Grid Stability Analysis for High Penetration Solar Photovoltaics

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Abstract—**The ever growing global energy needs and the immediate need for an environment friendly sustainable growth have made us to focus on renewable energy sources, especially wind and solar. But these renewable energy resources when implemented in large scale without any specialized controls is found to impact the integrity, reliability, security and stability of the power grid. Solar PV has become the major portion among the utility level renewable energy power plants. Solar PV power penetration into the grid is on continuous rise and plants of order of hundreds of MW are coming up in India and at global level. In India, till now the utility scale solar PV installations do not follow any specialized controls for grid support and will just get disconnected when there is a grid disturbance. This will severely impact the grid when the size and scale of the solar PV plant is huge. In this paper, a brief study on the controls existing in a conventional power plant to manage grid stability has been presented, as the large upcoming utility scale solar plants are expected to behave similar to the existing conventional power plants when it comes to handing grid stability and support. Further, this paper is aimed at studying and analyzing the impact of the large scale penetration of solar PV power into the grid. The IEEE 9-bus system has been considered as a standard test bus platform for the analysis. The simulation has been performed with the help of ETAP v12.6 (Electrical Transient Analysis Program) software, which is a very suitable tool for power system simulation and analysis. This study investigates the impact of large penetration of solar PV systems on steady state performance as well as transient stability of a large power system. The steady state voltage and power loss in the system have been studied under various PV penetration levels. Also, the impact of increased solar penetration on the transient stability performance of the power system has been observed. The results have been analyzed and the observations and inferences are presented.**

Keywords-Large Solar PV penetration; Steady state analysis; Transient stability analysis; ETAP;

I. Introduction

Renewable energy, a term that is used to represent the energy from a source that is not depleted when used, viz. wind power or solar power, is gaining huge importance among all forms of energy resources and is being given thrust and emphasis across the globe. Climate change due to global warming and the depletion of fossil fuel reserves are two major challenges facing the planet earth right now. Immediate cut down in the usage of fossil fuel resources and reduction on its dependency is the need of the hour to bring down the emission of green-house gases and to secure the energy for the future. Switching to renewable energy is a promising solution for the present crisis. The high cost of renewable energy has been a main hindrance to its development till now. But in order to promote the renewable energy installations, the policies and regulations are being modified in its favor in all major countries. Also due to the recent advancements in technology and research, the cost of renewable energy has been continually decreasing, with the most significant price drop being observed in solar, which is 80% over the last seven years. Solar energy (especially solar PV) and wind energy are two major sources among the renewable energy resources which have been commercially well-established and are proven technologies for clean power generation. By the end of 2015, the global installed capacity of solar PV (Photovoltaic) and wind stood at 227 GW and 433 GW respectively out of 785 GW of total renewable installations. The renewable energy based power generation is growing at a faster pace recently, especially solar PV. It recorded a huge growth rate of 28% in 2015. The advancements in the field of PV panel manufacturing and the inherent advantages of solar PV over other sources and technologies have paved way for such a tremendous growth. Solar PV technology has several advantages over others like small size, ease of installation, no moving mechanical parts, smooth operation without any noise, requires less maintenance, etc. The statistical projections indicate that the global solar PV installations will grow at even faster pace in the coming years. The situation is same in India which has set an ambitious target of 100 GW of solar power by 2022. Hence it is high time to study and analyze the impact of such increased penetration of solar PV into the power grid, which presently is being dominated by the conventional sources. This will help in identifying the problems associated with the high penetration of solar PV into the grid.

Till now, the solar PV installations were small in size and quantity and were connected only at distribution level. But large solar parks of order of hundreds of MW are coming up and will be connected at transmission level. With such an extensive growth in the deployment of the solar PV, power system operators are expected to deal with a new set of issues due to the different nature of the generation. The solar PV has the ability to reverse the flow of the power from the loads towards the transmission system and has zero or very much reduced reactive power generation right now [1]. Also solar PV unlike thermal power plant is asynchronously integrated into the grid through inverter. Hence they do not contribute for grid inertia. It is a significant aspect of conventional synchronous generators that helps in the inertial response during frequency control [2]. Also at present the solar PV plant's anti-islanding protection immediately trips the plant when there is a grid fault. This will not be an issue when the plant capacity is less but will impact the stability of the grid when the capacity of the plant is large, as it will cause generation-load imbalance. Also the solar PV plant output heavily relies on the weather conditions and seasonal variations. Hence if the plant capacity is large, such variations will heavily impact the grid [3]. More such drawbacks are mentioned in [4], [5], and [6]. Large PV plants in grid are expected to behave similar to the conventional plants and support for managing grid stability. Hence large solar PV plants when implemented without any specialized controls will impact the stability and security of the grid. Hence it is important to analyze the issues of large penetration of solar PV into the power system.

Based on CEA (Central Electricity Authority, India) and MNRE (Ministry of New & Renewable Energy, India) data, the present solar penetration is about 2.23% (6,762.85 MW of solar among 3,02,833.2 MW in total as on April 2016). Renewable energy installments being order of the day and government's thrust in promoting renewable energy throughout the country the total penetration of solar is set to increase at a rapid pace. As per CEA projection and MNRE's JNNSM-2015 (Jawaharlal Nehru National Solar Mission) target, the penetration would be around 23% by 2022 (100 GW of solar among 434900 MW in total) [7], [8], [9], and [10].

II. Controls Existing in a Conventional Power Plant to Manage Grid Stability

A brief study has been done on the controls existing in a conventional power plant to manage the grid stability. It stands as a base for the performance requirements of large and upcoming solar PV plants. The upcoming large solar PV plants are expected to have the control mechanisms similar to that of the conventional power plants for supporting and managing grid stability. The generator-side control systems to maintain the power system equilibrium, system stability enhancement and improvement, system reliability and security have been studied. The control systems existing in a conventional power generation plant using a synchronous turbo alternator/generator has been listed down in this section. Useful inputs were obtained from the case study done on a thermal power plant to understand the various controls in practice to manage the stability issues in India.

A. Frequency stability and active power control

1) Grid Inertial Response - initial phase: This is the first phase of frequency response. Synchronous generators have a rotational kinetic energy which is stored in the power system as grid inertia or system inertia. This system inertia is an important inherent system property of frequency dynamics and stability [2].

2) Control Phase: Three types of controls are considered for frequency control based on the the timeline of initiation and functional need.

a) Primary Control: It is achieved through the turbine speed governor mechanism which makes the generating units respond quickly to the frequency deviation as per speed-droop characteristic of the generator. In India as per IEGC 2010 (Indian Electricity Grid Code), Restricted Governor Mode of Operation (RGMO) is in place, which defines the criteria for frequency control [6].

b) Secondary Control: It is a supplementary corrective action which involves Automatic Generation Control (AGC) which delivers reserve power in order to bring back the frequency and the area interchange programs to their target values.

c) Tertiary Control: It is done in case of a very large disturbance in the system that cannot be handled by secondary reserves alone. In Indian scenario, the tertiary reserve had been a luxury as our system was short of generation for a long time. As the generators reserve situation is getting better now, it is proposed to use such surplus reserves as tertiary reserves.

B. Voltage stability and reactive power control

The synchronous generators are equipped with automatic voltage regulators (AVR) which in a closed-loop fashion adjust the excitation to control the terminal voltage.

1) Steady state voltage regulation: AVR in the excitation system operating in voltage control mode helps in this.

2) VAR compensation and support: AVR in excitation system operating in VAR mode (Under or over excitation) helps in reactive power support.

Voltage profile improvement is also sometimes done by on-load or off-load tap changing transformers [11] and [12].

C. Angle stability

1) Small signal angle stability: PSS (Power System Stabilizer) present in excitation system helps in improving small signal angle stability of the system. [13]

2) Transient stability improvement: High speed excitation along with PSS and several other controls are present for large signal stability enhancement. [13]

III. IEEE 9-Bus System – Modelling in ETAP

A. IEEE 9-bus system

The IEEE 9-bus test system, which is also known as P.M Anderson 9-bus system, has been modelled in ETAP software. It represents a simple approximation of the Western System Coordinating Council (WSCC) system with 9 buses and 3 generators. Solar PV plant has been integrated into this system. The single-line diagram of the WSCC 9-bus system is as shown in Fig. 1. The voltage levels and transmission line impedances are also indicated in the same. This test system also includes 3 two-winding transformers of 100 MVA each, 6 lines and 3 loads (135.532MVA, 94.45MVA, and 102.64 MVA). The base kV levels are 13.8 kV, 16.5 kV, 18 kV, and 230 kV.

B. Developing the Model of Solar PV Plant Integrated to IEEE 9-Bus System in ETAP

The complete test bus system has been first constructed in ETAP. Then a model of a typical solar PV plant is developed with the help of PV array block. Many small PV panels of 200 Watt each have been combined in series and parallel combinations to arrive at a PV array with a maximum power of 24.5 MW (MPP power) roughly and a DC bus voltage around 1000V (V_{dc}). Each of the PV arrays has an inverter unit with a AC rating of 11kV and 26.2 MVA roughly. Several such PV arrays have been created and pooled into a common 11kV bus called solar bus. The output of the solar bus is then given to a station transformer which steps up the 11kV generation voltage to 230kV, which would be suitable for penetration into transmission bus. Initially this solar plant setup has been integrated into the Bus No. 5 of the IEEE 9-bus system as shown in the Fig. 2.

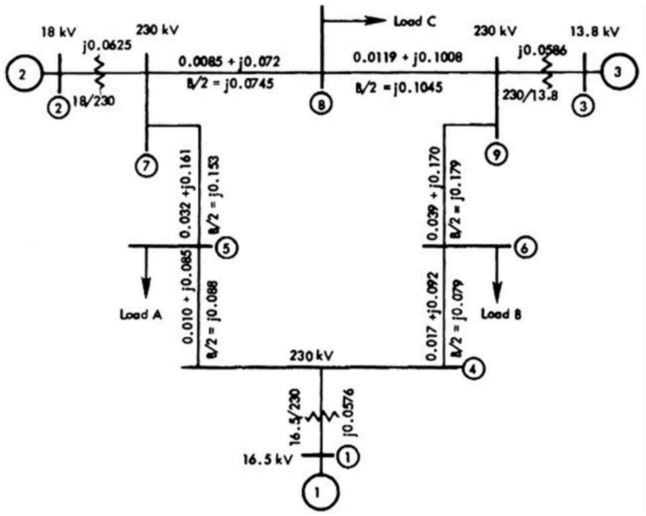

Fig. 1. ETAP model of IEEE 9 – bus system single line diagram

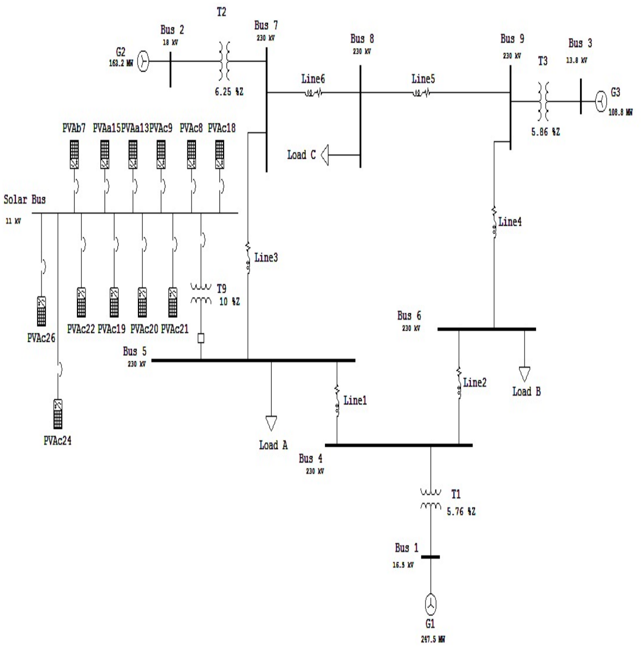

Fig. 2. IEEE 9-bus system integrated with Solar PV plant

IV. Steady State Analysis

The IEEE 9-bus system model without solar integration has been considered as the base case with 0% solar penetration. Then solar plant has been integrated into bus-5 first as it has the largest load connected to it. The base case slack bus power (Generator G1) has been taken as reference for the calculation of solar PV penetration percentage. The power injected by solar PV plant into the grid through bus-5 is slowly increased from 0% till around 100% in steps of 10% approximately. Load flow calculation has been performed in each step and various parameters are noted. Steady state power flows in lines, bus voltages, generation details, and system losses were observed. The process is repeated with solar PV integration into other buses namely bus-8 and bus-6.

A. *Effect of Solar PV Penetration on Steady State Voltages*

Three different cases of solar PV integration namely penetration at bus-5, bus-6 and bus-8 have been considered for analysis. The bus voltages on all buses in the system have been observed. The complete bus data for all solar PV penetration levels from 0 MW till 243 MW are considered for all three cases. The bus voltages are plotted with respect to the penetration level. The bus voltages of 11kV solar bus is also indicated. Buses 1, 2 and 3 are excluded from the plot as they are constant throughout the penetration. This is because Bus 1 is modelled in swing mode and buses 2 & 3 are modelled in voltage control mode. The plots for all 3 cases are as shown in Figs. 3, 4, and 5.

As seen in plots of bus voltages, the voltage profile seemed to be improving initially as the solar penetration is increasing but it starts dropping beyond a certain percentage. Similar trend of voltage variation is observed in all three cases. The voltage starts collapsing as the solar penetration beyond a certain point causes the line drop to increase. But the intensity of variation in voltages varied with the location of penetration. The maximum of the variation in bus voltages observed in all three cases is listed below,

- Case 1: 2.5% variation of voltage @Bus 5
- Case 2: 3.35% variation of voltage @Bus 4
- Case 3: 8.35% variation of voltage @Bus 5

The peak point of the curve also varies with the location of penetration. Hence solar PV penetration into the system can only be allowed up to the point where the voltage profile improves. In case 1 the voltage in most of the buses seemed to be improving till about 30% and after that it collapses. In case 2 the voltage variation is little severe compared to the case 1, where in couple of buses the voltage started crashing right from the beginning. Also in this case at several instances the voltage were close to the under-voltage and over-voltage limits of the system. The case -3 was even severe with almost all bus voltages were starting to collapse right from the beginning and many voltages were close to steady state voltage limits. The variation was also severe compared to the other cases. Hence, it is seen from the study that among the three cases, PV injection at bus 5 was better as it allowed for more penetration with less severe variation in voltages.

B. *Effect on the System Loss*

The system losses in both MW (real power) and MVAR (reactive power) have been observed for all penetration levels as done for the voltages and has been plotted as shown in the Figs. 6 and 7. Initially the losses were decreasing till a point and started increasing for the penetration beyond that. In case 1 the losses were decreasing till about 20% and whereas for case 2 it was just about 10%. In case 3, the system losses were increasing right from the beginning. Similar trend was observed in case of the plot of the system losses in terms of reactive power i.e. MVAR. Optimal penetration level with respect to the system losses can be identified from the system loss profile and also the best location for penetration can also be identified from this analysis.

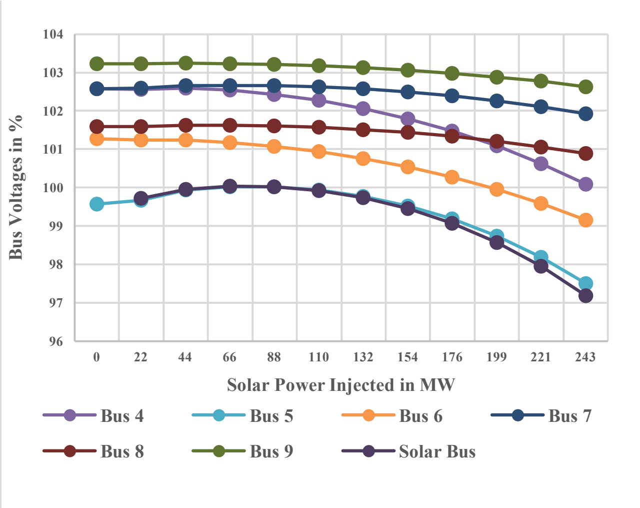

Fig. 3. Bus voltages at various PV penetration levels for case 1 (@ Bus-5)

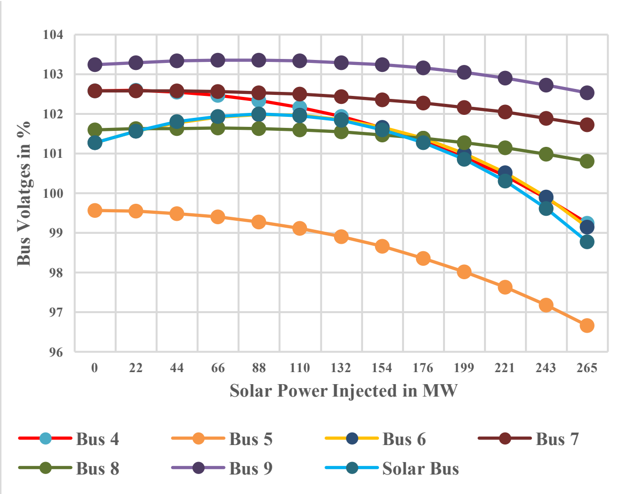

Fig. 4. Bus voltages at various solar penetration levels for case 2 (@ Bus-6)

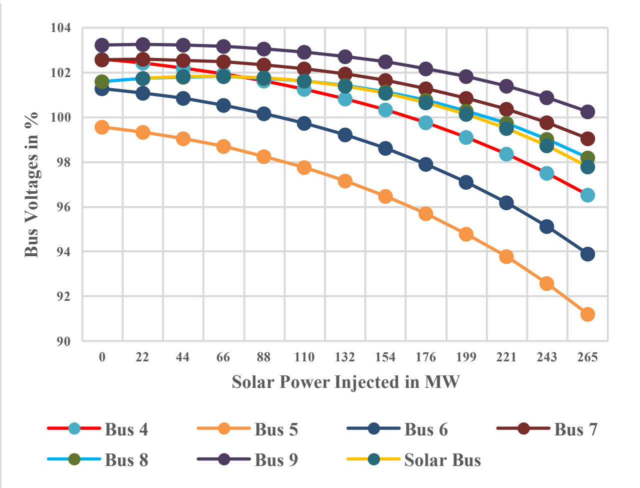

Fig. 5. Bus voltages at various solar penetration levels for case 3 (@ Bus-8)

C. *Effect on Transmission Line Power Flow*

The real and reactive power loading of all the transmission lines existing in the network are observed and plotted for all penetration levels as shown in the Figs. 8 and 9. This is observed for case 1. The variation in loading of the transmission lines was mixed with few lines experiencing increase in power and few line experiencing decrease in power. Few of the lines experienced even sign changes in the power flow causing the power reversal beyond a point. The changes in loading of line 1 is severe of all. Thus, it is very important to consider the impact of solar penetration on transmission line loading parameters while planning the network.

D. *Summary of Steady State Analysis*

The summary of the case study is presented in Table 1. Increase in PV penetration can bring variations in steady state bus voltage levels and can be really critical at times and might even contribute to affecting the voltage stability of grid. Also, it might bring about severe changes into other parameters like steady state real power and reactive power loading of transmission lines and other equipment in the system and also affect the system losses. Hence it is important in performing such a study, which will help engineers in planning the system with high penetration levels of solar PV power and in identifying the critical PV penetration levels for a given network.

TABLE I. SUMMARY OF STEADY STATE ANALYSIS

Case	Appropriate location	Maximum possible penetration
Based on bus voltage	Bus 5	66 MW
Based on system loss	Bus 5	44 MW

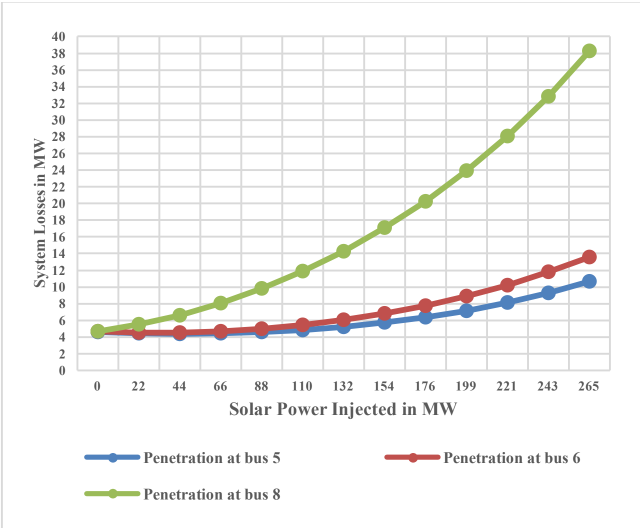

Fig. 6. Plot of system losses in MW v/s solar penetration levels for injection at various bus locations

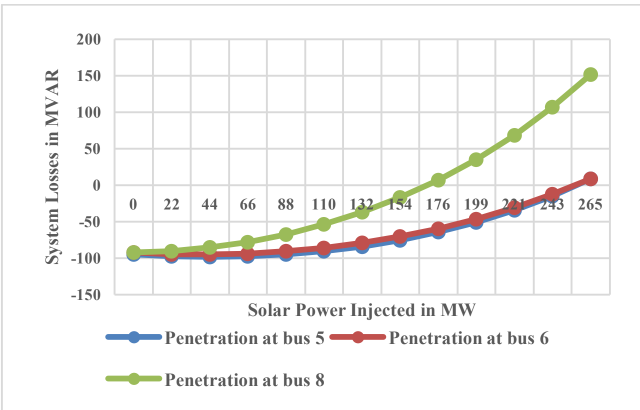

Fig. 7. Plot of system losses in MVAR v/s solar penetration levels for injection at various bus locations

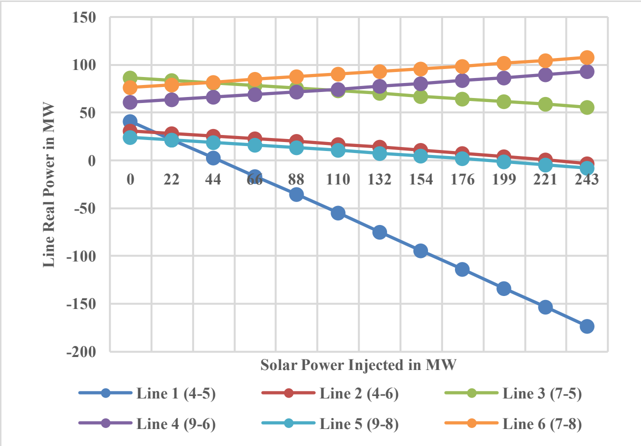

Fig. 8 Plot of real power in transmission lines at various solar PV penetration levels

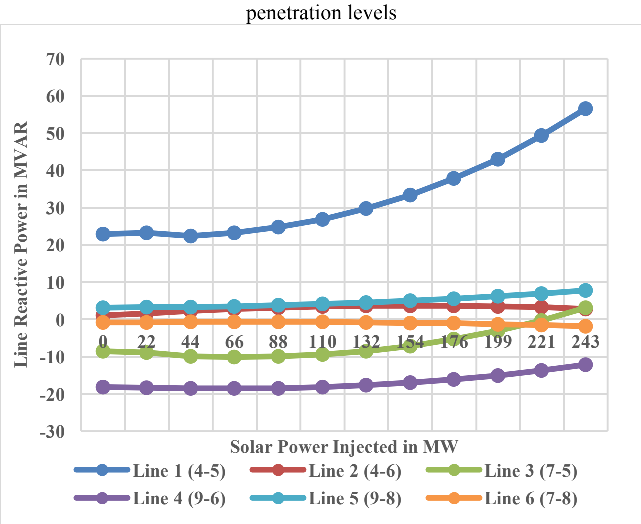

Fig. 9. Plot of reactive power in transmission lines at various solar PV penetration levels

V. Transient Stability Analysis

Transient stability is defined as the ability of the power system to maintain synchronism during large disturbances [14]. These disturbances could be a fault in bus or a fault in a transmission line or its disconnection, equipment outages, loss of generation or loss of a large load. The aim of the transient analysis, that is discussed in this section, is to examine if such large system disturbances affect the system in a different way with high PV penetration levels. Simulations have been done considering various cases of disturbances like bus fault, loss of a large load and loss of a transmission line, under various solar PV penetration levels. The effect of solar PV penetration on the critical clearing time is also studied. Solar PV plant has been integrated into the bus 5 of the IEEE 9-bus system, as described in previous section. The same system that was used for steady state analysis has been considered for transient analysis too. "Transient Stability Analysis" module of the ETAP has been used for the simulation and analysis.

A. Effect on Critical Clearing Time

A bus fault has been considered at bus-7, as it experiences the maximum short circuit current for its 3 phase bus fault. First the simulation has been done for the system without any solar PV. The clearing time of the fault has been continuously decreased until the system becomes unstable. The maximum allowed time within which the fault has to be cleared is called critical clearing time. If the fault is not cleared within the critical clearing time of the system, it will severely affect the stability of the system. Thus the critical clearing time has been found for system with various penetration levels and results are shown in Table II. The trend is also plotted as shown in the Fig. 10. The critical clearing time continuously decreases as the solar PV penetration increases. And for the penetration beyond 20%, the system is unstable for any clearing time.

TABLE II. Effect on Critical Clearing Time

Solar penetration (%)	Critical clearing time (second)
0	0.193
5	0.19
10	0.187
15	0.161
20	0.146
> 20	Unstable for any clearing time

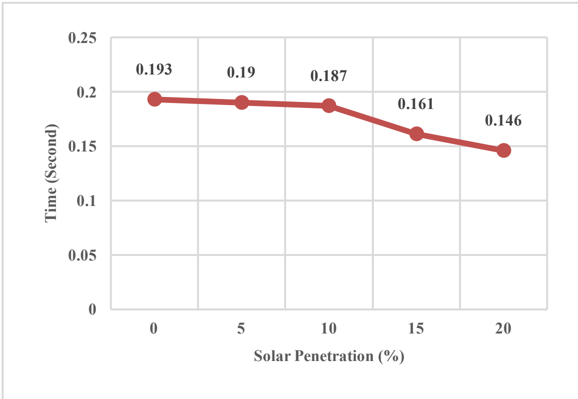

Fig. 10. Variation in critical clearing time with percentage penetration of Solar PV

B. Effect due to Bus Fault

Next, the effect on the system transient behavior due to a bus fault occurring in it at various solar PV penetration levels have been studied. A fault has been introduced at bus 7 at "3.00 second" and was cleared at "3.12 second". The relative rotor angle and bus voltages have been observed and plotted for a "20 second" time duration, as shown in the Figs. 11 and 12. The relative rotor angle plot of the generator G2 is shown in Fig.11. The oscillations following the disturbance for the base case with 0% solar PV penetration is smooth and is converging towards a stable value. For the case with 10% solar penetration, the amplitude of oscillations is a bit more and is getting little irregular. Yet it was converging and the system was stable. Similar trend has been observed for the case with 20% penetration, but with little higher amplitude. Beyond 20% penetration the system was becoming unstable. As shown in the Fig. 11, for 30 % penetration the oscillations have been completely irregular and didn't converge to a stable value. Similar trend has been observed in the relative rotor angle plot of the generator G3. The voltages at bus 7 and bus 4 is plotted as shown in the Fig. 12. Both the voltages have been examined as bus 7 is the faulty bus and bus 4 is little away from the fault. The oscillations after the fault for the base case are minute and converging to a stable value. The oscillations for 10% penetration case was with higher amplitude and was getting irregular. The voltage dips are quite high. But it was getting stabilized after a while. Whereas for the 30% penetration case the oscillations and voltage dips have been very severe and was not stabilizing. Hence as the level penetration increases the system becomes unstable and goes out of synchronism after some penetration percentage.

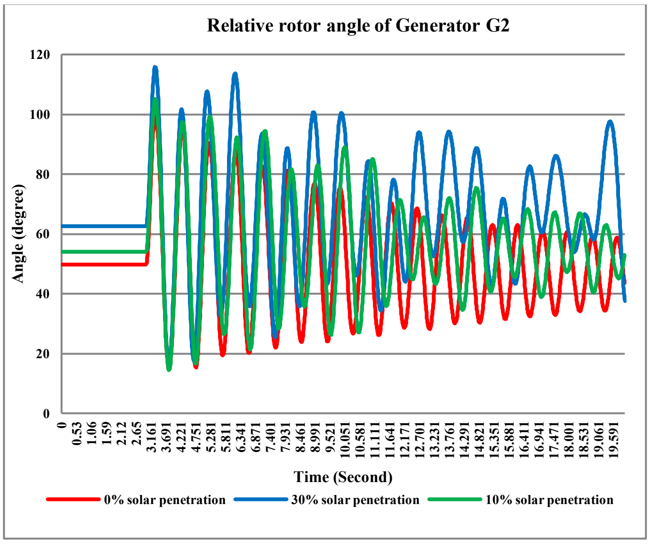

Fig. 11. Plot of relative rotor angles of generator G2 for a fault at bus-7 at various solar PV penetration levels

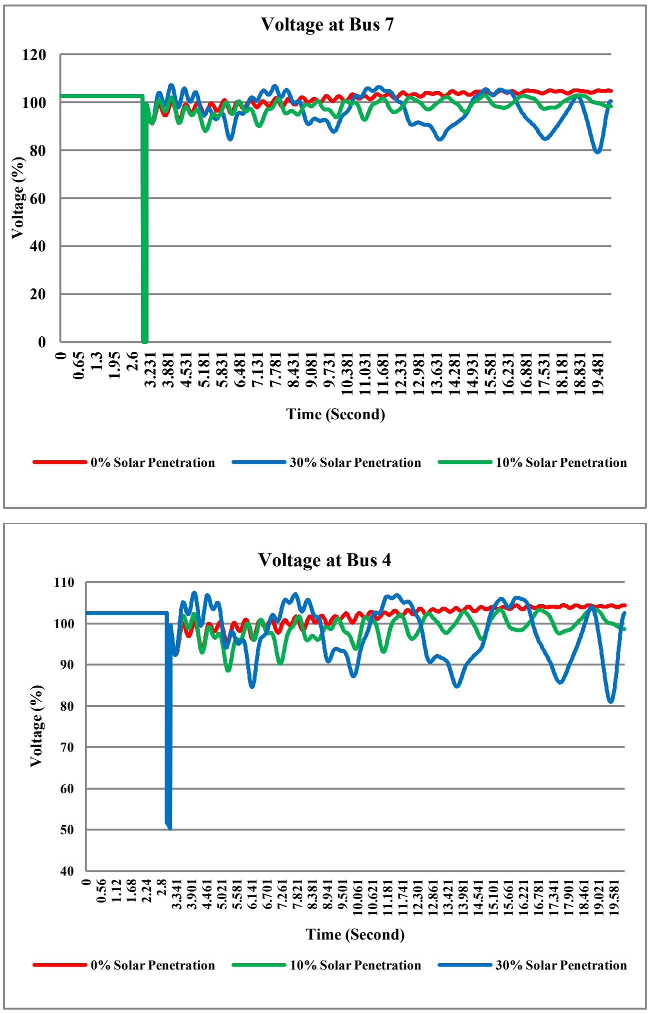

Fig. 12. Plot of bus voltages at buses 7 and 4 (in %) for a fault at bus-7 at various solar PV penetration levels

C. *Effect due to Load Rejection*

The largest load in the network, load A connected to bus 5, has been disconnected suddenly and effects are studied for various penetration levels. The rotor angle plot for generator G2 and voltages at bus 5 (from where the load is disconnected) and at bus 9 (little away from the load loss location) are as shown in the Figs. 13, 14 and 15 respectively. The oscillations for the base case have been uniform and is converging and settling to a new value. The oscillations for the 10 % and 20% penetration case is also less in amplitude but is little irregular compared to the base case. Yet it is converging to a finite one. Beyond 20% penetration the system is unstable. The oscillations for the 30% penetration case are severe and completely irregular from the base case. It is not converging and going out of step. The rotor angle plot of generator G3 is similar to that of the generator G2 and hence not shown.

The voltage plot of both the buses are similar. In the base case voltage undergoes minor disturbance after the disconnection and smoothly settles towards the new value. The oscillation frequency is quite high for the 10% penetration case but is converging towards the new value. For 30% penetration case the oscillations are severe and irregular. The frequency is also less and is not converging. Hence, in case of the load rejection too, the system is getting unstable as the level of solar penetration increases.

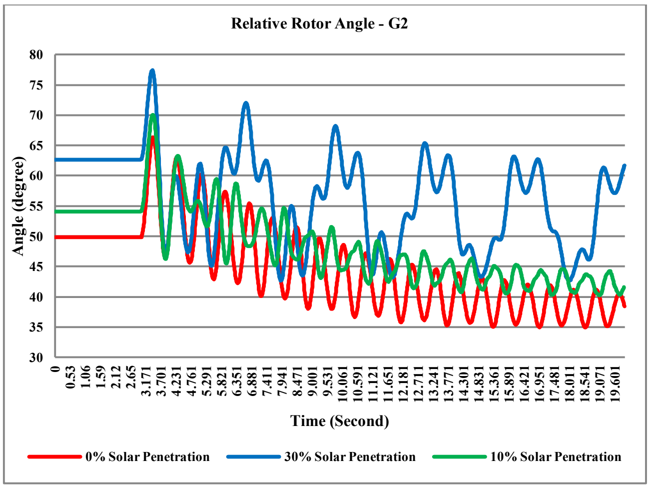

Fig. 13. Plot of bus voltages at buses 7 and 4 (in %) for a fault at bus-7 at various solar PV penetration levels

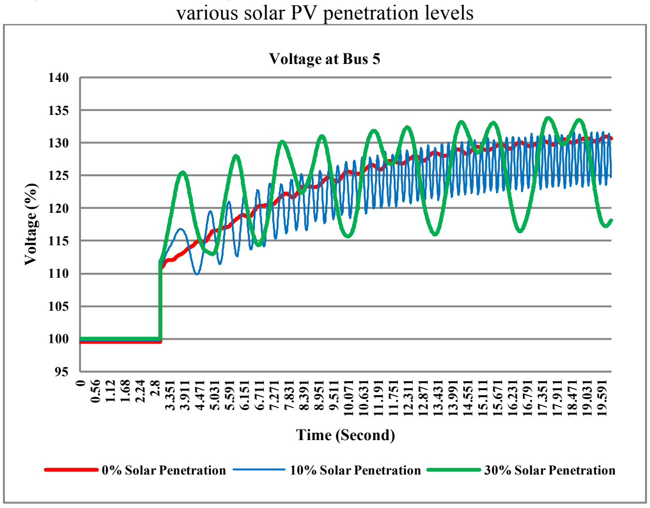

Fig. 14. Plot of voltage at bus 5 for loss of load A at various solar PV penetration levels

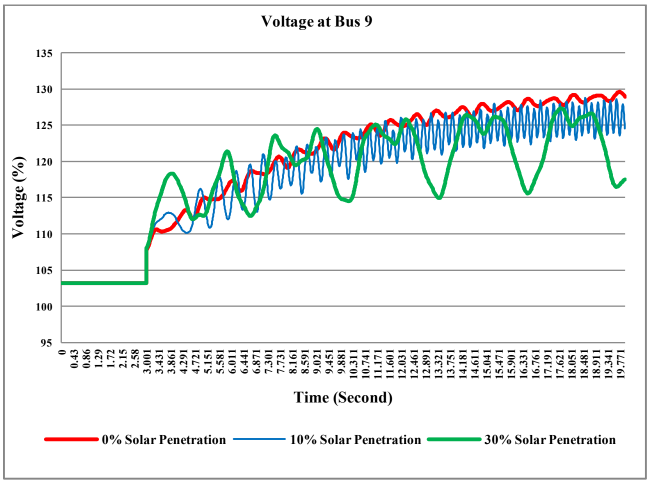

Fig. 15. Plot of voltage at bus 9 for loss of load A at various solar PV penetration levels

D. *Effect due to Loss of a Transmission Line*

The effects due to sudden loss of transmission line 6 has been studied next. Here also both the relative rotor angles of the generators and the voltage at buses have been studied. The relative rotor angle plot, plot of voltages at bus 8 (from where transmission line is disconnected) and bus 5 (away from the fault) are shown in the Figs. 16, 17 and 18 respectively.

The oscillations for the base case is uniform and is converging and settling to a new value. The oscillations for the 10 % case is very similar compared to the base case and is converging to a finite value. Beyond 20% penetration the system is unstable in this case too. The oscillations for the 30% penetration are severe and completely irregular from the base case. It is not converging and is going out of step. The rotor angle plot of generator G3 is similar to that of the generator G2 and hence not shown. Severe drop in voltage occurs for bus 8 as the line 6 is disconnected from that bus. In the base case, the voltage slowly recovers and settles to the new value. Heavy high frequency oscillations occur in case of 10% penetration but moves towards the new value. In case of 30% penetration, irregular low frequency oscillations occur and doesn't converge to a stable value. Thus the system is getting unstable for the loss of a transmission line as the level of penetration increases.

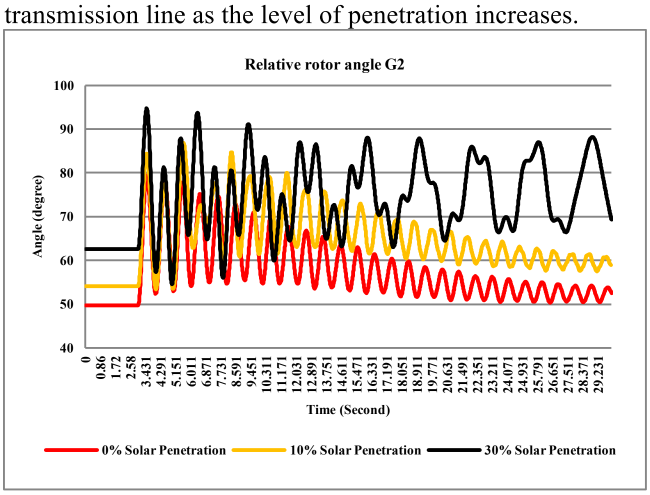

Fig. 16. Plot of relative rotor angle of generator G2 for loss of line 6 at various solar PV penetration levels

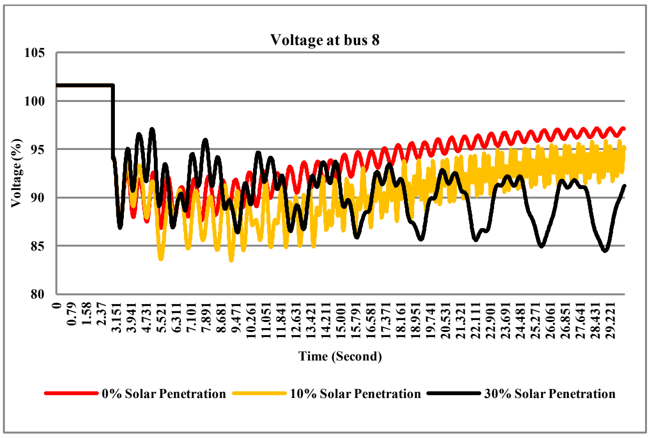

Fig. 17. Plot of voltage at bus 8 for loss of line 6 at various solar PV penetration levels

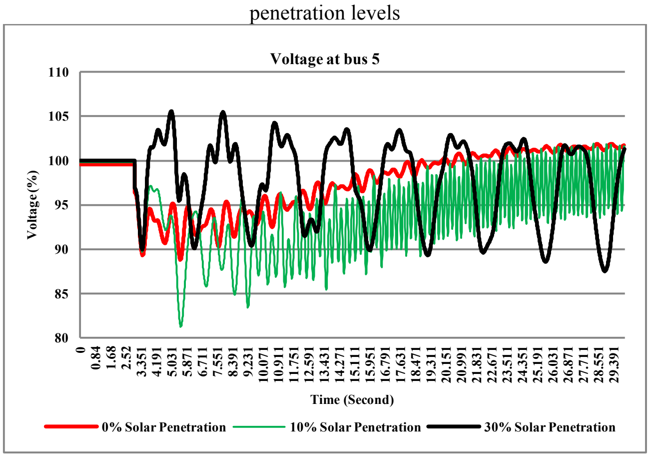

Fig. 18. Plot of voltage at bus 5 for loss of line 6 at various solar PV penetration levels

E. *Summary of Transient Stability Analysis*

Thus in all the case studies discussed here, the system was getting unstable for a transient disturbance as the level of PV penetration is increased. The bus voltage magnitudes and relative rotor angle and hence synchronism are the most adversely affected system parameters during the transients in the system with high penetration of PV. It is observed that systems with high PV penetration levels achieve greater voltage dips following most of the disturbances. Thus it is very important in taking into account the transient performance of the system with high penetration levels of the PV to maintain the stability and integrity of the system following faults. The generator—turbine inertia present in the synchronous generators which plays a key role in providing synchronizing capability of the system after a disturbance causes mismatch in between the mechanical power input and electrical power output of the generator. The total system inertia is very less in systems with high PV penetration leading to severe issue during various system disturbances.

VI. Conclusion

The solar power industry is growing at an exponential rate. India's policies and regulatory framework is promoting the renewable energy like never before especially solar PV. Hence the penetration of solar photovoltaics in to the Indian grid is set to increase and large scale plants are coming up. It is at this outset that this analysis has been done. The drawbacks of high penetration solar photovoltaics into the power system have been identified. The study on the conventional power plant helped in identifying the generation side controls that are required from the upcoming solar PV plants to manage grid stability, that is presently lacking. Thus initially, the need and importance in analyzing the impact of the high penetration photovoltaics into the grid was clearly understood.

The increased penetration of solar PV into the grid without any specialized controls has been proved to affect both the steady state performance and the transient stability of the grid. The steady state voltages are affected adversely with the location and the level of penetration. The impact on the system loss and slack bus power have also been studied. Several cases have been discussed and appropriate location and maximum possible level of penetration for the system under consideration is identified. Several transient disturbance cases have been dealt and the impact of increased penetration on the transient stability of the grid after those disturbances have been analyzed. In all cases the bus voltage magnitudes, the relative rotor angle and hence synchronism are the most adversely affected system parameters during the transients in the system with high penetration of PV. Thus suitable control mechanisms are required from the upcoming large solar plants to address such issues and to mitigate the stability issues arising out of increased solar PV penetration.

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