Mitigating the Detrimental Impacts of Solar PV Penetration on Electric Power Transmission Systems

by

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ABSTRACT

At present, almost 70% of the electric energy in the United States is produced utilizing fossil fuels. Combustion of fossil fuels contributes CO_2 to the atmosphere, potentially exacerbating the impact on global warming. To make the electric power system (EPS) more sustainable for the future, there has been an emphasis on scaling up generation of electric energy from wind and solar resources. These resources are renewable in nature and have pollution free operation. Various states in the US have set up different goals for achieving certain amount of electrical energy to be produced from renewable resources. The Southwestern region of the United States receives significant solar radiation throughout the year. High solar radiation makes concentrated solar power and solar PV the most suitable means of renewable energy production in this region. However, the majority of the projects that are presently being developed are either residential or utility owned solar PV plants.

This research explores the impact of significant PV penetration on the steady state voltage profile of the electric power transmission system. This study also identifies the impact of PV penetration on the dynamic response of the transmission system such as rotor angle stability, frequency response and voltage response after a contingency. The light load case of spring 2010 and the peak load case of summer 2018 have been considered for analyzing the impact of PV. If the impact is found to be detrimental to the normal operation of the EPS, mitigation measures have been devised and presented in the thesis. Commercially available software tools/packages such as PSLF, PSS/E, DSA Tools have been used to analyze the power network and validate the results.

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NOMENCLATURE

AD	Average deviation
DG	Distributed generation
EPS	Electric power system
EIA	Energy Information Administration
GE	General Electric
PSLF	Positive Sequence Load Flow
I_D	Direct axis current
I_Q	Quadrature axis current
IEEE	Institute of Electrical and Electronics Engineer
n	number of buses in the network
NREL	National Renewable Energy Laboratory
PCC	Point of common coupling
P_{gen}	Real (active) power generation
Q_{gen}	Reactive power generation
RES	Renewable Energy Standard
SEIA	Solar Energy Industries Association
US	United States
V_{base}	bus voltage magnitude in the base case
V_{pv}	bus voltage magnitude in a PV scenario

CHAPTER 1

GRID INTEGRATION OF SOLAR PV: AN INTRODUCTION

1.1 Solar PV as a Source of Electrical Energy

Solar photovoltaic (PV) as a source of electrical energy has grown from the research labs and making its presence felt in everyday life. The total installed capacity of more than 100 GW of PV worldwide by end of year 2012 stands testimony to this fact [1]. In this chapter, a brief introduction to the subject of solar PV is given, and the background of the technical subjects related to the integration of solar PV to the transmission grid is discussed.

Environmental perspective

One of the major factors driving the effort to replace conventional generators with non-carbon fueled renewable sources of energy is the much lower carbon footprint of the latter. To generate one kWh of electricity from a typical PV system located in southern Europe, the amount of CO_2 produced ranges from 16 to 32 g CO_2 equivalent. This includes the entire product life cycle of the PV panel from material sourcing through manufacturing, transportation, construction, operation, dismantling to recycling. This amount of CO_2 produced is much less compared to 300 to 1000 g CO_2 equivalent produced per kWh of electricity when fossil fuel powered generators are used [2]. Solar radiation, which is freely available in nature, acts as fuel for PV panels. PV panels do not produce noise while generating the electricity and are low maintenance device. These panels can be recycled as well [3], [4]. Despite the benefits provided by the PV from an environmental perspective there are some major economic and technical roadblocks to its widespread installation which are discussed below.

Economic perspective

Continuously falling global PV module prices [5], [6], and reduction in cost of installation [5] of these panels is making solar PV more economically feasible for consumers. However, solar PV still lags behind conventional generators in terms of the total cost including installation cost for producing one unit of electric energy. According to a projection by the United States Energy Information Administration (EIA), the total cost including installation cost for generating one MWh of electric energy from solar PV would be 144$, compared to 100$ for conventional coal and 108 $ for nuclear energy in year 2018 [7]. This makes PV almost 1.5 times costlier in terms of energy produced, and including investment costs, compared to conventional coal fired energy production. In addition to this aspect of cost, a low capacity factor and less than 100% efficiency of inverters connected to PV resources are currently putting PV resources at a disadvantage compared to other sources of electric energy generation.

Grid operation and technical perspective

One of the most important differences between a conventional and renewable source of electricity is the amount of control available for generating the desired amount of electric power. Even though the power electronic circuitry connected to PV resources provide some amount of control of the electric power generated, power generation capability highly depends on the weather conditions which are not controllable. Based on this difference, conventional sources of energy are categorized as “dispatchable” sources of power while renewable resources such as wind and solar are categorized as "nondispatchable" sources [8]. The important parameters of an EPS such as voltage and frequency can be kept within limits by controlling the power output of conventional generators. In the case of solar PV panels, operators have limited flexibility in terms of varying the power output because of the dependence on weather conditions. Installation of storage devices does enhance the control on power output in solar PV, but their high cost and efficiency are hindrances in their widespread use.

1.2 Solar PV in the United States

As of the end of 2011, the US was the fourth largest solar market in the world in terms of total installed capacity [6]. The total cumulative installed PV power in United States grew from 28 MW in 2002 to 7924 MW in March 2013 [9][10]. From year 2002 to year 2011, the average price for a residential scale PV installation has decreased from approximately 10 $/W to 6 $/W [5]. According to a report by National Renewable Energy Laboratory (NREL), a leading research agency for renewable energy in the United States, by the end of 2011, solar PV accounted for 0.38 % of the total installed capacity of electricity generation in the USA [10]. Solar Energy Industries Association (SEIA) predicts the total cumulative installed PV capacity to be 31 GW in the USA by the end of 2016 [11]. California is the leading state in terms of total cumulative installed PV followed by Arizona and New Jersey. As of April 2013, the world's largest individual solar PV plant is the Agua Caliente Solar Project located at Yuma County in Arizona with an installed capacity of 250 MW [11].

Solar PV as a major contributor for RES compliance in the Southwestern states of US

According to the USA solar radiation map provided by NREL, the annual average amount of solar PV resources potential for many regions in Southwest US is more than 6 kWh/m^2/day which puts them among leading regions in the USA in terms of potential to generate electricity from solar energy [14], [15].

1.3 The Impact of Solar PV Penetration on the Transmission Grid

In a traditional structure of an EPS, generating units of the network are concentrated and centralized in nature. With the addition of distributed generation (DG) in the network, the amount of power flowing from those centralized conventional generators will reduce and possibly flow in the opposite direction for some cases for significant DG penetration. The system requires less reactive power support to transfer the reduced power from distant generators to load centers compared to the no-DG case. This creates a situation of more reactive power support in the system than needed to keep the voltage profile within acceptable limits. This results in the problem of overvoltage near the load centers. In some cases, it can also create the problem of undervoltage on buses that are close to conventional generators [16-18].

Unlike conventional synchronous generators, there are no rotating masses (and rotating inertia) connected to the electronic converters of solar PV panels for generation of electricity. The reduced inertia per unit of power generated in the system, can lead to increased aggregate angular acceleration of synchronous generators following a fault. Frequency dips in the system may also be higher following a loss of generating unit. As a result, transient stability performance of the EPS may be affected [19].

To maintain the power load balance in the system, some conventional generators need to be decommitted when the presence of solar PV becomes substantial in the system. Many of these conventional generators have significant capacity to both absorb and provide reactive power to the system. Residential rooftop PVs, which are the replacement for majority of the conventional generators, are not allowed to actively control the voltage at the point of common coupling (PCC) to the grid according to IEEE standard 1547.2 [20]. This restriction affects the flexibility in terms of maneuvering reactive power in the EPS to maintain acceptable voltage profile throughout the system. In addition, voltage stability may be affected due to lack of reactive power maneuverability.

The penetration of solar PV panels as sources of electricity also has an impact on net real power loss in the system and total reactive power consumption in the transmission lines. The net real power loss in the system depends on the location and amount of solar PV in the system. Rooftop PVs generally reduce the real power losses in the system because of their proximity to the load centers.

There are other important aspects of EPS affected by solar PV such as EPS ground protection, protective relay settings, voltage regulation, voltage unbalance, harmonics, and unintentional islanding [20]. It is beyond the scope of this thesis work to discuss each impact in detail. The impact on the steady state voltage profile and dynamic performance of the system including rotor angle stability, frequency response and voltage response will be analyzed in detail keeping in view their importance from the perspective of transmission system security and reliability.

1.4 Research Motivation and Objective

There is no dearth of research analyzing the impact of DG on the EPS. However, the majority of research has been focused on distribution systems. This work focuses on the impact of substantial penetration of PV in the transmission system. A further motivation is that the nature of the impact of DG in the EPS varies from one area to another and depends on the location of solar PV in the system. The impact is system dependent as well as operating point dependent. As a result, studies conducted for one area of the EPS cannot in general suffice for all other areas.

To facilitate the penetration of solar PV, it is necessary to know the required changes in the existing transmission infrastructure to maintain secure and reliable operation in case of significant PV penetration.

The objective of this research work is to determine the impact of varying amount of solar PV penetration on the steady state voltage profile of the transmission network which is a part of an electric interconnection located in the Southwest US. The study has been conducted for both spring light load of year 2010 and forecasted summer peak load case of year 2018. The network has also been analyzed to find the dynamic response of the system such as frequency, voltage and rotor angle stability after a large disturbance for cases of significant PV penetration. Causes for the change in voltage profile and dynamic response in case of PV penetration have been analyzed. If the impact of PV penetration is found to be *detrimental* to the secure operation of the grid, mitigation measures have been devised and included in the report.

1.5 Organization of This Thesis

This thesis is divided into five main chapters. The first chapter provides an introduction and includes a survey of the research work already conducted in this area. To conduct the study for different amount of PV penetration, power flow study files with varying amount of PV penetration need to be prepared very carefully and in a specific way. Chapter two describes in detail the method which has been be followed to prepare the data files in a quick and efficient manner to conduct these type of studies. Chapter three focuses on the impact of PV penetration on steady state voltage profile of the transmission network. Solutions have also been devised and proposed to mitigate detrimental impacts on the voltage profile. Chapter four describes the dynamic behavior of the network in case of significant PV penetration. Chapter five concludes the thesis by describing important results of the research work. A detailed list of buses facing overvoltage for varying amount of PV penetration for the 2018 summer peak load case for the Southwestern US transmission system has been included in Appendix A.

CHAPTER 2

DATA PREPERATION

2.1 Electric Power Flow Studies and Their Data Requirements

Preparing the power flow study files and dynamic data for varying amount of PV penetration is a vital step in conducting the study of the impact of PV penetration on the transmission grid. Developing the power flow study files having varying amount of solar PV generation is not very straightforward and requires some precaution. In many ways, the data preparation is an art as well as an engineering science. This chapter describes the methodology by which power flow study files for different PV penetration scenarios have been developed. All the precautionary measures to be taken have also been mentioned in detail. The data used in all the studies described were obtained from an operating utility in the Southwest US. Also, the operating conditions, load levels, transmission assets in services, and other details were matched as closely to actual operating conditions as possible.

This chapter describes the modeling of rooftop solar PV panels and utility scale solar PV plants. For this study, rooftop PVs have not been allowed to exchange reactive power with the grid and hence modeled as a source of active power only. Utility scale solar PV plants have been represented through dynamic models of full converters using the models in the General Electric-Positive Sequence Load Flow (GE-PSLF) software module [21]. For simulation study purposes, the configuration of the solar PV generators in the transmission grid, in terms location of the panels, has been decided based on the data provided by the operating utility.

When the presence of solar PVs becomes significant in the system, conventional generators need to be switched off to maintain the power load balance. The choice of conventional generators to be switched off for solar PV penetration has been made based on advice from the operating utility. A detailed list of conventional generators that have been switched off for the 2018 summer peak load case has been included in this chapter.

The impact of PV penetration on the 2010 spring light load case has already been studied in [22]. This thesis studies the 2018 summer peak load case in detail and analyzes the important differences in results from the 2010 spring light load case. The data preparation methodology described here is for the 2018 summer peak load case.

2.2 Summer Peak Load Case Data Description

The important details related to the 2018 summer peak load case are detailed in this section. Table 2.1 summarizes the important aspects of the transmission system used for this study. The transmission system is a part of the Southwest US electric interconnection.

Table 2.1 Data description for the Southwest US transmission system in the 2018 summer peak load base case

Power flow file	basesr18.sav
Area	The Southwestern electric interconnection
Total number of buses	2680
Total number of generators in service	198
Total real power generation (MW)	28959
Total reactive power generation (MVAr)	4831
Total real power load (MW)	21130
Total reactive power load (MVAr)	3001
Total power interchange to other areas (MW)	7015
Total number of shunt devices	225

2.3 Solar PV Modeling

This section describes the models which have been used to represent rooftop PV panels and utility scale PV plants.

Rooftop PV panels

As per the advice of the operating utility, rooftop PVs have not been allowed to either provide or absorb reactive power to the grid. These PVs have been modeled as negative real power loads in the power flow data. To conduct the study at the transmission level, rooftop PVs have been lumped and represented at specifically identified 69 kV buses. To explain the modeling in more detail, Figure 2.1 shows the one-line diagram of a typical bus in the Southwestern transmission system connected to the rooftop PV generator. Total real power provided by this PV generator is 45.6 MW.

Figure 2.1 Modeling of rooftop PV in power flow studies

Utility scale PV plants

Utility scale PV plants have been modeled in the power flow study file as conventional generators having the capability to provide or absorb reactive power from the grid through the converters connected to it. New buses have been added to the power flow case to model these plants. Figure 2.2 shows the one-line diagram representing the utility scale PV in the grid. The schematic shown in the Figure 2.2 has been generated using the PTI PSS/E software module [25].

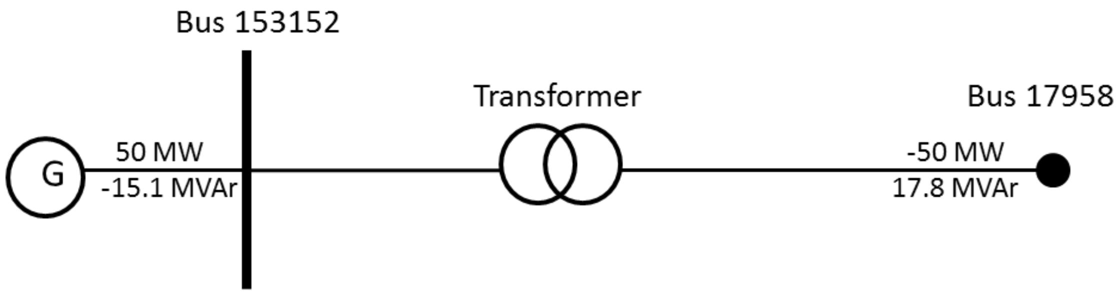

Figure 2.2 Modeling of utility scale solar PV plant in power flow studies

Dynamic model used for utility scale PV

Utility scale PV plants have the capability to control the voltage at the generator bus through reactive power exchange with the grid. The converters through which these PV plants have been connected to the grid have the reactive power and the current control capabilities. As suggested in [23], full converter models provided in GE-PSLF software module for wind turbine type 4 generators can be used to represent solar PV plant converters.

To represent the dynamic model for PV plants, two separate models need to be used from the GE-PSLF software module. One of these models represents the full converter for the PV plants named “gewtg” in the GE-PSLF software. The other model named “ewtgfc” acts as a controller for the full converter model. Figure 2.3 and 2.4 provide the description of the dynamic model used for utility scale PV. These schematics have been obtained from [22].

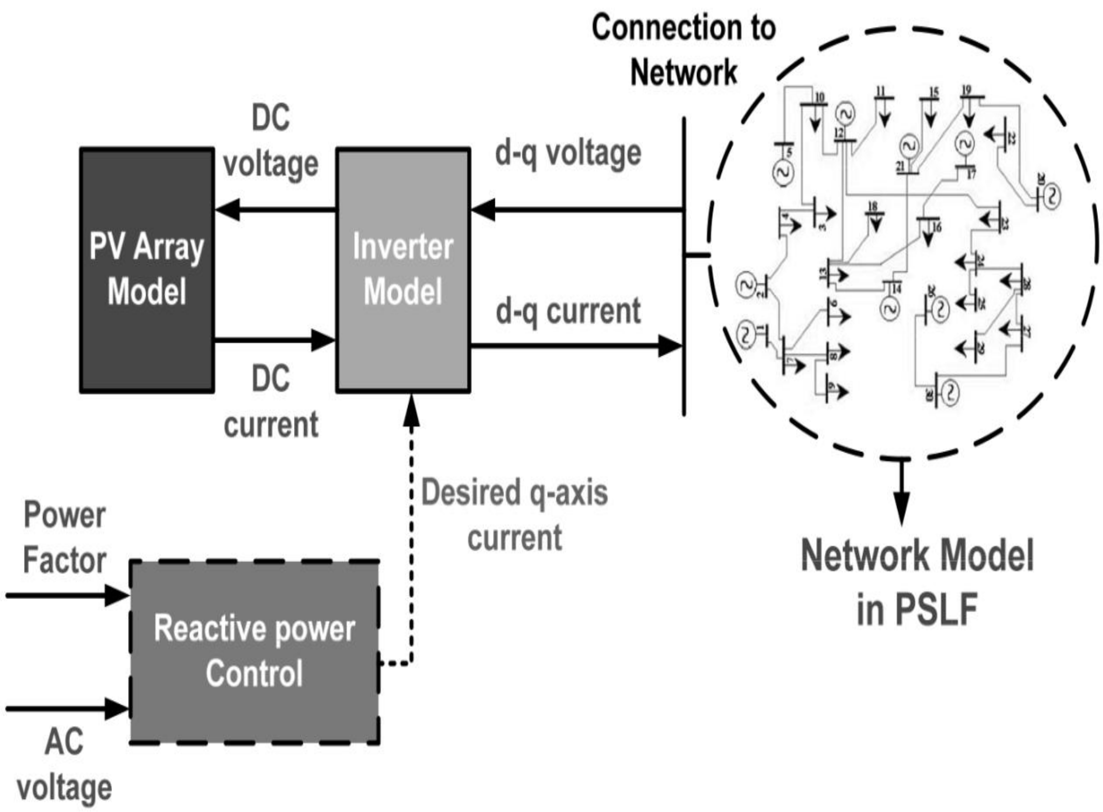

Figure 2.3 Dynamic representation for solar PV generation in GE-PSLF [22]

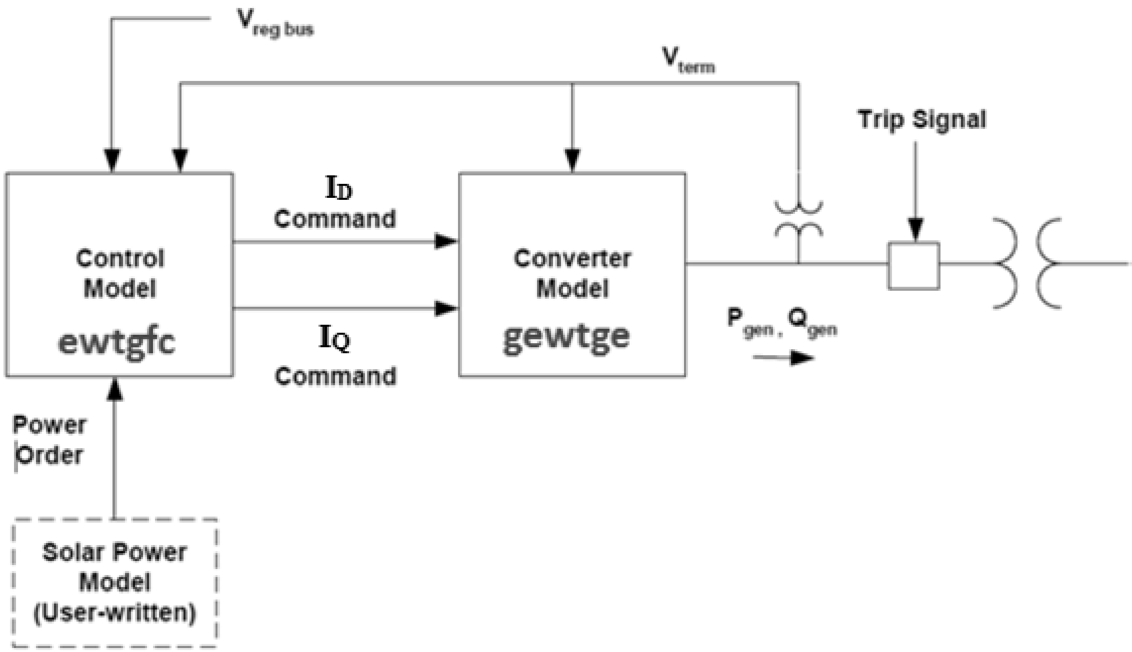

Figure 2.4 A PSLF model used for representing utility scale PV in power flow studies [22]

As seen in Figure 2.4, the control model "ewtgfc" provides the control signal I_D and I_Q to the full converter model for generating the appropriate amount of real and reactive power as required by the system. A detailed description of these models is provided in [21].

2.4 Description of PV Scenarios

Six different scenarios with varying amount of solar PV penetration have been considered in this study. The amount of PV in the system is varied from 7.5% to 45 % of the total real power generation in the area considered for study. Percentage of solar PV considered here is by installed capacity. Table 2.2 contains the details of all the PV scenarios considered for study. The following formula is used to calculate the percentage PV penetration,

$$\%\ \text{PV penetration} = \frac{\text{Total installed capacity of solar PV (MW)}}{\text{Total generation in studied area (MW)}} * 100$$

Table 2.2 Description of different PV scenarios for the 2018 summer peak load case

Scenarios	Percent PV penetration in the system	Amount of PV penetration in the system (MW)
Scenario 1	7.5	2172
Scenario 2	15	4344
Scenario 3	22.5	6516
Scenario 4	30	8688
Scenario 5	37.5	10860
Scenario 6	45	13032

2.5 Preparation of PV Scenarios

To prepare the power flow study files with varying amount of solar PV, a methodology was followed as described in this section. Moreover, this section contains the description of buses where PV have been added and the list of conventional generators which have been switched off to maintain power load balance.

Method for creating the power flow case with solar PV resources

A step-by-step procedure to generate the power flow study case files with solar PV resources is given below:

1. Identify and prepare the list of buses where solar PV is installed.
2. Add a small amount of PV generation at each bus identified in step 1.

3. Solve the power flow case. If it converges, slowly increment the PV generation level at buses. If it diverges, further reduce the PV generation level at concerned buses before solving the power flow.
4. When the amount of PV generation added in the system reaches the generation level of one of the conventional generators from the list of generators to be switched off, decommit the concerned generator.
5. Solve the power flow case. If it converges, go to step 3 and repeat the procedure till required amount of PV generation is installed in the system. If power flow case diverges, go to the next step.
6. Prioritize switching off those conventional generators which have limited reactive power exchange with the network. If power flow case still diverges, it means system does not have enough reactive power support. In this case real power output of the conventional generator will have to be reduced to zero keeping them committed to maintain power load balance. Alternatively, new shunt devices may have to be installed in the system for reactive power support.

List of buses for adding PV resources

As per the data provided by the operating utility, Table 2.3 and 2.4 contain the list of buses for adding the rooftop PV generation in the Southwest US transmission region. Table 2.3 and 2.4 also provide the amount of PV currently added at those buses. To calculate the amount of PV to be added at each bus, for the different amount of PV penetration, existing PV generation has been scaled up proportionally.

Table 2.3 Utility #1 residential rooftop buses

Bus number	Capacity (kW)	Bus number	Capacity (kW)	Bus number	Capacity (kW)	Bus number	Capacity (kW)
17747	370	17871	510	86590	550	86987	220
17741	520	17870	260	17716	660	18035	220
17902	180	17683	930	17874	260	18104	580
17736	340	17684	530	17913	220	18039	580
17897	290	17723	270	18107	850	17794	500
17734	190	17718	560	18120	210	17665	500
17730	120	17843	790	18053	510	17957	500
17737	300	17691	540	17768	250	17852	520
17765	120	17961	880	17775	200	18016	880
17779	600	17697	280	17823	520	17853	290
17873	70	18080	510	17830	360	18103	340
17655	1050	18074	650	17831	2290	17847	260
17867	50	18063	120	17772	50	18098	360
17892	170	18062	770	17811	530	18096	30
17886	260	18059	390	17819	490	18233	880
17880	390	18114	670	17832	420	17929	1370
17900	50	17997	620	17820	970	18188	470
17891	390	17996	620	17795	880	17990	620
17651	170	17998	610	17829	360	18000	640
17660	150	18093	280	86706	620	17981	600
17649	360	17912	680	17798	760	17932	670
17654	400	17914	550	17803	270	17705	780
18219	350	17977	810	17783	730	18018	570
17868	510	17996	640	18211	1840	86568	590
17975	730	17665	870				

Table 2.4 Utility #2 residential rooftop buses

Bus number	Capacity (kW)	Bus number	Capacity (kW)	Bus number	Capacity (kW)	Bus number	Capacity (kW)
86342	5	86571	86.1	86635	8	86644	48.8
86345	76.9	86574	81.5	86558	755.1	86628	25.1
86348	14.5	86575	52.5	86561	66.8	86662	18.6
86351	14.4	86577	46.6	86562	34.1	86664	12
86360	62	86580	47.1	86565	101.8	86672	41.7
86363	7	86582	47	86566	102.2	86676	38.5
86366	19	86585	6	86568	5.1	86679	106.4
86369	85.8	86587	14	86569	65.9	86681	166
86377	36.8	86435	30	86691	96.9	86684	22.1
86383	6	86588	16	86693	62.1	86686	5
86386	19.1	86589	76.8	86695	20.2	86687	46.8
86390	75	86590	43	86697	13.3	86689	70.1
86393	42	86591	54.7	86699	18.2	86689	8.2
86397	38.7	86593	40.1	86701	20.1	86702	4
86399	24	86596	9	86744	10	86704	86.1
86406	14	86597	2	86747	7	86706	169.3
86409	4	86599	94.7	86749	13	86708	33
86411	46.3	86601	77.5	86426	3	86714	31.7
86413	77.8	86612	17	86751	24.1	86717	33.4
86415	20	86614	51	86774	5.7	86722	92.3
86417	22	86618	184.4	86778	6	86725	39.7
86420	158.9	86620	55	86785	12.1	86728	186.7
86424	61.6	86623	132.8	86786	5	86740	6
86648	8.3	86626	22.8	86789	19.5	86741	12.4
86439	42.5	86650	92.1	86441	23	86792	4
86432	28.9	86437	35.9	86654	23	86657	15.2
86427	3	86638	40.1	86659	50.5		

List of conventional generators switched off for different PV scenarios

Tables 2.5-2.10 contain the list of conventional generators which switched off for the different PV scenarios. A zone based strategy is followed for switching off the generators. The amount of generation switched off in the Utility #1 and the Utility #2 zones correspond to the amount of solar PV added in those zones.

Table 2.3 List of switched off generators for 7.5% PV penetration for the 2018 summer peak load case

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)		Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
17287	80	6.2		17498	72	0
17254	170	6.4		17498	72	0
17253	170	6.6		17585	30	8.4
17255	220	8.5		17587	42.6	9.0
17305	52	9.2		17588	42.6	8.9
17306	51	9.2		17589	42.6	9.0
17284	99	12.6		17590	42.6	8.9
17283	110	13.2		17591	42.6	9.0
17292	42	16.4		17592	42.6	8.9
17300	68	17.9		17594	42.6	8.9
17293	85	25.6		17603	91	7.1
17294	85	25.7		17604	91	7.1
17266	110	27.7		18283	49	-1.1
17242	110	-16.1		18293	30	6.7

Table 2.4 List of turned off generators for 15% PV penetration for the 2018 summer peak load case

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)		Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
17318	160	-13.4		17593	42.6	9.0
17317	160	-12.0		17586	42.6	9.0
17319	160	-11.9		17584	30	15.0
17324	172	-11.4		18256	40	16.2
17325	172	-11.2		17482	164	20.1
17316	160	-15.9		17500	115	20.1
17267	110	27.0		17502	115	20.1
17308	172	32.0		17504	115	20.1
17309	172	50.6		18263	85	26.3

Table 2.5 List of turned off generators for 22.5% PV penetration for the 2018 summer peak load case

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)		Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
17142	160	6.2		17143	160	-70
96762	140	-12.5		17144	160	-70
17310	185.6	-94		17483	235	-110
17154	21	-8.9		17487	42.6	-96
17155	21	-8.9		18270	42.6	-65
17156	21	-8.9		17160	42.6	-70
17158	21	-8.9		17145	21	-8.9
17159	21	-8.9		17146	42.6	38.3
17147	235	48.1				

Table 2.6 List of turned off generators for 30% PV penetration for the 2018 summer peak load case

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)		Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
17148	160	-48.8		18265	85	41.0
17243	245	-4.03		18266	85	41.8
17244	260	-2.4		18268	264	114.4
17245	150	-4.7		17484	249	42.5
17256	787	115.6		18264	85	42.1

Table 2.7 List of turned off generators for 37.5% PV penetration for the 2018 summer peak load case

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)		Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
17257	787	165.6		18243	110	50.6
17149	160	-48.8		18244	110	50.6
17150	235	-38.5		18269	70	77.1
17151	142	-50.6		18271	140	58.1
17152	142	-37.8		18272	132	74.3

Table 2.8 List of turned off generator for 45% PV penetration for the 2018 summer peak load case

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)		Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
17153	210	-9.7		19371	195	21.4
19366	10	0		19372	195	21.4
19367	19	0.2		96672	290	-7.5
19368	66	-3.1		18323	350	59.5
19369	40	-7.9		18273	10	3.3
19370	75	-2.7		18273	10	3.3
96344	17	0		18273	10	3.3
96346	18	0		18276	90	31.3
96348	18	0		18324	234	59.1
96350	15	0				

CHAPTER 3

STEADY STATE VOLTAGE ANALYSIS

3.1 Overvoltages in Electric Power Transmission Systems

The impact of solar PV penetration on the voltage profile of an EPS network has been studied before and is well-documented, e.g., [3, 8, 16-18, 22, 24]. Overvoltages in a network have been identified as one of the most common problematic operating condition in cases of significantly high PV penetration. The extent of overvoltages in the network depends on following factors:

- Configuration of the electric power network
- Amount (MW) of PV being integrated
- Location of the PV in the network
- Number and the types of shunt devices in the network
- Availability of other voltage regulating devices in the system.

Eftekharnejad et al. have studied the extent of overvoltages in the transmission network of Southwestern US for varying amounts of PV penetration under the 2010 spring light load conditions [22]. To develop an effective solution for solving the over-voltage problem, the system should be analyzed for both peak load and light load conditions. Keeping this in view, this chapter first identifies the extent of overvoltage on the transmission network of Southwestern US for the projected 2018 summer peak load conditions under varying levels of PV penetration. Then, a comparison of overvoltages in the networks for both the 2018 peak and the previously studied the 2010 light load conditions is made. Finally, a strategy is developed to solve the issue of overvoltage for both the peak load and the light load conditions.

3.2 Extent of overvoltage in the network

As mentioned in chapter two, six different scenarios of PV penetration are considered for studying the impact of PV penetration on the steady state voltage profile of the network. This section identifies the list of buses that face the most severe overvoltage situation for the PV scenario of 30% PV penetration. The 30% PV penetration scenario is selected for detailed illustration because in this scenario the system faces the highest overvoltages. A comprehensive list of buses facing overvoltages for different PV penetration scenarios is provided in Appendix A. The power flow study case provided by Utility #1 for the 2018 summer peak load scenario is considered as the base case for the study.

30% PV penetration

For 30% PV penetration, 77% buses in the Utility #1 region and 80% buses in the Utility #2 region face more than 2% overvoltage in comparison to the base case scenario. Fifty buses with maximum increase in the voltage magnitude over the base case scenario for Utility #1 and Utility #2 region are given in Tables 3.1 and 3.2 respectively. For illustration purposes, voltage magnitudes on all the buses in the Utility #1 and Utility #2 regions have been plotted for the base case and the 30% PV penetration case as shown in Figure 3.1. It is evident from Figure 3.1 that most of the buses are facing overvoltage condition in the system.

Table 3.1 List of 50 buses facing the most severe overvoltage in the Utility #1 region for 30% PV during the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\lvert V_{pv}\rvert$ - $\lvert V_{base}\rvert$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\lvert V_{pv}\rvert$ - $\lvert V_{base}\rvert$)
18211	1.0052	0.0886		17820	1.0199	0.0668
18210	1.0043	0.0863		17821	1.0198	0.0668
18060	1.0036	0.0816		17822	1.0197	0.0668
18039	1.0035	0.0776		17832	1.0199	0.0662
18040	1.006	0.0742		17795	1.0187	0.0658
18032	1.0076	0.0735		17796	1.0189	0.0655
18037	1.0076	0.0735		17797	1.019	0.0653
17831	1.0184	0.0717		17793	1.0187	0.0644
17833	1.0183	0.0716		17798	1.019	0.0642
18034	1.0097	0.0715		18283	1.0222	0.0638
17823	1.0169	0.071		17829	1.022	0.0634
17830	1.0167	0.0697		17814	1.023	0.0628
18035	1.0085	0.0695		18033	1.0082	0.0628
18104	1.0122	0.0688		18038	1.0082	0.0628
18036	1.0124	0.0685		17816	1.0235	0.0628
17802	1.0141	0.0683		17819	1.0246	0.0627
17783	1.016	0.0681		18028	1.0236	0.0627
17801	1.0144	0.068		17815	1.0232	0.0626
17800	1.0145	0.0679		18155	1.024	0.0625
17826	1.0182	0.0677		17817	1.0244	0.0622
17813	1.021	0.0676		17818	1.0244	0.0622
17825	1.0184	0.0675		18154	1.025	0.0617
17824	1.0185	0.0675		17828	1.026	0.0608
17812	1.0213	0.0673		17810	1.0269	0.0603
17811	1.0215	0.0671		17847	1.0177	0.0603

Table 3.2 List of 50 buses facing the most severe overvoltage in the Utility #2 region for 30% PV during the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\|$ - $\|V_{base}\|$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\|$ - $\|V_{base}\|$)
87618	0.9828	0.1237		87575	0.9835	0.1016
87617	0.9832	0.1236		86579	0.9844	0.1014
86623	0.9877	0.1227		86593	0.9822	0.1014
87562	1.0148	0.1139		86594	0.9822	0.1014
87355	1.0021	0.112		87574	0.9869	0.1013
87356	0.9811	0.1096		87576	0.9871	0.1012
86539	0.9921	0.1089		87609	0.9709	0.101
86565	0.9954	0.1076		86566	0.9829	0.1008
87416	0.9944	0.1063		86567	0.9829	0.1008
86360	0.986	0.1063		86573	0.9984	0.1007
86359	0.986	0.1062		86574	0.9982	0.1007
87415	0.9687	0.1052		87417	1.0031	0.1005
87578	0.9745	0.1045		87584	0.9797	0.1001
87572	0.9919	0.1041		87610	0.9758	0.1
87591	0.9837	0.1041		86582	0.9939	0.0996
87592	0.9804	0.104		86583	0.9939	0.0996
87573	0.9949	0.1038		87597	0.976	0.099
86424	0.9861	0.1029		87598	0.9756	0.0989
86425	0.9861	0.1029		86619	0.9883	0.0985
86580	0.9831	0.1028		87542	0.9686	0.0985
87565	0.9697	0.1025		86618	0.9884	0.0984
87625	0.9913	0.1023		86577	0.9945	0.0983
87631	1.0112	0.1021		86617	0.9885	0.0983
87564	0.9761	0.102		86578	0.9945	0.0982
87577	0.9881	0.1017		87543	0.9726	0.0981

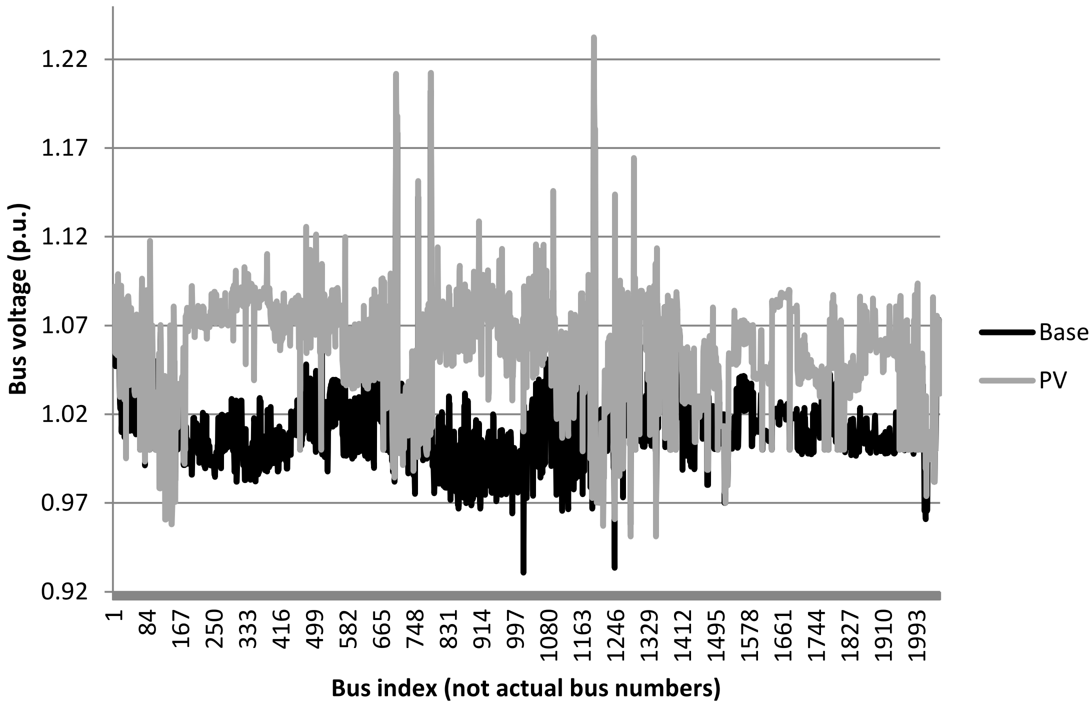

Figure 3.1 Comparison of voltage profile of the system for the base and the 30% PV penetration case during the 2018 summer peak load case

3.3 Comparison of PV Scenarios

To observe the changes in the overvoltage condition as the amount of PV penetration is increased from 7.5% to 45%, average deviation (AD) has been calculated for the voltage magnitude on the buses compared to the base case scenario. The following formula is used to calculate the AD for different PV scenarios,

$$AD = \frac{\sum_{i=1}^{n} \left|V_{pv}\right| - \left|V_{base}\right|}{n}$$

where n represents the number of buses in the system, V_{pv} represents the bus voltage magnitude in the respective PV scenario, and V_{base} is the bus voltage magnitude in the base case scenario.

Table 3.3 provides the AD under different PV scenarios for Utility #1, Utility #2 and the whole region combined. Two important observations can be made from the data given in the Table 3.3:

- Overvoltages in the Utility #2 region are higher than that in the Utility #1 region
- AD decreases after 37.5% of PV penetration in both the regions; this implies that overvoltages decrease after 37.5% of PV penetration.

Table 3.3 Average deviation in the base case voltage for varying PV penetration for the 2018 summer peak load case

% PV penetration	*AD* for Utility #1 region (p.u.)	*AD* for Utility #2 region (p.u.)	*AD* for Utility #1 and Utility #2 region combined (p.u.)
7.5	0.010	0.014	0.013
15	0.021	0.030	0.027
22.5	0.029	0.042	0.037
30	0.034	0.048	0.043
37.5	0.034	0.048	0.043
45	0.031	0.039	0.037

Figure 3.2 illustrates the variation in average deviation from the base case voltage for varying amount of PV penetration. It can be observed that for both the Utility #1 and Utility #2 regions, AD increases until 30% PV penetration, and then it remains approximately fixed until 37.5% PV, and then AD declines.

One of the reasons for Utility #2 region facing higher overvoltages could be the distribution of PV resources in the network. Utility #1 region has 15 % of its buses installed with rooftop PVs while this number is only 7% for Utility #2 region. A more uniform distribution of PV resources in the Utility #1 network could be the reason for less severe overvoltage conditions. The PV scenario during which the system faces the highest overvoltages has been termed as the worst-case PV scenario in this report. Both the terms namely system with highest overvoltages and worst-case PV scenario will be used interchangeably but convey the same meaning.

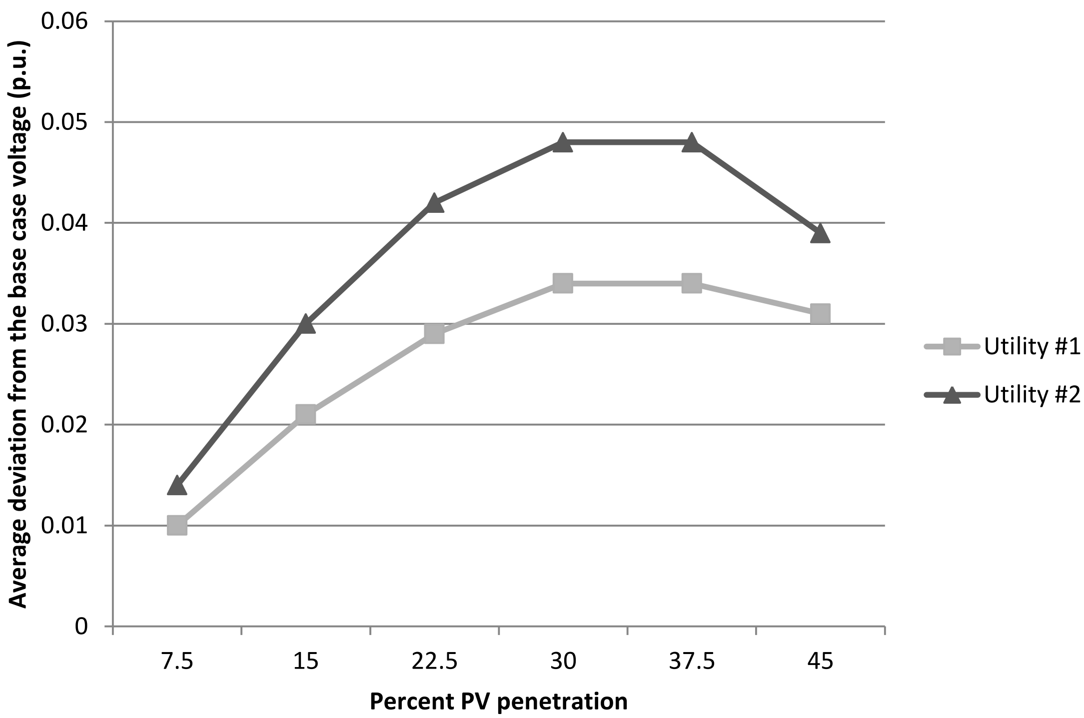

Figure 3.2 Average deviation in voltage from the base case for varying PV penetration in Utility #1 and Utility #2 region for the 2018 summer peak load case

As shown in [24], the problem of overvoltage increases with the increasing PV penetration and decreases after a certain point. For the case of 2018 summer peak load being studied here, the overvoltage condition is highest but same for both 30% and 37.5% PV penetration. Of these two scenarios, the 30% PV penetration being more probable in the near future has been considered as the worst-case scenario and selected for detailed study. Mitigation measures are developed to solve the issue of overvoltage based on the detailed study of this scenario.

3.4 Comparison of Peak Load and Light Load Conditions

To understand the impact of PV penetration on the electric power transmission network, it is necessary to analyze the effect of PV resources on various loading conditions. This section compares the impact of PV on the 2010 spring light load and the 2018 summer peak load conditions.

As mentioned in [22], 30% PV penetration causes the worst-case overvoltage condition for the 2010 spring light load case. As identified in the previous section, the same percentage of PV penetration creates the worst-case scenario for the 2018 summer peak load case as well. However, the important point to note here is the difference between the total power generation in both cases which is approximately 7000 MW. Approximately 6475 MW of PV creates the highest overvoltage under the 2010 light load case while a PV generation of 8687 MW causes the highest overvoltage for the 2018 summer peak load case. Compared to the light load case, an additional 2212 MW of PV is needed in the system to reach the worst-case PV scenario for peak load conditions. This phenomenon happens because of the increased requirement of reactive power during the summer season

Another interesting approach to compare the peak and the light loading conditions is to identify the extent of overvoltage in both conditions for the same level of PV penetration in megawatts. Table 3.4 compares the AD for both loading conditions for 6475 MW of PV penetration in the system.

Table 3.4 Average deviation in the base case voltage for 6475 MW of PV penetration in the 2018 summer peak and the 2010 spring light load conditions

Loading condition	Utility #1		Utility #2	
	AD (p.u.)	Percent of buses facing more than 2% overvoltage	*AD* (p.u.)	Percent of buses facing more than 2% overvoltage
2010 spring light load case	0.015	28	0.018	63
2018 summer peak load case	0.034	77	0.048	80

It can be observed from the Table 3.4 that for the same amount of PV penetration in megawatts overvoltage condition in the case of the 2018 summer peak load conditions is worse compared to the the 2010 spring light load case. This happens because of the larger number of fixed shunts operating in the case of the 2010 summer peak load case. A total of 89 fixed shunts operate in the Utility #1 and Utility #2 regions for the light load case while this number is 132 in the case of the summer peak load.

3.5 Strategy for Mitigating the Overvoltage Condition

To identify the measures to mitigate the issue of overvoltage condition in the case of PV penetration in the network, the worst-case scenario of 30% PV penetration has been selected for both light and peak loading conditions. It is assumed that solutions for other PV scenarios will always be the subset of this stated assumption.

VSAT software module developed by DSA Tech labs is used for finding the mitigation measures required to keep the voltage magnitude on buses within acceptable limits. The mitigation methods are prioritized and the solution that requires installing new shunt devices is given the least priority. The mitigation measures used to remove the voltage violations are given below in the order of priority:

1. Reconfiguring shunt devices, by changing the switching status (i.e. ON or OFF)
2. Changing generator voltage set points
3. Installing new shunt devices.

A case for increasing the voltage limits on all the buses is put forward. The extent of the improvement that can be achieved in terms of reducing the overvoltage on buses has been quantified for voltage limit relaxation of 1% and 2% beyond the existing limits.

Mitigation measures for light loading conditions

The chart shown in Figure 3.3 shows the various mitigation measures deployed and the extent of improvement achieved in reducing the overvoltages after each mitigation measure. The mitigation measures are applied sequentially in the order of the priority mentioned earlier.

It can be seen from the Figure 3.3 that, after applying the measure of changing generator voltage set-points, very few buses in the Utility #1 and the Utility #2 regions face overvoltage conditions. In order to completely remove the voltage violations in the network, new shunt devices were needed to be installed at some of the buses. Table 3.5 and 3.6 summarize the list of buses at which new shunt devices are installed along with the magnitude of reactive power provided by these devices.

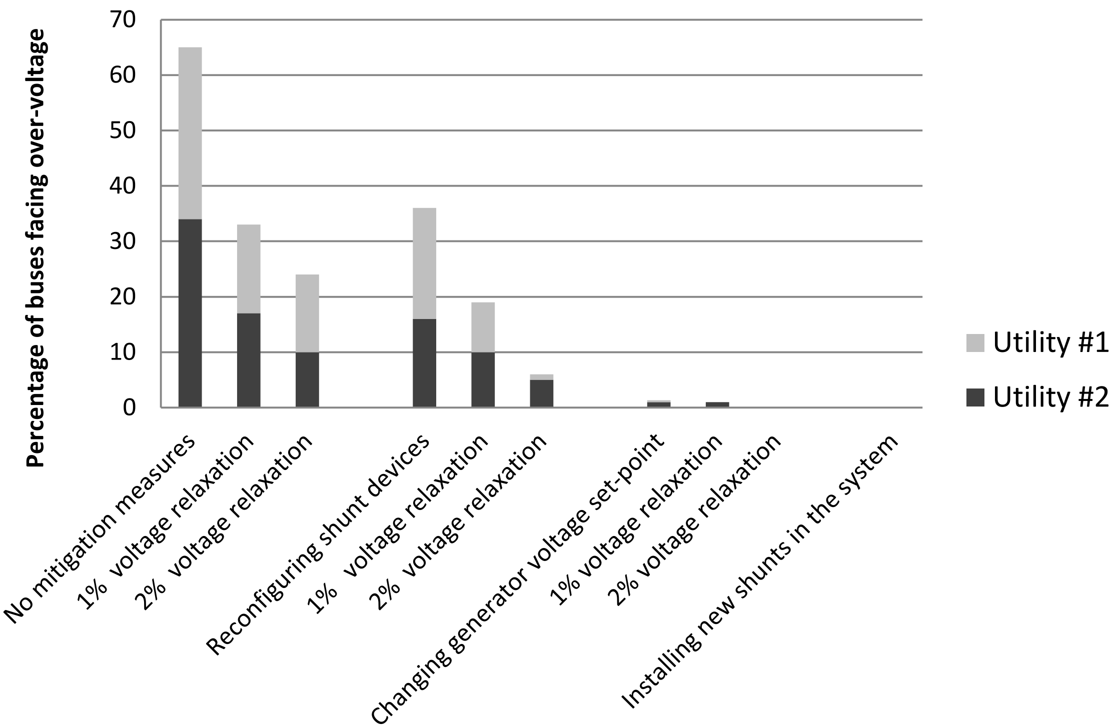

Figure 3.1 Improvement in the voltage profile after implementation of mitigation measures for the 2010 spring light load case

Table 3.9 List of new capacitive shunts required to remove voltage violation for 30% PV in the 2010 light load case

Shunt capacitors		
Bus number	Bus zone	Reactive power capacity (MVAr)
17453	Utility #2	9.1
86759	Utility #2	6.9
86766	Utility #2	2
87182	Utility #2	2.9
87959	Utility #2	0.1
88153	Utility #2	3.3
88214	Utility #2	0.3
88144	Utility #2	0.5
17443	Utility #1	28.5
Total capacitive shunt required		**53.6 MVAr**

Table 3.6 List of new reactive shunts required to remove voltage violation for 30% PV in the 2010 light load case

Shunt reactors		
Bus number	Bus zone	Reactive power capacity (MVAr)
86865	Utility #2	1.7
87045	Utility #2	0.6
87067	Utility #2	1.5
87057	Utility #2	1.6
87056	Utility #2	1.7
18211	Utility #1	3.3
Total reactive shunt required		**10.4 MVAr**

Mitigation measures for peak load condition

The procedure followed to remove the voltage violation for light load conditions is repeated to solve the overvoltage issue for peak load conditions. The chart shown in Figure 3.4 shows the improvement achieved in terms of reduction in overvoltage conditions after deployment of various mitigation measures.

It can be seen from Figure 3.4 that after changing the generator set-point in the network, only 0.4% buses in Utility #1 and 0.1% buses in Utility #2 face an overvoltage condition. In order to completely remove the voltage violation, new shunt devices have been installed at a few selected buses. Table 3.7 and 3.8 summarize the list of buses at which new shunt devices are installed.

Table 3.7 List of new capacitive shunts required to remove voltage violation for 30% PV in the 2018 peak load case

Shunt capacitors		
Bus number	Bus zone	Reactive power capacity (MVAr)
88203	Utility #2	1.1
87182	Utility #2	7.7
Total capacitive shunt required		**8.8 MVAr**

Table 3.10 List of new reactive shunts required to remove voltage violation for 30% PV in the 2018 summer peak load case

Shunt reactors		
Bus number	Bus zone	Reactive power capacity (MVAr)
84223	Utility #2	2.9
15869	Utility #1	12.8
Total reactive shunt required		**15.7 MVAr**

Comparison of mitigation measures for peak and light load conditions

Comparing the mitigation measures deployed to solve the issue of overvoltage between the peak and the light loading conditions, it can be observed that, the peak loading condition required less number of new shunt devices to be installed to solve the problem. This happened despite the fact that summer peak loading condition had more severe overvoltage conditions. Based on this fact, it can be implied that the 2018 summer peak load case faces more severe overvoltages only because of a greater number of fixed shunt devices operating in the grid compared to the 2010 light load case. Moreover, because of the presence of higher number of shunt devices during the 2018 summer peak load case, there is more flexibility in terms of changing the switching status of those devices in keeping the bus voltage magnitudes under acceptable limit.

3.6 Effect of PV Penetration on System Losses

This section discusses the impact of solar PV penetration on the net real power losses and total reactive power consumption in the system. Figures 3.5 and 3.6 illustrate the real power loss and reactive power consumption in the system for varying PV levels for the 2018 peak load scenario. It is observed that the losses reduce as the PV penetration level rises in the system up to 30% of PV penetration; it remains constant for 37.5% and then starts rising again. The same trend is observed for reactive power consumption. It happens because after significant PV penetration of 37.5%, the local rooftop PV generation exceeds the local load demand of nearby areas and starts serving far away loads as well contributing to the increase in real power losses and reactive power consumption.

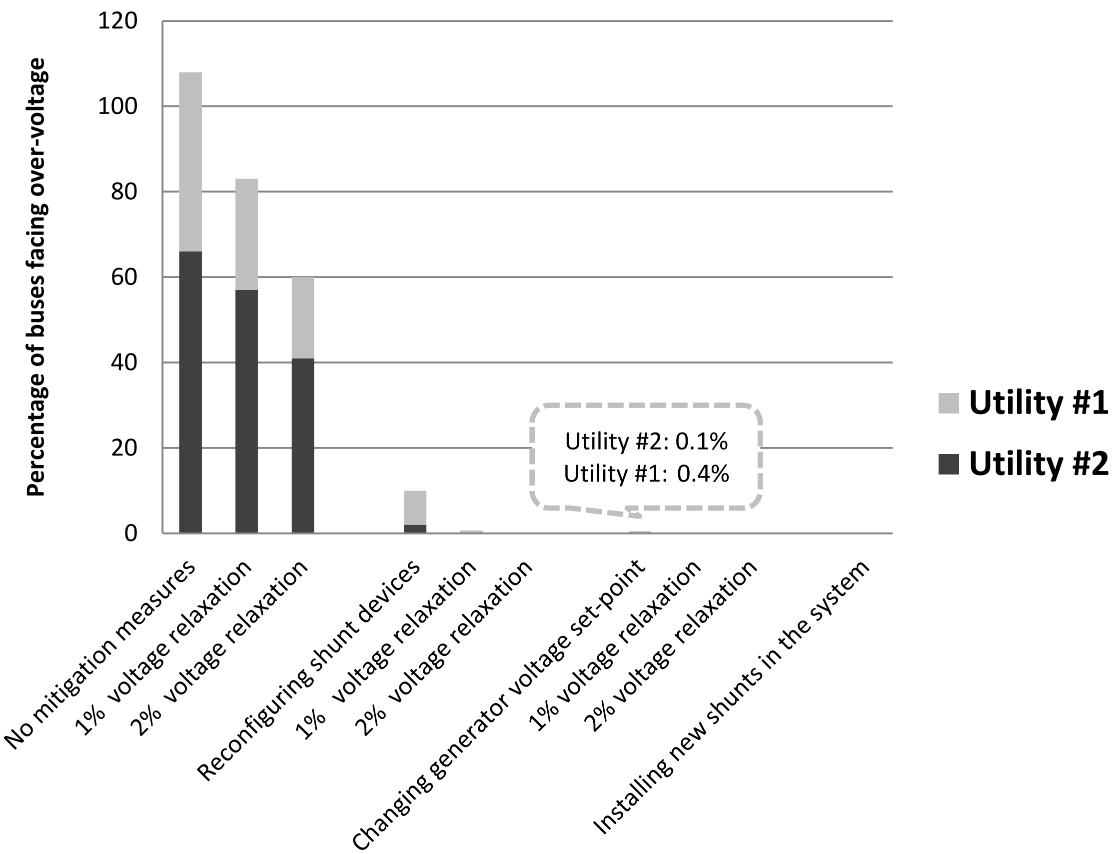

Figure 3.2 Improvement in the voltage profile after implementation of mitigation measures for the 2018 summer peak load case

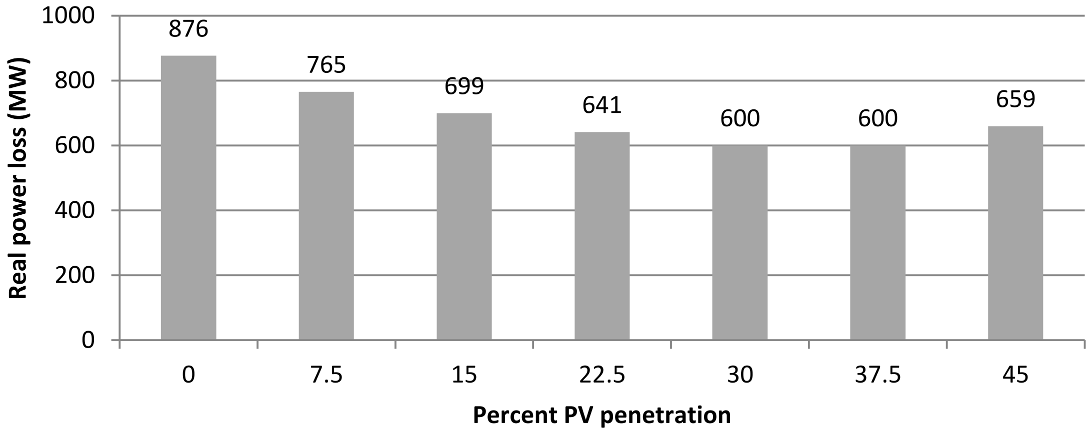

Figure 3.5 Total real power losses in the system for varying PV penetration for the 2018 summer peak load case

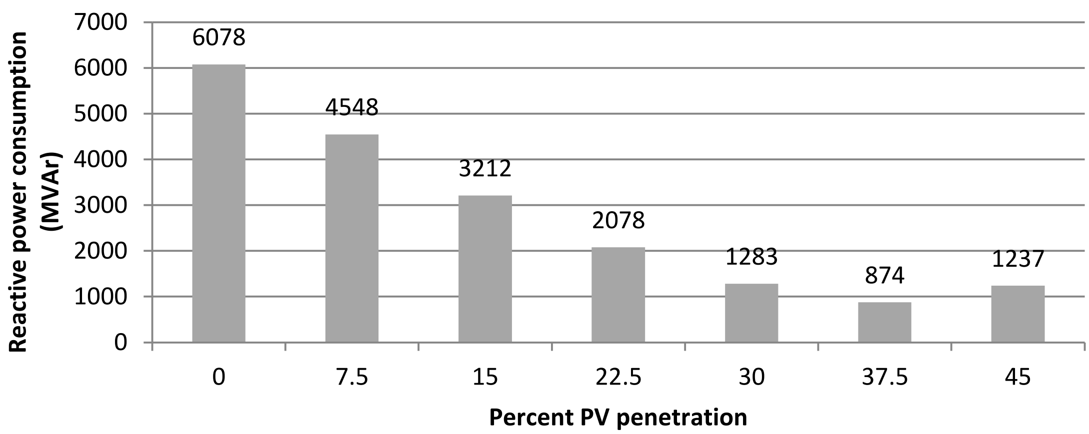

Figure 3.6 Total reactive power consumption in the system for varying PV penetration for the 2018 summer peak load case

3.7 Conclusions

Based on the study detailed in this chapter, it can be said that the impact of solar PV penetration on steady state voltage profile of the Southwestern US transmission system is significant and the system faces potential overvoltage situations that are not acceptable for secure and reliable operation. It is observed that the overvoltage in the network increases with increasing PV penetration until a certain PV penetration level and then the extent of overvoltage decreases. A scenario of 30% PV penetration is identified as the worst-case overvoltage scenario for both the 2010 light and the 2018 peak load conditions. Peak load conditions in the network face more severe overvoltages compared to light load conditions for the same amount of PV integrated into the system. This behavior is as a result of more number of shunts operating during the summer.

Various mitigation measures have been developed to solve the issue of overvoltage condition in the network. It is observed that, solving the overvoltage issues is easier under summer peak loading conditions because the reactive power requirement in the system is greater during the summer. The higher lagging reactive power demand results in lower bus voltage magnitudes. The foregoing voltage scenarios can be validated by the fact that, compared to light load case, the summer peak load case requires fewer new shunt devices to eliminate the voltage violations.

The impact of PV penetration is found to be significant on the net real power losses and total reactive power consumption in the system. The net real power losses reduce as the amount of PV increases from 0% to 37.5%. The active power losses show a decreasing trend after 37.5% of PV penetration is reached. The total reactive power consumption in the system follows the same trend decreasing until the 37.5% PV penetration level is reached; subsequently, above 37.5% penetration, the reactive power 'losses' rise with increasing PV penetration.

CHAPTER 4

DYNAMIC ANALYSIS

4.1 Dynamic System Performance in the Presence of PV

This chapter contains the analysis of the impact of PV penetration on the dynamic performance of the Southwestern US transmission system. The dynamic response includes frequency response, voltage response and rotor angle stability after a large disturbance. Solar PV resources affect two important aspects of EPS:

- Availability of inertia in the system
- Availability of reactive power support in the system.

Solar PV resources are unable to provide inertia to the system because of the lack of rotating masses in electronic converters. When solar PV replaces conventional synchronous generators, the amount of total generation in case of solar PV penetration remains the same but the number of committed conventional synchronous generator which provide inertia to the system decrease. This causes the system inertia per unit of power generated in the system to reduce.

As far as reactive power capability is concerned, converters connected to PV resources do have the capability to provide reactive power support to the network. However, for this study, rooftop PVs, which form the assumed bulk of PV penetration, have been modeled as strictly active power sources. This consideration is as per the advice of the operating utility. The absence of reactive power generation by the rooftop PVs results in a significant reduction in the reactive power support in the system as PV penetration increases. Reduction in the reactive power support may cause the power flow solution to diverge for the system with significant PV penetration. As mentioned in Chapter 2, switching off conventional synchronous generators with significant reactive power exchange with the system may cause the power flow to diverge because of lack of reactive power support in the system. For this study, some of the conventional generators are retained online to provide reactive power support to the system, even though their real power output was reduced to zero to maintain power load balance.

Both the aforementioned aspects of EPSs, namely system inertia and reactive power support, have an impact on the dynamic performance of the system. Reduced inertia may result in reduced damping to disturbances and may increase the possibility of rotor angle instability. Moreover, a reduction in damping may cause an increase in acceleration of conventional synchronous generator rotors after a system disturbance (e.g., a fault). The decreased per unit inertia can also result in deeper frequency nadirs after the loss of a large generating unit. On the other hand, reduced reactive power support can affect the voltage response of the system after a contingency.

In view of the aforementioned facts, it becomes necessary to analyze the impact of PV penetration on the dynamic performance of transmission system. This analysis can help operating utilities to identify those locations in the network that are more vulnerable to instability and poor damping after a system disturbance. Dynamic analysis can help in identifying the location in the network for PV resource installation to minimize the detrimental impacts of PV on dynamic performance.

There are two main objectives of this chapter:

- To compare the dynamic performance of the 2010 spring light load case and the 2018 summer peak load case for contingencies which were critical for the spring light load case.
- To identify the critical contingencies for 2018 summer peak load case and analyze the dynamic performance of the system for these contingencies.

The next section discusses the dynamic performance of the 2018 summer peak load case for those contingencies which were found to be critical in the 2010 spring light load case. Subsequently, in the third section critical contingencies for the peak load case are identified and analyzed. The fourth section summarizes the important results of the chapter.

4.2 Comparison of Light and Peak Load Case Dynamic Performance

The impact of PV penetration on dynamic performance of the Southwestern US transmission system for the light load case of spring 2010 was conducted in [22]. The critical contingencies had been identified for the spring light load case and are summarized in Table 4.1. This thesis analyzes the dynamic performance of the 2018 summer peak load case for the same contingencies identified in Table 4.1 for the purpose of comparison with the 2010 spring light load case. The cases, in which differences in the dynamic performance are found, have been discussed in detail in this thesis. A brief discussion of the factors that cause these differences have also been presented in this work.

With reference to the several cases listed in Table 4.1, it is observed that except for the case 3 contingency, all other contingencies have the same dynamic performance behavior for both the 2010 spring light load case and the 2018 summer peak load case. In

Table 4.1 Comparison of dynamic performance between the 2010 spring light load and the 2018 summer peak load conditions for critical contingencies of the 2010 spring light load case

Contingency name	Contingency description	Dynamic performance comparison between peak and light load
Case 1	Loss of generating unit at bus 18324	Same behavior
Case 2	Loss of generating unit at bus 18269	Same behavior
Case 3	Double line outage between 17431 and 16349	Different behavior
Case 4	Double line outage between 17431-17353 and 17363- 17403	Same behavior
Case 5	Bus fault at 17363	Same behavior
Case 6	Bus fault at 17958	Same behavior

this work a comparison of dynamic performance of the 2018 peak and the 2010 light load case, for the case 3 contingency is presented. Details of the dynamic performance for other contingencies in 2010 spring light load case can be found in [22].

In the 2010 spring light load scenarios it had been identified that, solar PV penetration could have a benefecial impact in terms of better voltage and frequency response after some of the double line outage contingencies. Figure 4.1 and 4.2 illustrate one such example showing the benefial impact of PV penetration. Figure 4.1 and 4.2 show the voltage and freuqncy reposnse of the system respectively at bus 16349 after the double line outage between buses 16349 and 17431. It can be seen that the system becomes unstable in the no-PV (base case) scenarios unlike the PV scenario, where it remains stable. This phenomenon can be attributed to the the reduced flow of power on the double circuit line between buses 17431 and 16349 in the case of PV penetration.

In the case of the 2018 summer peak load, PV penetration may not have the beneficial impact in terms of stablilizing the system after the double line outage contingencies as previously seen for the 2010 spring light load case. This fact is validated by observing the voltage and frequency response for the same contingencies (double line outage between 16349 and 17431) as shown in Figure 4.3 and 4.4. It can be seen that system fails to stabilize for both the base and the PV case. This difference in

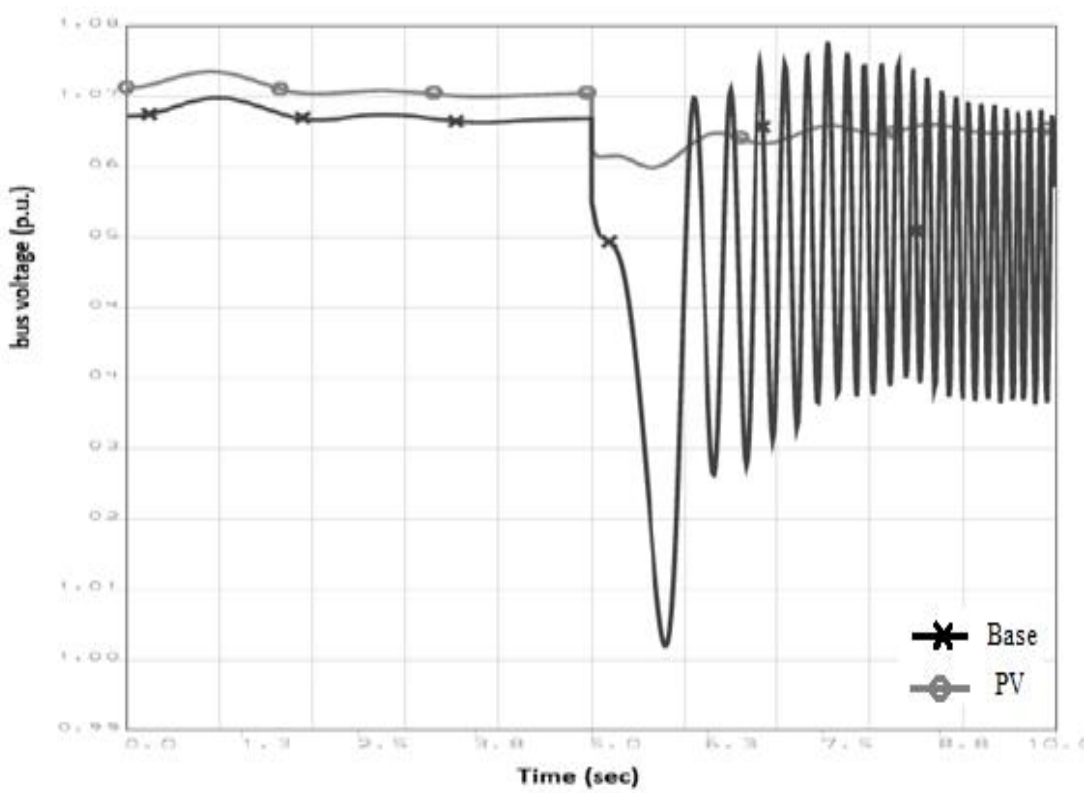

Figure 4.1 17431 bus voltage in response to the case 3 contingency in the 2010 spring light load case [22]

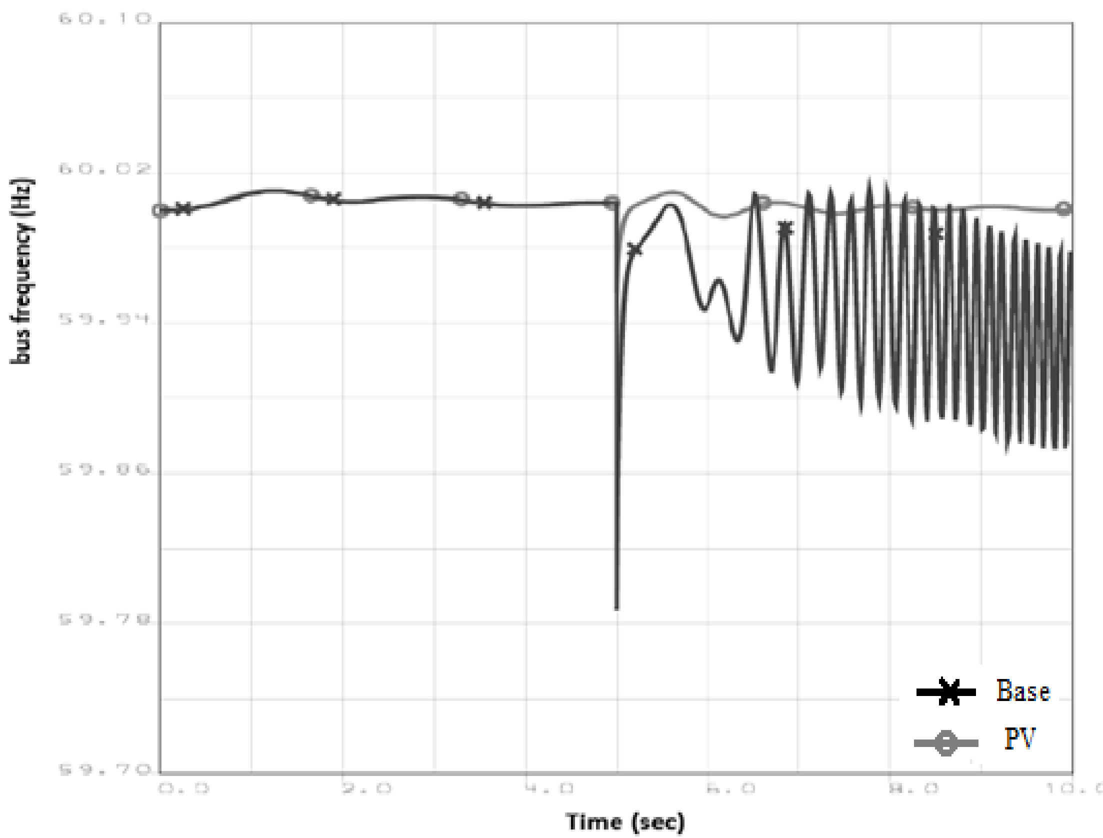

Figure 4.2 17431 bus frequency in response to the case 3 contingency in the 2010 spring light load case [22]

behavior for the peak and the light load arises because of the heavier loading of the lines during the summer peak load case compared to spring light load case. Even after significant penetration of PV in the system, loadings on the lines do not decrease enough to have a beneficial impact on voltage and frequency response of the system.

Figure 4.5-4.8 illustrate the reduction in power flow on the double circuit line between buses 16349 and 17431 for the 2010 spring light load and the 2018 summer peak load case. It can be seen from Figure 4.5-4.8 that during the spring light load, the assumed installed PV penetration reduces the flow on lines between buses 17431 and 16349 from 1298 MW to 294 MW. While in the summer peak load scenario, PV penetration reduces the flow from 1980 MW to 790 MW. Even after the cited reduction in power flow, 500 MW more power is flowing in the parallel lines between 16349 and 17431 in the peak load case as compared to the light load case. This causes the system to destabilize after the loss of these parallel lines between 16349 and 17431 in PV scenario during peak load conditions.

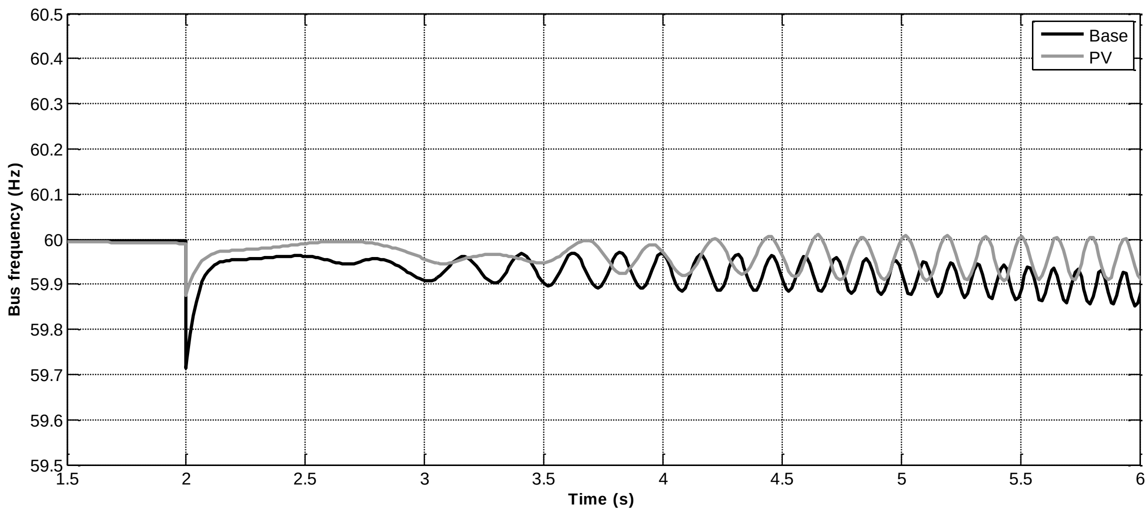

Figure 4.3 17431 bus frequency in response to the case 3 contingency for the 2018 summer peak load case

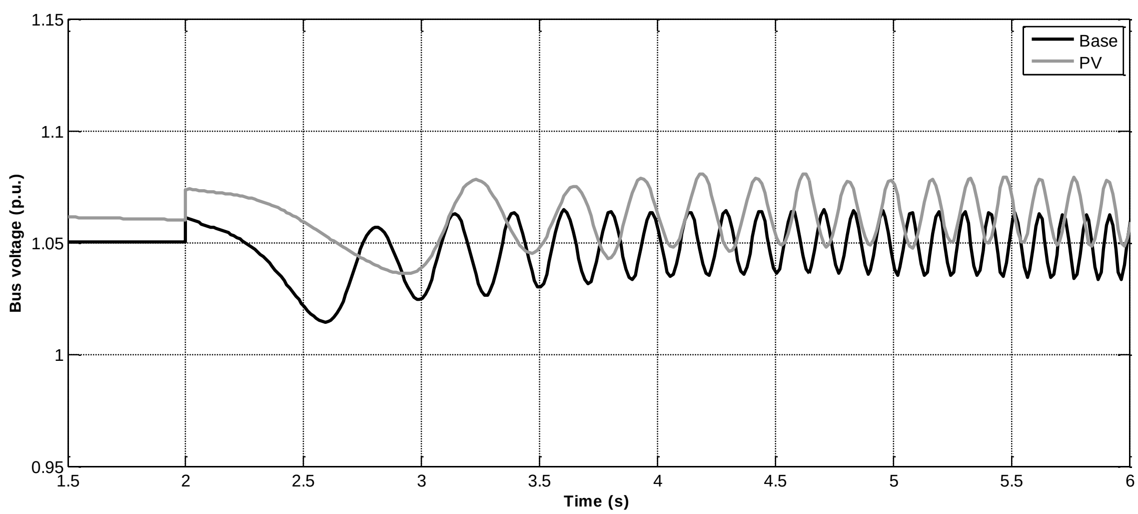

Figure 4.4 17431 bus voltage in response to the case 3 contingency for the 2018 summer peak load case

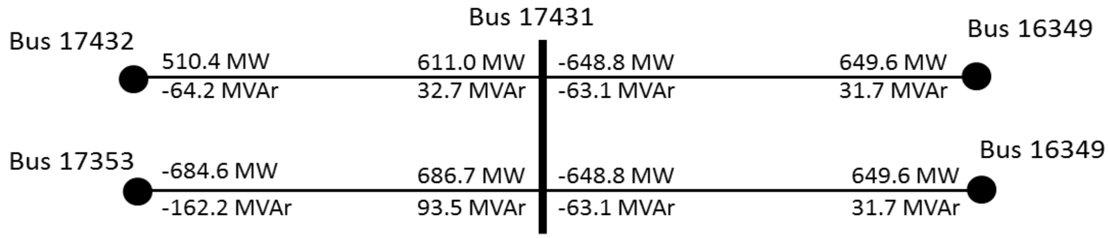

Figure 4.5 One-line diagram showing the power flow on 17431-16349 double circuit line during the 2010 spring light load base case

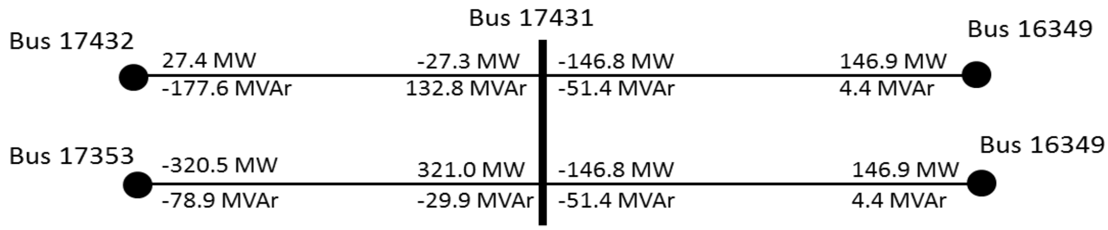

Figure 4.6 One-line diagram showing the power flow on the 17431-16349 double circuit line during the 2010 spring light load PV case

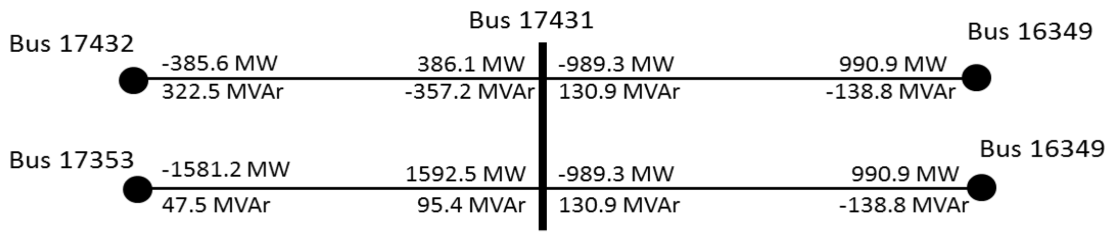

Figure 4.7 One-line diagram showing the power flow on the 17431-16349 double circuit line during the 2018 summer peak load base case

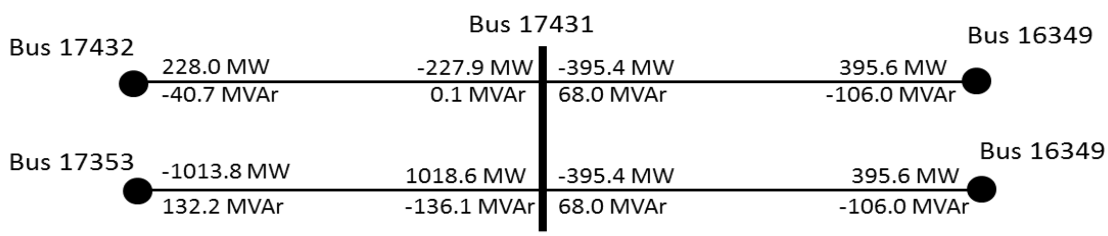

Figure 4.8 One-line diagram showing the power flow on the 17431-16349 double circuit line during the 2018 summer peak load PV case

4.3 The 2010 Summer Peak Load Case Critical Contingencies

This section analyzes the dynamic performance of the 2018 summer peak load case for contingencies that are critical and have the potential to cause instabilities in the system in the peak load scenario. These contingencies have been identified with the help of VSAT software module developed by DSA Tech Labs. Table 4.2 summarizes all the identified critical contingencies.

Table 4.2 List of critical contingencies for the 2018 summer peak load case

Contingency number	Contingency description
Case 7	Line outage between buses 17990 and 17997
Case 8	Loss of generator at bus 18845
Case 9	Line outage between buses 81366 and 81374
Case 10	Loss of generator at bus 19371
Case 11	Double line outage between buses 86977 and 86988

Case 7 analysis

The case 7 contingency refers to the scenario of line outage between the buses 17990 and 17997. It is interesting to analyze the impact of PV penetration for this contingency because of the reversal in the power flow direction on this line in the PV scenario compared to the base case scenario. In the base case scenario, the real power is flowing from bus 17990 to bus 17997, while in the PV scenario power flow direction reverses because of the 26.8 MW of PV generation added at bus 17990. This is illustrated in Figures 4.9 and 4.10.

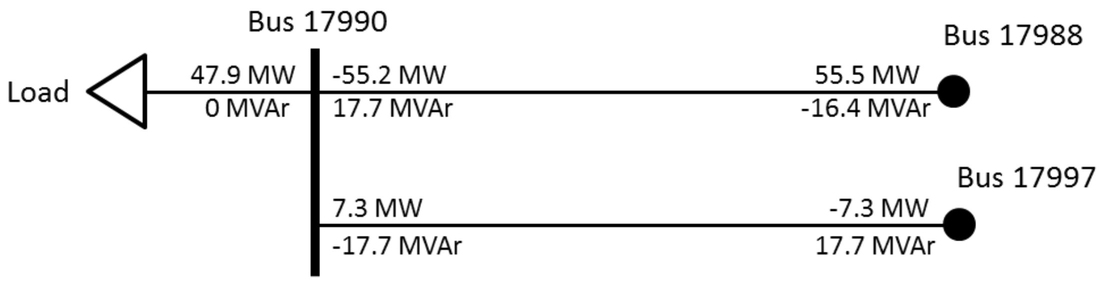

Figure 4.9 One-line diagram showing the power flow on bus 17990 during the 2018 summer peak load base case

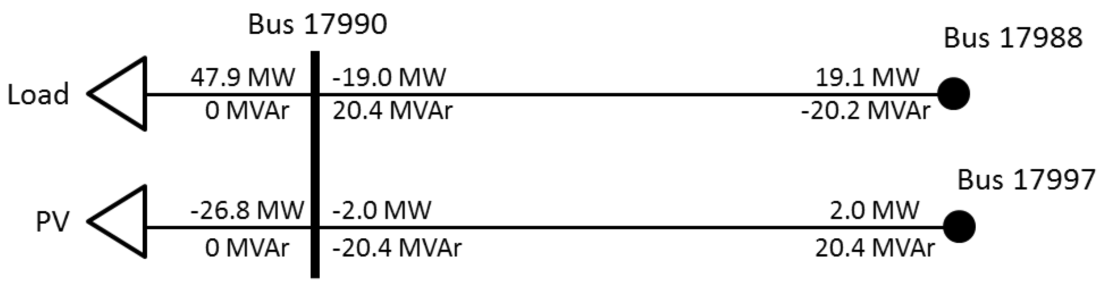

Figure 4.10 One-line diagram showing the power flow on bus 17990 during the 2018 peak load PV case

The post contingency voltage and frequency response at bus 17990 and voltage response at bus 17997 is shown in Figures 4.11-4.13. It can be observed from Figure 4.11 that frequency excursion is upward for the base case while it is downward for the PV case. This difference in behavior can be attributed to the change in direction of real power flow on the line. In the base case, the real power is flowing from bus 17990 to the bus 17997. The loss of line connecting these buses makes more power available at bus 17990 than required to serve the load connected at that bus, resulting in the increase in frequency at the bus. After some time the excess power at bus 17990 is redistributed among loads connected to neighboring buses resulting in the frequency decrease. The frequency finally settles down at almost the same value as before the contingency. In the

PV scenario, the real power flow on line between bus 17990 and bus 17997 is in the opposite direction as compared to the base case scenario. This reversal of active power flow results in the availability of less real power at bus 17990 to serve the local load after the contingency in the PV scenario. The availability of less power than required to serve the local load causes a frequency excursion in the downward direction at bus 17990 in the PV scenario.

Figure 4.12 and 4.13 show the voltage response at bus 17990 and 17997 after the loss of line between them. The voltage magnitude at bus 17990 increases after the contingency unlike the base case where $|V_{17990}|$ decreases. This reduction in voltage magnitude is attributed to the lighter loading of line between bus 17990 and 17988. The lower line load leads to less reactive power consumption in the line and hence more reactive power support at bus 17990 after the contingency.

The opposite is true at bus 17997 where the direction of impedance drop in the line between 17990 and 17988 is reversed because of the reversal in power flow direction from the base case to the PV case. The impedance drop from bus 17997 to bus 17990 in the base case causes the voltage magnitude to increase at bus 17997 after the loss of the connecting line. In the PV case, the impedance drop is from 17990 to 17997 leading to the drop in voltage magnitude after the loss of line between 17990 and 17997.

Case 8 analysis

The case 8 refers to the contingency scenario of a loss of generator at bus 18845. The generator has an operational real power output of 195 MW for the study. Simulation results are presented in Figures 4.14-4.18. It can be observed from Figure 4.14 and 4.16 that there is no difference in frequency response of the system for the PV and the base

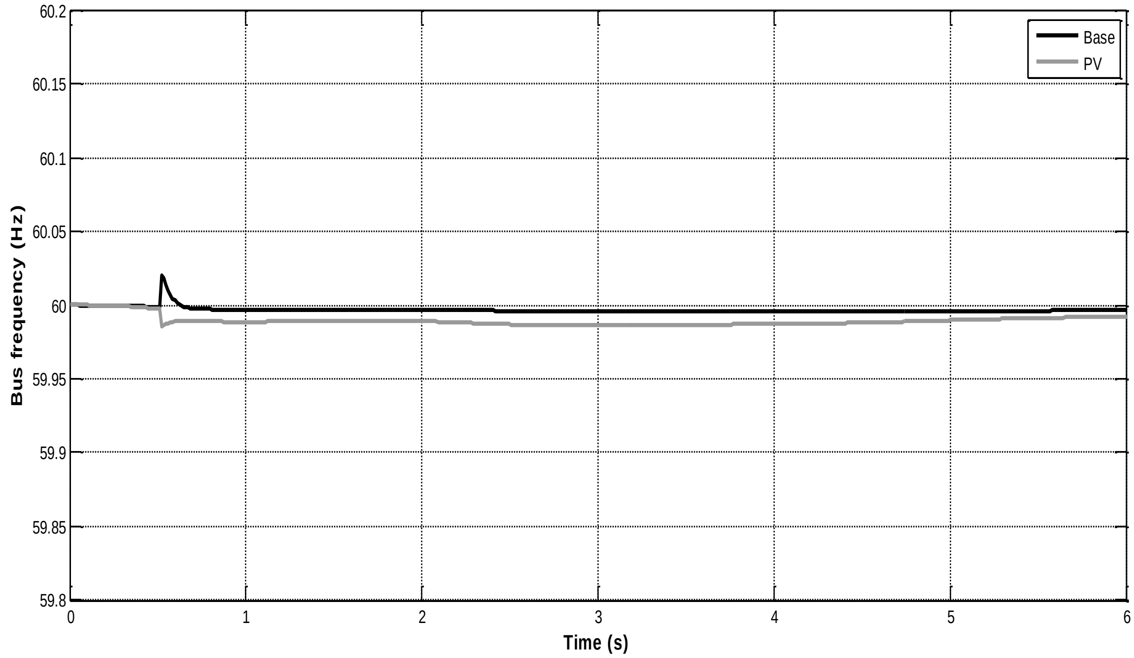

Figure 4.11 17990 bus frequency in response to the case 7 contingency for the 2018 summer peak load case

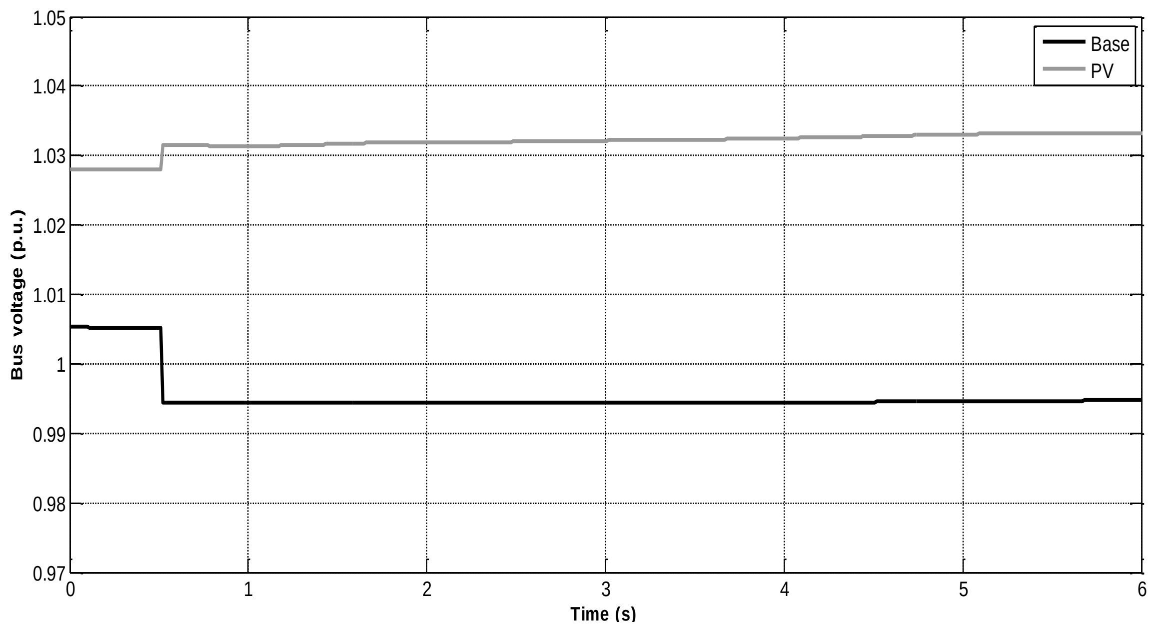

Figure 4.12 17990 bus voltage in response to the case 7 contingency for the 2018 summer peak load case

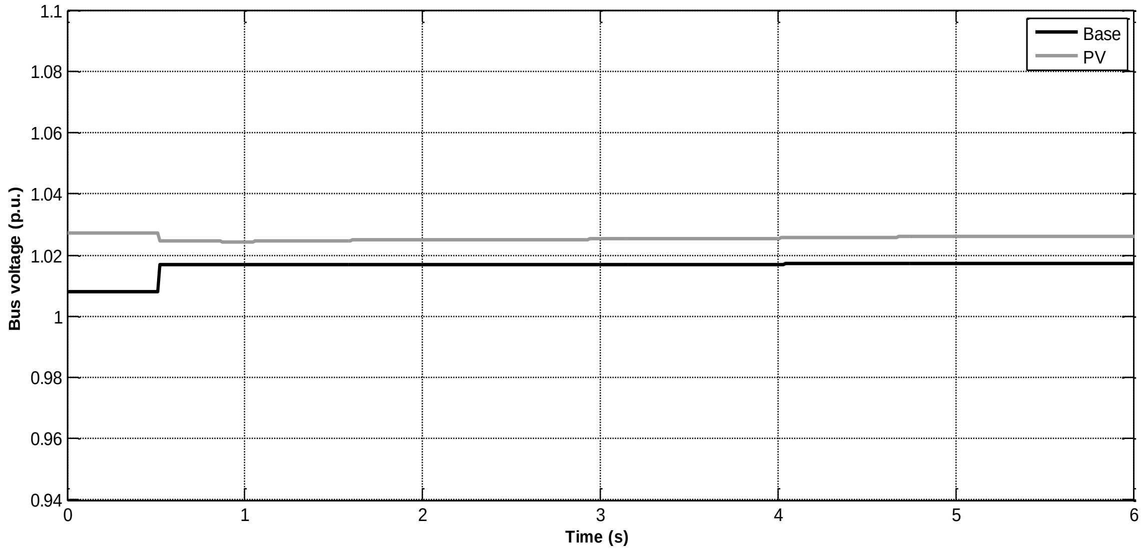

Figure 4.13 17997 bus voltage in response to case 7 contingency for the 2018 summer peak load case

case. Frequency dips and recovers quickly for both the PV and the base case.

However, there is a difference in the voltage response of the system. In the base case, the voltage at the generator bus 18845 dips by approximately 2% after the generator tripping. On the other hand, in case of PV scenario, the voltage magnitude increases initially and then dips before settling down at the pre-disturbance voltage level. This can be attributed to the difference in reactive power supply by the generator in the base and the PV case. In the base case, the generator is providing 3.9 MVAr of reactive power to the system. In the event of generator being switched off, there is reduction in the reactive power support to the bus resulting in the decrease in the voltage magnitude after the contingency. On the contrary, in the PV case the generator at bus 18845 is consuming 10.2 MVAr which leads to an excess reactive power at the generator bus after the generator tripping. This causes the momentary increase in voltage magnitude for the PV case. After some time the excess reactive power redistributes among other reactive power consuming devices bringing the voltage at pre-disturbance level.

Plots for real power output, voltage and frequency response of the neighboring generator has also been shown in Figures 4.14-4.18. Oscillations are observed in real power output of the neighboring synchronous generators because, the loss of power output from the generator at bus 18845 is immediately shared by electrically close generators before being distributed throughout the system. However, there is no difference in the behavior for the PV and the base case.

Case 9 analysis

This case analyzes the impact of a loss of 345 kV line between bus 81366 and bus 81374 on the dynamic performance of the system. Figure 4.19-4.22 shows the simulation results for this contingency. As shown in Figure 4.19, frequency nadir on bus 81366 is

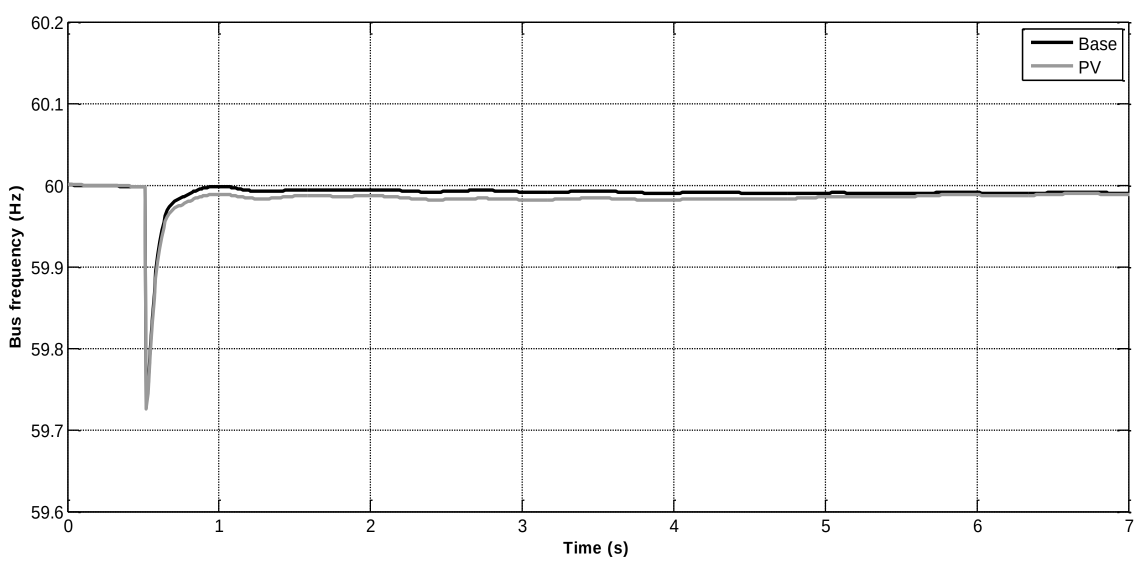

Figure 4.14 18845 bus frequency in response to the case 8 contingency for the 2018 summer peak load case

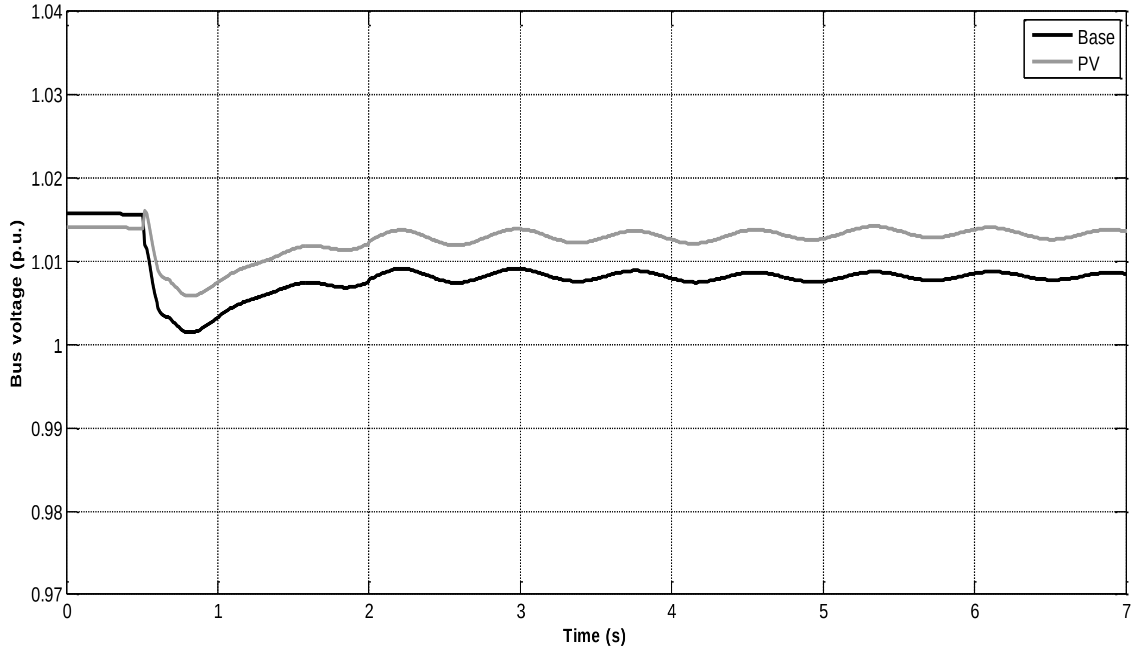

Figure 4.15 18845 bus voltage in response to the case 8 contingency for the 2018 summer peak load case

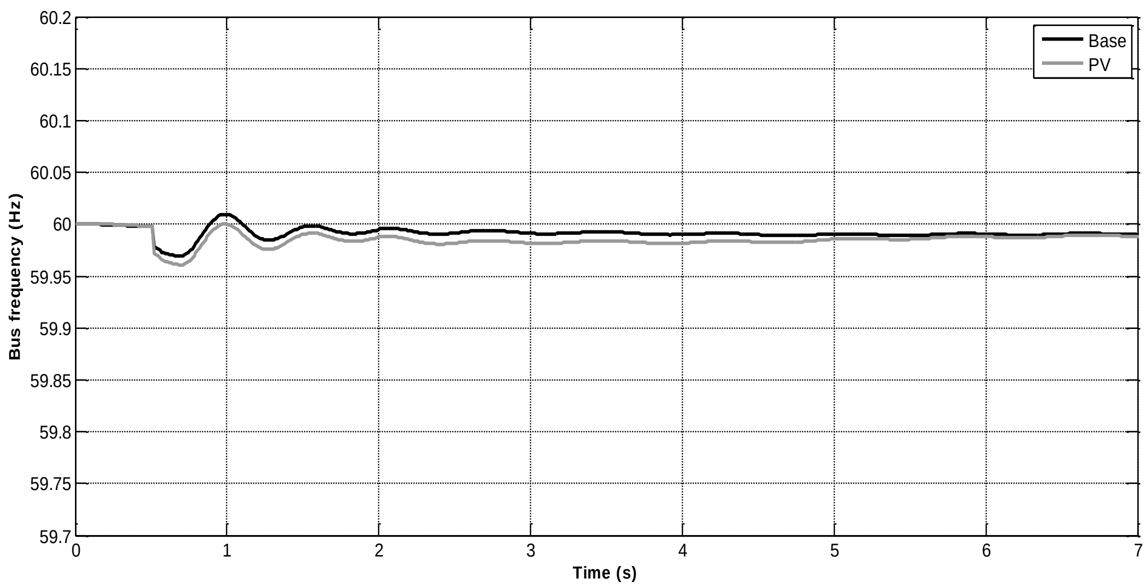

Figure 4.16 18849 bus frequency in response to the case 8 contingency for the 2018 summer peak load case

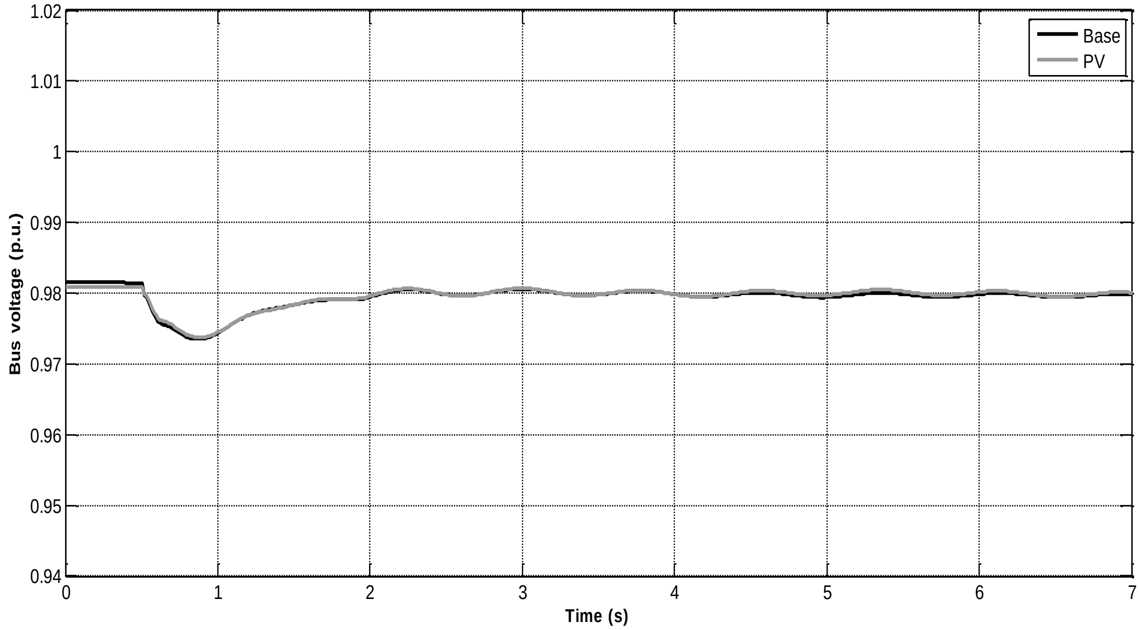

Figure 4.17 18849 bus voltage in response to the case 8 contingency for the 2018 summer peak load case

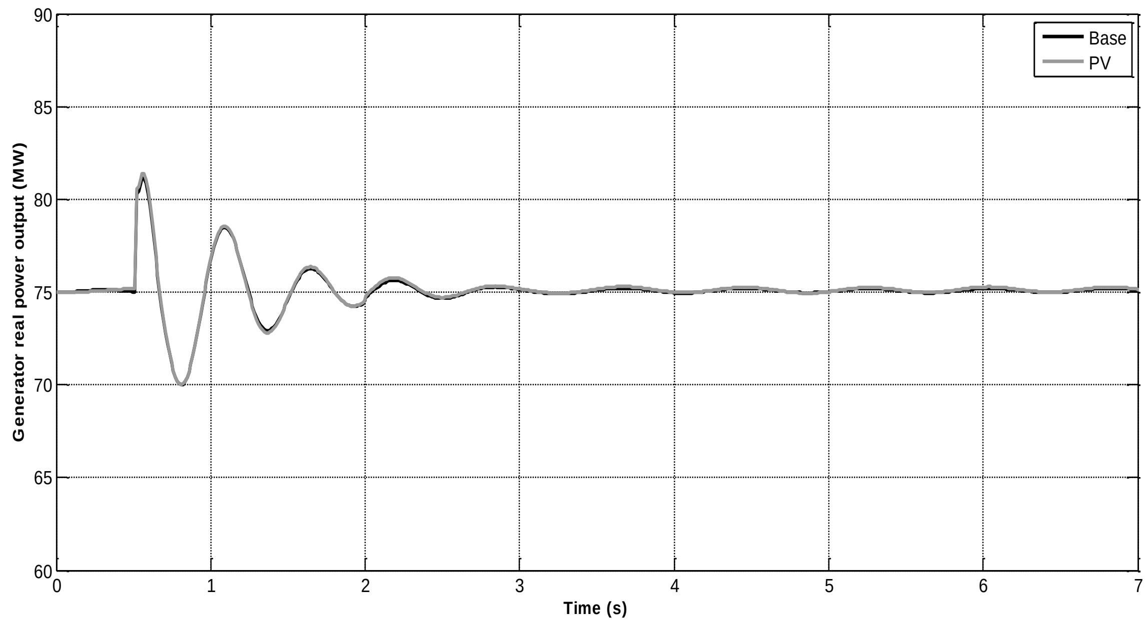

Figure 4.18 18849 real power output in response to the case 8 contingency for the 2018 summer peak load case

deeper during the base case compared to the PV case. This can be attributed to the lighter loading of the line between bus 81366 and bus 81374 during the PV case vis-a-vis the base case. Voltage response behavior at buses 81366 and 81374 is similar for both the PV and the base case as shown in Figure 4.20 and 4.22.

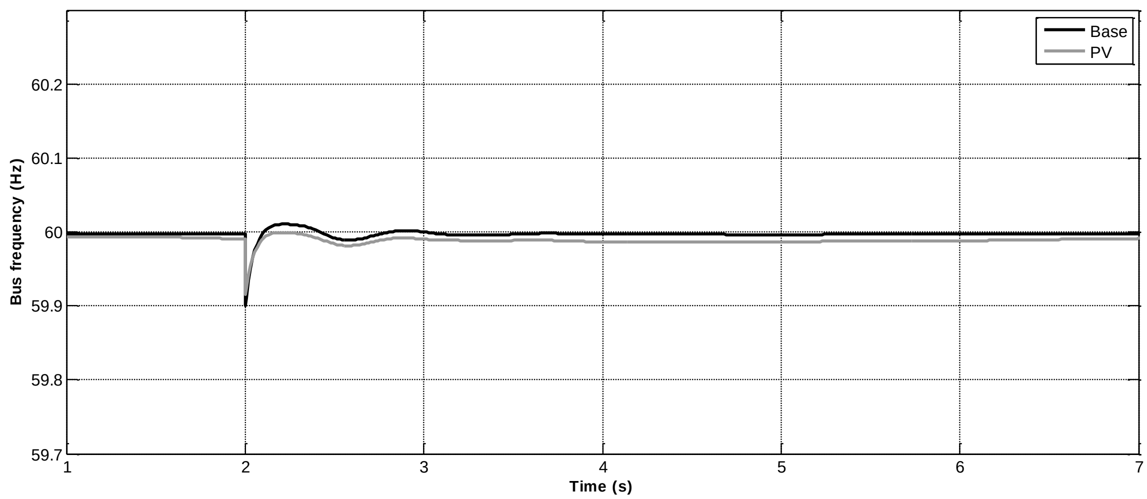

Figure 4.19 81366 bus frequency in response to case 9 contingency for the 2018 summer peak load case

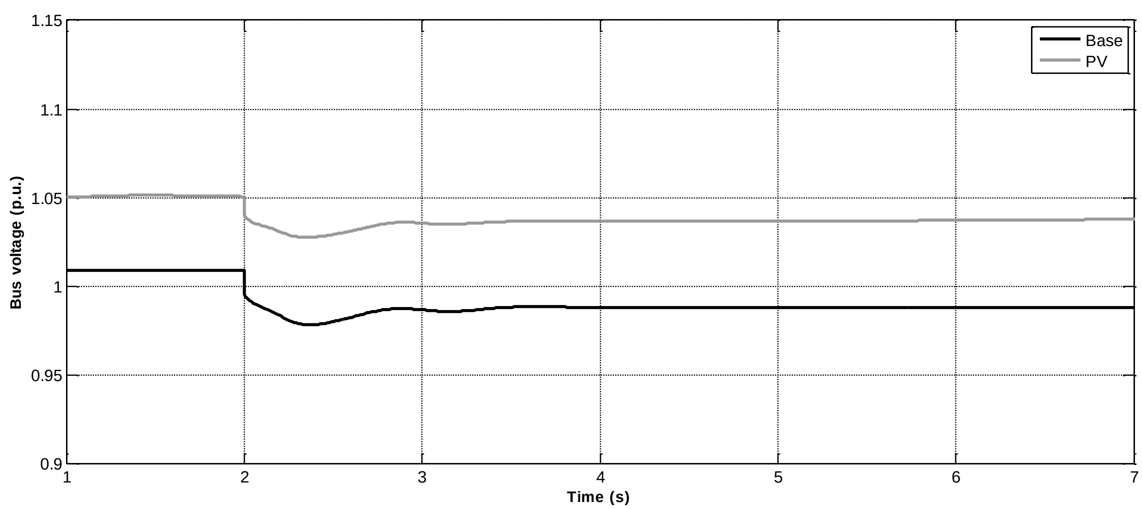

Figure 4.20 81366 bus voltage in response to the case 9 contingency for the 2018 summer peak load case

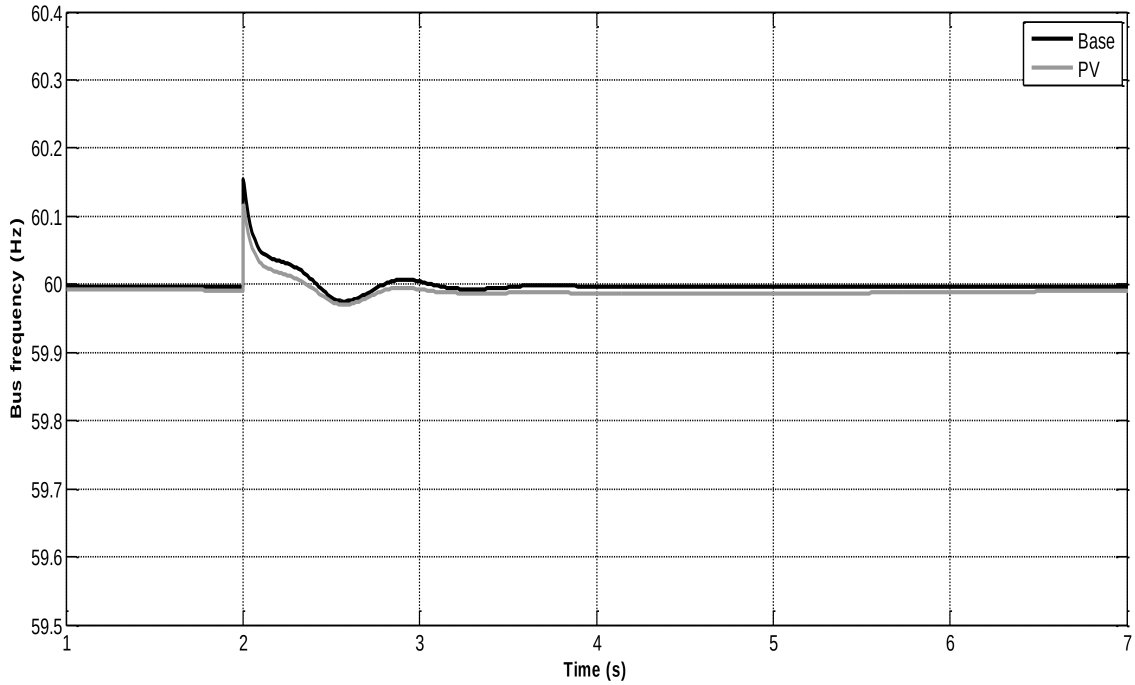

Figure 4.21 81374 bus frequency in response to the case 9 contingency for the 2018 summer peak load case

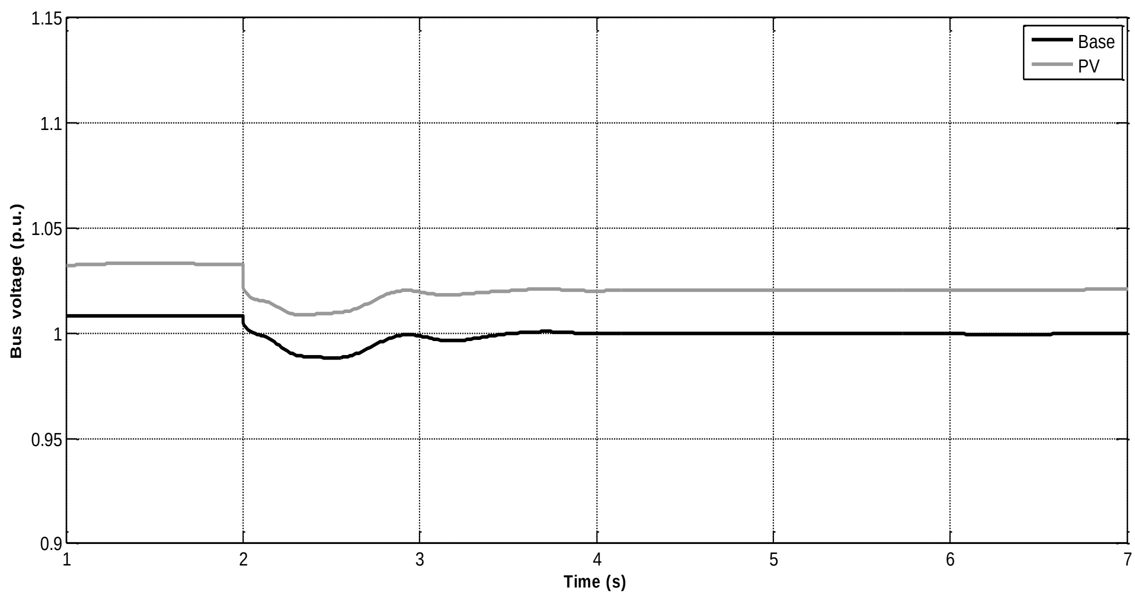

Figure 4.22 81374 bus voltage in response to the case 9 contingency for the 2018 summer peak load case

Case 10 analysis

The impact of a loss of generator at bus 17029 on the dynamic performance of the system has been analyzed in this case. Simulation results are presented in Figures 4.23-4.24. It can be observed that there is no difference in frequency response behavior for PV and the base case. The only difference found is in terms of post contingency voltage magnitude at the generator bus 17029. As shown in Figure 4.24 the voltage magnitude settles at a higher value post contingency in the PV scenario compared to the base case. This can be attributed to the reduced reactive power consumption in the neighboring lines during the PV scenario because of lighter loading of lines. The voltage and frequency response has been found to be similar at neighboring buses for the PV and the base case for this contingency.

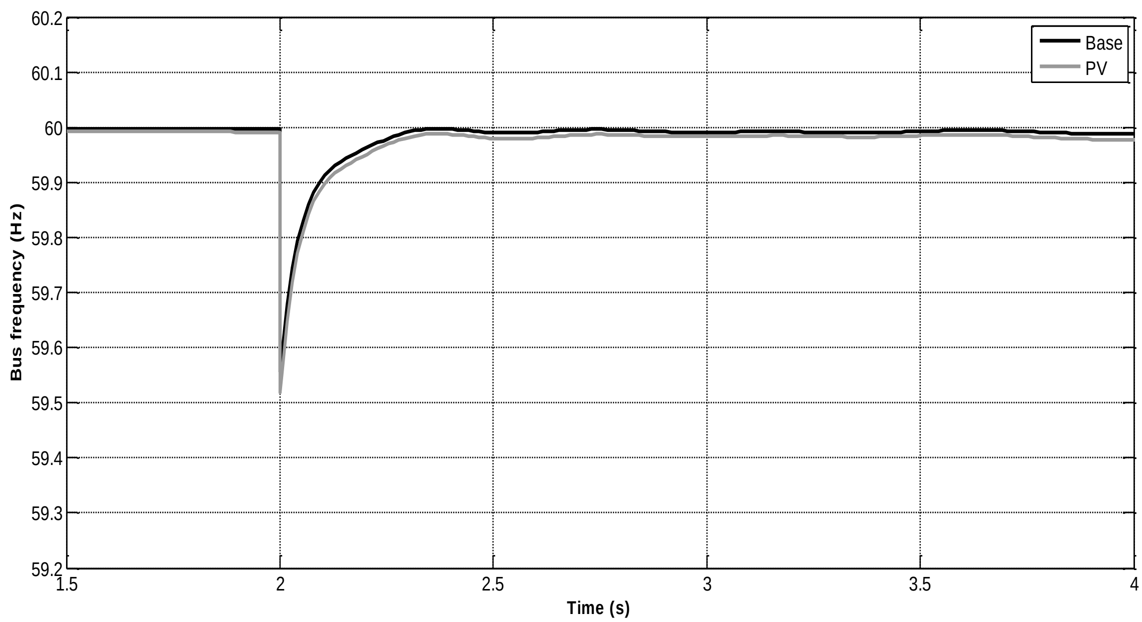

Figure 4.23 19371 bus frequency in response to case 10 contingency for the 2018 summer peak load case

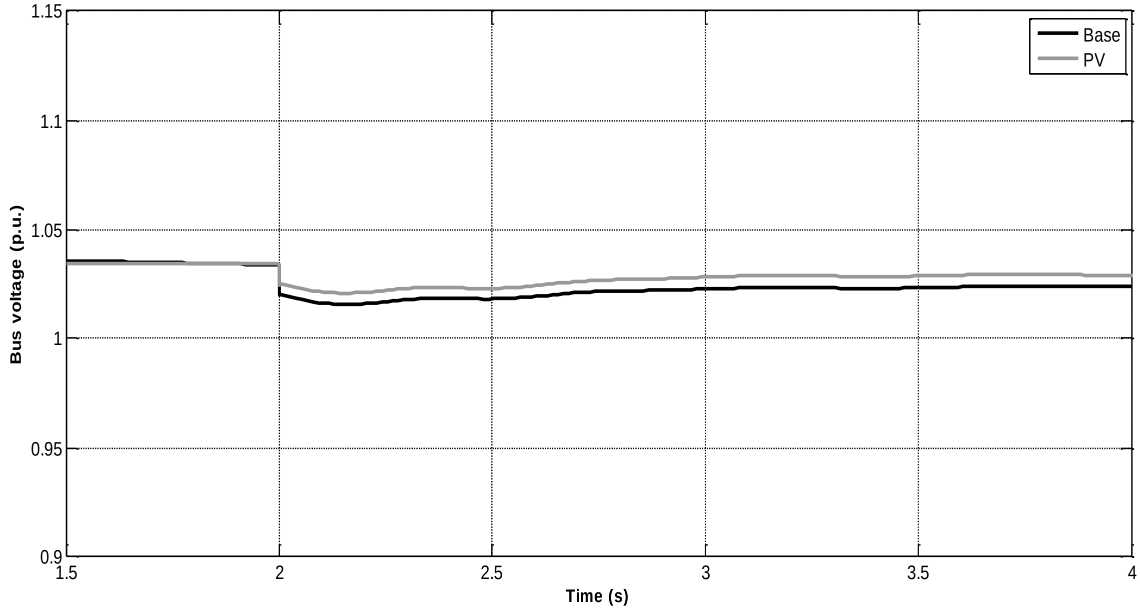

Figure 4.24 19371 bus voltage in response to case 10 contingency for the 2018 summer peak load case

Case 11 analysis

In this case, two parallel 69 kV lines are tripped between buses 86977 and 86988 for analyzing its impact on the dynamic response of the system for both the PV and the base case. The amount of power flowing on these parallel lines between buses 86977 and 86888 during the base case and the PV case has been shown in Figures 4.25 and 4.26. It can be seen that both real and reactive power flow reduce on these lines in the case of PV penetration.

Simulation results for this contingency are shown in Figures 4.27-4.30. As seen in Figure 4.27, the frequency excursion in the base case is higher because of the higher loading of double circuit line during the base case vis-à-vis the PV case. The voltage response is almost the same at bus 86977 for the PV and the base case as shown in Figure 4.28. However, there is a significant difference in the voltage and frequency response for bus 86988. The frequency nadir is much deeper in the base case compared to the PV case at bus 86988. This can be attributed to the higher amount of real power flowing on the lines in the base case compared to the PV case. How the higher loading on lines affect post-contingency frequency nadir has been explained in detail before, during the case 7 contingency analysis. Analyzing the voltage response at bus 86988, as shown in Figure 4.30, it can be seen that, voltage settles down at an unacceptable voltage level of 0.8 per unit post-contingency in the base case. While in the PV case, voltage magnitude settles down at a much higher value of 0.92 per unit. This difference in behavior is observed because of the reduced amount of reactive power flowing on the lines from bus 86977 to bus 86988 in the case of PV scenario. This causes aless severe ‘shortage’ of reactive power support at bus 86988 during the PV scenario.

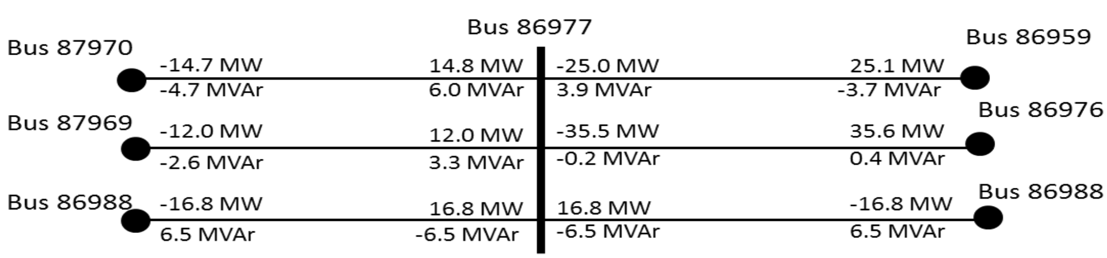

Figure 4.25 One-line diagram showing the power flow on bus 86977 for the 2018 summer peak load base case

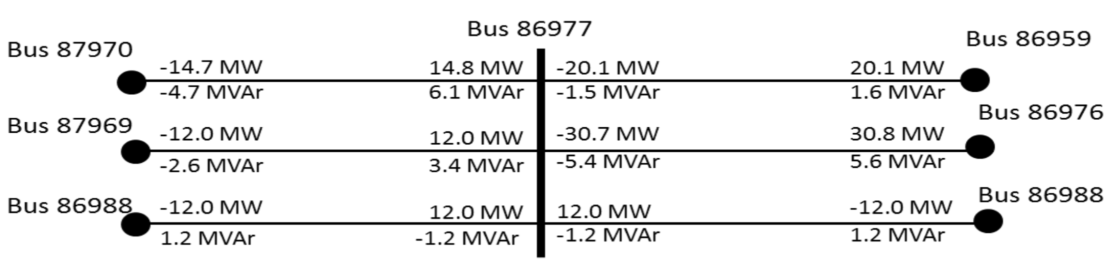

Figure 4.26 One-line diagram showing the power flow on bus 86977 for the 2018 summer peak load PV case

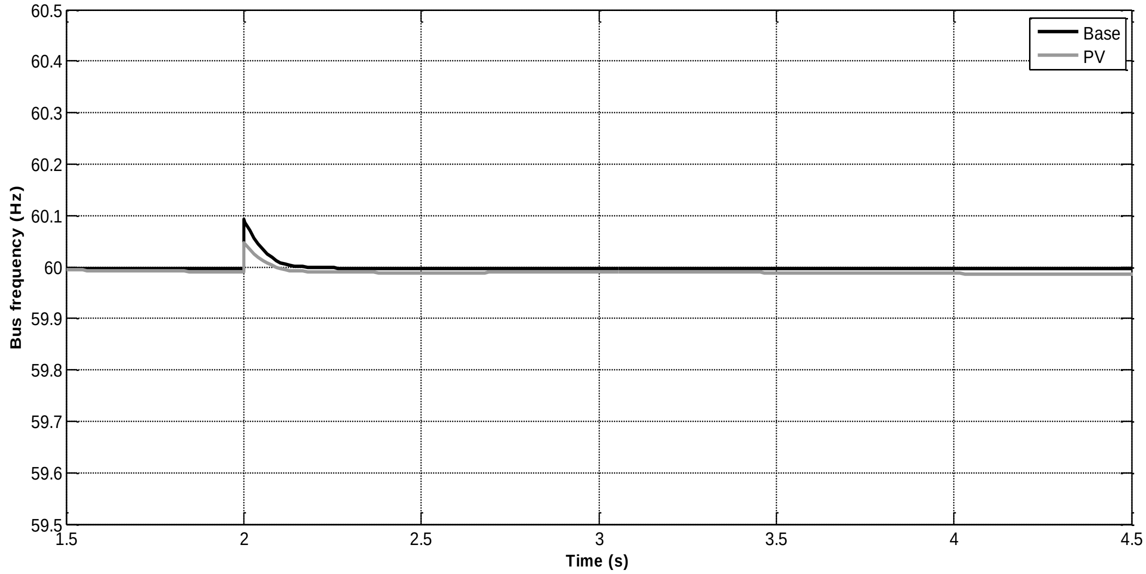

Figure 4.27 86977 bus frequency in response to the case 11 contingency for the 2018 summer peak load case

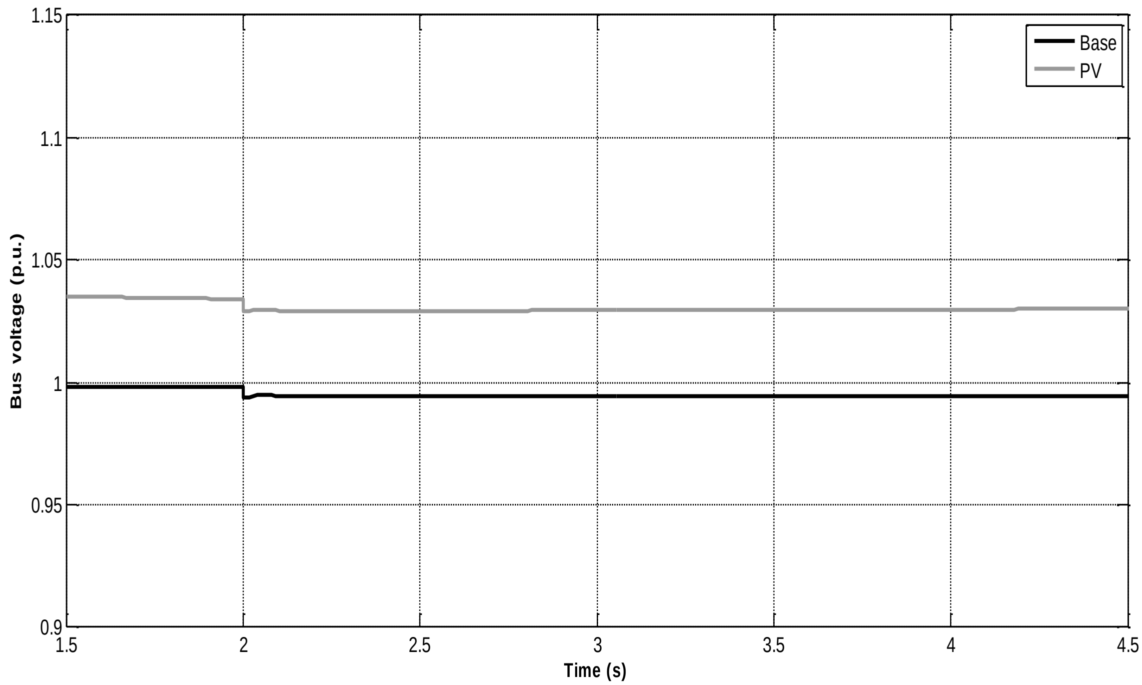

Figure 4.28 86977 bus voltage in response to the case 11 contingency for the 2018 summer peak load case

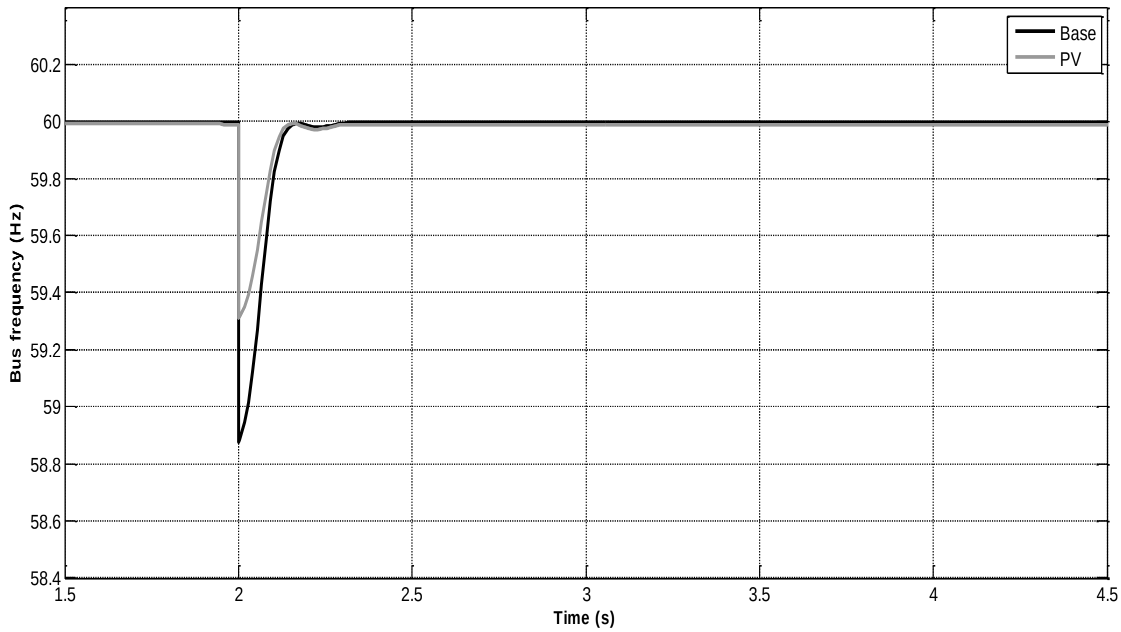

Figure 4.29 86988 bus frequency in response to the case 11 contingency for the 2018 summer peak load case

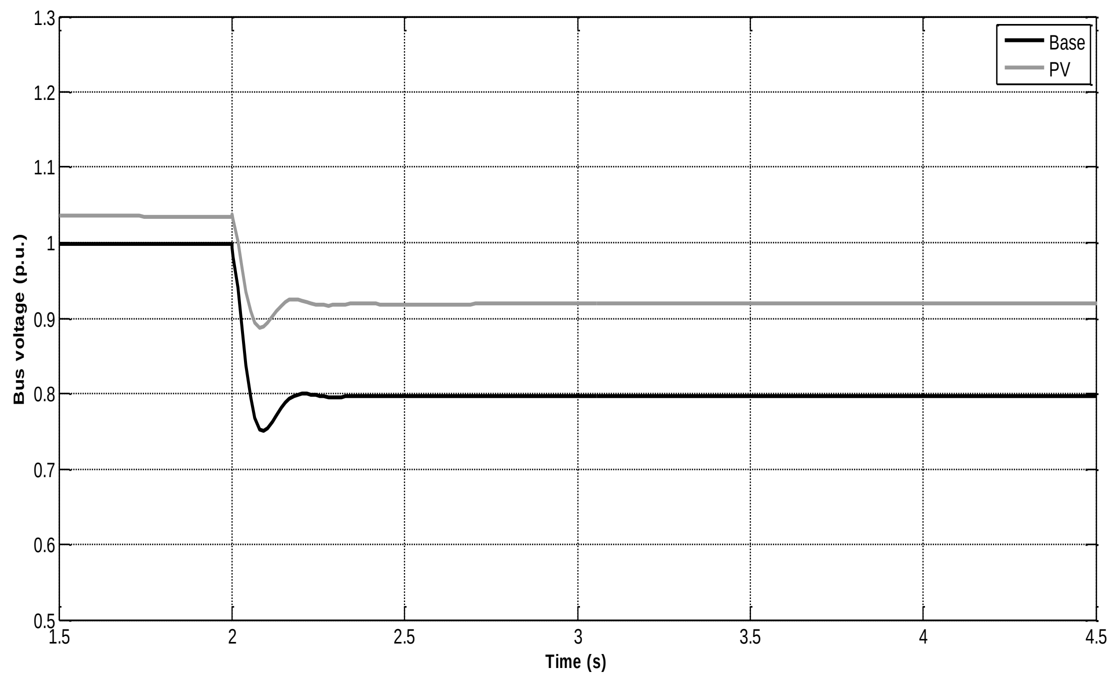

Figure 4.30 86988 bus voltage in response to the case 11 contingency for the 2018 summer peak load case

4.4 Conclusions

This chapter contains an analysis of the impact of PV penetration on the dynamic response of the Southwestern US transmission system. It is found that the replacement of significant amount of conventional generators with solar PV resources does not have a major impact on the frequency response of the system after a large disturbance in the 2018 summer peak load scenario. The beneficial impact of PV in stabilizing the system after the loss of two parallel 500 kV voltage lines between buses 16349 and 17431 for the 2010 spring load case does not have a similar effect for the 2018 summer peak load case. This happens because of the heavier loading of these high voltage lines in the peak load scenario.

The solar PV penetration is found to have some beneficial impact in terms of the voltage response of the system. In the PV scenarios, transmission lines are lightly loaded compared to the base case scenario which reduces the amount of reactive power consumed by these transmission lines. Consequently, the voltage magnitude decrease is found to be lower in cases with PV penetration after a large disturbance. As seen in the case 11 disturbance scenario, the voltage magnitude decreases and settles down at an unacceptable voltage level of 0.8 per unit in the base case. While in case of PV inclusion, the voltage magnitude dip occurs to a lesser degree.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Main Conclusions

This report analyzes the impact of varying amount of solar photovoltaic penetration on the Southwestern US electric power transmission system for the 2018 summer peak load. The analysis compares the results of similar investigation and analysis conducted for the 2010 spring light loading conditions [22]. If the impact of the PV penetration has been found to be *detrimental* to the secure and reliable operation of the studied transmission system, mitigation measures have been recommended to reduce the detrimental effects.

Solar PV penetration has significant detrimental impact on the steady state voltage profile of the system. Overvoltage conditions exist throughout the system in case of significant PV penetration. Overvoltage condition increases with the increase in PV penetration until certain level of penetration, after which the overvoltage severity ameliorates. For the Southwestern US bulk electric power system, overvoltage increases for up to 30% PV penetration (by total MW generation) after which the overvoltage severity decreases. Overvoltage in the system have been found to be higher during the 2018 summer peak load scenario compared to the 2010 spring light loading conditions for the same PV penetration by megawatts. Higher overvoltage during the 2018 summer peak load case can be attributed to the more number of fixed shunts operating during the summer peak load case compared to the 2010 spring load case

Several mitigation measures have been devised to solve the issue of overvoltage in the system for both the 2018 peak and 2010 light load scenario. A combination of measures have been used to reduce the voltage in the system to acceptable limits including reconfiguration of shunt devices (changing the switching status of shunt devices) in the system, rescheduling the reactive power generation by changing voltage set-points of generators, and installing new shunt devices at appropriate locations. It was found that even though overvoltage during the 2018 peak load case is more severe compared to the 2010 light load case, the system required fewer new shunt devices in the system to remove voltage violations. This design strategy occurs because of the higher number of fixed shunts operating during the 2018 summer peak load case compared to the 2010 spring light load case. Moreover, a greater number of online generators to serve higher load during summer provided more options in terms of maneuvering reactive power in the system to remove voltage violations.

To remove the overvoltage conditions, a switching sequence of shunt devices (i.e., ON or OFF) has been found to be useful. Uncoordinated switching of shunt devices at buses facing overvoltage might lead to undervoltage conditions.

The impact of the solar PV penetration on the dynamic performance of the system has been analyzed in detail. A comparison has been drawn between the dynamic performance of the 2018 peak load and the 2010 light load scenario. The critical contingencies have been identified in the system for the 2018 summer peak load case and dynamic performance has been compared for the PV and the base case scenario.

It is found that some of the beneficial impacts of PV in terms of its stabilizing effects after a large disturbance in light load case might not be valid in the summer load scenario. This is observed in the contingency case of the double line outage between buses 17431 and 16349. For this contingency, PV penetration alleviates poor damping in the 2010 light load conditions. In the 2018 peak load scenario, the system exhibits destabilization even in the PV scenario because of the heavier loading of this double circuit line between buses 17431 and 16349 during the 2018 summer peak load case.

For critical contingencies of the 2018 summer peak load case, there was no major impact found on the frequency response of the system. Even though reduced per unit inertia might lead to system instability in case of PV penetration, the studied bulk transmission system has been found to be robust in terms of availability of per unit inertia in the system. As far as voltage response is concerned, the impact of PV was found to be beneficial for the system. PV penetration reduces the severity of voltage magnitude dips on the buses after large disturbances. In one of the cases, as mentioned in Chapter 4, bus voltage magnitude decreased to unacceptable levels after the contingency in the 2018 base case scenario while in the 2018 PV scenario, the voltage magnitude dip was much lower and within an acceptable range.

Another important phenomenon which has been observed in the system with PV penetration is the reduced active power losses. There is also significant reduction in the reactive power consumption in the system. Since a major portion of the load is served by the locally installed PV resources, there is reduced amount of power flowing on the lines connected to distant conventional generators. These lines consume less reactive power for reduced loading levels resulting in decreased requirement of reactive power support in the system.

5.2 Future Work

In light of the mitigation measures proposed in this report, the following future work is recommended for utilities to be prepared to keep the system secure and reliable for PV scenario:

- A rigorous study is required on existing shunt devices available in the system. The control capabilities and response time of these devices need to be studied in detail, keeping in view the fast changing voltage profile in the network.
- The switching sequence of shunt devices has been found to be critical in removing voltage violations. The switching sequence requires centralized control of shunt devices in the system. A feasibility study needs to be conducted on installing the centralized control for shunt devices.
- Algorithms need to be developed for deciding the switching sequence of shunt devices for removing voltage violations. These algorithms can be used for developing software for controlling shunts devices in the system from a central location.

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APPENDIX A

LIST OF BUSES FACING OVERVOLTAGE FOR VARYING PV PENETRATION

This appendix contains several tables that list overvoltages for varying levels of PV penetration.

Table A.1 is a list of 50 buses facing maximum voltage rise over the base case for 7.5% PV penetration in Utility #1 and Utility #2 region for the 2018 summer peak load case. Table A.2 contains a list of buses facing maximum voltage rise over the base case for 7.5% PV in Utility #2 region for the 2018 summer peak load case. Table A.3 is a list of buses facing maximum voltage rise over the base case for 15% PV in Utility #1 region for the 2018 summer peak load case; and Table A.4 is a list of buses facing maximum voltage rise over the base case for 15% PV in Utility #2 region for the 2018 summer peak load case. Table A.5 is a list of buses facing maximum voltage rise over the base case for 22.5% PV in Utility #1 region for the 2018 summer peak load case; and Table A.6 is a list of buses facing maximum voltage rise over the base case for 22.5% PV in Utility #2 region for the 2018 summer peak load case. Table A.7 is a list of buses facing maximum voltage rise over the base case for 37.5% PV in Utility #1 region for the 2018 summer peak load case; and Table A.8 is a list of buses facing maximum voltage rise over the base case for 37.5% PV in Utility #2 region for the 2018 summer peak load case. Table A.9 is a list of buses facing maximum voltage rise over the base case for 45% PV in Utility #1 region for the 2018 summer peak load case; and Table A.10 is a list of buses facing maximum voltage rise over the base case for 45% PV in Utility #2 region for the 2018 summer peak load case.

Table A.1 List of buses facing maximum voltage rise over the base case for 7.5% PV in Utility #1 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\|$ - $\|V_{base}\|$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\|$ - $\|V_{base}\|$)
18283	1.0222	0.0437		17830	1.0167	0.0218
18211	1.0052	0.0393		17797	1.019	0.0217
18210	1.0043	0.0385		17825	1.0184	0.0214
18060	1.0036	0.0364		17826	1.0182	0.0214
18104	1.0122	0.0359		17813	1.021	0.0213
18036	1.0124	0.0358		17824	1.0185	0.0213
18039	1.0035	0.0345		17811	1.0215	0.0212
18035	1.0085	0.0335		17812	1.0213	0.0212
18040	1.006	0.0332		17820	1.0199	0.0211
18032	1.0076	0.0295		17821	1.0198	0.0211
18037	1.0076	0.0295		17822	1.0197	0.0211
18033	1.0082	0.0286		17832	1.0199	0.021
18038	1.0082	0.0286		17829	1.022	0.0208
18034	1.0097	0.0275		17816	1.0235	0.0203
17802	1.0141	0.0241		17814	1.023	0.0202
17800	1.0145	0.024		17815	1.0232	0.0202
17801	1.0144	0.024		17819	1.0246	0.0202
17783	1.016	0.0232		18028	1.0236	0.0202
17831	1.0184	0.0222		18155	1.024	0.0202
17833	1.0183	0.0222		17790	1.0219	0.0201
17793	1.0187	0.0221		17791	1.0219	0.0201
17823	1.0169	0.0221		17817	1.0244	0.0201
17798	1.019	0.022		17818	1.0244	0.0201
17795	1.0187	0.0219		17788	1.0223	0.02
17796	1.0189	0.0218		17789	1.0221	0.02

Table A.2 List of buses facing maximum voltage rise over the base case for 7.5% PV in Utility #2 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) (|V_{pv}| - |V_{base}|)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) (|V_{pv}| - |V_{base}|)
87618	0.9828	0.0394		86425	0.9861	0.0322
87617	0.9832	0.0393		86578	0.9945	0.0322
86623	0.9877	0.039		87592	0.9804	0.0322
87562	1.0148	0.0361		86582	0.9939	0.0321
86539	0.9921	0.0357		86583	0.9939	0.0321
87355	1.0021	0.0352		87575	0.9835	0.0319
17242	1	0.0348		87574	0.9869	0.0319
87572	0.9919	0.0345		87578	0.9745	0.0317
87356	0.9811	0.0344		87565	0.9697	0.0316
87573	0.9949	0.0344		87408	0.9938	0.0315
86565	0.9954	0.0341		87564	0.9761	0.0315
87577	0.9881	0.0335		86593	0.9822	0.0314
86573	0.9984	0.0333		87584	0.9797	0.0314
86574	0.9982	0.0333		86594	0.9822	0.0313
87416	0.9944	0.0333		87542	0.9686	0.0312
86359	0.986	0.0332		86580	0.9831	0.0311
86360	0.986	0.0332		86426	0.9847	0.031
87576	0.9871	0.0332		86566	0.9829	0.031
87415	0.9687	0.033		86567	0.9829	0.031
87625	0.9913	0.033		87543	0.9726	0.031
87631	1.0112	0.0329		86579	0.9844	0.0308
87417	1.0031	0.0324		87622	0.9745	0.0308
87591	0.9837	0.0323		87609	0.9709	0.0307
86577	0.9945	0.0323		86575	0.9858	0.0307
86424	0.9861	0.0322		86576	0.9858	0.0307

Table A.3 List of buses facing maximum voltage rise over the base case for 15% PV in Utility #1 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) (|V_{pv}| - |V_{base}|)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) (|V_{pv}| - |V_{base}|)
18283	1.0222	0.052		17832	1.0199	0.0411
18211	1.0052	0.045		17795	1.0187	0.0405
18210	1.0043	0.0445		17796	1.0189	0.0404
17831	1.0184	0.0438		18040	1.006	0.0403
17833	1.0183	0.0438		17797	1.019	0.0403
17823	1.0169	0.0435		17793	1.0187	0.0396
18060	1.0036	0.0434		17798	1.019	0.0395
17830	1.0167	0.0429		17829	1.022	0.0395
18032	1.0076	0.0423		17814	1.023	0.0394
18037	1.0076	0.0423		17816	1.0235	0.0394
18034	1.0097	0.042		17819	1.0246	0.0393
18039	1.0035	0.0419		18028	1.0236	0.0393
17826	1.0182	0.0419		17815	1.0232	0.0392
17825	1.0184	0.0418		18155	1.024	0.0392
17813	1.021	0.0418		17817	1.0244	0.039
17824	1.0185	0.0417		17818	1.0244	0.039
17812	1.0213	0.0416		18154	1.025	0.0388
17811	1.0215	0.0415		17828	1.026	0.0383
17802	1.0141	0.0414		17810	1.0269	0.038
17783	1.016	0.0414		17954	1.0272	0.0379
17820	1.0199	0.0414		18195	1.0272	0.0379
17821	1.0198	0.0414		17790	1.0219	0.0376
17822	1.0197	0.0414		17791	1.0219	0.0376
17800	1.0145	0.0412		17847	1.0177	0.0375
17801	1.0144	0.0412		17788	1.0223	0.0374

Table A.4 List of buses facing maximum voltage rise over the base case for 15% PV in Utility #2 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\| - \|V_{base}\|$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\| - \|V_{base}\|$)
87618	0.9828	0.0779		87565	0.9697	0.064
87617	0.9832	0.0778		87417	1.0031	0.064
86623	0.9877	0.0772		87575	0.9835	0.0638
87562	1.0148	0.0716		87564	0.9761	0.0637
86539	0.9921	0.07		87574	0.9869	0.0636
87355	1.0021	0.07		86580	0.9831	0.0634
87356	0.9811	0.0685		86582	0.9939	0.0634
86565	0.9954	0.0676		86583	0.9939	0.0634
87572	0.9919	0.0674		86593	0.9822	0.0633
87573	0.9949	0.0672		86594	0.9822	0.0632
87416	0.9944	0.0665		86577	0.9945	0.0632
86359	0.986	0.0663		86578	0.9945	0.0632
86360	0.986	0.0663		86566	0.9829	0.0629
87415	0.9687	0.0658		86567	0.9829	0.0629
87577	0.9881	0.0655		87584	0.9797	0.0629
87576	0.9871	0.0652		86579	0.9844	0.0627
87625	0.9913	0.0651		87609	0.9709	0.0626
86573	0.9984	0.0651		87542	0.9686	0.0623
86574	0.9982	0.0651		87543	0.9726	0.062
87631	1.0112	0.065		87408	0.9938	0.0619
87591	0.9837	0.065		87610	0.9758	0.0619
87592	0.9804	0.0649		87566	0.9669	0.0618
87578	0.9745	0.0645		87597	0.976	0.0617
86424	0.9861	0.0643		87598	0.9756	0.0617
86425	0.9861	0.0643		87567	0.9689	0.0615

Table A.5 List of buses facing maximum voltage rise over the base case for 22.5% PV in Utility #1 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\|$ - $\|V_{base}\|$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\|$ - $\|V_{base}\|$)
18211	1.0052	0.0717		17821	1.0198	0.057
18210	1.0043	0.0703		17822	1.0197	0.057
18060	1.0036	0.0673		17832	1.0199	0.0566
18039	1.0035	0.0643		17795	1.0187	0.0561
18032	1.0076	0.0619		17796	1.0189	0.0559
18037	1.0076	0.0619		17797	1.019	0.0557
18040	1.006	0.0617		18104	1.0122	0.0552
17831	1.0184	0.0607		17793	1.0187	0.055
17833	1.0183	0.0606		18036	1.0124	0.0549
18034	1.0097	0.0605		17798	1.019	0.0548
17823	1.0169	0.0602		17829	1.022	0.0544
17830	1.0167	0.0592		17814	1.023	0.054
18283	1.0222	0.0582		17816	1.0235	0.054
17802	1.0141	0.0581		17819	1.0246	0.0539
17783	1.016	0.0579		18028	1.0236	0.0539
17800	1.0145	0.0578		17815	1.0232	0.0538
17801	1.0144	0.0578		18155	1.024	0.0537
17826	1.0182	0.0577		17818	1.0244	0.0535
17825	1.0184	0.0576		17817	1.0244	0.0534
17813	1.021	0.0576		18033	1.0082	0.0533
17824	1.0185	0.0575		18038	1.0082	0.0533
17812	1.0213	0.0574		18154	1.025	0.0531
18035	1.0085	0.0573		17828	1.026	0.0524
17811	1.0215	0.0572		17810	1.0269	0.052
17820	1.0199	0.057		17954	1.0272	0.0518

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Table A.6 List of buses facing maximum voltage rise over the base case for 22.5% PV in Utility #2 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\| - \|V_{base}\|$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\| - \|V_{base}\|$)
87618	0.9828	0.1062		86574	0.9982	0.0879
87617	0.9832	0.1061		86580	0.9831	0.0879
86623	0.9877	0.1053		87564	0.9761	0.0878
87562	1.0148	0.0978		87575	0.9835	0.0876
87355	1.0021	0.0958		87574	0.9869	0.0873
86539	0.9921	0.0946		86593	0.9822	0.0872
87356	0.9811	0.0938		86594	0.9822	0.0871
86565	0.9954	0.0924		87417	1.0031	0.0869
87416	0.9944	0.091		86579	0.9844	0.0868
87572	0.9919	0.0908		86566	0.9829	0.0867
86359	0.986	0.0908		86567	0.9829	0.0867
86360	0.986	0.0908		87609	0.9709	0.0866
87573	0.9949	0.0906		87584	0.9797	0.0863
87415	0.9687	0.0901		86582	0.9939	0.0861
87591	0.9837	0.0895		86583	0.9939	0.0861
87592	0.9804	0.0894		87610	0.9758	0.0857
87578	0.9745	0.0894		87597	0.976	0.0857
87577	0.9881	0.0886		87598	0.9756	0.0857
87625	0.9913	0.0884		86577	0.9945	0.0856
87565	0.9697	0.0882		86578	0.9945	0.0855
87631	1.0112	0.0882		87542	0.9686	0.0852
86424	0.9861	0.0881		87543	0.9726	0.0849
87576	0.9871	0.0881		87566	0.9669	0.0849
86425	0.9861	0.088		87567	0.9689	0.0845
86573	0.9984	0.0879		86619	0.9883	0.0844

Table A.7 List of buses facing maximum voltage rise over the base case for 37.5% PV in Utility #1 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\lvert V_{pv}\rvert$ - $\lvert V_{base}\rvert$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\lvert V_{pv}\rvert$ - $\lvert V_{base}\rvert$)
18211	1.0052	0.0946		17820	1.0199	0.0699
18210	1.0043	0.0915		17822	1.0197	0.0699
18060	1.0036	0.0854		17821	1.0198	0.0698
18039	1.0035	0.0807		17832	1.0199	0.0692
18040	1.006	0.0767		17795	1.0187	0.0686
18032	1.0076	0.0761		17796	1.0189	0.0682
18037	1.0076	0.0761		17797	1.019	0.068
17831	1.0184	0.0758		17793	1.0187	0.0667
17833	1.0183	0.0757		17798	1.019	0.0665
17823	1.0169	0.075		17829	1.022	0.0657
18034	1.0097	0.0741		18283	1.0222	0.0653
17830	1.0167	0.0734		17814	1.023	0.065
18104	1.0122	0.0718		17816	1.0235	0.065
18036	1.0124	0.0716		17819	1.0246	0.0649
18035	1.0085	0.0714		18028	1.0236	0.0649
17783	1.016	0.0711		17815	1.0232	0.0648
17802	1.0141	0.071		18155	1.024	0.0646
17826	1.0182	0.071		17818	1.0244	0.0642
17813	1.021	0.0709		17817	1.0244	0.0642
17801	1.0144	0.0707		18154	1.025	0.0636
17825	1.0184	0.0707		18033	1.0082	0.063
17824	1.0185	0.0707		17847	1.0177	0.063
17800	1.0145	0.0705		18038	1.0082	0.0629
17812	1.0213	0.0704		18045	1.0177	0.0629
17811	1.0215	0.0702		18043	1.0177	0.0629

Table A.8 List of buses facing maximum voltage rise over the base case for 37.5% PV in Utility #2 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\| - \|V_{base}\|$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\| - \|V_{base}\|$)
87618	0.9828	0.1271		86593	0.9822	0.1026
87617	0.9832	0.127		86594	0.9822	0.1025
86623	0.9877	0.1261		87575	0.9835	0.1023
87562	1.0148	0.117		87417	1.0031	0.1023
87355	1.0021	0.116		87609	0.9709	0.1022
87356	0.9811	0.1135		87574	0.9869	0.1019
86565	0.9954	0.1106		86567	0.9829	0.1019
86360	0.986	0.1101		86566	0.9829	0.1018
86359	0.986	0.11		87577	0.9881	0.1016
87416	0.9944	0.1098		86582	0.9939	0.1015
86539	0.9921	0.1095		86583	0.9939	0.1015
87415	0.9687	0.1086		87610	0.9758	0.1012
87578	0.9745	0.1064		87576	0.9871	0.1011
86424	0.9861	0.1062		87584	0.9797	0.1006
86425	0.9861	0.1062		86573	0.9984	0.1002
87591	0.9837	0.1054		86574	0.9982	0.1002
87592	0.9804	0.1052		86619	0.9883	0.0997
86580	0.9831	0.1048		86618	0.9884	0.0997
87625	0.9913	0.1042		86617	0.9885	0.0996
87631	1.0112	0.1041		86575	0.9858	0.0986
87572	0.9919	0.1036		86576	0.9858	0.0985
87565	0.9697	0.1036		87542	0.9686	0.0985
87573	0.9949	0.1033		87597	0.976	0.0984
87564	0.9761	0.1031		87598	0.9756	0.0983
86579	0.9844	0.103		86577	0.9945	0.0981

Table A.9 List of buses facing maximum voltage rise over the base case for 45% PV in Utility #1 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\|$ - $\|V_{base}\|$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\|V_{pv}\|$ - $\|V_{base}\|$)
18211	1.0052	0.0887		17832	1.0199	0.0645
18210	1.0043	0.0848		17795	1.0187	0.0636
18060	1.0036	0.0776		18104	1.0122	0.0634
18039	1.0035	0.0726		17796	1.0189	0.0632
17831	1.0184	0.0724		18036	1.0124	0.0632
17833	1.0183	0.0723		17797	1.019	0.0629
17823	1.0169	0.0714		18035	1.0085	0.0623
17830	1.0167	0.0695		17793	1.0187	0.0612
18032	1.0076	0.0689		17798	1.019	0.061
18037	1.0076	0.0689		17829	1.022	0.0604
18040	1.006	0.0682		17974	1.0278	0.0597
18034	1.0097	0.0673		17814	1.023	0.0596
17826	1.0182	0.0666		17819	1.0246	0.0596
17813	1.021	0.0665		17816	1.0235	0.0596
17825	1.0184	0.0663		18028	1.0236	0.0595
17824	1.0185	0.0663		17815	1.0232	0.0594
17783	1.016	0.066		18155	1.024	0.0591
17812	1.0213	0.066		17847	1.0177	0.059
17811	1.0215	0.0657		18043	1.0177	0.0589
17802	1.0141	0.0654		17818	1.0244	0.0588
17820	1.0199	0.0654		17817	1.0244	0.0588
17822	1.0197	0.0654		18045	1.0177	0.0588
17821	1.0198	0.0654		18044	1.0177	0.0588
17801	1.0144	0.065		18065	1.0178	0.0588
17800	1.0145	0.0649		18283	1.0222	0.0585

Table A.10 List of buses facing maximum voltage rise over the base case for 45% PV in Utility #2 region for the 2018 summer peak load case

Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\lvert V_{pv}\rvert$ - $\lvert V_{base}\rvert$)		Bus number	Base voltage (p.u.)	Overvoltage (p.u.) ($\lvert V_{pv}\rvert$ - $\lvert V_{base}\rvert$)
87618	0.9828	0.117		87631	1.0112	0.0948
87617	0.9832	0.1169		87591	0.9837	0.0943
86623	0.9877	0.1161		87592	0.9804	0.0941
87355	1.0021	0.1089		87417	1.0031	0.0931
87562	1.0148	0.1079		86579	0.9844	0.0929
87356	0.9811	0.1066		86582	0.9939	0.0925
86360	0.986	0.1033		86583	0.9939	0.0925
86359	0.986	0.1032		87565	0.9697	0.0923
87416	0.9944	0.1025		87564	0.9761	0.0919
86565	0.9954	0.1019		87609	0.9709	0.0919
87415	0.9687	0.1015		86593	0.9822	0.0918
87767	1.0129	0.101		86594	0.9822	0.0917
87743	1.0159	0.1003		87610	0.9758	0.0911
86424	0.9861	0.0992		86567	0.9829	0.0908
86425	0.9861	0.0992		86566	0.9829	0.0907
86787	0.9987	0.0984		87575	0.9835	0.0907
87332	1.0001	0.0982		87574	0.9869	0.0905
87333	1.0025	0.098		87572	0.9919	0.0899
87341	1.0026	0.098		86619	0.9883	0.0897
87331	1.0022	0.098		87573	0.9949	0.0897
86744	1.0023	0.0975		86618	0.9884	0.0896
86539	0.9921	0.0969		86617	0.9885	0.0895
87578	0.9745	0.0966		86426	0.9847	0.0892
86580	0.9831	0.0951		87584	0.9797	0.0892
87625	0.9913	0.095		87577	0.9881	0.0888

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