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Impact analysis of Solar Photovoltaic integration in Distribution Network

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Abstract- Generation of electricity from solar Photovoltaic (PV) is increasing exponentially as it is sustainable source of energy and also help to reduce Carbon Emission. Most of the PV generation is integrated at distribution side which is emerging new challenges to the distribution system planner and operator because the distribution system is radial and designed for the unidirectional flow power. This paper presents the impact of high penetration of solar PV system on low voltage distribution network. The high penetration of PV may cause of several undesirable impact such as overvoltage, voltage fluctuation and reverse power flow which may cause of protection issues in the system. The overvoltages and voltage fluctuation can damage the critical loads connected to the system and also cause of output loss of PV system. A 13 bus IEEE test case is modelled in OpenDSS (Open Distribution System Simulator) software and its interfacing done with MATLAB to investigate the impact of solar PV on distribution system. Without PV and with PV case are investigated and different parameters are identified such as voltage profile, operation of OLTC (Online Load Tap Changer) and system losses.

I. INTRODUCTION

In last few years the number of solar Photovoltaic (PV) integration in distribution system has increased exponentially and it is expected to increase continuously due to incentives from the government and increasing energy prices. Solar PV is a better option of electricity generation because it is a sustainable source of energy and produce pollution free electricity [1]. Distributed solar PV can provide various system benefits such as improved power quality and grid reliability, reduction in Transmission and Distribution losses etc. [2]. However, since the distribution network designed for radial unidirectional power flow. It was not designed keeping in mind the integration of distributed generation, there are different technical concerns from utility regarding power quality and general impact of high penetration of PV on low voltage distribution network [3].

According to literature, the high penetration of distributed PV gives several operational challenges for the distribution system [4], such as feeder overvoltages, voltage fluctuations and reverse power flow to the grid which will cause of protection issues for the distribution system. The present distribution system need a detailed analysis before integration of distributed PV that the system can accommodate maximum PV integration without the system modification [5].

As found from the literature reviews, most of the PV impact studies are of deterministic or probabilistic type, different case studies have taken to identify the potential impact of PV penetration in distribution system [6]–[9]. In [10] the technical aspects of solar PV integration in distribution system are discussed and growth of solar rooftop PV installation and its future challenges to the distribution system are described. In research work [11], [12] a deterministic approach is carried out to analyse the impact of high penetration of PV in distribution system . A detailed simulation model has been developed by [13] for the impact analysis of high penetration of grid interacted PV system. In [14] the impact assessment has been carried out for high penetration of PV on medium voltage distribution network.

Most of the literature discusses about the voltage profile and PV hosting capacity of the distribution system when performing the PV integration impact analysis. Further the minimum power loss condition can find out for different PV integration limits. In this paper, the impact of high PV penetration on voltage profile, system losses and maximum hosting capacity of distribution system are identified for different integration levels and different mitigation methods are discussed.

II. SIMULATION TOOLS AND METHODOLOGY

This section discusses the simulation tools used for the study, selected test system and analysis methodology. The PV impact analysis framework is implemented using OpenDSS and MATLAB.

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1. Distribution System Simulator (OpenDSS)

OpenDSS is a comprehensive electrical distribution system simulation tool supporting all frequency domain analysis for electric distribution system. It supports quasi-static unbalanced 3-phase power flow analysis for bidirectional radial and looped circuits while including user defined control algorithms for smart inverters, voltage regulators, Load Tap Changers (LTCs) and shunt capacitors. OpenDSS also facilitates distributed generation (DG) integration analysis provides in-built models of DGs and their control blocks. It can be run as stand-alone executable program and in-process COM (Component Object Model) server DLL which is designed to be executed by different existing software platforms. For this study, MATLAB program is used to drive the OpenDSS [15].

2. Test System used for Study

In this work, a modified 13 bus IEEE test case by EPRI as shown in Figure 2 has taken for the PV impact analysis. The circuit is simulated in OpenDSS (Open source software) and interfacing is done with the MATLAB. The system is connected to a 115-kV transmission line; the voltage is decreased to 4.16-kV using a 5000kVA distribution transformer also have the facility of On Load Tap Changer (OLTC). The system is an unbalance network having 3-phase and 1-phase loads.

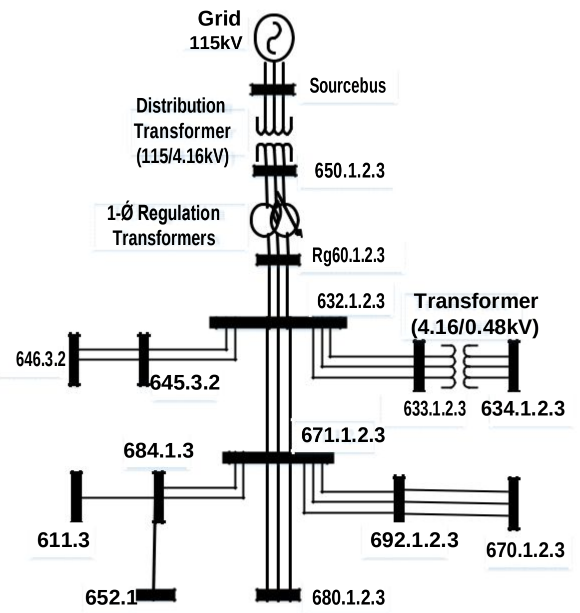


Figure 1: IEEE 13 bus Test System [16]

3. OpenDSS PV System Model

In OpenDSS, an in-built simulation model is available for solar PV system and it is capable of simulation studies in time steps of greater than or equal to 1 sec.

The model combines the PV array and PV inverter into a convenient model to be used for Distribution System impact studies. The PV system is modelled as a power delivery element producing power according to a generation function. Active power (P) is a function of temperature, irradiance and rated power (Pmpp) at an irradiance of 1.0kW/m^2 and at a selected temperature.

III. RESULTS AND DISCUSSION

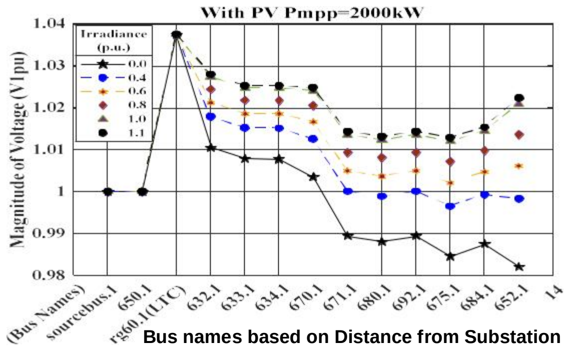
This section presents the impact analysis for high penetration of PV in the distribution network. A 13-bus system shown in Figure 1, has taken for the analysis of PV integration at different penetration level. It starts from the case without solar PV integration followed by the comparative analysis of the system with solar PV penetration.

1. Impact on the Bus Voltages

PV has integrated to each load bus and buses are arranged in order of increasing distance from substation. Sourcebus (Substation Bus) is infinite bus. The buses are arranged in the increasing order of the distance from substation.

Case-1 Pmpp=2000kW: - In this case, a fixed 2000kW capacity PV has installed the load buses and the irradiance value has increased from 0 to 1.1 pu. The power output of the PV directly dependent to the irradiance, it increases with the increase in the irradiance. The increase in the PV output causes to voltages rise at the load buses.

The increment in the voltage is directly proportional to the power injected by the PV. In the figures below the per unit bus voltage has shown at vertical axis with reference to bus names at horizontal axis.



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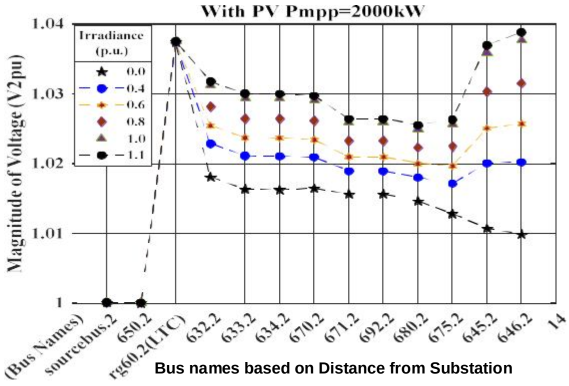

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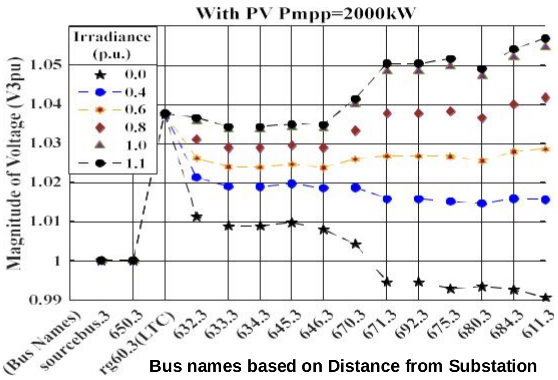


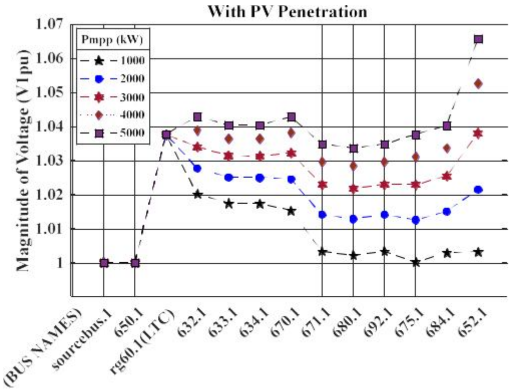
(c)

Figure 2: Per Unit Bus Voltages with 2000kW PV a) Phase-1, b) Phase-2, c) Phase-3

The figures 2, shows the per unit voltage of all three-phases with reference to the buses at horizontal axis. It can be observed that the voltage is increasing with the increase of irradiance. The voltage has further increased with increase of PV penetration and also identified that the voltage limits get violated for phase-2 at bus-645, 646 and for phase-3 at bus-684,611.

Since the loads connected to the system are highly unbalanced and voltage rise has seen irrespective to the other phases. The voltage rises more at single phase buses. The above figures show that voltage fluctuation is less at the bus near the substation and the voltage fluctuated more at the bus far away from the substation.

Case-2 (Pmpp=1000kW to 5000kW) -To analyse the impact of high PV penetration the PV capacity has increased from 1000kW to 5000kW. It has considered that the PV injecting the maximum power to system for each penetration level. The voltages with high PV penetration shown in figures.



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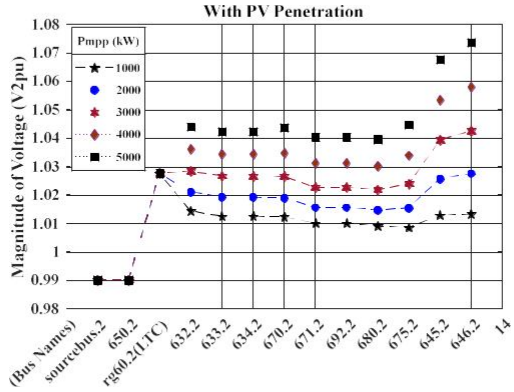

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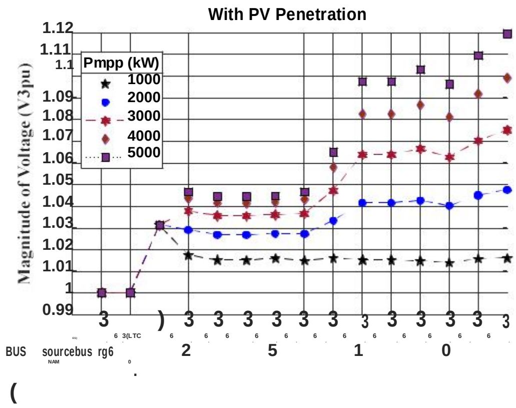

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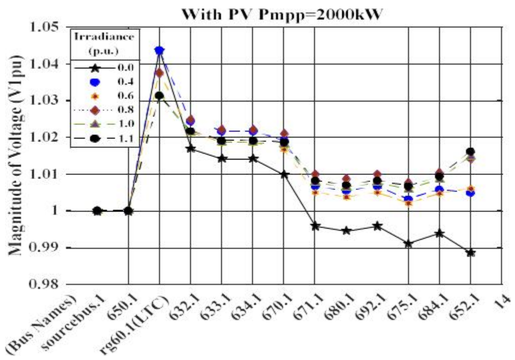
Figure 3: Per Unit Bus Voltages with PV Penetration a) Phase-1, b) Phase-2, c) Phase-3

Figure 3 shows that a high penetration of PV in the distribution network causes voltage violation at the load buses. The voltage goes out limit as defined by the ANSI [17]. The overvoltage can damage the critical loads. Hence a limited amount of PV can be integrated to the particular distribution network.

2. Impact on Legacy Devices (OLTC)

In this case auto control of voltage regulation transformer OLTC has enabled which is incorporated between bus-650 and bus-rg60 to mitigate the overvoltages and to analyse the impact of high PV penetration on the tap operation of OLTC. The PV capacity Pmpp=2000kW has integrated to each load bus of the distribution system and irradiance has increased from 0 to 1.1pu.



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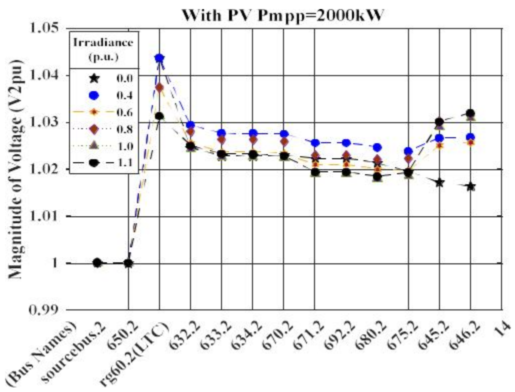

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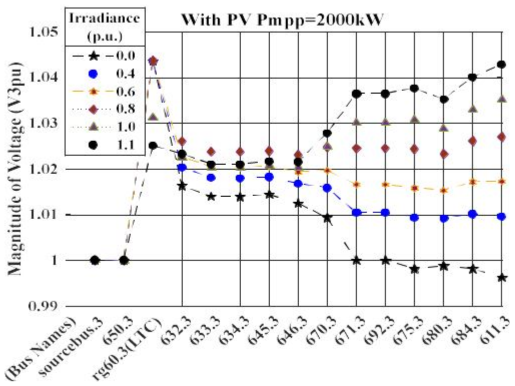

(c)

Figure 4: Per Unit Bus Voltages with 2000kW PV a) Phase-1, b) Phase-2, c) Phase-3

Figures 4. shows the impact of variable PV output on the operation of OLTC. The per unit voltages have plotted for different irradiance level. It can be observed that as the PV penetration level is increasing from 0 to 1.1pu, the Taps of LTC decreasing at rg60 to maintain the system voltage within the ANSI limits [17]. The continuous variation in the PV output due the irradiance variation, causes to voltage fluctuations in the distribution system. To mitigate the voltage fluctuations at the customer buses the OLTC continuously changes its setting the results in the increased number of tap operation. Hence it can be observed that the total number of Tap operations increases with the integration of PV and its penetration in the distribution system.

3. Impact on System Losses

The system power losses depend on the power exchange from the grid. The system losses decrease with the integration of the PV system in the distribution system upto certain limits. After the integration limit exceed the power losses in the system start to increase with the increase in the penetration level.

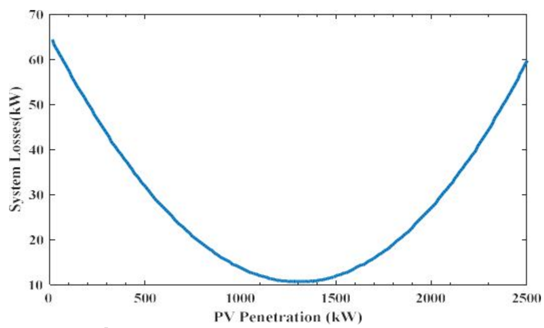

Figure 5: System Power Losses

Figure 5, shows the U shape trajectory of power losses in the distribution system due integration of PV. The PV system has integrated to each bus of the distribution system and PV capacity increased from 0 to 2500kW at a step of 10kW.

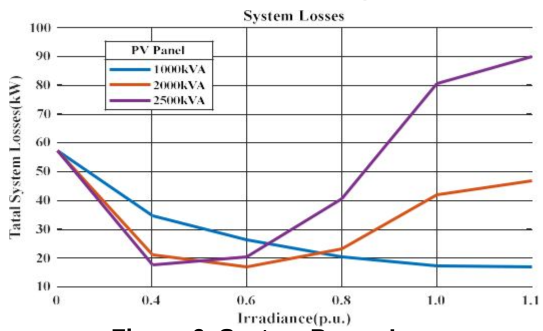

Figure 6. System Power Losses

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From the above figures 6, it can be observed that for 1000kVA the system losses decrease but as the PV capacity increased to 2000kVA and 2500kVA the system losses start to increase after a certain level of PV penetration.

4. Comparison of Voltage Control Methods A case of 2MVA PV capacity has been taken

and the voltages of buses have plotted for all 3-phases, with the different control methods. Four conditions have been presented in this case-

Without PV - The power flow has performed without PV, loads are directly supplied by the grid and voltages of the buses are plotted.

With PV No Control – PV has integrated to each bus except Sourcebus, 650 and rg60 and no voltage control method has applied.

With PV with OLTC - The On-line Load Tap Changer (OLTC) is enabled, the taps of the OLTC can be changed according to the overvoltage or undervoltage.

With PV with Smart Inverter Control – The reactive power control of the PV inverter is enabled, inverter can absorb reactive in case of overvoltage and supply the reactive power in case of undervoltage.

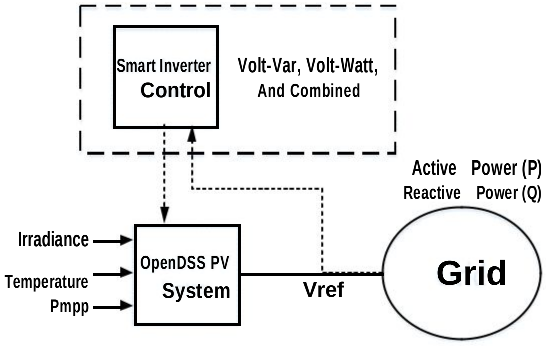

Figure 7: Block Diagram of Smart Inverter Control

Figure 7, shows the simple block diagram of inverter control. The inverter can generate or absorb the reactive power according to the voltage at the connection point in the reactive power control mode. The available reactive power by the inverter can be calculated using the given formula.

$$= \left(\_ \right) - \left(\_ \right)$$

Voltage control range depends on the reactive power supplied and absorbed by the inverter. The inverter works as a reactive power controller in the distribution system.

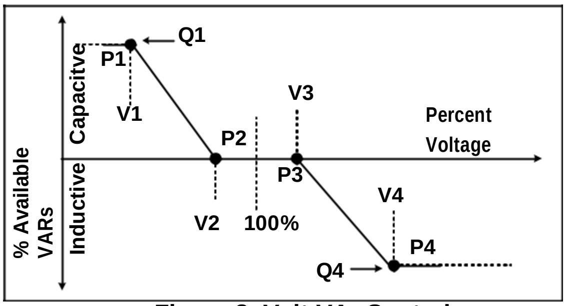

Figure 8: Volt-VAr Control

The graph in Figure 8, shows the Volt-VAr behavior of the smart inverter under the reactive power control mode. The inverter absorbs the reactive power i.e. operate in inductive region when the voltage rises at the PV bus whereas if the voltage of the PV bus drops, the inverter delivers the reactive power. The reactive power absorbed or delivered by the inverter depends on the kVA capacity of the inverter.

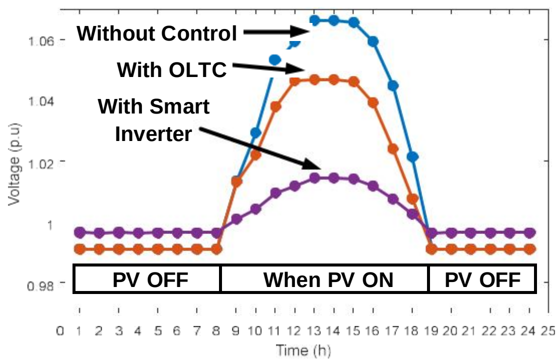

Figure 9: Voltages with PV with Smart Inverter

Figure 9, shows the voltage plot form 24-hours with variable irradiance with smart inverter control method to mitigate the voltage overvoltage problems. Without control the voltage is going out of limit when irradiance is maximum between 12 to 16. The OLTC can mitigate the overvoltage but in case of instant voltage fluctuation a short duration peak has observed which cannot be mitigated by OLTC because of its slow mechanical response. The smart inverter helps to mitigate the overvoltages by controlling the flow of reactive power in the system. It can mitigate the short duration peak due to fast response of power electronic devices used in the inverter, that is by it is called smart inverter. The third plot is showing that with smart inverter control the voltage is near to 1pu.

Conclusions

In this dissertation, the impact of PV integration in distribution system was investigated. A 13bus IEEE

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test system was taken for the analysis and PV was integrated to load buses with different penetration level. It has been identified that with increase of PV penetration in the low voltage distribution system, the voltage of the system increases and after a certain level of penetration the voltage limits gets violated. The voltage rise is a significant parameter for deciding the PV capacity that can be accommodated without violating the system constraints and without system modification. The integration of the PV in distribution system minimizes the overall power losses in the system by reducing the total power demand from the substation. But as the integration of the PV increases upto a limit the system losses reduce but after the limit exceed the losses are increasing.

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