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Voltage Profile and Stability Analysis for High Penetration Solar Photovoltaics

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***Abstract*—**The enormous amount of energy from sun has led to a rapid growth of the use of Solar Photovoltaic power. The solar PV power can be used in stand-alone, grid connected, and hybrid configurations. Grid connected solar PV power plants are huge and are increasing rapidly because of the diminishing of conventional fossil fuels' resources for power generation. The solar PV power plants are connected to existing power system at transmission and distribution levels. This solar PV power integration is likely to have impacts on the power system. The steady state impacts of integrating solar PV power were studied on an IEEE 9 Bus test system. Impacts on voltage levels and profile, voltage drop, voltage stability, line losses and loading of the system were studied. A comparative analysis of system without solar PV power, with PV power and different levels of penetration of solar PV power was done with the aid of a power system software namely ETAP. The study revealed that the integration of solar PV power improves the voltage levels and drops and voltage stability. However, the increase in level of penetration beyond a certain point had negative impacts on the power system i.e. worsening of voltage profile, increase of losses which can also lead the system to become unstable. From this the hosting capacity (limit to which maximum power can be penetrated) of the system is determined.

***Keywords*—** Solar PV Power, Power Integration, Grid Impacts, Hosting Capacity, IEEE 9 Bus System

I. Introduction

Demand of electrical energy is increasing day by day. The depletion of fossil fuels and its high prices had motivated researches and developments in the field of Renewable Energy Systems (RES). The greater use of RES will help reduce the CO2 emission, a pollutant from burning fossil fuel for energy generation. Several countries are working on electricity generation from renewable sources and have set goals in this regard to meet the ever-increasing demand of electricity.

Among sources of renewable energy, the energy from the sun is an important one. The sun is a huge ball of heat produced from the fusion reaction of hydrogen. Energy from the sun can be utilized in two different ways; i) heat energy and ii) light energy. Electric power can be produced by exploiting the solar radiations and converting it to electrical energy. Based on how the solar energy is converted in to electrical energy, there are two types of solar power technologies. They are following:

- Concentrated Solar Power (CSP) Systems.
- Photovoltaic (PV) Solar Power Systems.

CSP is some time also known as Concentrated Solar Thermal. Utilization of solar energy by using CSP is like the conventional thermal power generating units. In this technology reflecting mirrors are used which concentrate the solar radiation at single point. This produces enormous amount of heat which can convert a fluid (mainly water) into steam and that steam turbine can be rotated for electric energy generation. By using CSP technology solar energy is indirectly utilized while in the photovoltaic (PV) technology electric energy is directly generated by utilizing solar radiations through semiconductor materials. When radiations from sun strikes the semiconductor material it converts into electrical energy by the photovoltaic property of the material. Operation of the CSP system is pretty much similar to that conventional thermal generating units and its impact on the power system is same as that of a conventional power plant (hydel and thermal). The Photovoltaic (PV) solar power system is of much interest because it operates differently from other conventional generating systems. Hence before integration of such systems in existing grid it is much needed to study the effects solar PV distribution and transmission systems of grid.

Either stand-alone or grid-tied solar PV can operate in both scenarios. At a small level, it can directly be connected to the load and the power be utilized. At a large level, it can be a solar power plant and be connected to a power grid. But in this case, it can alter the grid operating conditions either in a positive or negative way.

II. Impacts of Solar Photovoltaic Power Integration

During the last decade (2007-2017) solar PV has evolved from a niche market of small scale applications to a mainstream electricity generation source. The enormous potential of solar power and the worldwide energy demand which is calculated to increase by 41% till 2035, [1], has led to

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an increased research in the field of solar power systems and its integration to existing power system.

The sun does not shine uniformly throughout the world because of difference in latitude of places. There are a several factors such as seasonal variation and cloud cover that affect the amount of sunlight hitting the earth surface. According to [2], the cloud cover affects the generated power of large scale PV power plants to a great extent. This paper states that the variation of clouds mainly impact the output of the PV power plant. To overcome this problem, special modelling of the systems is done for better operations of PV power plants with changing climatic conditions. This implies that it is very crucial to conceive the effects of climatic changes especially cloud cover while studying the impacts of solar PV power integration to a power system.

Today the world is moving towards an increased use of renewable energy sources. The generation of power from solar PVs is increasing day by day and the integration of this power to the network is a challenge for the companies managing the transmission and distribution of power. Therefore, there is a need to fully understand the impacts of integrating a solar PV power plant to the existing power system, both at transmission and distribution level. According to research findings by [3], the integration of solar PV poses a number of challenges from the system's modelling and simulation point of view.

A. Impacts on Voltage Stability

Voltage stability is an important parameter of a grid. It shows the ability of the grid to restore initial operating conditions after the occurrence of a fault [4]. At a feeder PV integration delivers locally active power for a unity power factor and also has capability to deliver the support of reactive power needed for less than unity power factor [5], [6]. According to [7] and [8], the steady state voltage stability of a grid improved after PV integration. These studies also suggested methods for determining the steady state voltage stability of a grid.

B. Impacts on Voltage Level and Profile

Researches in [7], [9] and [10] suggest that the voltage level and profile of an existing grid varies after the integration of photovoltaic power to the grid. Studies in [9] and [10] has attempted to find the impacts of distributed solar PVs on network voltages and determination and increasing of hosting capacities for photovoltaics in the distribution grids in Sweden. According to these studies, the voltage rise at buses was increased without voltage violations in two of the grids. In one of the grids studied, over voltages at some buses were experienced in the studies. Furthermore, the studies in [10] described that voltage level and profile was not the only factor to be considered in the determination the solar PV power hosting capacity. It also showed that line losses and loading should also be considered for determining the hosting capacities of grids. According to [5], [11], and [12], the voltage level and profile can show an increase because of integration of solar PV power but this increase is dependent on the configuration of the grid to which the power is integrated. Distance from the power source also has an impact on the grid. The feeders which are far from the source get lower voltage than sending end voltage [13]. The solar PV integration improves the voltage profile along the feeders.

C. Impacts on Line Loading and Losses

Solar PV power has the potential to affect the two important parameters i.e. line loading and losses of a grid to which the power is integrated. Every transmission line and distribution feeder have their own capacity up to which they can be loaded. Similarly, losses in a power system can either increase or decrease the operational cost of grid [14]. Work done in [9] and [13] shows the effect of losses in a grid due to PV integration. In these studies, different levels of penetration of solar PV power were applied to grid and its impact on losses was determined. According to [9], the penetration level has a direct impact on grid losses as the losses increased with increase in level of penetration and vice versa. However, work done in [13], shows that the losses increased in grid with rise in penetration levels were attributed to the radial grid's reverse power flow. The reason is the feeder line loading increases with reverse power flow and hence the losses are increased. Also, this can disturb the protection system of the grid. Studies in [6] and [13] describe the variation in line loading with PV power integration. According to these, the increased levels of penetration reduces the line loading in a radial grid as long as no reverse flow of power occur. When reverse flow of power occurs, then with rise in penetration level, increase in line loading occurs.

To summarize, the impacts of solar PV power integration to a power system need broad research because of the speedy growth of use of this renewable energy resource. It is not necessary that the impacts of solar PV integration would be same across the world. There is a need to study and understand particular grids in different countries where there is extensive use of solar PV power and its integration to the power system [6]. The impacts of PV integration are likely to change and affect:

- Line loading, Voltage profile, voltage level and losses, voltage stability (both transient and steady state), power quality fault currents and load mismatch and generation.
- Voltage controlled devices operation, hence can affect the maintenance, life span and reliability of these equipment.
- Changes in power flow direction because of the possibility of reverse power flow which can affect the protection relays.

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

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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.

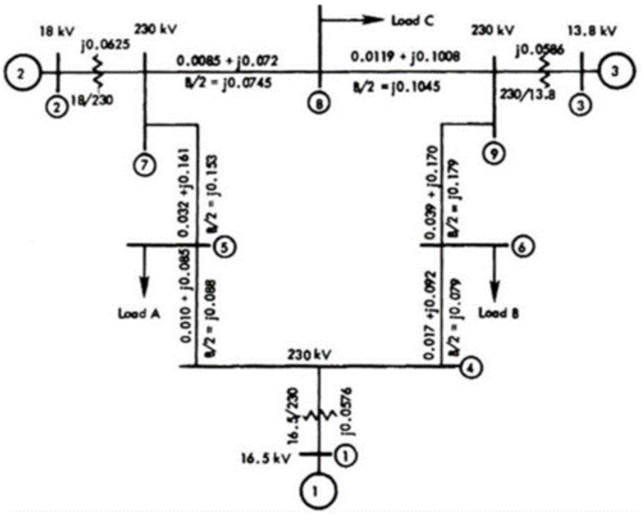

Figure 1. ETAP model of IEEE 9 – bus system single line diagram

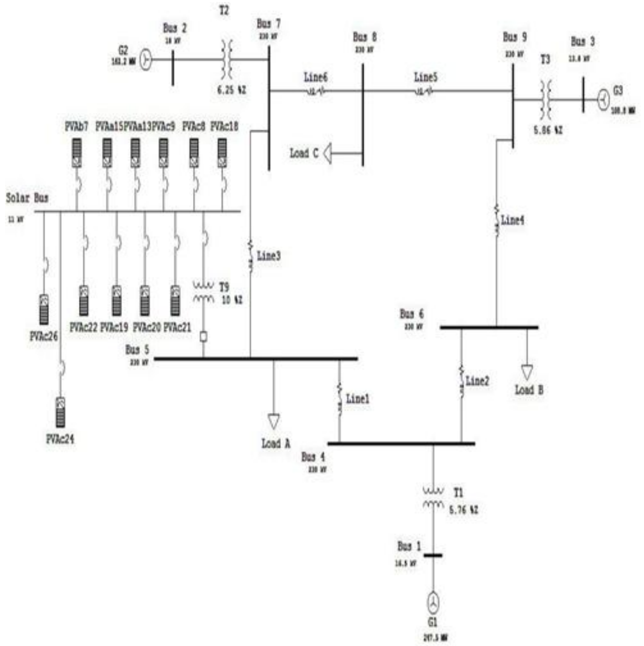

Figure 2. Solar PV plant integrated with Bus 5 of IEEE 9-Bus System

IV. Steady State Analysis

The complete IEEE 9 Bus system has been made in ETAP software as shown in Fig 1. A model of a typical solar PV power plant is then designed with the help of PV array block in ETAP. Small PV panels of 230 Watts each were combined together in parallel & series combination to form PV array with a maximum power of 24.8MW (MPP power) and a DC bus voltage of 32.2kV (Vdc). Each of the PV array was provided with an inverter with AC rating of 11kV and 26.7MVA (approx.). Ten such arrays were created and connected through low voltage circuit breakers to a common 11kV bus known as Solar Bus. The solar PV plant designed in ETAP is shown in Fig 2.

The output of the solar bus was the fed to a transformer through a low voltage circuit breaker. The transformer stepped up the 11kV generation voltage to 230kV and thus injected into the transmission bus.

Studies were performed by integrating the solar PV plant at three different buses (Bus 5, Bus 6, and Bus 8). Load flow study was performed for each case and various parameters were noted and results were plotted.

A. Impact on Voltage Level, Profile and Drop

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% till 100% 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: 3.45% variation of voltage at Bus 5
- Case 2: 2.82% variation of voltage at Bus 6
- Case 3: 5.8% variation of voltage at Bus 5

The peak point of the curve also varied with the location of penetration. Hence hosting capacities are different for different location of penetrations. For case 1 i.e. PV power penetration at Bus 5, the voltage improved on all buses till about 30% of penetration and after that the voltages started collapsing. For the case 2 when PV power is penetrated at Bus 6, some buses showed voltage improvement till 30% penetration where as two of the buses i.e. Bus 7 and Bus 8 voltages improved only for 20% of penetration and started collapsing then. Case 3 was the severe one where voltages some buses started collapsing right from the beginning. Also, in Case 2 and 3, at some instances the voltages were close to under-voltage or over-voltage limits of the system.

Hence, it is concluded from the results of the study that injection of solar PV power at Bus 5 proved to be better among the three cases. Penetration at Bus 5 allowed more penetration and the variations in voltages was also not that much severe as in the other cases of penetration at Bus 6 and Bus 8.

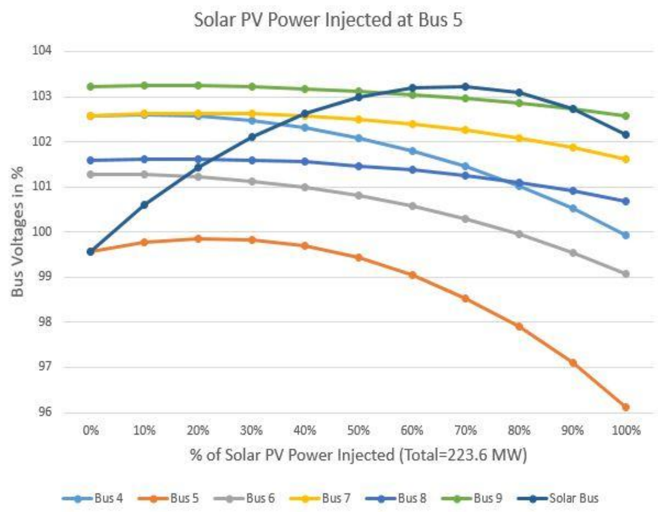

Figure 3. Bus voltages at various PV penetration levels for case 1 (@ Bus-5)

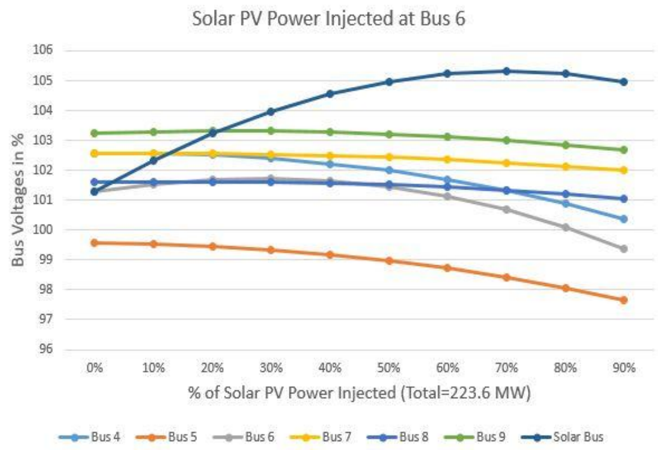

Figure 4. Bus voltages at various PV penetration levels for case 1 (@ Bus-6)

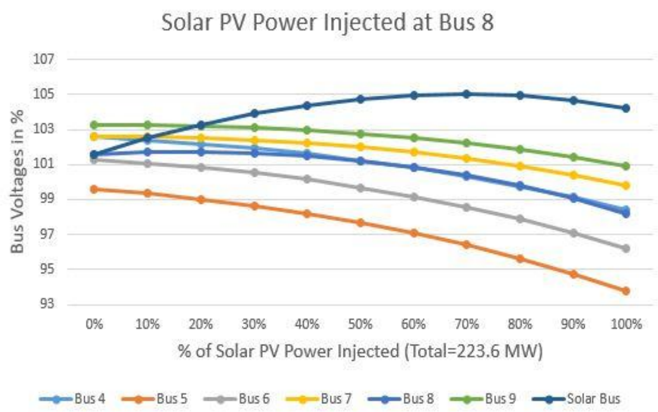

FIG. 5. Bus voltages at various PV penetration levels for case 1 (@ Bus-8)

B. *Impact on System Losses*

Fig 5 and 6, shows the plots of the system's real (MW) and reactive (MVAR) power losses respectively. These plots depicts that initially the both the losses (real and reactive) decreased till a point and started increasing for higher penetration levels. For case 1, the losses decreased till 20% of solar PV power penetration and after that the losses started increasing. For case 2, the losses decreased only for 10% of penetration and increased then. Case 3 i.e. penetration at Bus 8 was the worse one as the losses started increasing right from the beginning of the PV power penetration. Also, the increase in this case was drastic.

From the loss profile as discussed, it can be concluded that the best point for penetration of Solar PV power is at Bus 5.

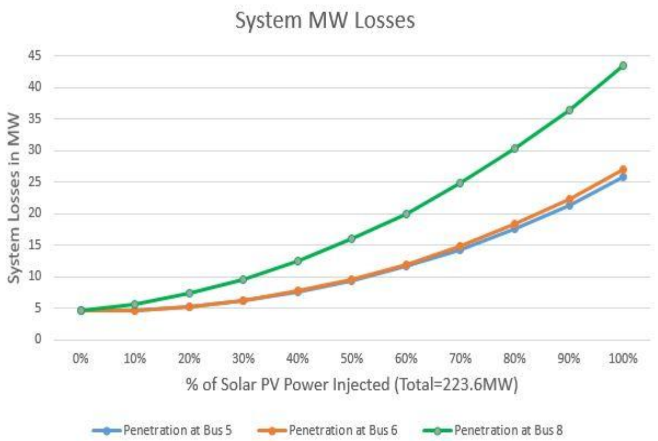

Figure 6. Plot of system losses in MW v/s solar penetration levels for injection at various bus locations

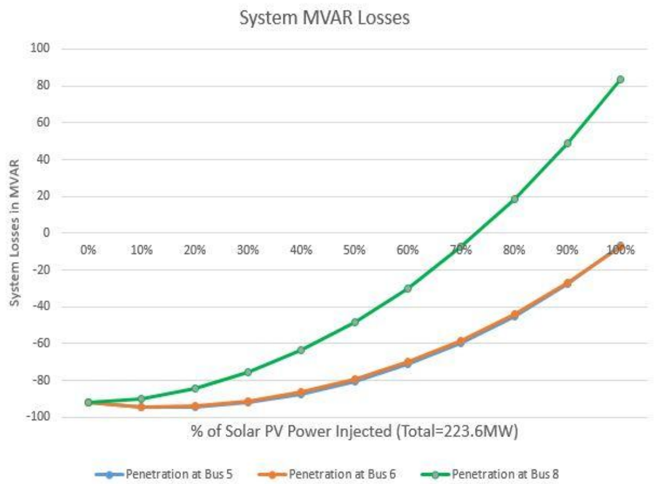

Figure 7. Plot of system losses in MVAR v/s solar penetration levels for injection at various bus locations

C. *Impact on Transmisison Lines Voltage Drop and Power Flow*

Fig 8, 9, and 10, shows the plots of %voltage drop, real (MW) power flow and reactive (MVAR) power flow in lines respectively. The plots shows that variations in %voltage drops in lines are mixed. Some lines' (line 1, 5 and 6) %voltage drop decreased initially for certain levels of penetration and voltage drop increased for higher levels of penetration. The variations in voltage drops of these lines were observed to be very slight. Whereas in some lines (lines 2, 3 and 4) the trend was same as that of other line but the variation observed in these lines was more.

The variations in line loading are also mixed. Lines 3 and 5 experienced an increase in real (MW) power flow with the increase of more PV power whereas lines 1, 4 and 6 experienced a decrease in real (MW) power flow. In line 2, initially, the real (MW) power flow decreased but after some levels of penetration the real (MW) power flow in line 2 increased drastically. Similarly for reactive (MVAR) power flow, the lines showed a different trend. Lines 2, 3 and 4 experienced sign changes for reactive power flow causing the power reversal beyond a certain point.

Hence, it is concluded from the discussion that while integrating a solar PV power plant to a power system, it is very important to consider its impacts on the loading of the transmission lines.

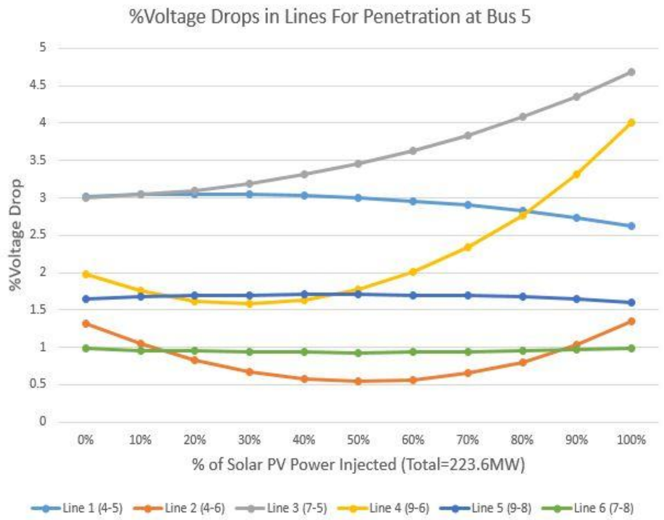

Figure 8. Plot of %Voltage drops in transmission lines vs solar penetation levels for penetration at Bus 5

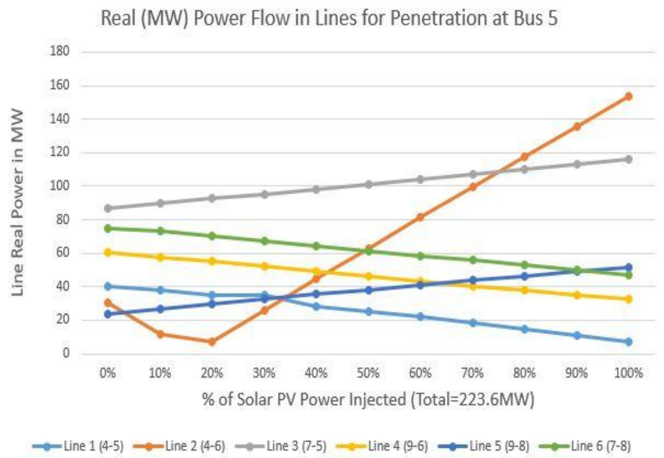

Figure 9. Plot of real power flow in transmission lines at various solar pentration levels

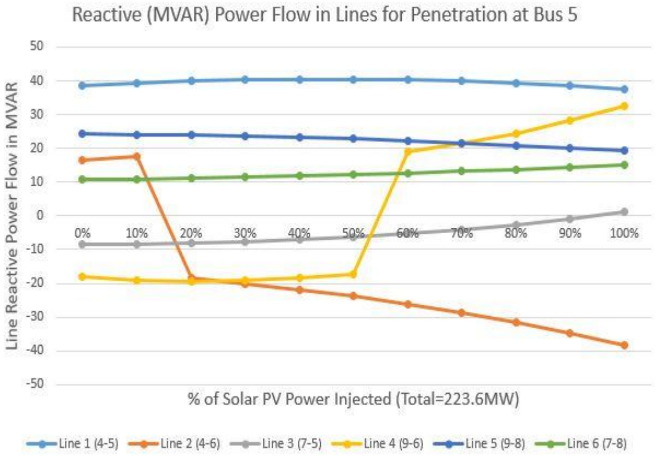

Figure 10. Plot of reactive power flow in transmission lines at various solar penetration levels

D. Summary of Steady State Analyses

Table 1 presents the summary of the overall analyses of the IEEE 9 Bus system while integrating a Solar PV power plant to this system. Integrating solar PV power can bring changes in the steady state bus voltages of the system which can affect the voltage stability of the system. The solar PV power integration can also bring variations in others system parameters like steady state real and reactive power flow in the transmission lines and can also affect system losses. Thus it is necessary to perform such studies which will help engineers in planning systems with high penetration levels of solar PV power and in identifying optimal hosting capacities of the system.

Table 1. Summary of Steady State Analyses

Case	**Best Location**	**Maximum Possible Solar PV Power Penetration**
Based on Bus Voltage Levels	Bus 5	30% (67MW)
Based on System Losses	Bus 5	20% (45MW)

V. CONCLUSION

The solar power industry is growing at an exponential rate. Pakistan's policies and regulatory framework is promoting the renewable energy like never before especially solar PV. Hence the penetration of solar photovoltaics in to Pakistan's power system 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 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

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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. 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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