS (Geographic Information System). The model dataset includes:

- Westplan substation consisting of two 60 kV subtransmission voltage sources each feeding one 60 kV :12 kV substation transformer
- Seven 12 kV feeders (and one additional standby feeder, Westplan 10) including the 12 kV : 240 V distribution transformers and portions of the 240 V secondary side of each distribution transformer.

In addition, Roseville verified the accuracy of important data in the Westplan model including:

- Positive and zero sequence Thevenin equivalent impedances of the 60 kV voltage sources
- Phasing of distribution line sections by manual field verification,
- Open points preventing loops in the distribution feeders
- Load tap changer (LTC) and load drop compensation (LDC) settings of the two 60/12 kV substation transformers, and
- KVAR capacities of all capacitor banks as well as the control settings of switched capacitor banks

See Appendix A for a detailed summary of the base case Westplan model, substation transformer parameters, and capacitor parameters.

3.2 SCADA Demand Data

The SCADA demand data files contain 1-minute resolution, measured current, voltage, and power data for representative peak and minimum demand days. The peak demand day occurred on August 13, 2012 (*Wplan SCADA Data – Peak.xlsx*), and the minimum demand day occurred on May 30, 2013 (*Westplan_Data_5_30_13.xlsx*). Table 3-1, below, summarizes the exact measurements contained in the demand data files. Note that Westplan 10 (i.e. FDR#10) is not included as it is a standby feeder.

Table 3-1: Measurement Quantities in SCADA Demand Data Files

Worksheet Name	Measured Quantities				
TX#1 - 60kV Volts	A-Phase kV	B-Phase kV	C-Phase kV		
TX#2 - 60kV Volts	A-Phase kV	B-Phase kV	C-Phase kV		
TX#1 - 12kV Volts	A-Phase kV	B-Phase kV	C-Phase kV		
TX#2 - 12kV Volts	A-Phase kV	B-Phase kV	C-Phase kV		
TX#1 - Tap Pos.	Position				
TX#2 - Tap Pos.	Position				
TX#1 - 12kV MW-Mvar	MW	MVAR			
TX#2 - 12kV MW-Mvar	MW	MVAR			
FDR#1	MW	MVAR	A-Phase Amps	B-Phase Amps	C-Phase Amps
FDR#3	MW	MVAR	A-Phase Amps	B-Phase Amps	C-Phase Amps
FDR#4	MW	MVAR	A-Phase Amps	B-Phase Amps	C-Phase Amps
FDR#5	MW	MVAR	A-Phase Amps	B-Phase Amps	C-Phase Amps
FDR#6	MW	MVAR	A-Phase Amps	B-Phase Amps	C-Phase Amps
FDR#7	MW	MVAR	A-Phase Amps	B-Phase Amps	C-Phase Amps
FDR#8	MW	MVAR	A-Phase Amps	B-Phase Amps	C-Phase Amps

3.3 Customer Voltage Data Measured in the Field

The customer voltage data measured by Boomerang power quality analyzers in the field contain 240 V measurements at 1-second resolution for six locations on multiple feeders within the Westplan region. This data is used with the SCADA data to validate the Westplan model by comparing load flow simulation voltages to measured voltages at each hour in the minimum demand day. Table 3-2 details the locations of each of the six Boomerang devices installed in the field.

Table 3-2: Boomerang Power Quality Analyzer Locations

Location	Boomerang Serial Number	FeederId	SynerGEE Model SectionId
1072 Kirkhill Dr	603331	WEST PLAN 4	34620_UG_SEC
3177 Ardley Drive	603301	WEST PLAN 6	53719_UG_SEC
2600 Pipestone Way	603334	WEST PLAN 8	40355_UG_SEC
2176 Devonport Loop	603341	WEST PLAN 4	35003_UG_SEC
2519 Woodgate Way	603350	WEST PLAN 7	40279_UG_SEC
2532 Roxby Way	603356	WEST PLAN 6	40307_UG_SEC

3.4 Existing PV Generator Records

The existing PV generator records contain important details for the distributed PV generators already installed on the Roseville Electric system. The records show 1,189 PV generators installed on the Roseville Electric system, 829 of which are installed on feeders in the Westplan region (see Table 3-3). Information for each PV record includes street address, in-service date, peak kW rating, PV module and inverter manufacturer and model, servicing distribution transformer, etc.

Table 3-3: Distributed PV Totals: Westplan vs. All of Roseville

	Roseville System	Westplan Region Only
Number of PV Generators	1,189	829
% of PV Generators	100%	70%
Total PV Peak kW	2,812	1,653
% of Total PV kVA Capacity	100%	59%

3.5 Weather Data

The weather data file provides 1-second irradiance and ambient temperature measured at the Westplan substation on the minimum demand day (Fiddyment substation weather data is also included in the file but is not discussed in this report). Figure 3.1 depicts the irradiance and temperature measured at the Westplan substation on the minimum demand day.

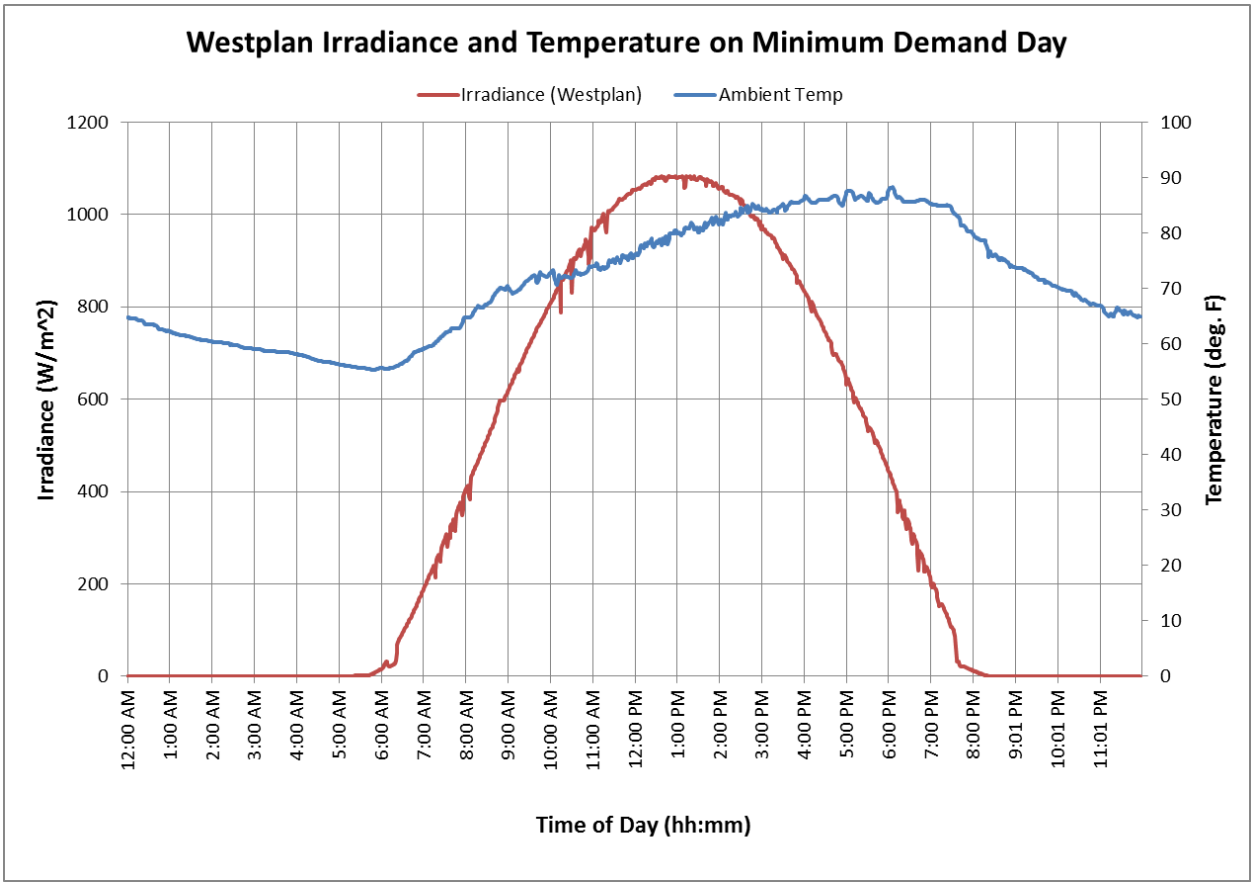

Figure 3.1: Westplan Irradiance and Temperature on Minimum Demand Day

Since solar PV generation is generally proportional to solar irradiance, irradiance is used for input to the PV generators in the model to provide time-dependent real power output. Time-dependent ambient temperature is used as input to the model so the capacitors which are controlled by temperature can respond accordingly.

4. Solar PV Penetration Study Setup

The solar PV penetration study involves adding new (i.e. potential) PV generator locations to the base case Westplan model, and increasing the size of the potential PV generators until a voltage violation occurs or until the total amount of existing and potential PV generation on a feeder equals the 2012 peak demand of that feeder. PV penetration is defined as the total amount of PV on a feeder as a percent of the feeder's 2012 peak demand. Therefore, the maximum PV penetration considered in this study is 100% PV penetration. A voltage violation occurs if the voltage at any point in the system exceeds +/- 5% of nominal. On a 120 V base, the acceptable voltage range is between 114 V and 126V. The PV penetration

study consists of the following two types of analysis: 1) Twenty-Four Hour Load Flow Analysis, and 2) One-Minute PV Ramp Analysis.

The Twenty-Four Hour Load Flow Analysis simulates the entire peak and minimum demand day profiles in hourly steps under varying potential PV generation. The purpose of this analysis is to identify prolonged voltage issues that may arise. Typically a prolonged voltage issue can arise if the LTC reaches an upper or lower tap limit (thereby preventing voltage regulation), or if a PV generator exists near the end of a feeder where the equivalent impedance between the PV generator and the substation is high.

The One-Minute PV Ramp Analysis simulates large changes in PV generation during a one-minute interval where the LTC is unable to respond to changes in net demand. The purpose of this analysis is to identify temporary voltage issues that may arise due to large irradiance fluctuations or multiple PV generators tripping off-line or reconnecting at the same time.

4.1 Peak and Minimum Day Feeder Demands

The primary inputs to the Westplan model for the PV penetration analyses are the unbalanced feeder demands for the day and time of interest. Figure 4.1 shows the peak demand day profiles for the Westplan feeders at 1-minute resolution. This demand profile is derived directly from the measured SCADA data and does not have any adjustments made to account for distributed PV generation or capacitor kVAR injection.

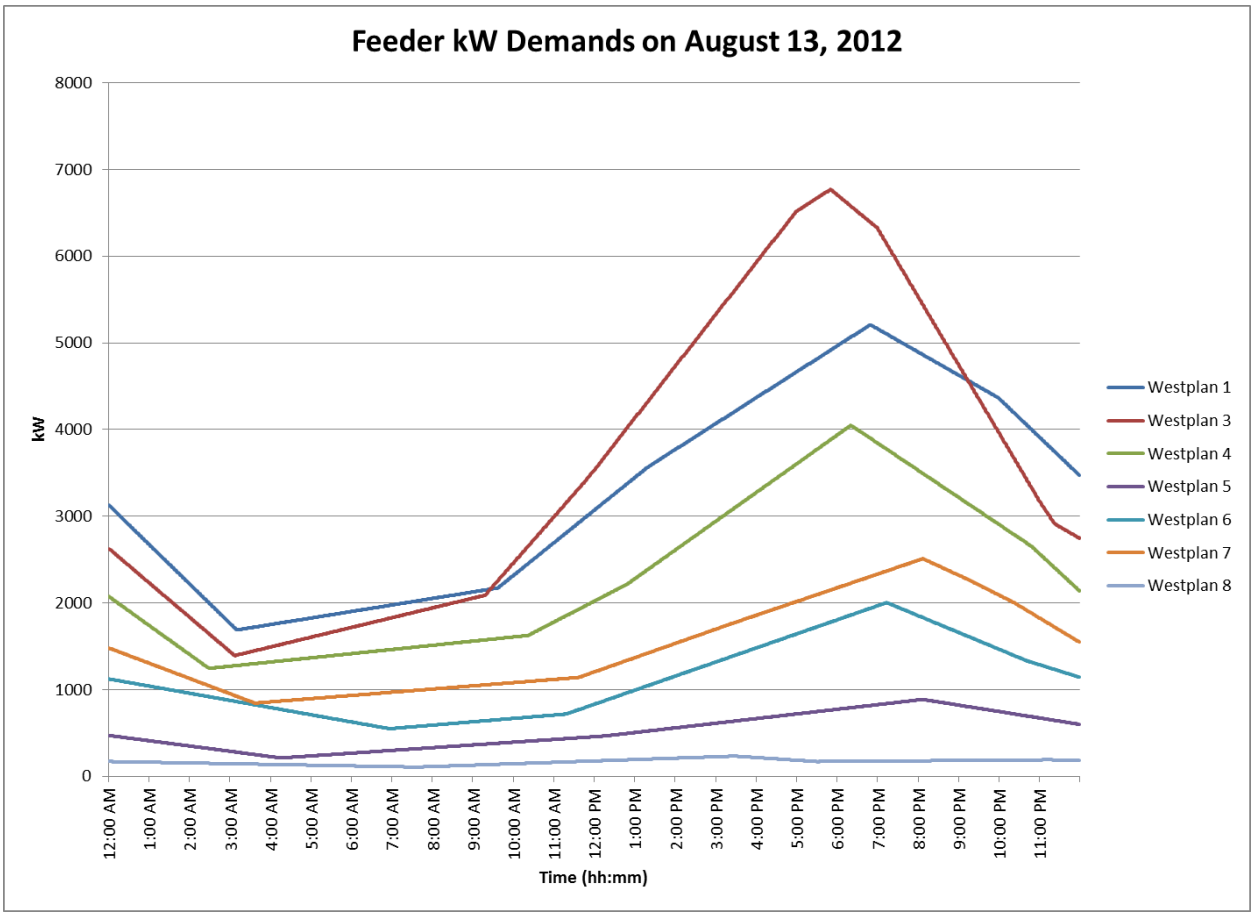

Figure 4.1: Westplan Feeder Demands on Peak Day 8/13/12

Figure 4.2 shows the minimum demand day profiles for the Westplan feeders at 1-minute resolution. Just as for Figure 4.1, the minimum demand profile is derived directly from the measured SCADA data, and does not have any adjustments to account for distributed PV generation or capacitor kVAR injection. Note that for the minimum demand of Westplan 8, the demand becomes negative between 1PM and 2PM, indicating backfeeding during high solar irradiance. This indicates a significantly high penetration of PV already exists on Westplan 8.

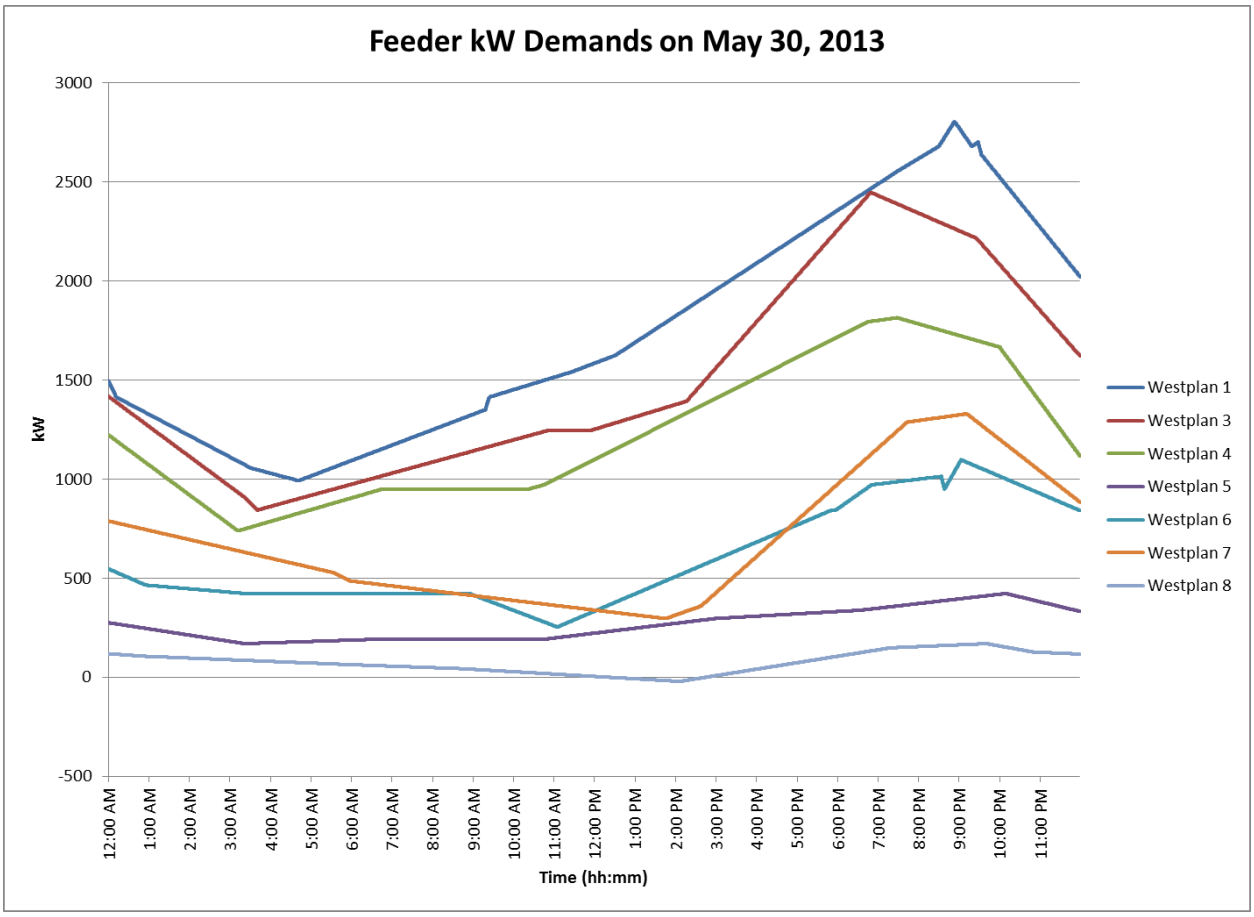

Figure 4.2: Westplan Feeder Demands on Minimum Day 5/30/13

Table 4-1 shows the absolute peak and minimum demands – and the time of occurrence – for each Westplan feeder, as well as for the entire substation.

Table 4-1: 2012 Absolute Peak and Minimum Demands by Feeder

	Absolute Peak Demand 8/13/2012		Absolute Minimum Demand 5/30/2013	
Feeder	**Demand (kW)**	**Time**	**Demand (kW)**	**Time**
WEST PLAN 1	5,363	6:07 PM	992	4:40 AM
WEST PLAN 3	6,836	6:06 PM	844	3:40 AM
WEST PLAN 4	4,287	6:14 PM	739	3:11 AM
WEST PLAN 5	1,151	6:12 PM	169	3:21 AM
WEST PLAN 6	2,090	6:43 PM	254	11:04 AM
WEST PLAN 7	2,715	6:56 PM	296	1:45 PM
WEST PLAN 8	386	5:38 PM	-21	2:03 PM
Total	**22,440**	**6:11 PM**	**3,950**	**3:41 AM**

Table 4-2 shows the daytime peak and minimum demands – and the time of occurrence – for each Westplan feeder, as well as for the entire substation. The daytime hours are defined here as between 10AM and 2PM, when solar irradiance is typically above 750 W/m^2.

Table 4-2: 2012 Daytime Peak and Minimum Demands by Feeder

	Daytime Peak Demand 8/13/2012		Daytime Minimum Demand 5/30/2013	
Feeder	**Demand (kW)**	**Time**	**Demand (kW)**	**Time**
WEST PLAN 1	3,972	1:58 PM	1,451	10:00 AM
WEST PLAN 3	4,855	1:59 PM	1,198	10:00 AM
WEST PLAN 4	3,134	1:55 PM	950	10:00 AM
WEST PLAN 5	752	1:59 PM	190	10:00 AM
WEST PLAN 6	1,525	1:58 PM	254	11:04 PM
WEST PLAN 7	2,097	1:54 PM	296	1:45 PM
WEST PLAN 8	288	1:57 PM	-20	1:59 PM
Total	**16,476**	**1:58 PM**	**4,542**	**10:00 AM**

Since SCADA real and reactive power measurements are three-phase measurements, in order to maintain the phase imbalances of the feeders, the three-phase power measurements are split among phases A, B, and C in the SynerGEE model in proportion to the respective measured phase currents.

4.2 Existing PV Generation

The existing PV generating capacity as of August 2012 is added to the base case Westplan model and held constant. The instantaneous generation from existing PV generators changes only with time-varying irradiance. The existing PV locations in the Westplan model are selected using a geographical PV placement tool developed by DNV KEMA. The tool uses the street address of each PV site and feeder designation. The street address is converted to X & Y coordinates in the California Zone II State Plane Coordinate System. The feeder designation for each PV unit is determined from distribution transformer information, i.e. by comparing the "Transformer #" (column B in *pv.xlsx*) to the "InstDTrans" Access table of the full Roseville SynerGEE model dataset. The PV placement tool matches each PV unit to the closest SynerGEE node within the correct feeder. The result of the PV placement tool is that 94% of the existing PV units are placed within 300 feet of the distribution transformer it is known to be fed by, indicating the PV placement tool is reliably accurate.

There are 829 existing PV units in the Westplan model, with a total kW capacity of 1,653 kW. The amount of PV on each Westplan feeder, along with the % PV penetration per feeder, is shown in Table 4-3. The % PV penetration is the ratio of total PV to the peak demand of the feeder. For an individual

feeder, the peak demand is the non-coincident peak, and for the whole Westplan substation ("Total" below) the peak demand is the coincident peak of all feeder demands combined.

Table 4-3: Westplan Existing PV Summary

Feeder	PV Count	Total PV (kW)	Peak Demand (kW)	% PV Penetration
WEST PLAN 1	8	30	5,360	0.6%
WEST PLAN 3	6	16	6,835	0.2%
WEST PLAN 4	228	443	4,287	10.3%
WEST PLAN 5	2	13	1,150	1.1%
WEST PLAN 6	216	428	2,090	20.5%
WEST PLAN 7	306	601	2,715	22.1%
WEST PLAN 8	63	122	380	32.1%
Total	**829**	**1653**	**22,292**	**7.4%**

4.3 Potential PV Generation

The future potential PV generation does not exist on the Westplan system, but is a fundamental part of the PV penetration study. Modeling and simulating load flows with the existing PV generation in the Westplan model is only the starting point of the study. The penetration of total distributed PV generation in the Westplan model is increased to stress the system.

There are many methods to extrapolate the distributed PV in the Westplan model (or any model for that matter) to see PV penetration issues. For example, the existing PV generator capacities can be scaled up, additional PV generators can be added at new locations in the model, or a combination of both. The capacities of new or increased PV generators depend on available information regarding PV expected to interconnect to the Westplan system in the future, such as a generator interconnection queue.

Given the limited information as to the sizes and locations of future PV generation, the methodology chosen to allocate potential PV to the Westplan feeders is as follows. The maximum potential PV capacity on each distribution feeder is chosen to be 100% of the non-coincident peak load for that feeder. This is a very high potential PV penetration scenario, but is chosen for this analysis to force system limitations to occur. For each feeder, the potential PV is distributed proportionally to customer locations across the feeder according to the connected kVA (c.kVA) value of the customer load as in Equation 1. The c.kVA approximates the maximum load at the customer location. Note that a customer location in the Westplan model may be the aggregate of multiple individual customers that are electrically connected in a small area such as a neighborhood.

$$kW\ of\ potential\ PV\ on\ a\ section = (total\ kW\ of\ potential\ PV\ on\ feeder) \cdot \frac{(c.kVA\ at\ customer\ site)}{(total\ c.kVA\ on\ feeder)} \quad (1)$$

With slight modifications, this methodology is used to create and simulate a variety of potential PV distributions from very highly distributed (numerous smaller PV generators) to highly concentrated (a few very large PV generators). For this study, a large number of smaller potential PV generators are distributed along the feeders because the majority of future PV generation is expected to be residential.

4.4 Twenty-Four Hour Load Flow Analysis

A twenty-four hour load flow analysis is performed for both maximum daytime peak and minimum daytime peak demand days. Due to the amount of computation time for each load flow, only the top peak load of each hour is simulated. For each hour, the unbalanced 60 kV voltage sources and unbalanced feeder demands from SCADA are input to the model. In addition, measured irradiance is changed hour by hour and applied to each PV generator. The capacity of potential PV generation is increased incrementally so that the total PV penetration sweeps from the existing PV (base case) to 100% PV penetration. Potential PV penetration is increased in increments of roughly 10% penetration. The analysis steps through each hour of the day for each time the potential PV is increased.

4.5 One-Minute PV Ramp Analysis

The One-Minute PV Ramp Analysis involves simulating large changes in PV generation that may occur within a one-minute interval. Since the LTCs operate on a one-minute delay, these are not capable of regulating voltage in response to such rapid changes in PV generation and corresponding changes in net demand. During the one-minute interval, the transformer tap position remains fixed. Under this condition, low voltages can occur under a rapid decrease in PV generation, and high voltages can occur in the case of a rapid increase in PV generation. For this analysis, the following worst-case scenarios are considered:

1. Minimum Demand Day at 1PM
2. Peak Demand Day at 6PM
3. Future Minimum Demand
4. Future Peak Demand

The future demand scenarios are added to this analysis because the demand on the feeders is expected to increase over time concurrently with future PV installations. These scenarios are not included in the Twenty-Four Hour Load Flow Analysis because daily profiles do not exist. Table 4-4 shows the total future load on each feeder for the Future Peak Demand scenario. This total future load is comprised of a "future build out load" added to the 2012 peak feeder load. The future build out load for a feeder is added to the end of the feeder as an aggregate spot load. Both the sizes and locations of future build out loads

are specified by Roseville Electric. Each spot load modeled as a future build out load is connected to the end of the feeder by a 750 MCM underground conductor specified by Roseville Electric.

Table 4-4: Future Peak Demands

Feeder	2012 Peak Demand (kVA)	Existing PV (kW)	2012 Peak Load (kVA)	Future Build Out Load (kVA)	Total Future Load (kVA)	% of Feeder kVA Capacity
WESTPLAN 1	5,045	30	5,117	267	5,384	64%
WESTPLAN 3	6,719	16	6,748	-	6,748	80%
WESTPLAN 4	4,445	443	4,777	2,107	6,884	81%
WESTPLAN 5	1,001	13	1,021	5,024	6,046	72%
WESTPLAN 6	2,268	428	2,761	4,007	6,768	80%
WESTPLAN 7	2,801	601	2,808	3,903	6,711	79%
WESTPLAN 8	300	122	296	5,981	6,277	74%

Table 4-5 shows the total future load on each feeder for the Future Minimum Demand scenario. This total future load is comprised of half of the peak future build out load added to the 2013 minimum feeder load.

Table 4-5: Future Minimum Demands

Feeder	2013 Min Daytime Demand (kVA)	Existing PV (kW)	2013 Min Daytime Load (kVA)	Future Build Out Load (kVA)	Total Future Load (kVA)	% of Feeder kVA Capacity
WESTPLAN 1	1,727	30	1,736	134	1,870	22%
WESTPLAN 3	1,856	16	1,502	-	1,502	18%
WESTPLAN 4	1,659	443	1,647	1,054	2,700	32%
WESTPLAN 5	290	13	302	2,512	2,814	33%
WESTPLAN 6	868	428	849	2,004	2,853	34%
WESTPLAN 7	921	601	913	1,952	2,865	34%
WESTPLAN 8	139	122	119	2,990	3,110	37%

To stay consistent with the PV modeling of the existing feeder, both existing and potential PV generations are added as aggregate PV generators to the future build out locations. The size of the existing PV generator on the future build out of each feeder is equivalent to a certain percentage of the future build out spot load. This percentage is carried over from the existing PV percent penetration as given in Table 4-3. The potential PV generator is increased up to 100% of the future build out spot load. The One-Minute PV Ramp Analysis considers PV generation ramping both up and down within one minute. The PV generation ramps chosen are as follows:

1. PV ramp down from 100% output to 30% output
2. PV ramp down from 100% output to 20% output

3. PV ramp down from 100% output to 0% output
4. PV ramp up from 30% output to 100% output
5. PV ramp up from 20% output to 100% output
6. PV ramp up from 0% output to 100% output

PV ramps to and from 30% output approximate a large change in PV generation due to a change in solar irradiance that is likely to occur frequently. PV ramps to and from 20% output approximate a large change in PV generation due to a change in solar irradiance that is likely to occur less frequently. PV ramps from 100% to 0% output approximate a large change in PV generation due to PV tripping off-line due to a substation, bus or transmission trip or outage. This occurs because distributed PV generators are required to disconnect at 59.3 Hz to conform to IEEE Standard 1547. PV ramps from 0% to 100% output approximate a large change in PV generation due to PV reconnecting after such an outage event. This can occur because distributed PV generators are required by UL 1741 to wait to reconnect until at least five minutes after system frequency and voltage return to normal. During this five minute period, the LTC has sufficient time to adjust its tap position to account for the lack of PV generation.

For each of the six PV ramps, a load flow is completed with the LTCs enabled (automatic voltage regulation) with the first state of PV output. Then the PV output is transitioned to the second state, and a second load flow is completed with the LTCs disabled (transformer tap positions fixed as in the first load flow) to simulate voltage deviations within the one-minute LTC delay period. Finally, a third load flow is completed with the LTCs enabled to adjust the tap position in response to the change in PV generation.

5. Model Validation

Model validation is collecting real-time measurements of power flow (e.g. current, voltage, real power, and reactive power) at two or more locations within the WESTPLAN system, inputting measured values appropriately into the SynerGEE model, and comparing SynerGEE load flow results to the measured values. Time-synced measured values input to the SynerGEE model include:

1. voltage at 60 kV voltage source (unbalanced three-phase voltages),
2. voltage setting for substation transformer LTCs (unbalanced three-phase voltages), and
3. distribution feeder demands (unbalanced three-phase currents and power factor).

The SCADA measurement locations for the three types of SynerGEE input are shown in Figure 5.1.

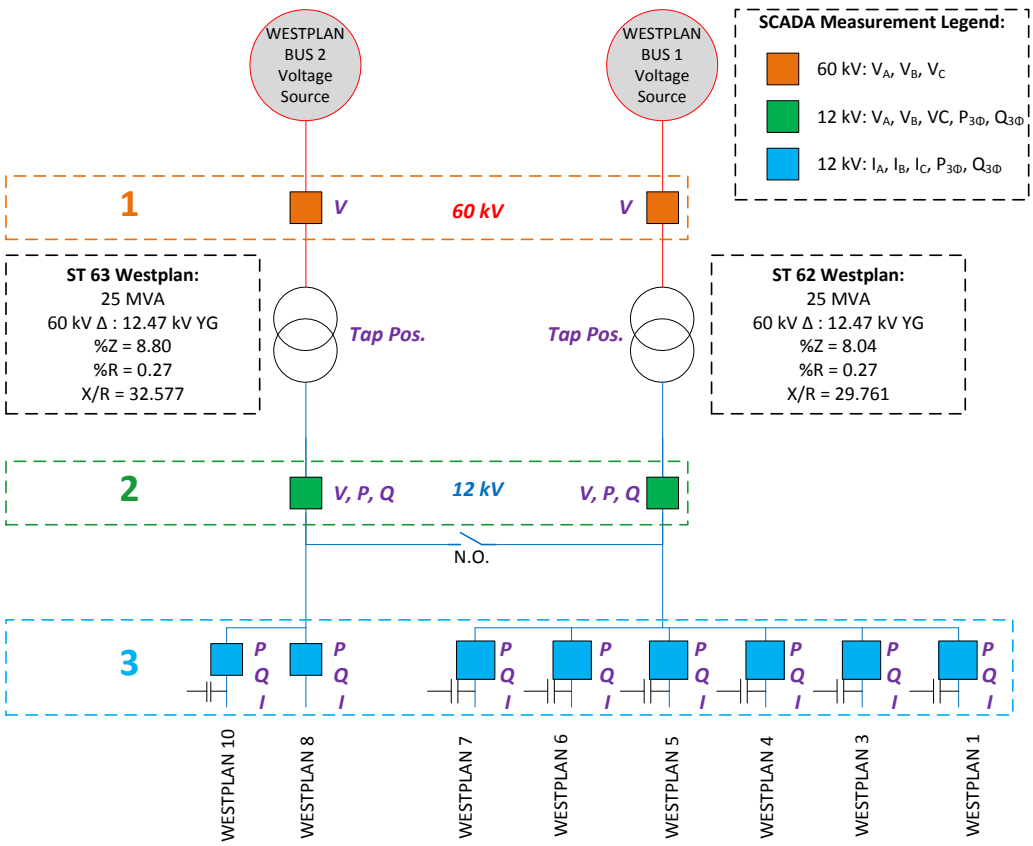

Figure 5.1: Westplan Substation, SCADA Data Locations

5.1 Methodology

The model validation methodology is a relatively straightforward procedure with the following steps:

1. Input time-synced measured values into the SynerGEE model (either manually, or automatically with a combination of recipe & script commands)
2. Change model simulation hour to the time of interest to capture time-varying irradiance and temperature
3. Run Load Allocation
4. Run Load Flow
5. Export Load Flow results to .csv files
6. Import selected Load Flow results from .csv files into an Excel workbook
7. Compute % error between simulated Load Flow results and measured values for selected results

This model validation procedure can be repeated for any series of timestamps of measured power flow data. For the Westplan base case model, the chosen timestamps are the top of each hour throughout either the peak or minimum demand day. The range of hours simulated is 6AM to 6PM because measured irradiance and temperature data is limited beyond this range, and there is little to no PV generation outside of this range. For validation of the Westplan base case model, a recipe (in SynerGEE format) is created to automatically process multiple timestamps, since this procedure can be time-consuming if done manually.

The hourly irradiance profiles control PV generation in SynerGEE and the temperature profiles control temperature-controlled capacitors, as shown in Figure 3.1. Currently, capacitors in the Westplan model remain in their original ON/OFF status, and existing PV generation are turned ON during the model validation process. The actual capacitor status and kVAR injection hour to hour is controlled either by the temperature profile included in the base case model, or voltage (depending on capacitor control settings defined in Table 7-2). The PV generation hour to hour is controlled by the irradiance profile for the day simulated. Currently, the same irradiance profile is applied to all PV generation since Westplan irradiance measurements are not available in August 2012. In addition, since temperature measurements from August 2012 are not available, the temperature in August 2012 is assumed to be high enough to turn on temperature-controlled capacitors. In the future, as additional irradiance sensors are deployed at various geographical locations, the irradiance profiles applied to PV generation can vary to capture geospatial variation of PV generation, hour by hour. It is not necessary to manually add estimated PV generation to the measured SCADA demands to approximate natural load prior to running Load Allocation. If PV generators are turned on prior to running the Load Allocation tool, this is done automatically.

5.2 Model Accuracy

The process of model validation is used to quantify the accuracy of a SynerGEE model by comparing simulated system results to real world measured system values. During the last step, comparing % error between simulated results and measured values, the % errors indicate the level of accuracy of one of two things depending on if the measured value is used as a SynerGEE input during the validation process.

1. **Validation parameter**: A measured value which **is** an input to SynerGEE. The % error for this measured value indicates the accuracy of the *model validation process*.
2. **Independent parameter**: A measured value which **is not** an input to SynerGEE. The % error for this measured value indicates the accuracy of the *SynerGEE model*.

Figure 5.2 shows where the validation parameters (measured SCADA values described in Figure 5.1) are input into the SynerGEE model. These values represent the minimum amount of measured data needed to apply an accurate model validation process to the Westplan model. For quantifying model accuracy, independent parameters are needed, that are additional measured values beyond what is represented in Figure 5.2. These additional values can be either different quantities measured by SCADA at the substation but not used as SynerGEE inputs, or similar quantities measured elsewhere in the Westplan region.

The independent parameters for the Westplan model are the tap positions of the two substation transformers and the 12 kV voltages at the beginning of the distribution feeders. For the minimum demand day, additional independent parameters include the 240 V voltages at select customer locations identified in Table 3-2.

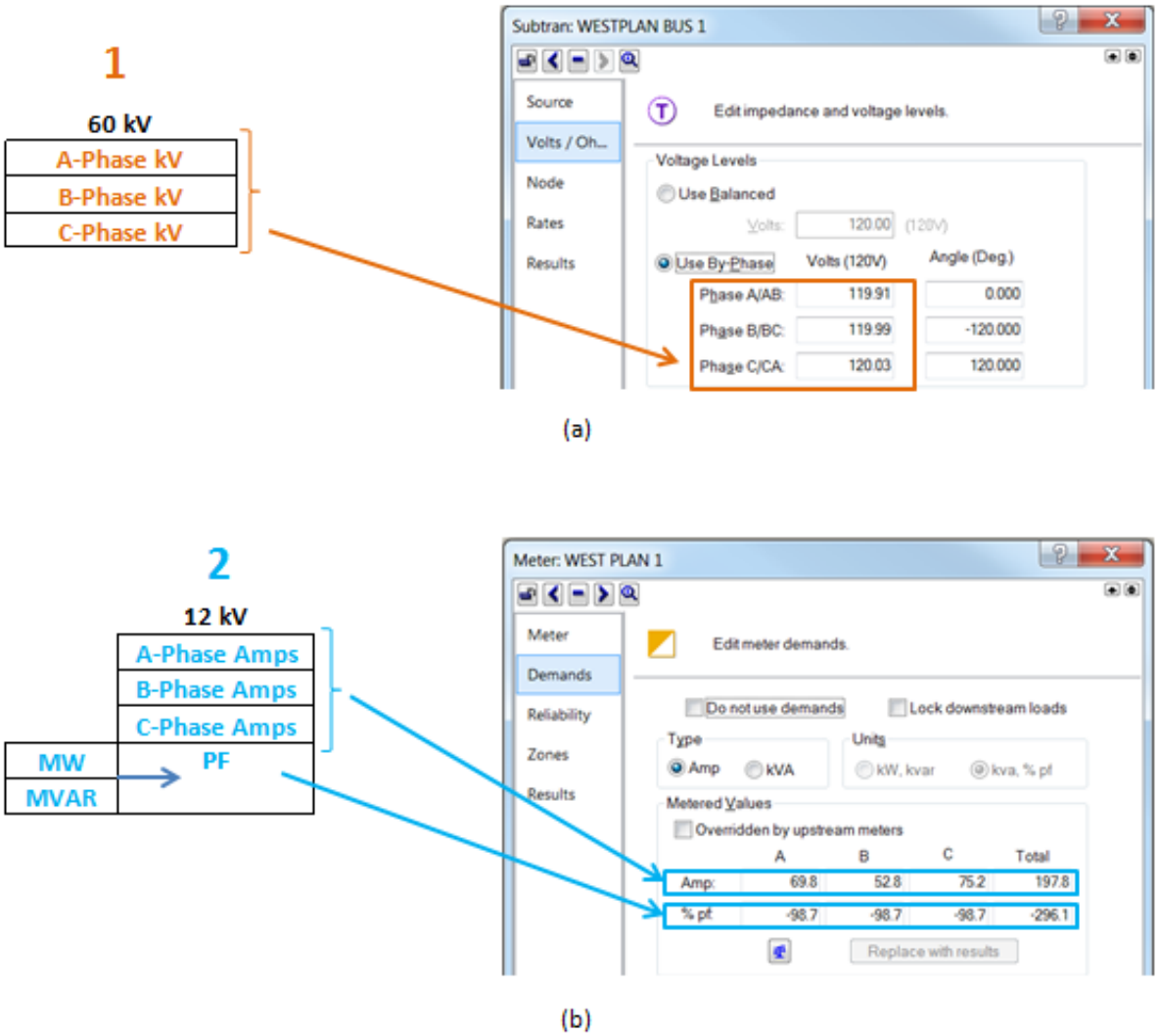

Figure 5.2: Locations in SynerGEE Model to Input SCADA Data for Model Validation

5.3 Results of Westplan Model Validation

Figure 5.3 shows the % error of the simulated feeder demands with respect to the measured feeder demands for the peak demand day. The real power % error is very small, within 2%, and the reactive power % error is within 5% for all feeders except for Westplan 5 and Westplan 8. One explanation why these two feeders exhibit higher % error is because both feeders also exhibit a much higher feeder imbalance.

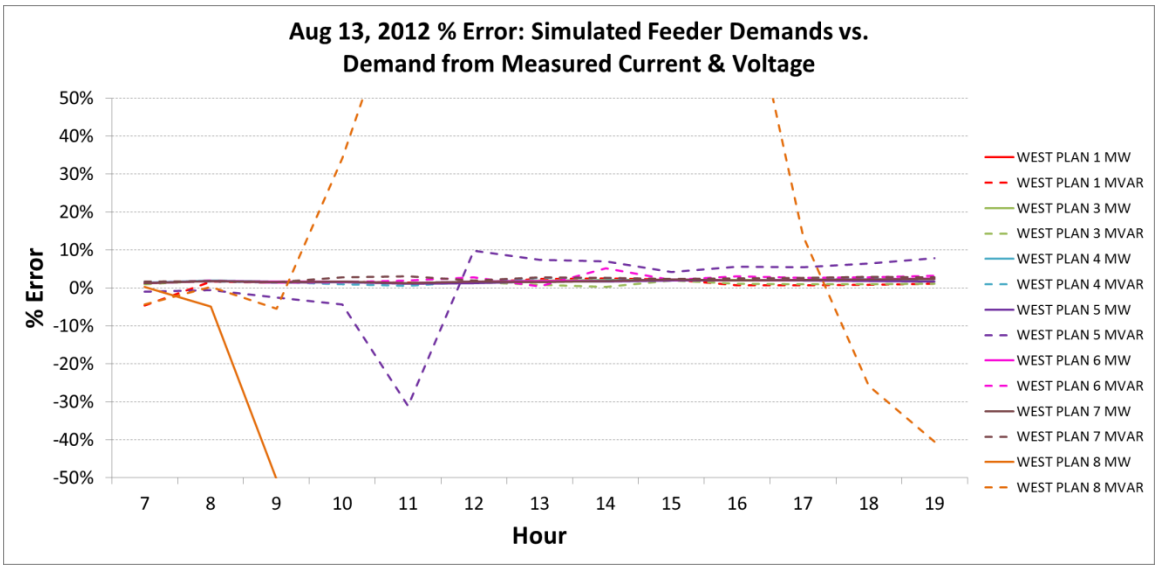

Figure 5.3: Comparison of Simulated and Measured Feeder Demand for Peak Day

Figure 5.4 shows the difference between the measured ("SCADA") and simulated ("SG") tap positions of the LTC for substation transformer ST 62 by hour for the peak day. The plots of SCADA and SG tap positions follow a similar shape, but the SG tap position is consistently higher than the SCADA by somewhere between 2.6 and 3.6. For reliable study results, the tap position of ST 62 should remain within +/- 12 (as opposed to +/- 16) to account for a conservative four tap position difference.

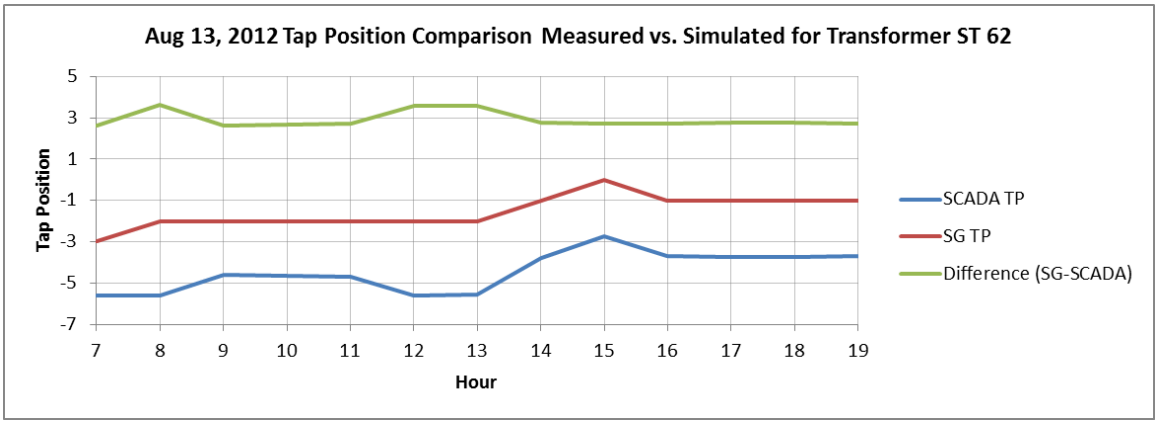

Figure 5.4: Comparison of Simulated and Measured Tap Position for ST 62 on Peak Day

Figure 5.5 shows the difference between the SCADA and SG tap positions of the LTC for substation transformer ST 63 by hour for the peak day. The SCADA and SG tap positions are closer for ST 63 than

for ST 62. For ST 63, the SG tap position is consistently higher than the SCADA by somewhere between 0.8 and 1.9. For reliable study results, the tap position of ST 63 should remain within +/- 14 (as opposed to +/- 16) to account for a conservative two tap position difference.

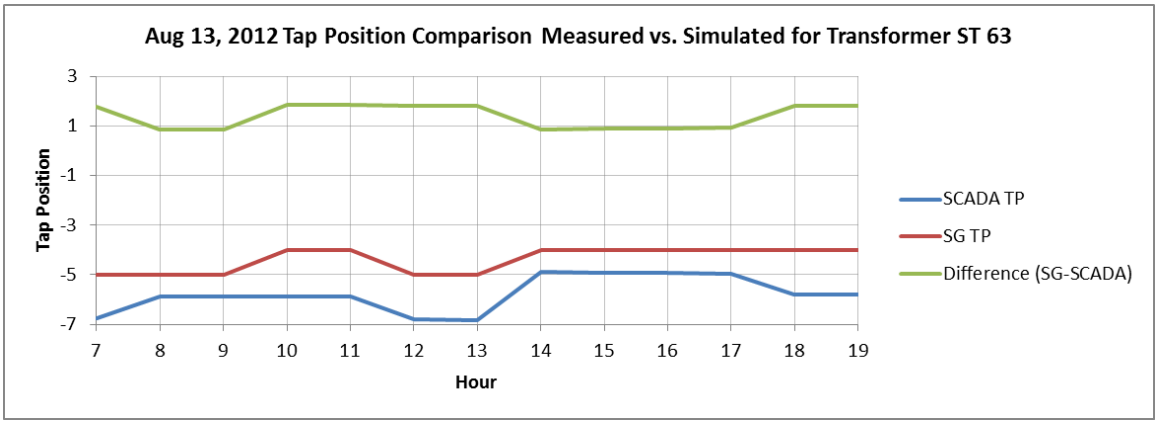

Figure 5.5: Comparison of Simulated and Measured Tap Position for ST 63 on Peak Day

Figure 5.6 shows the phase A, B, and C currents and % imbalance for Westplan 5 on the peak demand day. Notice that phases B and C follow the same profile closely and peak above 60 amperes, while phase A is greatly less, peaking at around 10 amperes. The % imbalance hovers around 50% which is close to the 45% imbalance represented in the base case model by the c.kVA (see).

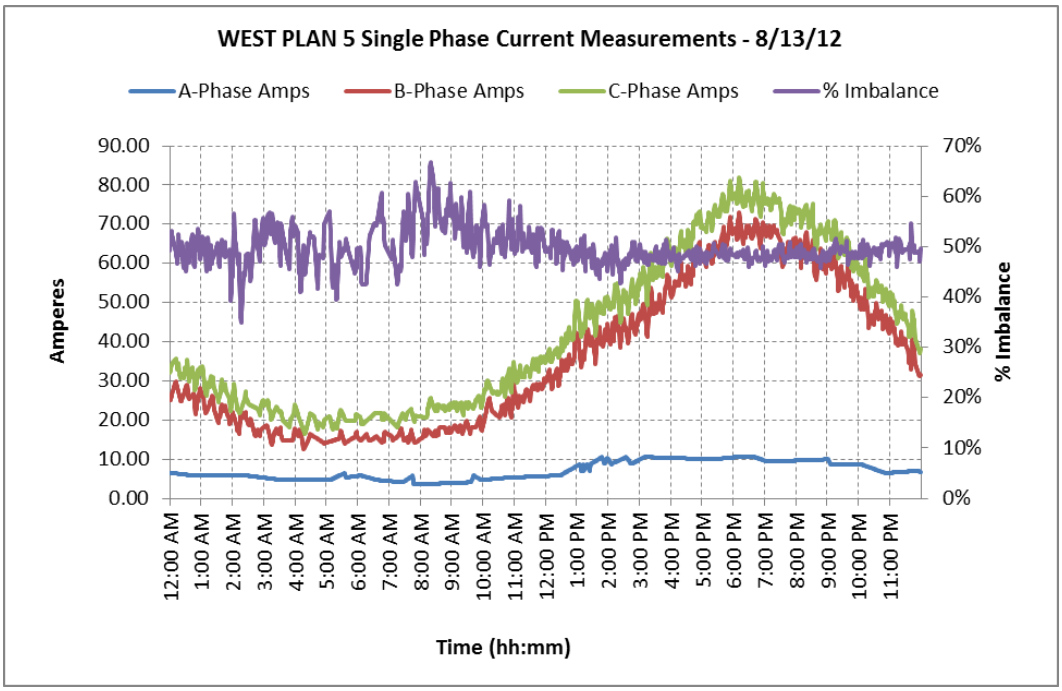

Figure 5.6: Westplan 5 Phase Currents and % Imbalance for Peak Demand Day

Figure 5.7 shows the phase A, B, and C currents and % imbalance for Westplan 8 on the peak demand day. Notice that phases B and C follow the same profile more closely than phase A, and phase A is very significantly lower than either phase B or C. The % imbalance hovers around 50% which is consistent with the 50% imbalance represented in the base case model by the c.kVA (see

Table 7-1). Figure 5.7 can help explain why the % errors for Westplan 8 in Figure 5.3 are dramatically higher than all other feeders (including Westplan 5). The highly imbalanced, low phase currents of Westplan 8 cause difficulty in accurately simulating the phase demands in SynerGEE.

After Load Allocation is run, a measurement of the error of the Load Allocation is given, and in the case of Westplan 5 and Westplan 8, this error is much higher than the other feeders. This higher error is due to limitations of the SynerGEE load flow engine to reach convergence amidst high feeder imbalances.

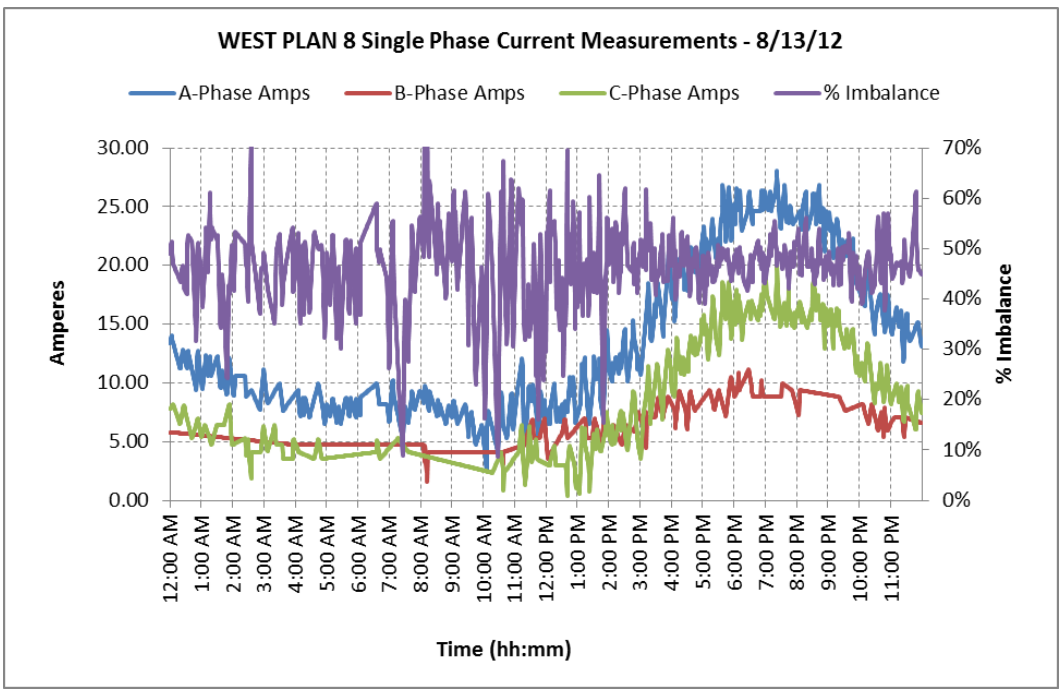

Figure 5.7: Westplan 8 Phase Currents and % Imbalance for Peak Demand Day

Figure 5.8 shows the % error of the simulated feeder demands with respect to the measured feeder demands for the minimum demand day. The real power % error is very small, within 2%, and the reactive power % error is within 5% for all feeders except for Westplan 8. The same issues with high feeder imbalance and low phase currents are seen with Westplan 8 for the minimum demand day.

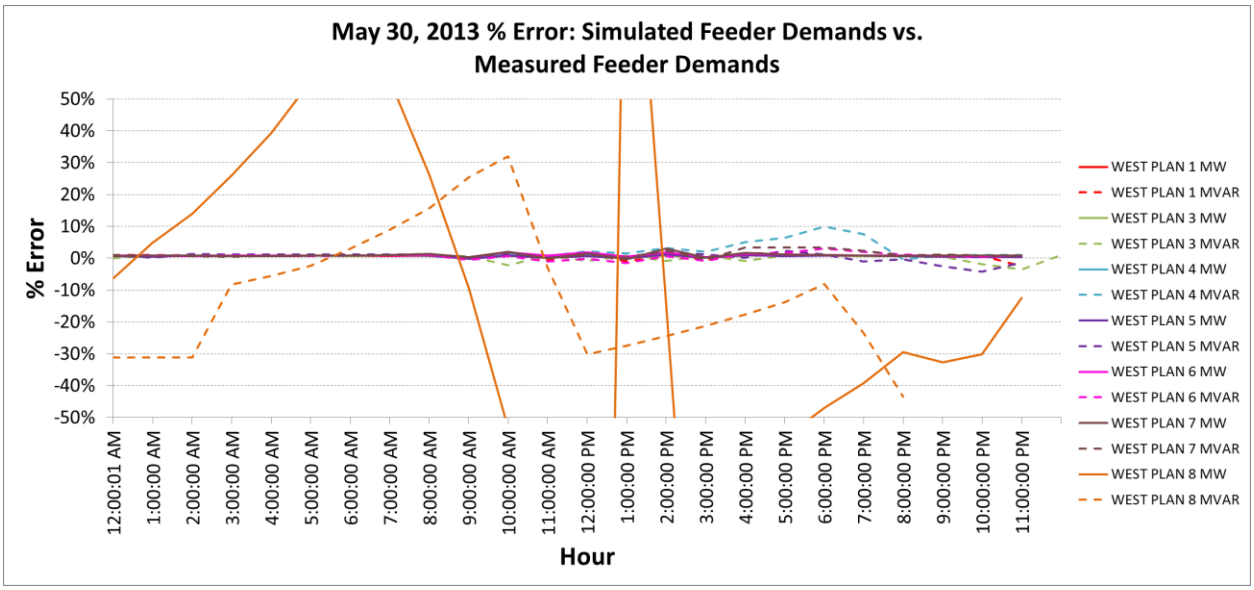

Figure 5.8: Comparison of Simulated and Measured Feeder Demand for Minimum Day

Figure 5.9 shows the difference between the SCADA and SG tap positions of the LTC for ST 62 by hour for the minimum day. The plots of the SCADA and SG tap positions follow a similar shape, but less similar than for the peak day. The difference in tap ranges between 1 and 3.

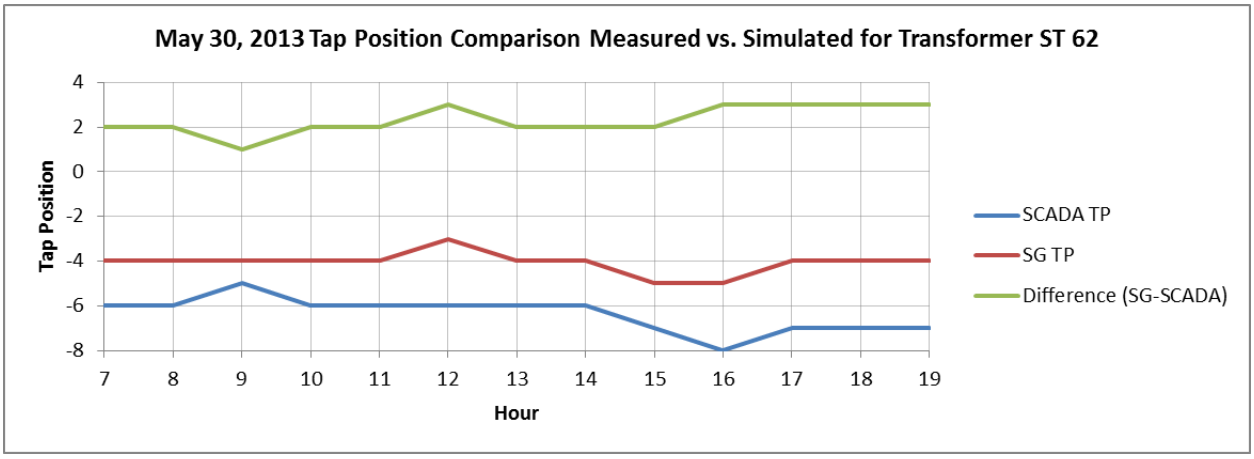

Figure 5.9: Comparison of Simulated and Measured Tap Position for ST 62 on Minimum Day

Figure 5.10 shows the difference between the SCADA and SG tap positions of the LTC for ST 63 by hour for the minimum day. The difference in tap position ranges between 1.8 and 2.5.

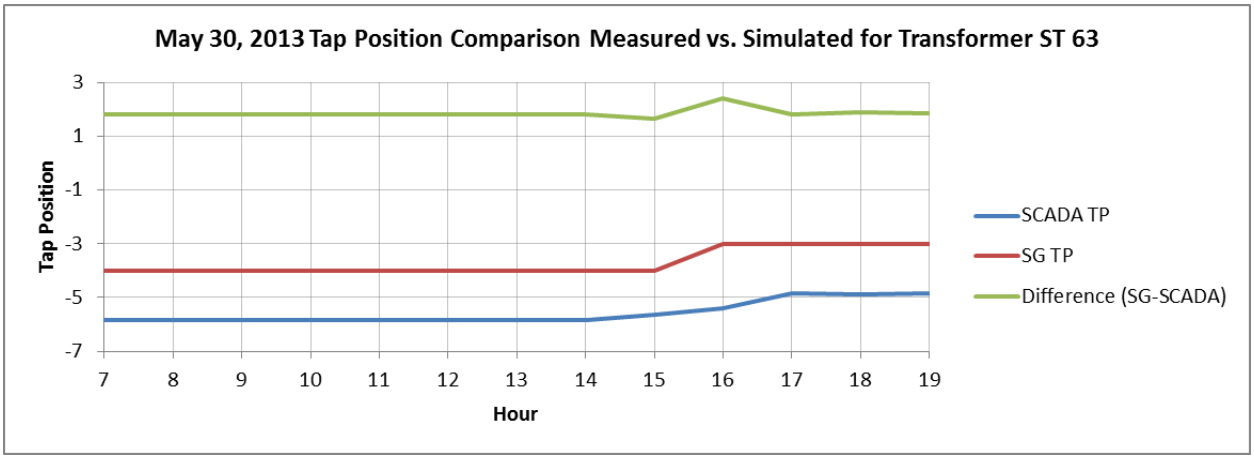

Figure 5.10: Comparison of Simulated and Measured Tap Position for ST 63 on Minimum Day

Figure 5.11 shows that the simulated customer voltages are all within a plus or minus five percent error band when compared to the measured customer voltages. This is a strong indication that the feeder topologies and impedances are accurate, and that customer voltages simulated in the PV penetration study are reliably accurate.

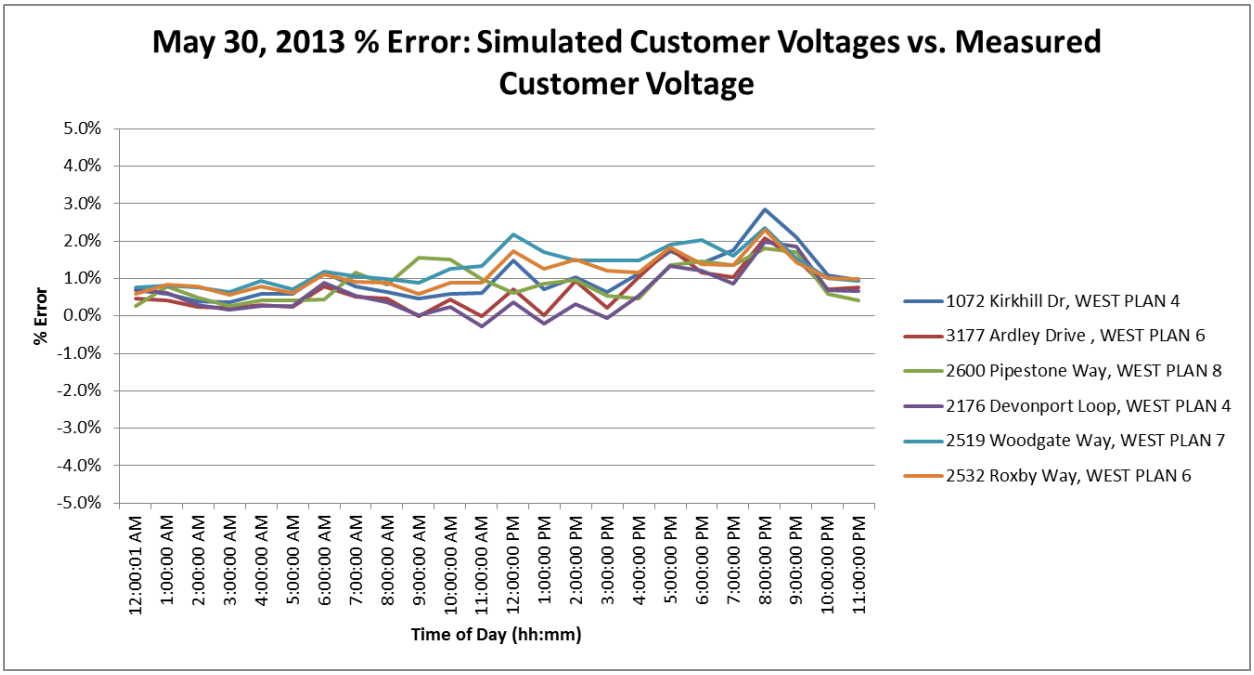

Figure 5.11: Simulated vs. Measured Customer Voltage

6. Results

6.1 Twenty-Four Hour Load Flow Analysis Results

There are no voltage violations in any hour in either the peak or minimum demand day, even at 100% PV penetration. The substation transformer LTCs never reach a tap position limit and are able to regulate voltage at each level of PV penetration. The feeder utilization for both peak and minimum demand days is relatively low for each feeder. Figure 6.1 shows the percent loading of conductors in the Westplan system on the peak demand day at the peak time of 6PM with no PV generation. Even with the representative peak load that exists today, most of the system is loaded at less than 40%. Consequently the equivalent impedance between the beginning and end of each feeder, as well as the voltage drop, is relatively low. During periods of backfeeding (high PV penetration at low load), the distributed PV generators create voltage rises near the ends of the feeders, but not enough to exceed the 126 V limit.

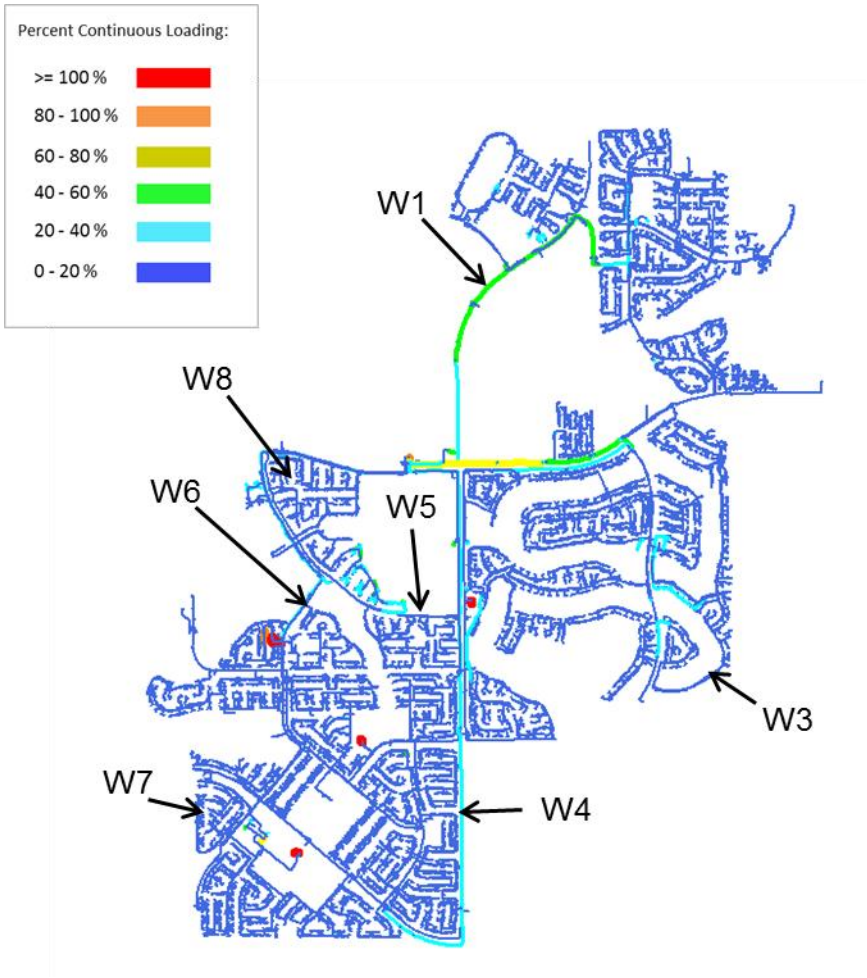

Figure 6.1: Westplan System Loading at 6PM on Peak Day, No PV Generation

The only potential issue identified from the Twenty-Four Hour Load Flow Analysis is the occurrence of backfeeding when total PV generation exceeds system load. Figure 6.2 depicts an example of backfeeding at ST 62 that occurs on the minimum demand day with 33% PV penetration across all feeders. The green dotted line is the actual load downstream of the transformer, and the blue line is the net demand at the transformer. The red plot is the total PV generation on Westplan 1, 3, 4, 5, 6, and 7, and is enough to cause backfeeding between 11AM and 2PM. Note that when the net kW demand is low the tap position more closely follows the changes in kVAR demand.

Backfeeding at the substation transformer can cause voltage regulation and protection devices at the substation to operate incorrectly if the devices are not designed or planned for backfeeding. This is not likely a limiting factor for Westplan since ST 63 (which feeds Westplan 8) already experiences backfeeding at the existing PV penetration of 32%. However, if backfeeding is to become frequent and widespread, further study (such as a protection coordination study) under this condition may be needed to ensure all devices will operate as expected.

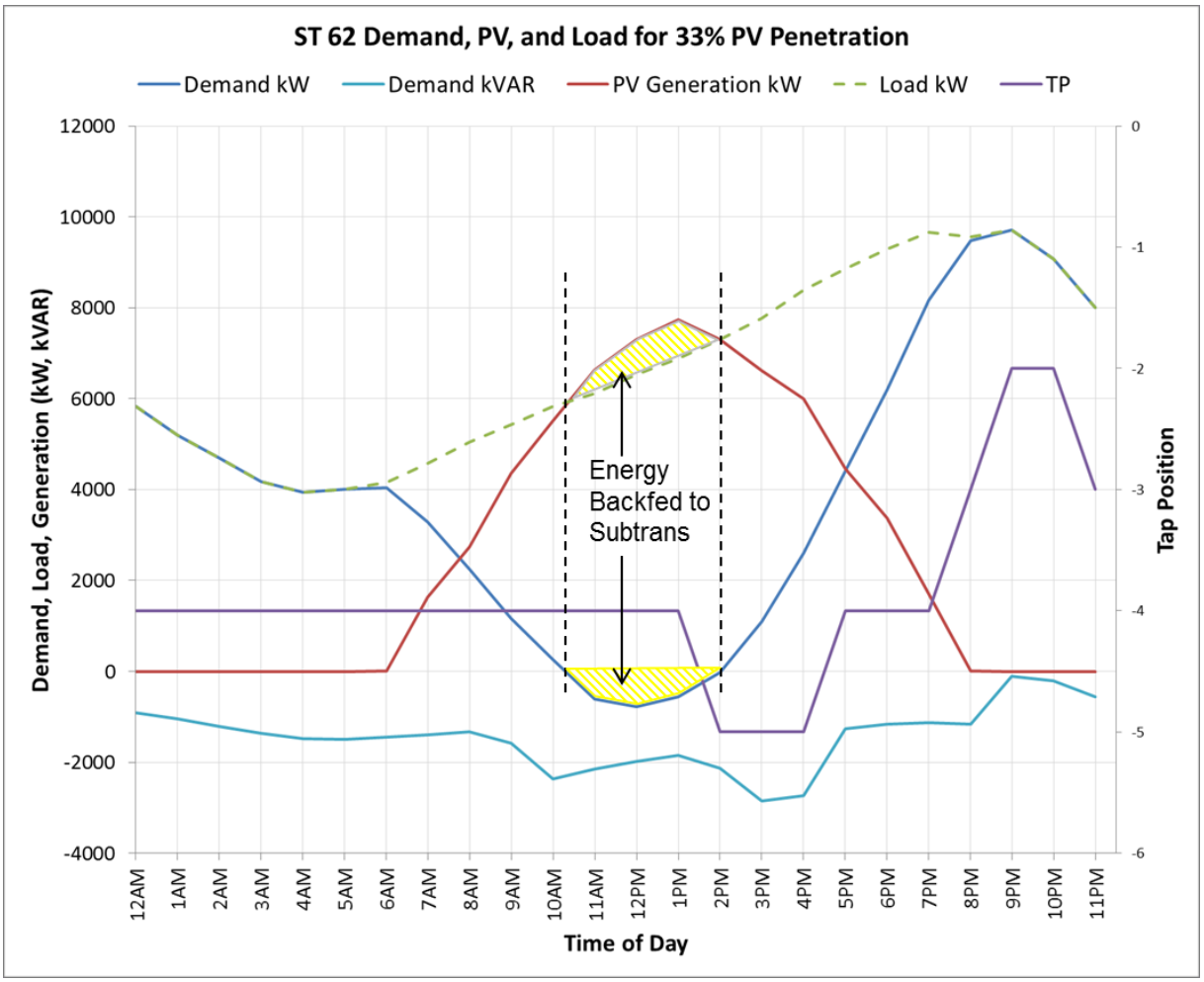

Figure 6.2: Backfeeding Scenario for ST 62

6.2 One-Minute PV Ramp Analysis Results

The One-Minute PV Ramp Analysis considers rapid decreases (ramp down) and increases (ramp up) of PV. No voltage violations are found for any ramp down scenario even in the worst-case transition from 100% to 0% output. There are, however, a number of voltage violations for the ramp up transitions from 20% to 100% output and from 0% to 100% output. Figure 6.3 provides some insight into the reasons why voltage issues occur when PV ramps up and not when PV ramps down.

The target voltage that both transformer LTCs regulate is 122 V. This target voltage is the starting point for the first state of PV output in each of the six PV ramps. Since the target voltage is closer to the 126 V upper voltage limit, there is a greater risk of high voltage violations occurring due to PV ramping up.

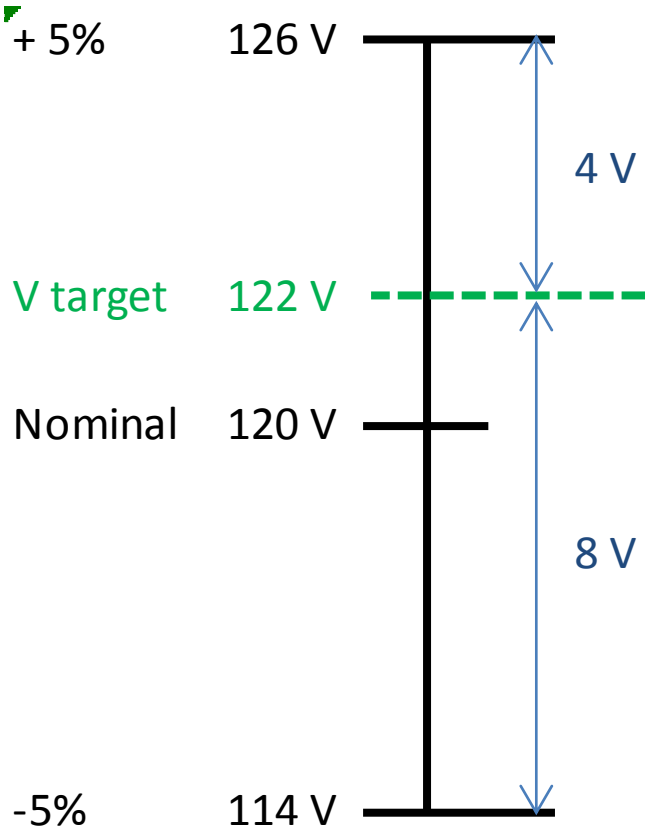

Figure 6.3: Substation LTC Voltage Target Shown Within Standard Voltage Range

6.2.1 Minimum Demand Day

No voltage violations occurred for any of the six PV ramps for the 2012 minimum demand day. The loading of the feeder conductors during minimum demand is low enough to prevent significant voltage deviations even during the one-minute LTC delay period.

6.2.2 Peak Demand Day

No voltage violations occurred for any of the six PV ramps for the 2012 peak demand day. Again, the loading of the feeder conductors is low enough to prevent significant voltage deviations even during the one-minute LTC delay period.

6.2.3 Future Minimum Demand Day

No voltage violations occurred for any of the six PV ramps for the future minimum demand case. Again, the loading of the feeder conductors is low enough to prevent significant voltage deviations even during the one-minute LTC delay period.

6.2.4 Future Peak Demand Day

For the future peak demand case, the feeder loading is large enough, and the change in feeder demands are large enough when PV generation ramps up, to cause high voltages for certain penetrations of distributed PV. High voltages occur when PV is ramped up from 0% to 100% generation and from 20% to 100% generation. No high voltages occur when PV is ramped up from 30% to 100% generation. Also, no low voltages occur for any PV ramp down scenario.

Table 6-1 shows the PV penetrations at each feeder when high voltages first appear when PV is ramped up from 20% to 100% generation output. PV penetrations limits are shown for both balanced and unbalanced voltages. When the PV penetration limit for a balanced voltage differs from that of a particular phase on the same feeder, the lower PV penetration is taken to be the limit for that feeder. The lowest PV penetration limit for each feeder is highlighted yellow.

Table 6-1: PV Penetration Limits from High Voltage Constraints - PV Ramp Up - 20% to 100%

20% --> 100% PV Output				
Feeder	**Balanced 3P**	**Phase A**	**Phase B**	**Phase C**
WEST PLAN 1	70%	-	70%	100%
WEST PLAN 3	70%	80%	70%	-
WEST PLAN 4	80%	-	80%	-
WEST PLAN 5	-	-	-	-
WEST PLAN 6	-	-	-	-
WEST PLAN 7	-	-	-	-
WEST PLAN 8	-	-	-	-

Table 6-2 shows the number high voltages that occur at distribution transformers and PV customer locations for the PV penetrations given in Table 6-1. Nearly all high voltages in the system occur at either distribution transformers or PV customer locations, with the majority of high voltages occurring at PV customer locations.

Table 6-2: High Voltages at Distribution Transformers / PV Generators - PV Ramp Up - 20% to 100%

20% --> 100% PV Output				
Feeder	**Balanced 3P**	**Phase A**	**Phase B**	**Phase C**
WEST PLAN 1	0 / 2	-	1 / 2	1 / 6
WEST PLAN 3	0 / 81	7 / 37	14 / 81	-
WEST PLAN 4	0 / 123	-	23 / 123	-
WEST PLAN 5	-	-	-	-
WEST PLAN 6	-	-	-	-
WEST PLAN 7	-	-	-	-
WEST PLAN 8	-	-	-	-

Table 6-3 shows the PV penetrations at each feeder when high voltages begin to appear when PV is ramped up from 0% to 100% generation output. PV penetrations limits are shown for both balanced and unbalanced voltages. When the PV penetration limit for a balanced voltage differs from that of a particular phase on the same feeder, the lower PV penetration is taken to be the limit for that feeder. The lowest PV penetration limit for each feeder is highlighted yellow.

Table 6-3: PV Penetration Limits from High Voltage Constraints - PV Ramp Up - 0% to 100%

0% --> 100% PV Output				
Feeder	**Balanced 3P**	**Phase A**	**Phase B**	**Phase C**
WEST PLAN 1	50%	-	50%	70%
WEST PLAN 3	40%	60%	40%	70%
WEST PLAN 4	50%	80%	50%	-
WEST PLAN 5	50%	-	80%	50%
WEST PLAN 6	90%	110%	80%	-
WEST PLAN 7	90%	-	80%	90%
WEST PLAN 8	-	-	-	-

Table 6-4 shows the number high voltages that occur at distribution transformers and PV customer locations for the PV penetrations given in Table 6-3. Nearly all high voltages in the system occur at either distribution transformers or PV customer locations, with the majority of high voltages occurring at PV customer locations.

Table 6-4: High Voltages at Distribution Transformers / PV Generators - PV Ramp Up - 0% to 100%

0% --> 100% PV Output				
Feeder	**Balanced 3P**	**Phase A**	**Phase B**	**Phase C**
WEST PLAN 1	5 / 267	-	63 / 268	14 / 57
WEST PLAN 3	0 / 53	16 / 96	9 / 53	14 / 51
WEST PLAN 4	0 / 114	2 / 0	21 / 114	-
WEST PLAN 5	0 / 19	-	0 / 0*	3 / 19
WEST PLAN 6	0 / 0*	3 / 12	0 / 0*	-
WEST PLAN 7	0 / 0*	-	0 / 0*	5 / 51
WEST PLAN 8	-	-	-	-

Figure 6.4 shows a worst-case example of high voltage deviations when PV ramps up from 0% to 100% output with 100% PV penetration. Shown are the maximum voltages recorded on each feeder for each stage in the analysis procedure. The blue and green bars represent the maximum voltages after the LTCs have reached steady-state equilibrium for 0% and 100% PV output, respectively. The yellow bar represents the maximum voltages that occur after the PV output has changed but before the LTC has time to respond.

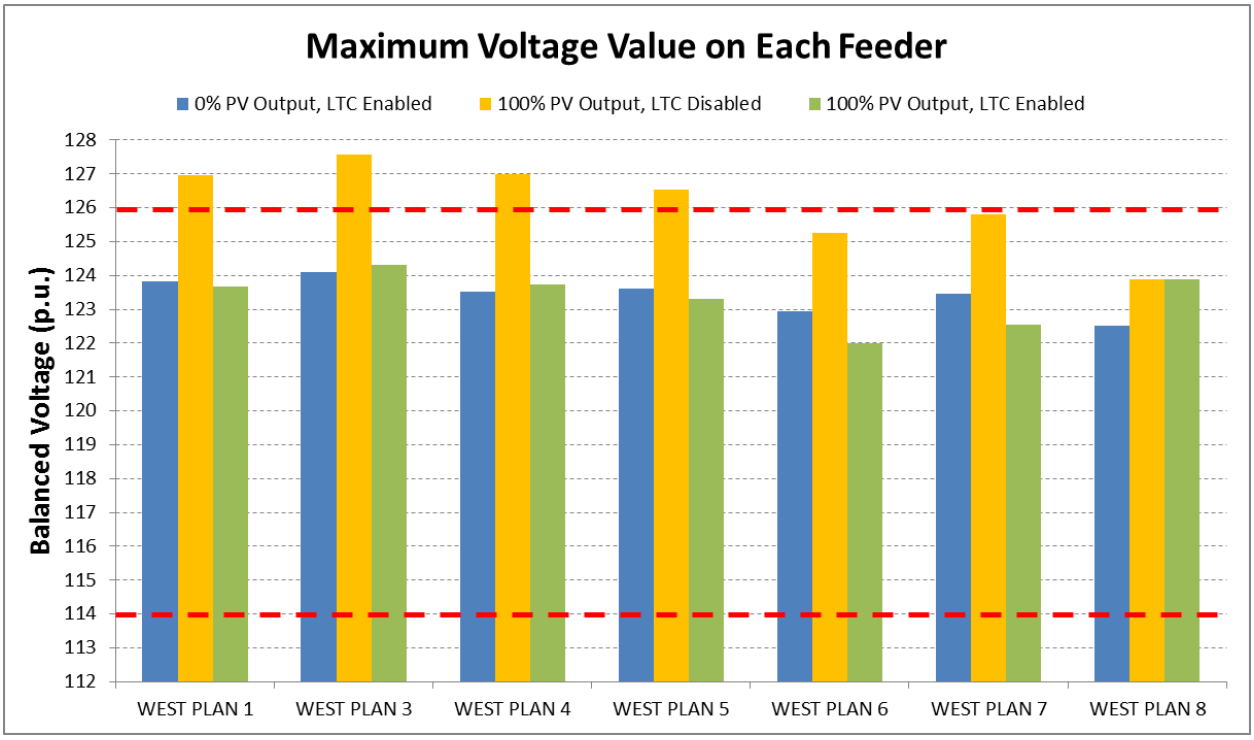

Figure 6.4: Maximum Voltage Per Feeder - PV Ramp Up - 0% to 100% Output

Figure 6.5 shows the tap positions and voltages at the secondary side of each substation transformer for the same scenario. A significant voltage deviation occurs at ST 62 because it is loaded more heavily by its six feeders (Westplan 1, 3, 4, 5, 6, and 7). In addition, once the LTC is able to respond to the change in PV output, four tap changes are needed to bring the voltage back to normal range. Since ST 63 feeds only Westplan 8 in the model, the voltage deviation is so small that it remains within the LTC bandwidth, and no tap change is needed once the LTC is able to respond. Consequently there were no voltage violations on Westplan 8 for any of the six PV ramp scenarios.

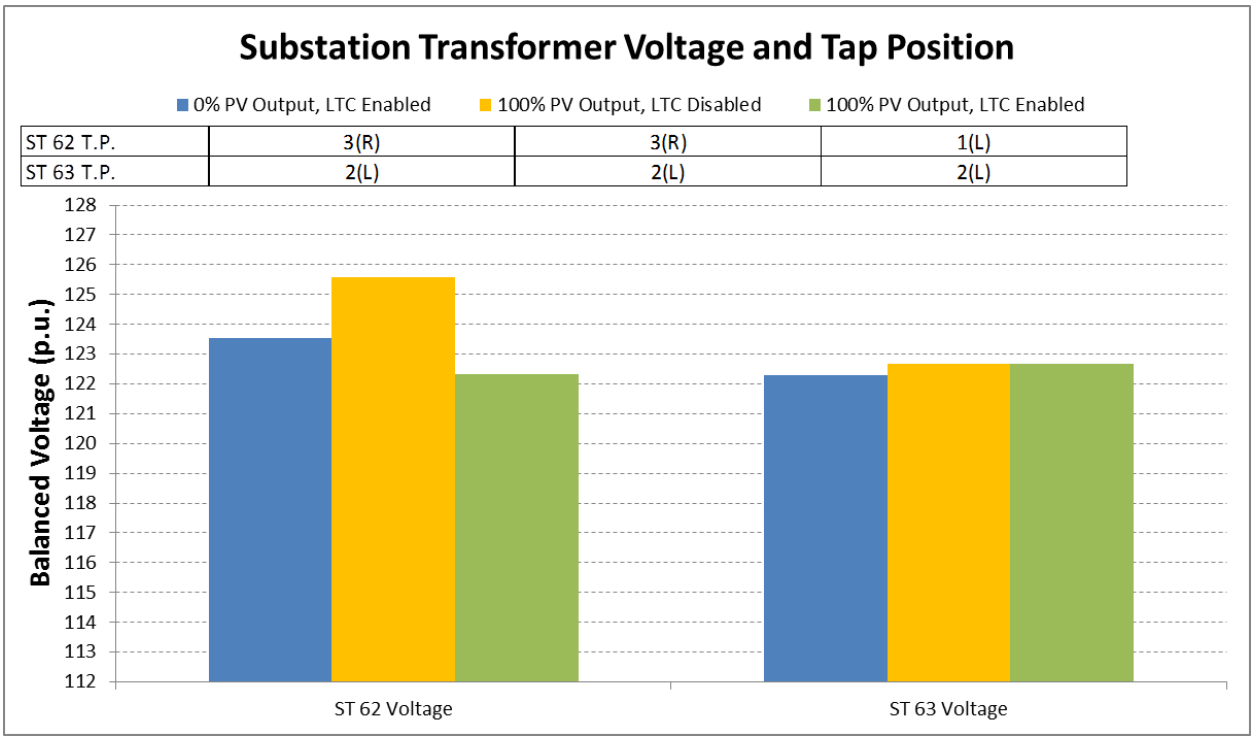

Figure 6.5: Substation Transformer Voltage – PV Ramp Up - 0% to 100% Output

7. Conclusions

The Westplan Solar PV Penetration Study focuses on potential voltage issues that may occur as the amount of distributed PV generation on the system increases. The study results indicate that prolonged voltage issues in the steady-state due to increasing PV penetration are not likely to occur so long as the system remains intact. The results do indicate, however, that temporary high voltages can occur as a result of rapid fluctuation in PV generation at PV penetrations as low as 40%. Although a 40% PV penetration does not cause voltage issues for all feeders or under all system conditions, the majority of the feeders

experience high voltage issues in the range of 40 to 50% PV penetration for the worst-case one-minute PV increase.

This study is based on the best available data and incorporates a number of necessary assumptions. The potential PV scenarios considered are reasonable given the limited knowledge of actual future system conditions, but they are not exhaustive. The SynerGEE model dataset used as the base case is the most comprehensive and up-to-date model of the Westplan system and has been validated against measured data that is available. However the steady-state SynerGEE model does have limitations. The SynerGEE model does not include any system or PV inverter dynamics and is likely to underestimate the effects that rapid changes in PV generation have on the system. Converting the distribution system model to a dynamic model format (such as PSLF) and performing similar analyses will likely produce a more accurate understanding of system impacts caused by dynamic PV events.

A. Overview of Westplan SynerGEE Datasets

The Westplan model has two 60 kV Thevenin equivalent voltage sources representing the 60 kV subtransmission system that feeds the Westplan substation. Each voltage source (represented as a capital "T" in Figure 3.2) provides a regulated voltage to the high side of a 60/12 kV substation transformer. There are eight 12 kV distribution feeders fed by the two substation transformers; note that Westplan 10 is a standby feeder.

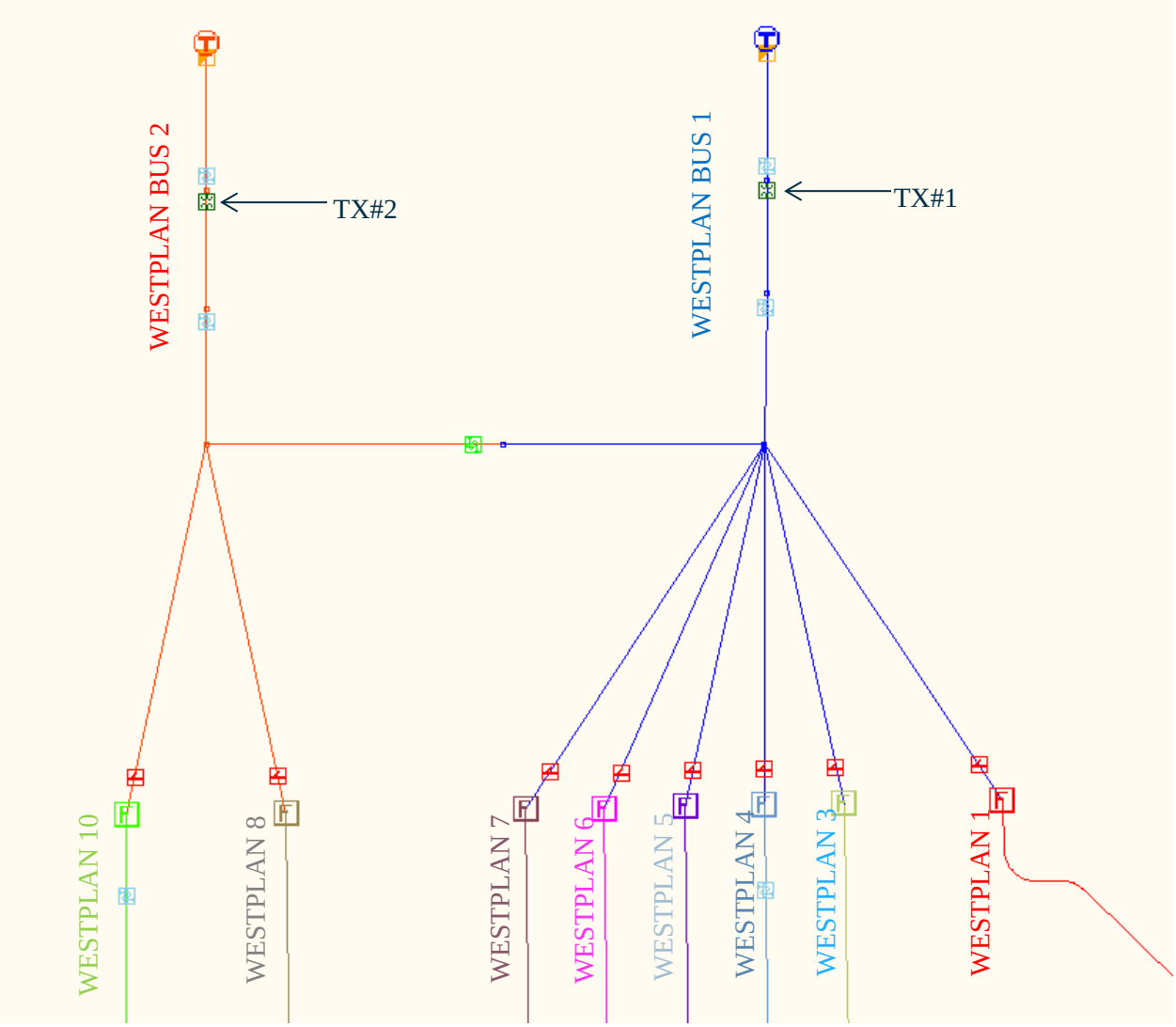

Figure 7.1: Westplan Substation, SynerGEE Electric Diagram

Figure 7.1 shows the entire Westplan model as it looks in SynerGEE. The majority of line sections in the Westplan model are two-phase with no neutral. There are no known errors in the model dataset or data mismatches between the model and warehouse datasets. There are no loops and no unfed line sections in the model.

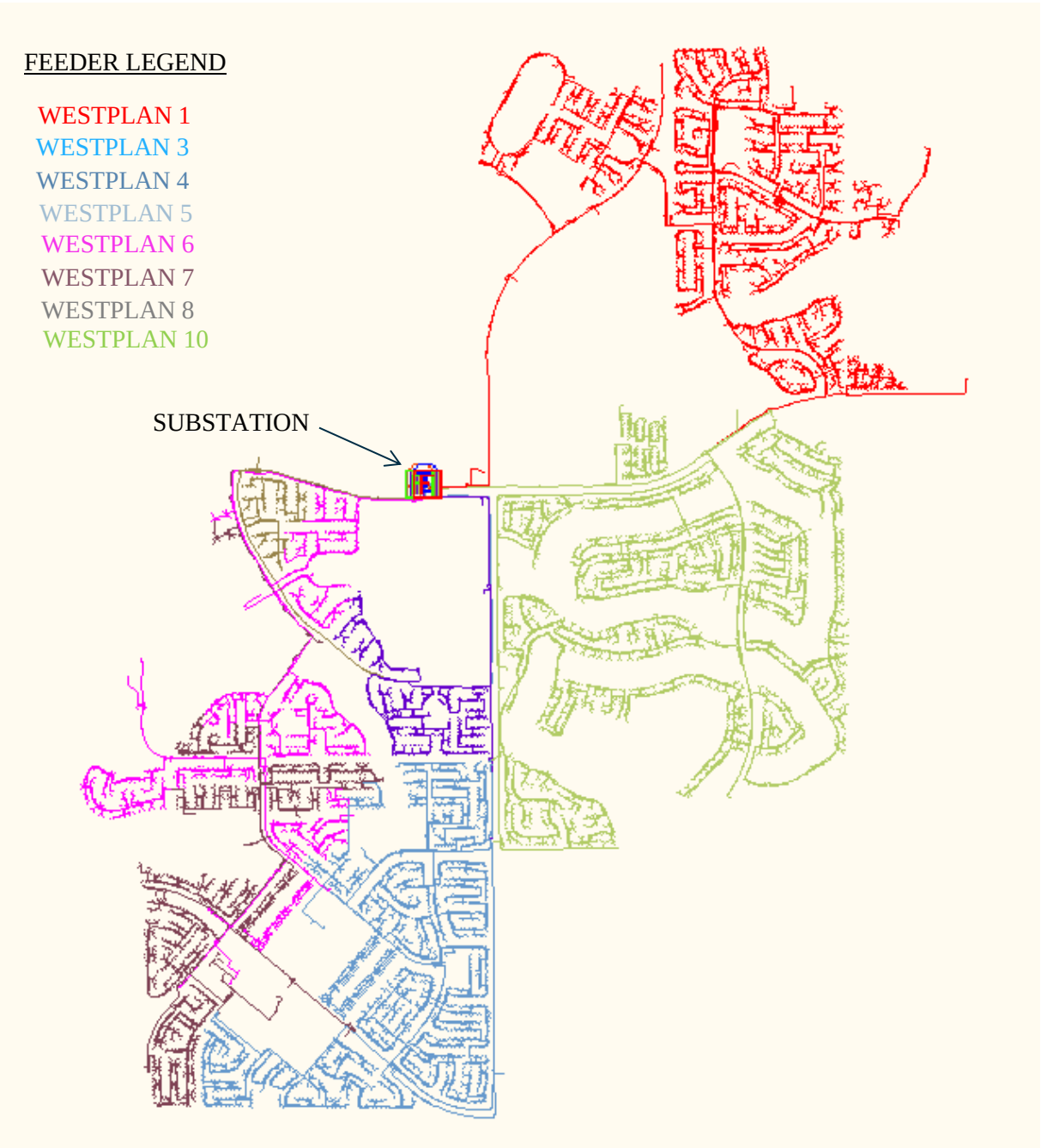

Figure 7.2: Westplan Model, SynerGEE Electric Diagram

A.1 Distributed Load Data

Distributed load information inherent in the Westplan model dataset exists as connected kVA (c.kVA) values assigned to each line section. These c.kVA values are used by the Load Allocation tool in SynerGEE to proportionally allocate known feeder demands (e.g. measured SCADA demands) from the substation to all line sections along each feeder.

Figure 7.3 shows how much c.kVA exists in the Westplan model and on each feeder by phasing. Some amount of phase imbalance exists on each feeder, and the model as a whole. Three-phase c.kVA makes up only 9% of the total c.kVA in the Westplan model.

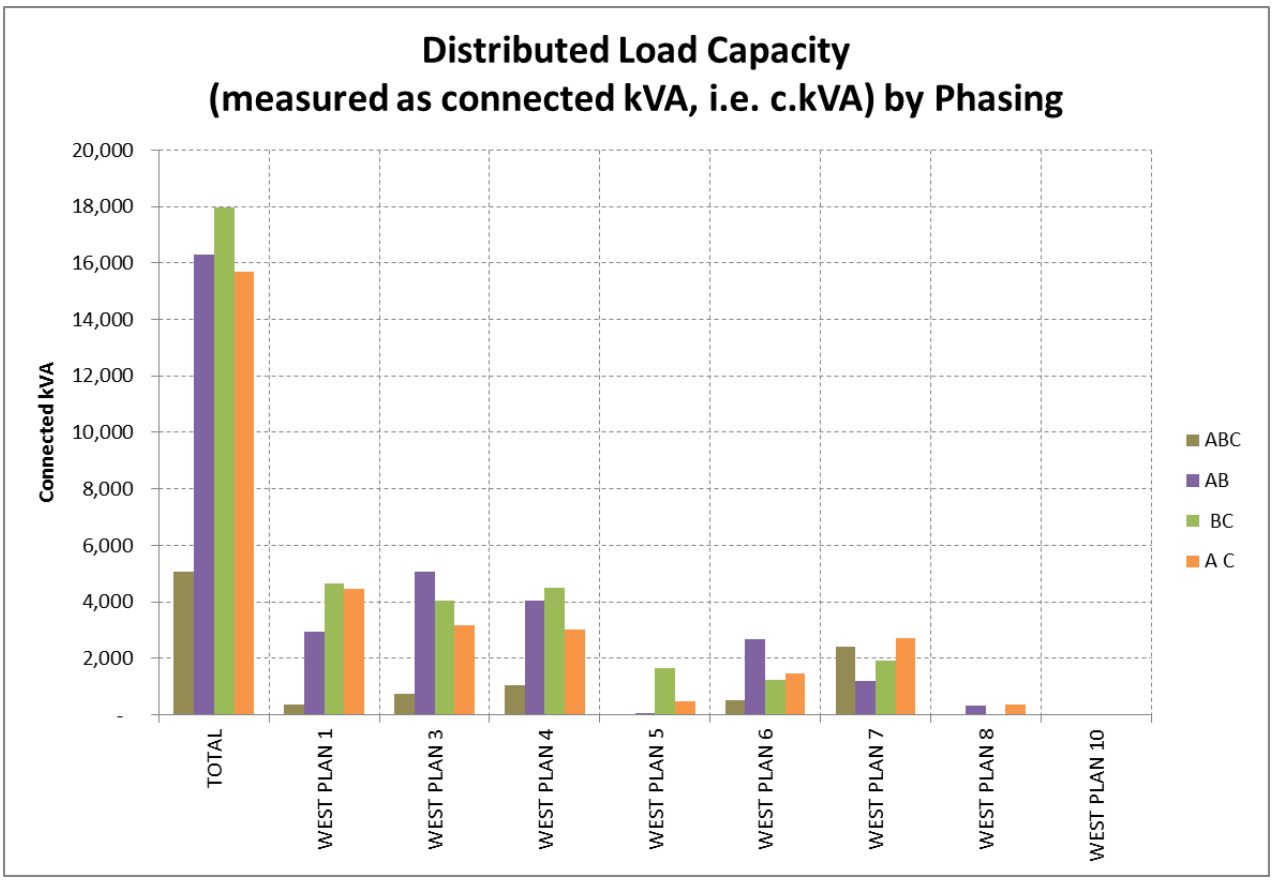

Figure 7.3: Total Distributed Load Capacity per Phasing per Feeder

Figure 7.4 shows the count of how many line sections have non-zero c.kVA, and therefore will have distributed load, in the Westplan model and on each feeder by phasing. The bar graphs for the most part mirror what can be seen in Figure 7.3. There are only 38 three-phase sections with distributed load (out of 3,339, about 1%) which contain 9% of the total c.kVA in the Westplan model.

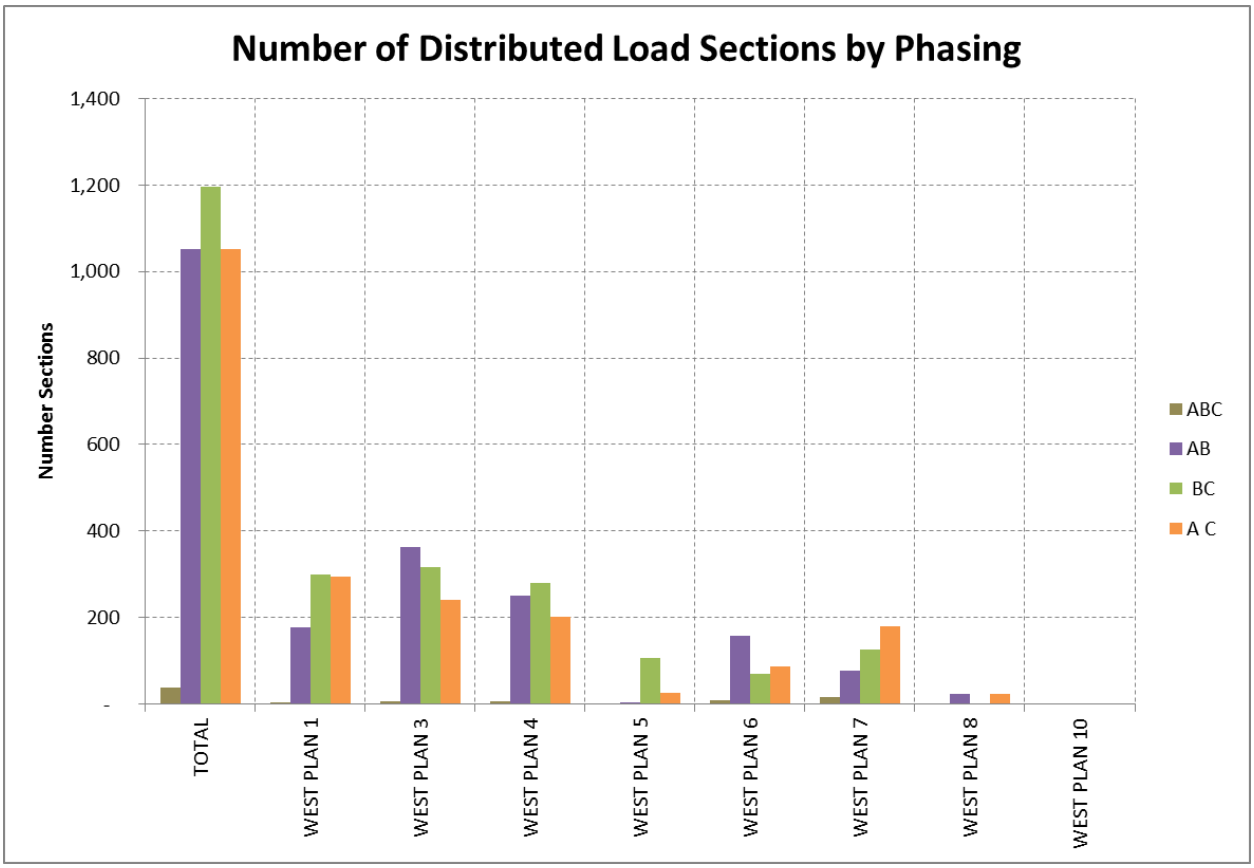

Figure 7.4: Number of Distributed Load Sections by Phasing by Feeder

In order to compute the percent load imbalance inherent to each feeder and the whole model, the by phase information in Figure 7.3 is equivalent to the canonical A, B, and C phases.

Table 7-1 shows the equivalent c.kVA for phases A, B, and C by feeder, and the percent load imbalances. The total percent imbalance is relatively low (3%), but the percent imbalance by feeder is much higher.

Table 7-1: Percent Imbalance by Feeder

	Equivalent Phase	Total c.kVA	% of Total	% Imbalance
TOTAL by kV	A	17,685	32%	3%
	B	18,814	34%	
	C	18,522	34%	
WEST PLAN 1	A	3,802	31%	13%
	B	3,898	32%	
	C	4,661	38%	
WEST PLAN 3	A	4,360	34%	11%
	B	4,792	37%	
	C	3,848	30%	
WEST PLAN 4	A	3,882	31%	10%
	B	4,615	37%	
	C	4,120	33%	
WEST PLAN 5	A	281	13%	45%
	B	856	39%	
	C	1,062	48%	
WEST PLAN 6	A	2,238	38%	14%
	B	2,120	36%	
	C	1,511	26%	
WEST PLAN 7	A	2,770	33%	14%
	B	2,370	29%	
	C	3,132	38%	
WEST PLAN 8	A	350	50%	50%
	B	162	23%	
	C	187	27%	
WEST PLAN 10	A	-	0%	-
	B	-	0%	
	C	-	0%	

A.2 Important Equipment Data

For load flow studies, it is important to verify that correct data (size, settings, etc.) exists in the model for certain major types of equipment such as capacitor banks, substation transformers, line voltage regulators, etc.

Table 7-2 summarizes the basic data for the fourteen capacitor banks in the Westplan model. Only one capacitor bank has a fixed capacitance which is always 1,200 kVAR if the capacitor bank is connected. All capacitor banks have 1,200 kVAR of switched capacitance. Switched capacitance means for each capacitor bank all 1,200 kVAR is either on or off depending on system conditions during the load flow, subject to the control settings of the capacitor bank. Five capacitor banks have switched capacitance controlled by the voltage at its terminals; three of these five capacitor banks are within a mile of the substation. The remaining nine capacitor banks have switched capacitance controlled by ambient temperature, which is a reason why ambient temperature is of particular interest among the quantities measured in the weather data.

Table 7-2: Summary of Capacitor Banks in Westplan Model

FeederId	SectionId	Unique Device Id	Control Mode	Miles from Source	Total Fixed kVAR	Total Switched kVAR
WEST PLAN 1	10218_UG	CB-117	TEMP	2.4	0	1200
WEST PLAN 1	11189_UG	CB-162	TEMP	2.12	0	1200
WEST PLAN 1	11344_UG	CB-116	TEMP	2.46	0	1200
WEST PLAN 1	11576_UG	CB-166	TEMP	1.49	0	1200
WEST PLAN 1	9593_UG	CB-115	TEMP	2.39	0	1200
WEST PLAN 3	10714_UG	CB-073	TEMP	1.72	0	1200
WEST PLAN 3	10973_UG	CB-141	VOLTS	0.74	0	1200
WEST PLAN 3	41393_UG	CB-059	TEMP	1.58	0	1200
WEST PLAN 4	10884_UG	CB-147	TEMP	2.97	0	1200
WEST PLAN 4	10886_UG	CB-146	VOLTS	2.42	0	1200
WEST PLAN 5	11160_UG	CB-139	VOLTS	0.08	0	1200
WEST PLAN 6	10882_UG	CB-148	VOLTS	1.87	1200	1200
WEST PLAN 7	10881_UG	CB-149	TEMP	1.77	0	1200
WEST PLAN 10	11528_UG	CB-140	VOLTS	0.05	0	1200

Table 7-3 summarizes the data that has been verified for the two Westplan substation 60/12 kV transformers. The table includes transformer ratings, LTC settings, and LDC settings. There are no line voltage regulators in the Westplan model.

Table 7-3: Substation Transformer Data

Transformer Basic Data & Ratings		
Transformer Name (in model)	ST 62	ST 63
Transformer Type (in warehouse)	ST 62 Westplan	ST 63 Westplan
SectionId	WEST_1_1	WEST_2_1
60 kV Bus Id	WESTPLAN BUS 1	WESTPLAN BUS 2
High-Side kV Rating	60	60
Low-Side kV Rating	12.47	12.47
High-Side Winding Configuration	Delta	Delta
Low-Side Winding Configuration	Wye-Gnd	Wye-Gnd
kVA Rating	25,000	25,000
%Z	8.04	8.8
%R	0.27	0.27
No Load Losses (kW)	0.8	0.8
On-Load Tap Changer Settings		
Voltage Regulation Range	±10%	±10%
Total # of Steps	32	32
PT Ratio	60	60
CT Rating	2400	2400
Load Drop Compensation Settings		
Target Voltage (on 120V Base)	117.5	117.5
R Dial / phase	1.6	1.6
X Dial / phase	0	0
Bandwidth Dial / phase	1.5	1.5