Impact of Increased Penetration of Photovoltaic Generation on Power Systems

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***Abstract*—Present renewable portfolio standards are changing power systems by replacing conventional generation with alternate energy resources such as photovoltaic (PV) systems. With the increase in penetration of PV resources, power systems are expected to experience a change in dynamic and operational characteristics. This paper studies the impact of increased penetration of PV systems on static performance as well as transient stability of a large power system, in particular the transmission system. Utility scale and residential rooftop PVs are added to the aforementioned system to replace a portion of conventional generation resources. While steady state voltages are observed under various PV penetration levels, the impact of reduced inertia on transient stability performance is also examined. The studied system is a large test system representing a portion of the Western U.S. interconnection. The simulation results obtained effectively identify both detrimental and beneficial impacts of increased PV penetration both for steady state stability and transient stability performance.**

***Index Terms*—Converter, distributed power generation, photovoltaic generation, power system stability, power transmission.**

I. Introduction

THE need for clean, renewable energy has resulted in new mandates to augment, and in some cases replace conventional, fossil based generation with renewable generation resources [1]. Solar and wind generation are among those resources that have been at the center of attention. These resources albeit currently more expensive (in $/MW installed comparison) are environmentally friendly, renewable, and they do not produce green house gases.

The structural changes in power systems result in new concerns regarding the reliable and secure operation of the system with high penetration of renewable energy resources. While higher amounts of photovoltaic (PV) penetration levels are expected based on the established Renewable Portfolio Standards (RPS), the exact effect of these resources are still to be fully identified. High PV penetration levels can significantly affect the steady state as well as the transient stability of the systems due to their distinct characteristics that differ from conventional generation resources. With high PV generation, a significant amount of conventional generation may be replaced with distributed PV resources. While a portion of this replaced generation is supplied by utility scale PVs, a majority of PV generation resources are expected to be provided by residential rooftop PVs that are located closer to the loads on the transmission system. Presently practiced standards, e.g., IEEE 1547 and UL 1741 suggest that PV inverters should not actively regulate the voltage at the point of common coupling (PCC) [2], [3]. Therefore, these units are mainly utilized as sources of active power and no reactive power is generated by these resources. Lack of reactive power support is an immediate concern in systems with high PV penetration. Reduced system inertia is another by-product of utilizing higher amounts of PV generation resources. These concerns have initiated practices in countries such as Germany to allow for the contribution of the distributed generation (DG) to voltage regulation.

Effects of photovoltaic systems on distribution systems have been the subject of many research investigations [4]–[6]. These studies focus on the behavior of the system while PV systems are connected to the grid, in terms of the location of the connection point and control strategies that could be considered for better system performance. Most of these research efforts are mainly conducted for the distribution system since the amount of PV installations is assumed to be small enough to have less significant effect on the transmission system. With more PV installations, high PV penetration has been recently awarded more attention among researchers. Ongoing studies investigate the effect of these systems on the power distribution systems [7]–[9]. As these papers suggest, high PV penetration can affect the voltage profile depending on the loading conditions and amount of PV penetration. Study results of these works suggest that the presently available regulation equipments are not capable of mitigating the adverse effects of the PV system transients such as the effects of clouds. Therefore, power inverters should to some extent have excess power capability to absorb or generate reactive power for additional voltage regulation [10]. The main theme in all these studies is the fact that high PV penetration levels can affect the steady state voltage magnitudes and therefore more control options may be required.

Although many of the cited works are effective in identifying some of the problems associated with high PV penetration levels, they are mainly focused on distribution systems. However, these levels of PV penetration can directly affect the transmission systems during normal operating conditions as well as

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during various transients. Since this is a rather recent topic, there are a limited number of topical research efforts reported in the literature [11]–[14]. It has been shown in [11] that depending on the amount of PV solar generation and the point of interconnection (POI), transient voltages could have better or worse behavior than the case without PV. Although most of these studies advocate the fact that high PV penetration can have diverse effects on system transients, the cases considered for system studies are not actual representations of a larger, interconnected power system. Authors in [14] have analyzed transmission system performance with high PV penetration on an IEEE 39-bus system. Various case studies have been conducted.

Unlike the aforementioned works, the present paper investigates the effect of high PV penetration on a considerably large system. The objective of this work is to identify the impact of high PV penetration on the transmission system in light of the fact that the impact of the PV systems will no longer be limited to the distribution system. Therefore, the PV systems are aggregated and modeled at a 69-kV bus electrically closest to the transmission level to study their impact on these systems. Both utility scale and distributed rooftop PVs are modeled in this work to cover a broad range of PV systems. In addition to steady state analysis, the effect of transients on the system is investigated by utilizing software packages such as DSATools and PSLF.

The procedures to identify the impact of high PV penetration, the choices of the proper study cases, and the procedure to equivalence the aggregated PV at the transmission level buses provide the required steps to identify the impact of high PV penetration on a large system. The impacts on the voltage stability as well as the rotor angle stability are analyzed in this work. The results presented in this work are based on a real system and developed in close consultation with the industry.

This paper is organized as follows. In Section II a brief description of the studied system is presented while Section III presents the modeling aspects of the PV systems. Section IV discusses the impacts associated with the high penetration of PV systems on power system stability. Sections V and VI analyze the impact on steady state stability. The analysis of transient stability is presented in Section VII. Conclusions that can be drawn from these analyses are presented in Section VIII.

II. Studies Utilizing a Test System

In order to better represent a case with high PV penetration a large power system is selected for study. The simulated case represents the entire Western Electricity Coordinating Council (WECC) with transmission voltage levels ranging from 34.5 kV and 69 kV, to 345 kV and 500 kV. The PVs are only added to a portion of the system with a relatively large amount of conventional generation and export to other areas within WECC. Table I presents a summary of the studied area with high concentration of utility scale and rooftop PVs. The studied area has a single slack bus and various synchronous generators are equipped with power system stabilizers (PSS), excitation systems, as well as governors for frequency regulation. In addition, the base case, i.e., the case with no PV systems, has been verified to be $(N-1)$ secure.

TABLE I
Summary of the Studied Area

Total Load	MW	13276.82
	MVAr	2187.90
Total Generation	MW	21571.03
	MVAr	2238.72
Total Export	MW	7650.83
	MVAr	63.4
Total Losses	MW	607.82
Total Number of Generators		226
Total Number of Buses		2419
Total Number of Lines		1861

TABLE II
Photovoltaic System Description and Capabilities

PV Type	Active Gen. (MW)	Reactive Gen. (MVAr)	Q-Enabled	Voltage Control	Frequency Control
Utility Scale	50	17	Yes	Yes	No
Rooftop	Varies	0	No	No	No

The case selected for this study is operating at light loading conditions. As seen from the load values in Table I, the active load in this case is about 13 GW while the summer peak load of the studied area is close to 20 GW. For the selected study area, these conditions are valid representations of a case with peak PV outputs and low loads. Under these conditions, specifically during the daylight off peak hours, the amount of load consumption might be less than the PV output generated. Hence, the excess PV generation can contribute to the reversal of the power flow from the load side to the transmission system. This can in effect cause additional disruption in system operating conditions.

Two types of PV systems are connected to the system considered. Table II lists important characteristics of these units. Rooftop PVs are connected at transmission/subtransmission voltage level of 69 kV across the studied area. These units have been added based on a zip code map of the studied area and are then equivalenced and added to the system at the closest 69 kV level buses. Therefore, an approximate total of 200 buses were chosen for the location of the rooftop PVs. The utility scale PVs are connected to the system via step-up transformers at the locations where they are present. The utility scale PV are only concentrated at a specific area of the system with high potential for utility scale installations and therefore their control capabilities can only be accounted for in a small portion of the studied system. Throughout this study, it is assumed that utility scale PVs are fixed at 600 MW of active power generation, accounting for only a small portion of the total installed PVs, while roof top PVs are varied depending on the amount of PV generation studied.

III. Modeling of PV Systems

A. Modeling for Power Flow Studies

Most of the residential rooftop photovoltaic systems have small outputs with no reactive power capability. Therefore, for

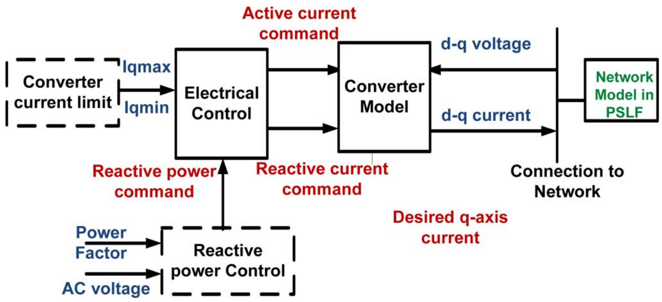

Fig. 1. Schematic of the PSLF model used to represent utility scale PVs.

the purpose of power flow studies, they are represented as negative active power loads which are fixed in power level. Only active power components are used. In other words, buses with residential PV systems are modeled as "PQ buses" with $Q = 0$. Utility scale PVs, however, have reactive power capability and therefore are modeled in a manner similar to conventional generators for steady state analysis: these units are represented as "PV buses" with appropriate VAr limits.

B. Modeling for Dynamic Studies

For dynamic studies, residential rooftop PVs are modeled as constant current loads corresponding to the negative power injections. However, the utility scale PV models differ from those used in power flow studies. This is due to the fact that these units are equipped with converters that need to be modeled in order to better represent their dynamic behavior. As suggested in [15], the General Electric Type 4 wind turbine converter models that are available in PSLF can approximately represent the full converter models for the PV units as well. Components that contribute to the dynamic behavior of these models are as follows:

- *converter model*—a full converter model is provided to fully represent the dynamic behavior of the utility scale PVs while due to the fast operation of the converters DC side dynamics are neglected;
- *control model*—controllers are included in this model to control active and reactive power as well as current of the converter.

The parameters of the aforementioned wind turbine model are hence modified to fully represent the utility scale PV resources [16]. Fig. 1 presents a schematic of the model described above.

IV. Impact on Power System Stability

Distributed PV resources that replace conventional generators are mostly located closer to the loads and at the lower voltage levels. Consequently, depending on the PV penetration level, a portion of the generation is transferred to the locations closer to the loads which may alter the amount of reactive power which is supplied to the loads. This alteration is mainly due to the limits imposed by the ratings of the lines and transmission system components (including transformers). One possible consequence is a change in the steady state bus voltage magnitudes due to the introduction of PV resources. In a large interconnected system, it is important to maintain steady state voltage stability among system buses. This translates to keeping their values within the limits allowed by the operators, typically $\pm 5\%$.

High PV penetration which results in replacing large scale generating units with the distributed PV systems can limit the availability of reactive power. This is due to the fact that most of the PV units are residential and are assumed to be mainly sources of active power only. This might affect the dynamic performance of the system specifically when reactive power supply to the loads is interrupted during a system disturbance. Therefore, bus voltages are expected to be more perturbed during the system transients. Increased PV penetration will also result in reduced inertia within the system which might be a reason for potential rotor angle stability problems. These problems mainly occur during various disturbances in the system ranging from bus faults to the loss of a generating unit and line removals. The categories of instability caused by high PV penetration are discussed in the following sections.

A. Steady State Stability

Steady state stability is the ability of the system to maintain a steady state equilibrium while satisfying system constraints [17]. These constraints range from bus injection limits to bus operating voltage magnitudes. High PV penetration levels can result in variations of bus voltage magnitudes at the transmission level. Studying various PV penetration levels can benefit the system operators in two ways:

1) identify the relationship between PV penetration levels and steady state voltage magnitudes;
2) locate the high voltage magnitudes caused by high PV penetration and take appropriate preventive actions.

Identifying the problematic buses in terms of the high voltage magnitudes is important since it will notify the system planners of the possible adverse effects of the addition of the PV systems. Additionally, the critical PV penetration levels will be attained by these studies.

B. Transient Stability

Transient stability is the ability of the power system to maintain synchronism during *large* disturbances. These disturbances range from equipment and line outages to bus faults or even a cloud cover in case of the photovoltaic generation. The time frame of interest is generally 3–5 s following a disturbance and depending on the system it might extend to 10–20 s [18].

Generator—turbine inertia generally plays a key role in providing synchronizing capability to the synchronous generators whenever a disturbance results in a mismatch between the mechanical power input and electrical power output of the generator. Since in a system with high PV penetration, some of the synchronous generators are replaced with PV units, the overall system inertia is dramatically decreased which can lead to potential system problems during various disturbances.

Synchronizing power capability of the systems can also be affected by the angle differences of the bus voltages. Large injection of power from PV resources will cause the voltage angles across the ac system to adjust to accommodate the injection of power from such resources. As a result, the angle differences between the ac bus voltages will increase, reducing the synchronizing power capability.

The effect of high PV penetration on system dynamic behavior is also impacted by other parameters such as the type

TABLE III
SUMMARY OF PV PENETRATION LEVELS

PV generation (MW)	2158	4316	6475	8633	10792
PV penetration level (%) (based on (1))	10	20	30	40	50
PV penetration level (%) (load based)	11.2	22.5	34	45	56
PV penetration level (%) (by energy)	2.5	5	7.5	10	12.5

of the disturbance and its location with respect to the PV systems and the large scale generating units. These effects will be studied in the subsequent sections.

V. STEADY STATE STABILITY ANALYSIS

Steady state analysis is carried out on the same system described before in the presence of high PV penetration levels. Within the studied area, various PV generation levels are studied for power flow studies. The equivalent active power generation for each generation scenario is illustrated in Table III. Calculation of the PV penetration percentages is carried out based on the following equation:

$$\text{PV Penetration }(\%) = \frac{\text{Total PV generation (MW)}}{\text{Total generation (MW)}}. \quad (1)$$

The definition of the PV penetration used in this work is based on the available generation in the base case. While there are other methods for defining PV penetration levels, i.e., based on the system peak load [14] or by the amount of energy served, these methods are not adopted in this work. For comparison purposes, PV penetration levels are also defined based on the aforementioned methods in Table III.

As the level of the PV generation in the studied case grows, more conventional generators are displaced to account for the generation and load balance within the system. In selection of the displaced generators the existence of adequate reactive power margin has been taken into account. Therefore, the critical generators in terms of the reactive power generation have not been switched off from the system. In all power flow studies, the amount of active power export to the other areas is kept constant. Steady state analyses are conducted utilizing PSAT, which is a toolbox in PowerTech Lab's DSATools software package intended for power flow studies [19]. Fig. 2 shows the bus voltages of the system under different PV penetration levels.

Simulation results presented in Fig. 2 reveal the behavior of the steady state bus voltages with the increase of PV generation. The results shown typify the results seen in a wide range of simulation studies. Although only few of the bus voltage magnitudes are shown, the same quadratic type behavior is observed in all the buses of the studied area.

Steady state voltages of the system increase with the increase of up to 30% in PV penetration, although for a few buses the peak value occurs at 20% PV generation. As more PV generation is added to the system, steady state voltage magnitudes drop until they reach closer to their base case values.

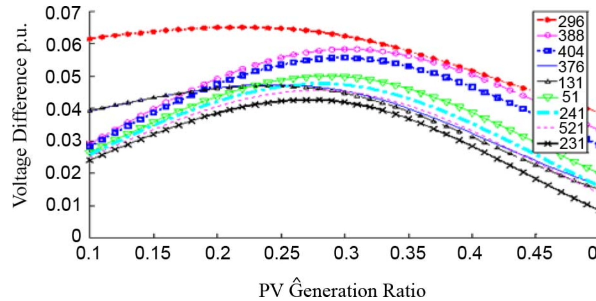

Fig. 2. Steady state voltage deviation of the system buses with varying PV penetration levels.

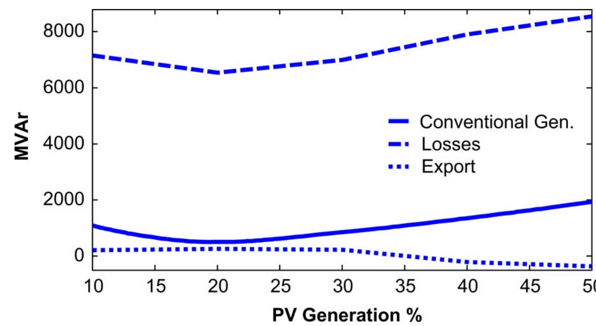

Fig. 3. Reactive power flow summary of the study area under various PV penetration levels.

Overvoltages caused by high PV penetration attain a peak of up to $+10\%$ in some buses within the study area. Thus, corrective actions are required to prevent these buses reaching their peak values once more PV systems are added. Switching off the capacitive shunts or adjusting the conventional generator voltages are some examples of the preventive measures that are taken to mitigate the adverse effects of high PV penetration.

Reactive power flows of the system with different scenarios are illustrated in Fig. 3. Due to their dependency, variation of the reactive power generation is consistent with the voltage magnitude changes across the system. Power flow study results presented in Fig. 3 show that reactive power losses tend to decrease while PV penetration is increased to 30%. The reactive power export is at its maximum value during this time period.

With the addition of more PV generation, reactive power export decreases while the reactive power generated by the synchronous generators tend to increase with a slower rate than the increase in the reactive power losses. Additional required reactive power is imported from other areas. This import results in the reversal of the reactive power flow in parts of the system. The reason for more reactive power generation after 30% PV generation is the fact that at this point the rooftop PV systems can contribute to the active power flow within the system and hence result in reversal of the active power flow from the loads towards the transmission system. Thus, the conventional generators are provided with more room for reactive power generation. Improved voltage magnitudes at PV generation levels higher than 30% result from this behavior of the reactive power flows due to the reversal of the active power from the load to the transmission system.

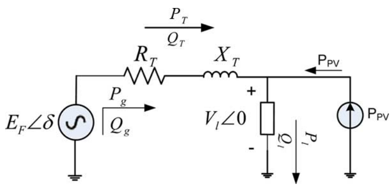

Fig. 4. Simplified two-bus representation of a system with PV.

VI. Analytical Study

Quadratic type behavior of the steady state voltages observed in the preceding section suggests an analytical study of a representative simplified system. It is useful to analytically corroborate the observed behavior. Fig. 4 presents the schematic of a simplified two-bus system used for studies carried out in this section. Steady state equations of the system presented in Fig. 4 are solved in order to represent the load voltage V_l, in terms of the amount of PV generation, P_{pv}:

$$\begin{aligned} S_g &= (E_F\angle\delta)\, I^* \\ &= \frac{|E_F|\,(\cos\delta + j\sin\delta)\,(|E_F|\,(\cos\delta - j\sin\delta) - |V_l|)}{R_l - jX_T} \end{aligned} \quad (2)$$

$$\begin{aligned} P_g &= \mathrm{Re}\,\{S_g\} \\ &= \frac{|E_F|}{{R_l}^2 + {X_T}^2}\,(R_l\,|E_F| + |V_l|\,(X_T\sin\delta - R_l\cos\delta)) \end{aligned} \quad (3)$$

$$\begin{aligned} Q_g &= \mathrm{Im}\,\{S_g\} \\ &= \frac{|E_F|\,(X_T\,|E_F| - |V_l|\,R_l\sin\delta - |V_l|\,X_T\cos\delta)}{{R_l}^2 + {X_T}^2} \end{aligned} \quad (4)$$

$$\begin{aligned} S_T &= V_T I^* \\ &= \frac{[|E_F|(\cos\delta + j\sin\delta) - |V_l|][|E_F|(\cos\delta - j\sin\delta) - |V_l|]}{R_l - jX_T} \end{aligned} \quad (5)$$

$$P_T = \mathrm{Re}\,\{S_T\} = \frac{|E_F|^2 R_l - 2\,|E_F|\,|V_l|\,R_l\cos\delta + |V_l|^2 R_l}{{R_l}^2 + {X_T}^2} \quad (6)$$

$$\begin{aligned} Q_T &= \mathrm{Im}\,\{S_T\} \\ &= \frac{|E_F|^2 X_T - 2\,|E_F|\,|V_l|\,X_T\cos\delta + |V_l|^2 X_T}{{R_l}^2 + {X_T}^2} \end{aligned} \quad (7)$$

$$Q_g = Q_T + Q_l \quad \text{assumption: } Q_l = kP_l. \quad (8)$$

Further simplification yields

$$\begin{aligned} |E_F|\,|V_l|\,(X_T\cos\delta - R_l\sin\delta) &= kP_l\left(R_l^2 + X_T^2\right) \\ &\quad + |V_l|^2 X_T \end{aligned} \quad (9)$$

$$P_l = P_{pv} + P_g - P_T. \quad (10)$$

Combining (3), (6), and (10) gives

$$\begin{aligned} &|E_F|\,|V_l|\,(-X_T\sin\delta - R_l\cos\delta) \\ &\quad = (P_{PV} - P_l)\left(R_l^2 + X_T^2\right) - |V_l|^2 R_l. \end{aligned} \quad (11)$$

Equations (9) and (11) are combined revealing a quadratic characteristic for load voltage V_l in terms of PV generation, P_{PV}:

$$\begin{aligned} &|V_l|^4 + (P_{PV} - P_l)^2\left({R_l}^2 + {X_T}^2\right)^2 - k^2{P_l}^2\left({R_l}^2 + {X_T}^2\right) \\ &-2|V_l|^2 R_l(P_{PV} - P_l) + 2kP_l X_T|V_l|^2 - |V_l|^2|E_F|^2 = 0. \end{aligned} \quad (12)$$

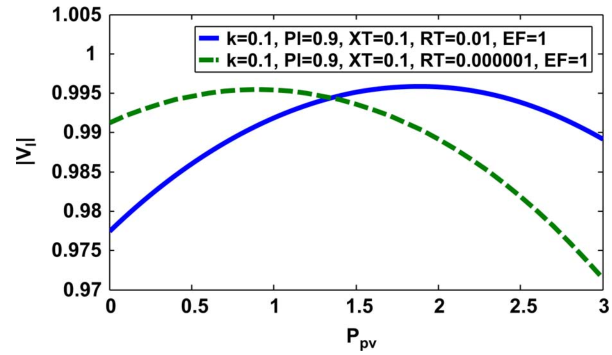

Fig. 5. Variations of the load voltage versus the amount of solar generation for a two-bus system.

Solving (12) yields four solutions from which only one is a feasible solution for the load bus voltage (the "open circuit solution"). This voltage magnitude is plotted versus the PV generation in Fig. 5 for two different values of R_T.

By comparing the voltage magnitudes plotted in Fig. 5 and the simulation results of Fig. 2 it is observed that the voltages exhibit a similar behavior in both cases as PV generation increases. Additionally, it is observed that variations in the system parameters would not affect the basic quadratic shape of the voltages. Hence, the analytical results corroborate the results obtained from simulation.

VII. Transient Stability Analysis

The objective of the transient analysis is to examine if various system disturbances affect the system in a different way with high PV penetration levels present in the system. Simulations are conducted for these disturbances that range from three-phase faults at several buses and double line outages to interruption of the output of the PV systems under various PV penetration levels. The PSLF software package is used for transient studies [20].

A. Three-Phase Fault on the Transmission System

It is believed that at higher PV penetration levels, the transmission system may exhibit a different behavior than the system with no PV. Therefore, the fault scenarios considered in this part are located at higher voltage levels, i.e., 500 kV and 345 kV for the purpose of transmission system studies.

1) Detrimental Impact on the Transmission System: A three-phase fault is simulated on a 500-kV level bus while it is cleared after 4 cycles which is a suitable time for this voltage level. The bus structure near the faulted bus is shown in Fig. 6. This fault is followed by outage of a 500-kV transmission line connecting the faulted bus, i.e., bus 1569, and the bus number 1886.

The speed and relative rotor angles of the generators in vicinity of the faulted bus are observed in the time domain. Figs. 7 and 8 show that this fault scenario has an adverse impact on the system with respect to the increased PV penetration. This impact is observed by comparing the behavior of the system with no PVs and the system with 20% PV penetration present as sources of power generation. Generator relative rotor angles tend to achieve larger oscillations during the post fault transients when PV systems are present. This leads to the fact

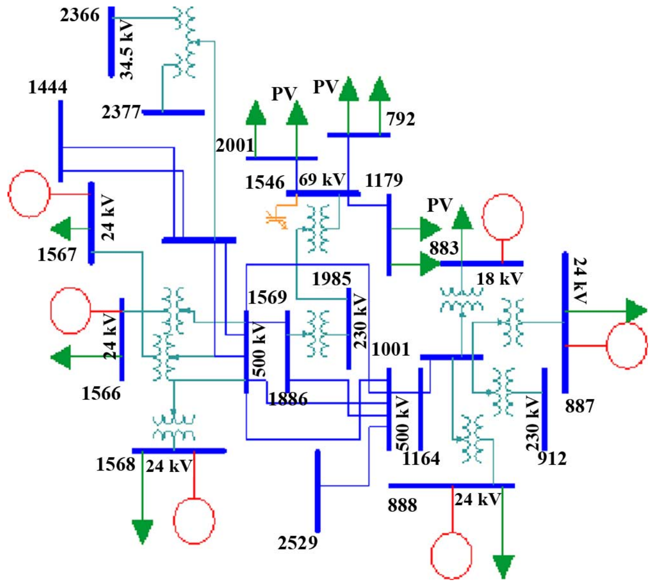

Fig. 6. Single diagram of the system near the faulted bus number 1569.

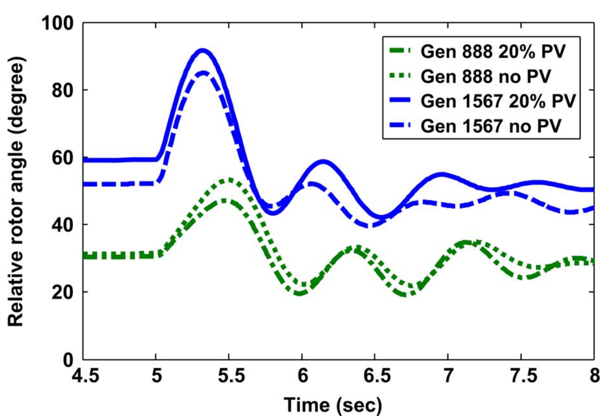

Fig. 7. Relative rotor angles of the generators 1567 and 888 following the fault.

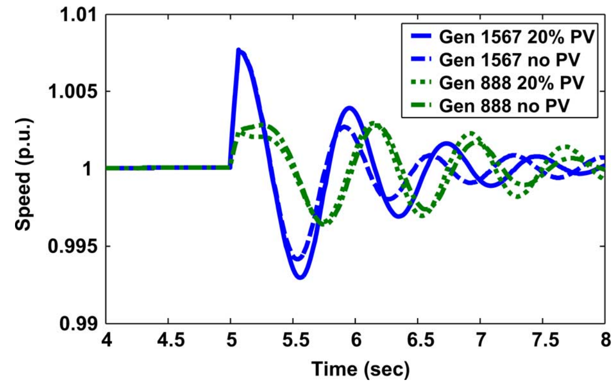

Fig. 8. Speeds of the generators 1567 and 888 following the fault.

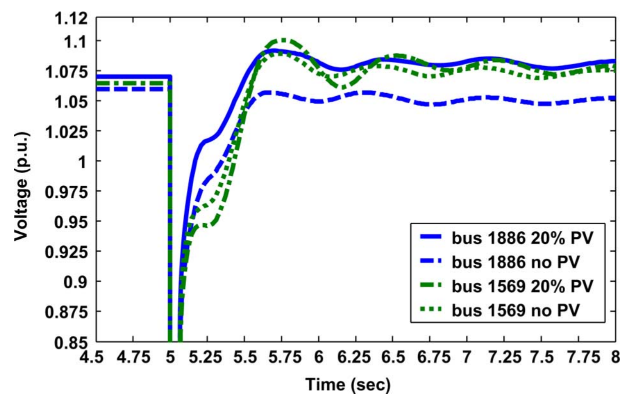

Fig. 9. Bus 1569 and 1886 voltages following the fault at bus 1569.

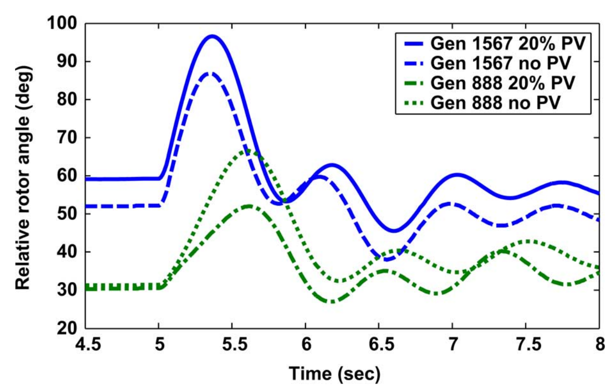

Fig. 10. Relative rotor angles of the generators 1567 and 888 following the fault at bus 1001.

that the system is more perturbed with higher PV penetration levels. Bus voltage magnitudes are shown in Fig. 9 for the time following the disturbance. Although, the voltage magnitudes have similar behavior in terms of the settling time and their peak values, the system equipped with photovoltaic systems shows increased voltage dips during the transients. The difference between the voltage dips can in some cases reach a value of 5%.

In another scenario, the same three-phase fault is applied to bus 1001 shown in Fig. 6 and the two connecting lines 1001–1164 and 1001–2529 are removed while the fault is cleared. Figs. 10–12 present the simulation results including the generator relative rotor angles and speeds as well as the voltage of the faulted bus. It is observed that in the second fault scenario, the speeds of the generator farther from the fault location are almost similar in both cases of 20% PV and no PV. However, the speed of the generator closer to the point of the fault will have higher frequency of oscillations following the fault clearance. Thus, relative rotor angle will take a longer time to settle down. Comparing Figs. 9 and 12, it is observed that in both fault scenarios the bus voltage magnitudes have higher oscillations as well as more significant voltage dips following the fault clearance.

2) Beneficial Impact on the Transmission System: Following the same procedure adopted in the previous two cases, a three-phase fault is applied at 500-kV bus 1164 shown in the bus structure of Fig. 13. The fault is cleared after 4 cycles followed by the double line outage of the two lines connecting bus 1164 and 913. The relative rotor angles of the neighboring generators are shown in Fig. 14. Figs. 15 and 16 present the voltage and frequency of bus 913 following the fault clearance. Simulation results show that the bus voltage and frequency oscillations in the studied area are well damped in the system equipped with 20% photovoltaic generation. On the contrary, the case with no PVs

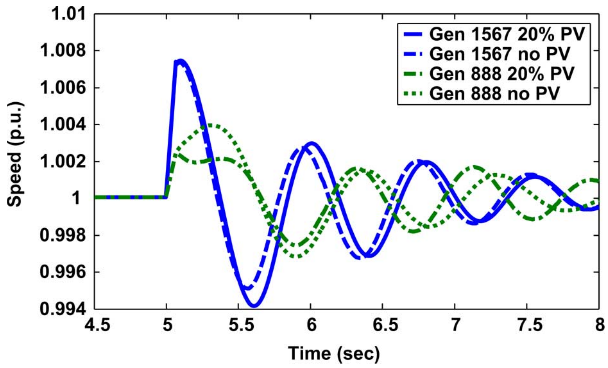

Fig. 11. Speeds of the generators 1567 and 888 following the fault at bus 1001.

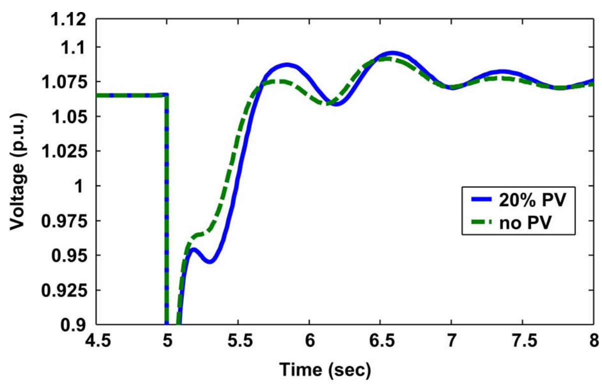

Fig. 12. Bus 1001 voltage following the fault at bus 1001.

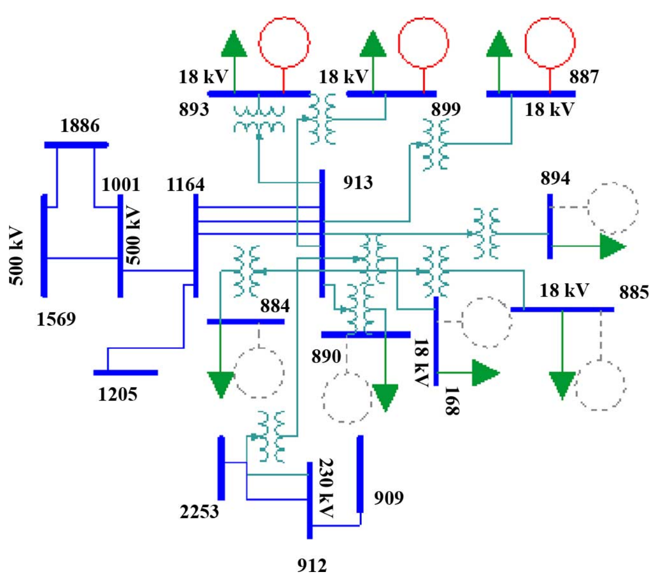

Fig. 13. Single diagram of the system near the faulted bus number 1164.

shows poorly damped oscillation of the voltages in addition to the rotor angle instability.

The double circuit outage will separate the neighboring generators from a major part of the system. In other words, bus 912 is the only remaining path for the output of the generating units close to the faulted bus. This will contribute to the system instability following the outages. On the other hand, in the system with 20% PV penetration most of these units are replaced with distributed generators, as shown in Fig. 13. Thus, outage of

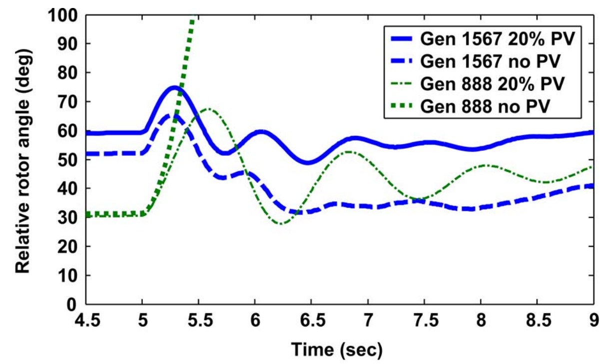

Fig. 14. Relative rotor angles of the generators 1567 and 888 following the fault at bus 1164.

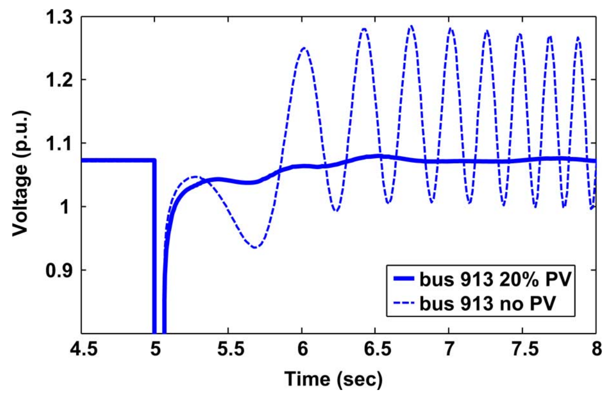

Fig. 15. Bus 913 voltage following the fault at bus 1164.

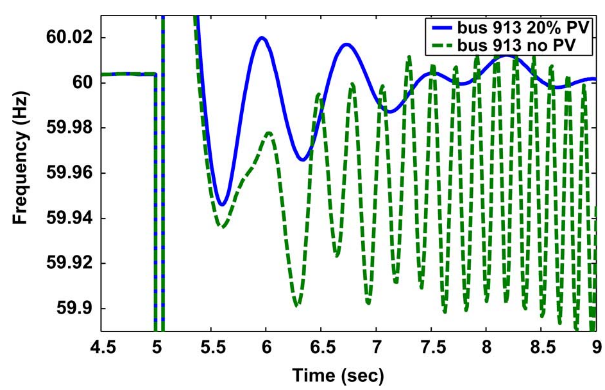

Fig. 16. Bus 913 frequency following the fault at bus 1164.

these two lines will have less effect on the system since it will cause less interruption in the flow of the power, and therefore results in improved behavior of the system with PVs.

B. Loss of Distributed PV

Being highly dependent on weather conditions, the output power delivered by photovoltaic systems can fluctuate due to climate variations such as cloud cover. These output fluctuations, in the worst case, can lead to loss of a large portion of the distributed PV generation. Additionally, the distributed PV systems can all trip simultaneously due to a single system event such as an extreme voltage dip condition [13]. This effect introduces one of the most important challenges associated with the systems with high PV penetration. In order to study the behavior

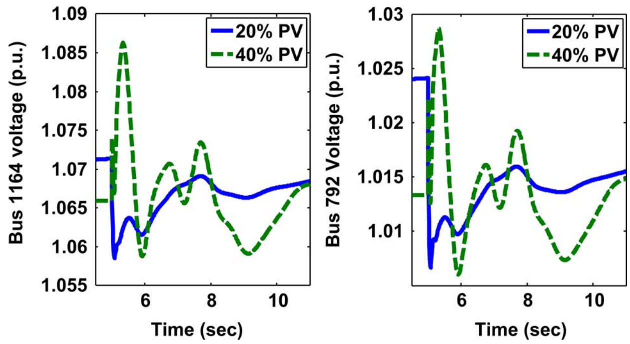

Fig. 17. Bus 1164 and 792 voltage magnitudes following loss of a major portion of rooftop PVs.

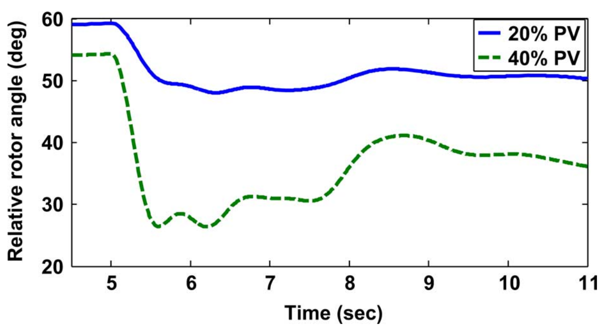

Fig. 18. Relative rotor angle of the generator 1567 following loss of a major portion of rooftop PVs.

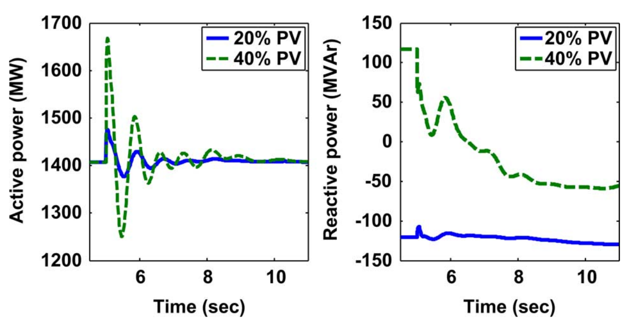

Fig. 19. Active and reactive power generation of the generator 1567 following loss of a major portion of rooftop PVs.

of the transmission system in occurrence of the aforementioned fault scenario, a large portion of the residential rooftop PVs, which are located in the same neighboring area, are tripped for the case of 20% as well as 40% PV penetration. Fig. 17 illustrates the voltage magnitudes of a few transmission system buses, which are located at various locations of the studied area, following the loss of the PV units. Relative rotor angles of a neighboring generator as well as the active and reactive power generated by this unit are presented in Figs. 18 and 19.

Simulation results presented in Figs. 17–19 indicate the fact that loss of a major portion of distributed PV systems, can lead to voltage fluctuations as well as deviations in the relative rotor angles of the neighboring synchronous generators. As the amount of PV penetration increases, these voltage fluctuations tend to be higher and they require a longer settling time. Judging from these results, it could be said that distributed PVs may need to have a measure of voltage tolerance.

VIII. Conclusions

In this paper, the impact of high penetration of photovoltaic systems on a large interconnected system is investigated. Photovoltaic generation is added to the studied system with both residential rooftop PVs and utility scale PVs. Both steady state and dynamic behavior of the system with and without the existence of these generation resources are studied and compared to identify improvements or adverse effects of photovoltaic systems on the power transmission systems. Various PV penetration levels up to 50% are considered for the steady state analysis, while conventional generators are replaced with PV systems in each step. For dynamic analysis, 20% PV penetration is deemed to be a valid representation of a case with high PV penetration.

The steady state analysis results reveal that increasing PV penetration levels can lead to alteration of the steady state voltage magnitudes. At some penetration levels, overvoltages are observed at transmission level buses. The majority of over voltages were observed in the case with 20% PV generation. Analytical studies conducted for a simplified system confirm the simulation results achieved for a larger system.

For the system considered, dynamic analyses conducted indicate that high PV penetration can have both detrimental and beneficial impact on the transmission system. These impacts are observed by case studies carried as indicated in this paper. Simulation results reveal that, PV penetration levels, system topology, type of the disturbance as well as the location of a fault are all important factors in determining the nature of the impact of the high PV penetration on the system.

In almost all the case studies, bus voltage magnitudes are the most adversely affected system parameters during the transients. It is observed that systems with high PV penetration levels achieve greater voltage dips following most of the disturbances. Loss of distributed PVs in a certain geographical area may result in more oscillations as the level of PV penetration increases.

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