VOLTAGE CONTROL IN DISTRIUTION FEEDERS WITH HIGH SOLAR PV PENETRATION: CASE STUDY FOR DIFFERENT APPROACHES

Neshwin RODRIGUES
The Energy & Resources Institute – India
n.rodrigues@teri.res.in

Alekhya DATTA
The Energy & Resources Institute – India
alekhya.datta@teri.res.in

Shashank VYAS
The Energy & Resources Institute - India
shashank.vyas@teri.res.in

ABSTRACT

Rising amount of distributed solar Photovoltaic (PV) power in distribution feeders is expected to impact the nodal voltage levels. This paper presents a case study of three different approaches – smart PV inverters with Volt-VAr functionality, on-load tap changers and battery systems to mitigate localized voltage issues. An actual 11 kV distribution feeder of a utility in Delhi, India has been extensively modeled, beyond the transformer secondary, incorporating the low-voltage 415 V network, to a certain extent, to present realistic voltage estimates. Load growth and solar PV capacity growth scenarios have been realistically designed to assist the utility in understanding the expected operational challenges of rising solar PV penetration levels. Distribution load-flow has been performed to estimate the voltage at different buses and to assess each mitigation technique. A practical estimate of the cost associated with each mitigation technique against the expected benefits has also been reported.

INTRODUCTION

The penetration levels of distributed solar Photovoltaic (PV) power on distribution feeders are set to increase as mandated by governments across various countries. India too has set itself a target of 40 GW of rooftop solar PV capacity integration by 2022. Since most of this capacity will be added to the distribution network (operating at 11 kV and 415 V levels in India), localized voltage issues are expected to occur. Bus over-voltages or voltage unbalance and even reverse power flows are some of the anticipated concerns of the distribution network operators. Since solar PV inverters are active sources, their introduction as distributed energy resources (DERs) on the downstream service delivery stream is expected to alter power flows (active and reactive) that will have a direct impact on the bus voltage levels.

Rooftop solar PV plants are becoming an extremely popular form of DERs in India given the encouraging policies as part of the nation-wide target mentioned above. Since these can be installed on rooftops of industrial, residential and commercial establishments, given the limited space in the urban landscape, they are usually connected at the Low Tension (LT) 415 V side of the distribution network. Such plants are mostly installed as net-metered connections wherein excess energy remaining after self-consumption is supplied back to the network. Small sized systems of the order of a few 100 kWs in small numbers are not expected to impact the local distribution network in a significant manner. However, a large number of such sub-MW scale systems, distributed across the network may affect the local parameters at different LT nodes, leading up to each individual distribution Transformer (DT). Voltage is one of the most important parameters that is quite visibly affected and hence impact on voltage must be studied with greater accuracy.

Many studies exist in the literature that present the voltage-related impacts of high solar PV penetration [1]. However, usually, the network is modelled till the secondary of a DT following the lumped LT network load approach. In order to understand the impacts on local LT buses from which many LT feeders emanate, it is important to model the network beyond DT secondary. Accordingly, the low voltage (415 V) network, beyond the secondary of each DT, has been modeled to some extent in this study to account for the physical distance and actual point of interconnection of PV systems. This has been done in order to have a realistic assessment of the impacts of integration of rooftop solar PV systems on local bus voltage levels. Three-phase distribution load flow based on a nodal matrices based variant of forward-backward sweep algorithm has been performed to observe the bus voltages.

This paper is organized as follows. Section II describes the feeder in terms of its topology, types of loads and amount of solar PV generation present currently. Section III describes the scenarios of load growth and solar PV generation capacity growth for the feeder in order to assess the impacts on bus voltages. Section IV presents the results of the analysis. The base-case and future-growth scenario voltage profiles are presented and compared with those obtained when the three mitigation techniques are employed.

FEEDER PROFILE

The feeder selected for this study is an urban feeder that mainly supplies to residential premises and a few commercial customers. The feeder is located in a prominent locality of Southern Delhi, in the National Capital Territory (NCT) of Delhi, India. The 11 kV feeder operates in an open-ring configuration and there are eleven DTs on the feeder. These eleven DTs are fed from the utility upstream supply through Ring-Main Units (RMUs), some individually while some are grouped together and are connected through a single RMU. The DT rated capacities on the feeder are 400 kVA (1), 630 kVA (4 nos.) and 990 kVA (6 nos.) and each one is rated as 11 kV/433 V. Each one of the DTs is housed inside a DT sub-station that is characteristic of the network in this licensee area of the utility.

Although 415 V is the standard recommended LT voltage level at the consumer side, the DTs are usually operated at a tap setting of 1.05 per unit (p.u.) so that 433 V is obtained at the secondary terminals to compensate for the drop along the downstream till the service points. The electrical characteristics of the conductors and other relevant data on short-circuit capacity, X/R ratios and DT parameters were used to model the feeder in OpenDSS, an open-source distribution modeling and analysis software. The DT has digital meters installed on its secondary terminals so that loading data for every half-hour interval is logged. This data was made available by the utility for three consecutive years and the data-set for the base year (FY 2016-17) was used to prepare the net- load data file. Three-phase loads were modeled to incorporate the unbalance in the system. The 'load-buses' in the model were modeled at a certain physical distance from the DT secondary sides (the cable lengths were ascertained by the utility) so as to obtain realistic values of nodal voltages at these LT buses. Hence the approach of lumping the load at the DT secondary was not followed.

The feeder, at the time of modelling, had a cumulative solar PV capacity of 25 kWp split into two rooftop plants of capacities 20 kW and 5 kW and connected to nodes that connect to two DTs respectively. Accordingly the solar PV generation in the system was modeled to incorporate the physical characteristics including yearly solar irradiation profile at the location, module characteristics and inverter efficiency. For the feeder base-case scenario, two solar PV generation systems were modeled and connected to the 'load buses'. The actual physical distance of the rooftop from the local DT could be availed through Geographical Information System (GIS) mapping. Hence, the solar PV generation systems were incorporated into the model as single lumped sources of generation at the 'load bus', affecting the 'net-load' on that bus for the power flow program. Also, the DT meter loading data was essentially net-load on the DT since the solar PV generation had been accounted for. As the solar PV systems were individually modeled as independent generators connected to a bus, the 'load bus' characteristic of each of such buses (the '433 V rated' node in the power flow program) having a solar PV connected to it was kept intact by adding the time-series of the modeled solar PV systems to the time-series of the net-load. Thus, an extensive exercise of adding corrected solar PV generation (since there were irregularities in recorded actual generation) to the DT meter net-loading data was done to represent the gross-load in the load-data file in the script. Helioscope was used to estimate the corresponding generation of the modeled solar PV plants so as to correct the gaps in the recorded generation values (obtained through remote monitoring access to the inverter meter).

The next section describes how the loading or gross-loading values on each DT were scaled up to represent load growth on the feeder based on consultations with the utility. The section also describes how the scenarios of growth in solar PV capacity were meticulously designed to consider almost all the aspects of rooftop solar PV potential, year-on-year growth and various expected growth rates.

SCENARIO DESIGN

The base case scenario represents the feeder 'as-it-is' in the base year considered i.e. 2016-17. The cumulative solar PV capacity on the feeder stands as 25 kWp and is distributed over two 433 V buses in sizes of 20 kWp and 5 kWp. The loading values on the LT load buses as obtained for the base year were used. The three-phase load-flow program was then run for the base-case dataset used in the model and the nodal voltages at each LT bus were obtained and analysed. These values are presented under the Results section.

Design of Load Growth Scenarios

The feeder load growth scenarios were meticulously designed to represent realistic future year DT wise loading. A clustering approach was implemented to group RMUs (with one or more DTs) based on their proximity to each other. Three such clusters were created. The sum of current peak loading of each DT in a particular cluster was computed. In consultation with the utility, it was realized that the sum of current peak loading would be a good parameter to estimate the increase in loading for the future year scenario for each of the three clusters. Based on peak-loading values for the past 3 years, the feeder Compounded Annual Growth Rate (CAGR) was calculated to be 6%.

Accordingly, RMU clusters with a higher peak capacity were assumed to proportionally have a higher growth rate. Since all DTs in any RMU are in proximity to each other, load distribution on these DTs would be determined by their existing loading i.e. future addition of load would take place on the lightly loaded DT, in accordance with the present utility practice. There are 11 DTs on the feeder of capacities 400 kVA, 630 kVA and 990 kVA. There are 8 RMUs to which the DTs are connected. Leaving one, each RMU has 2 DTs connected to it. Accordingly, 3 clusters were formed. The current cluster-wise peak and the increased peak in the 4th year were then taken to find the new peak-load on a DT. Consequently, this increased peak loading over the current peak load was used as the scaling factor for individual phase-wise loading values for each DT. This is how the gross-loading on each DT, in a future year scenario after adding the corresponding solar PV generation values was obtained.

Design of Solar PV Capacity Growth Scenarios

As the first step, the technical potential of solar PV for the feeder was estimated by GIS based modeling. The physical extent of the feeder was mapped on a GIS tool and the rooftops of individual buildings near each RMU were identified in the digital terrain map. The usable area for installing Rooftop Solar PV (RSPV) plants was then estimated. Considering 30% of the total area of a rooftop as available for installing a RSPV plant and taking 15 m^2/ kWp as the area requirement, the total potential for rooftop solar PV for the feeder was estimated to be 1071.84 kWp. Based on the number of years (from the base year) in which the total potential can be achieved, the proportion of total rooftop area available for RSPV plant installation, the rate of growth curve and the load growth CAGR, the scenarios for solar PV capacity growth were designed.

For designing the scenarios, a few parameters were kept constant while the remaining were varied in a range. It was considered that the total RSPV potential could be achieved in the 5th year from the base year. Hence, 5 was taken as the number of years to achieve the total potential. It was considered that the annual growth followed a cubic curve hence 3 was taken as the growth rate number. The feeder growth CAGR was kept as 6% and hence the numeral 6 was used. The usable area (proportion of rooftop area for RSPV) was varied as 30%, 40% and 50%. Year-on-Year (Y-o-Y) capacity additions were considered for the 3rd and the 4th year. In total, six number of such scenarios were designed. Each one of them were uniquely named to identify one form another. For example, a scenario wherein the RSPV addition was considered for year 4 at 50% usable area was named as 4YO50536. Among all the RSPV capacity growth scenarios, this one was chosen and the load flow was run to observe the nodal voltages without any mitigation technique and after applying each one of the three techniques.

RESULTS

The 'gross-loading' values for each load bus and the estimated solar PV generation values, for different scenarios, were input in the model script. Three-phase distribution load flow was programmed in the script and run for each scenario studied. The load-flow program was a variant of the forward-backward sweep algorithm in which a nodal admittance based matrix analysis was used to calculate the node voltages. The voltages at the 'load-buses', modeled at a physical distance from each DT secondary were observed and have been reported below for different scenarios. Yearly load-flow simulations were run and typical days for which voltage-deviations at selected buses were significant have been reported in this paper. Phase-wise voltage values were observed and 0.95 p.u. to 1.05 p.u. was selected as the operating voltage range.

Base-case Results

There are 11 DTs on the feeder. However, since the loads were not lumped on the DT secondary sides, 'load buses' were created for the load-flow as explained before. Therefore, the number assigned to each load bus does not correspond to the serial number of the DT on the single line diagram, used for the model. Figure 1 shows the power flow along the feeder in the base-case scenario, for the base year. The phase-wise active power (in the above portion of the graph) and the reactive power magnitudes and direction indicate that there is no reverse power flow at the present RSPV penetration level. Reverse power flow are also a reason for voltage deviations [2]. However, in the sub-sequent sub-sections, a few load buses where voltage deviations were outside the considered limits for a typical day in the 4YO50536 scenario have been presented for analysis.

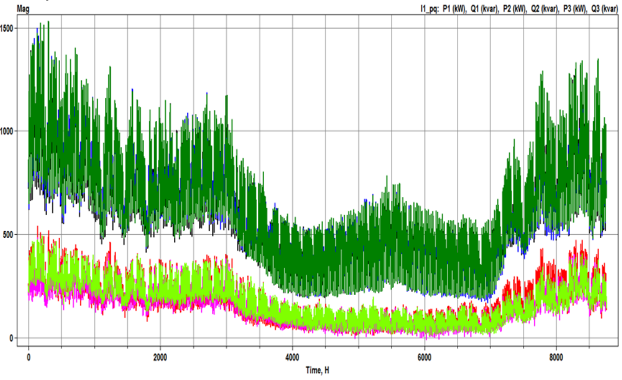

Figure 1: Power flow along the feeder in base case

Mitigation Techniques

Changes in voltage magnitude at the load buses were reported from the load-flow results for the 4YO50536 scenario. To control the voltage excursions, three mitigation techniques were proposed in the study. The voltage values over the day, without any mitigation technique and with each of the three mitigation techniques in the future scenario considered, for selected buses (having significant over-voltages), have been presented subsequently.

Smart PV Inverter Control

The solar PV generation system model in OpenDSS, incorporating the physical characteristics, was modified by including the Volt-VAr capability of a RSPV inverter. The reactive power based voltage control functionality can modulate inverter's output power according to the utility grid conditions. Injection/absorption of reactive power based on the grid-voltage (bus voltage precisely) is one of the methods to provide voltage control [3]. This feature is analogous to the Q-V droop characteristics of synchronous generators and is a very useful and effective localized method for voltage control. The Volt-VAr characteristics used inside the smart solar PV inverter modeled in this study is shown in Figure 2 in p.u. It was observed that during certain under-voltage instances (below 0.9 p.u.) occurring during solar hours the Volt-VAr characteristics as per Figure 2 should not be followed, instead the inverter should supply watts instead of VArs, owing to the low X/R ratio of the distribution network.

For the Indian market, it was found that the incremental

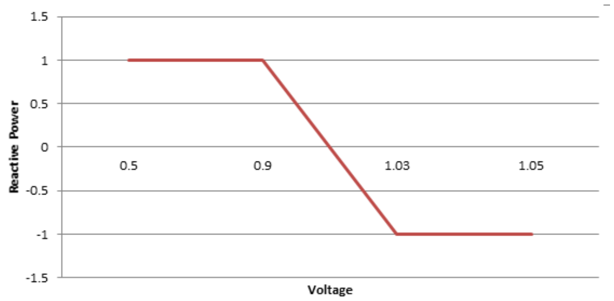

Figure 2: Volt-VAr characteristics of the smart inverter used in the study

cost for a grid-tied RSPV inverter over a unity power factor operation RSPV inverter is minimal in comparison to the benefits that it can offer. The increment is just under 10%. Although it may be difficult to quantify the evident benefits of local voltage control in monetary terms, the incremental cost of a smart solar PV inverter over a normal one strongly justifies its selection as a mitigation technique.

In this study, load buses 5, 10 and 11 were observed to have voltage variations outside the limits (mainly over-voltages) throughout the year in the 4Y050536 scenario. Hence these buses have been termed as 'critical' and results of voltage magnitudes at these buses, with and without each mitigation technique have been reported in Figures 4-7.

On-Load Tap Changer Control

One of the effective methods of voltage control is from the utility side through the supply side voltage transformation ratio. On-load Tap Changer (OLTC) control is one such method of regulating downstream voltage. Three-phase OLTC in the form of three 1-phase transformers was modeled in OpenDSS for the selected buses. The control/regulation set-point were accordingly modeled to run the three-phase load flow. The results are evident in Figures 4-6.

Although OLTC can be used to effectively regulate the voltage but the control point or setting that is used to compensate for the line loss requires the control point to be properly defined. In reality there are multiple control points (so a compromise has to be reached) or end points however in our case there was only one control point per phase per DT. The cost of installing an OLTC per DT is significant, speaking for the Indian setup.

Battery Energy Storage Control

A Battery Energy Storage System (BESS) was modeled to examine its capability as a voltage control technique. The sizing of the battery for this application was based on shifting 10% of the peak solar power at a load bus during continuous overvoltage instances to instances of under-voltage so as to ensure complete replenishment of the State of Charge (SoC) at the end of the seasonal 24 hour cycle.

The annual per phase bus wise hourly voltage for the base case was divided into summer month values and winter month values, as a different charge and discharge logic is required for each season. The per phase average of voltages of each hour of the day i.e. hour 1-24 was calculated for each season. The extent of charge/discharge was being determined by the extent of overvoltage/ under-voltage respectively. This BESS control logic in Figure 3.

A voltage based trigger could have been used for controlling the charging/discharging of the BESS based on comparison of V_{bus} with a voltage based threshold, V_{th} such that the charging of the BESS occurs whenever $V_{bus} > V_{th}$. A power based trigger could also be used for controlling the charging/discharging of the BESS based on comparison of P_{bus} with a $P_{threshold.}$ However, for both voltage and power trigger based BESS control logics, the limitation is that there are chances that the BESS may not have the desired cycling of returning back to the original state of charge of full charge at the end of the 24 hour operation.

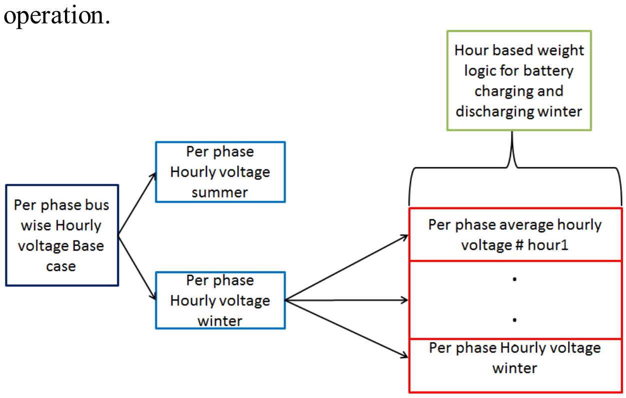

Figure 3: Voltage trigger based BESS control logic

The upfront investment in a BESS for such an application may not be justifiable presently. At BESS costs of 300 USD/kWh roughly, the cost-economics may work out to even 8-10 years of pay back for the utility, when the monetary benefits of improving localized voltage profile are considered. During the simulations, it was also observed that there may be days in summer/winter season which have a voltage profile substantially different from the average hourly voltage profile for the summer/winter season, which caused over-voltage / under voltage due to battery discharge/charge instead of mitigating the same. So alongside issues on effectiveness, the cost of operation while ensuring desired results from a BESS is also an associated concern.

Yearly simulations of three-phase distribution load flow were run for the 4YO50536 scenario. Buses 5, 10 and 11 were observed to have significant over-voltages for a considerable amount of time. From the yearly simulations, a typical day of summer and a typical winter day of winter was selected and the hourly voltage magnitudes were plotted in Figure 4, 5, 6 and 7. These plots contain the values observed without any mitigation technique (herein 'base scenario') and with each individual technique in place. For buses 10 and 11, the load in summer was too high and hence no over-voltages were observed.

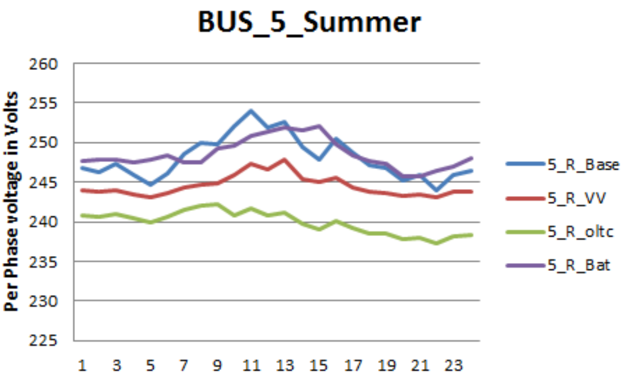

Figure 4: Phase R voltages for Bus 5 on a typical summer day. VV stands for Volt-VAr smart inverter control.

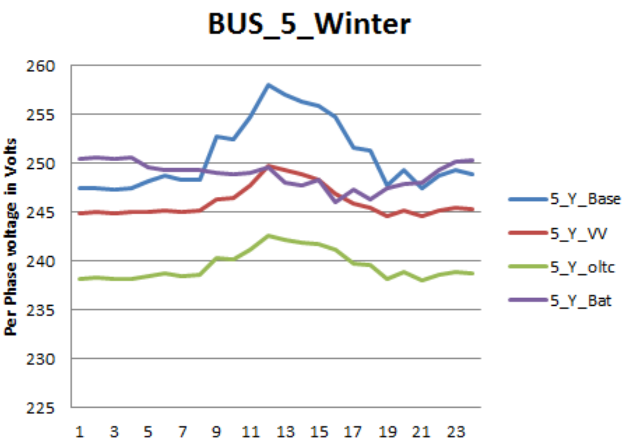

Figure 5: Phase Y voltages for Bus 5 on a typical winter day

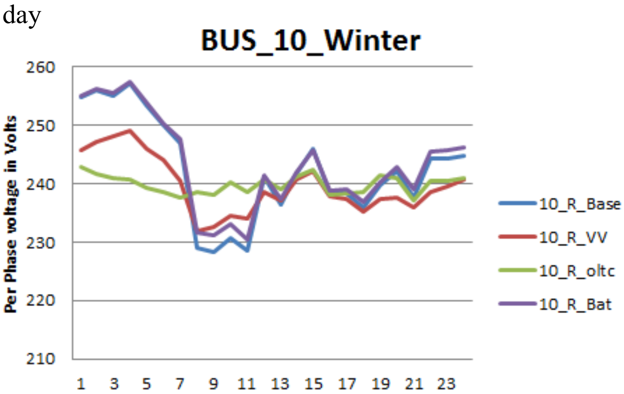

Figure 6: Phase R voltages for Bus 10 on a typical winter day

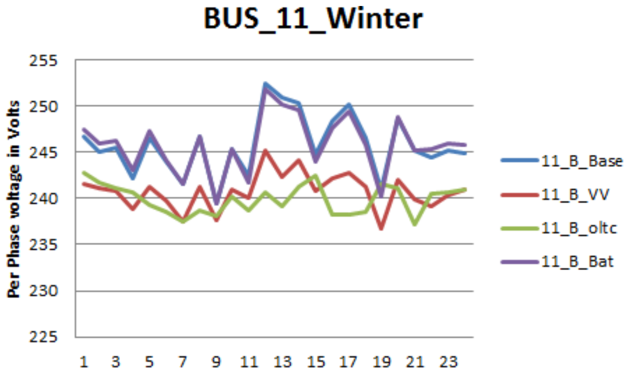

Figure 7: Phase B voltages for Bus 11 on a typical winter day

CONCLUSIONS

Detailed feeder, load and solar PV system modeling was performed for an actual 11 kV feeder in Delhi, India. The observed voltage excursions and their mitigation via three techniques was discussed. Based on the cost factor analysis, for the same benefits accrued from voltage improvement, a Volt-VAr based smart PV inverter control emerged to be a viable solution although detailed cost-benefit analysis would give more justifiable results.

Acknowledgments

The authors MacArthur Foundation for funding this study. The authors also acknowledge BSES Rajdhani Power Limited for their constant support and for sharing the data of their feeder that was modeled in this study.

REFERENCES

[1] M. Rylander, J. Smith, D. Lewis and S. Steffel, 2013, "Voltage impacts from distributed photovoltaics on two distribution feeders", *Proceedings IEEE Power & Energy Society General Meeting* Vancouver, 1-5

[2] M. Hasheminamin, V.G. Agelidis, V. Salehi, R. Teodorescu and B. Hredzak, 2015, "Index-Based Assessment of Voltage Rise and Reverse Power Flow Phenomena in a Distribution Feeder under High PV Penetration", *IEEE Journal of Photovoltaics* Vol 5, 1158-1168.

[3] F Ding, A Pratt, T Bialek, F Bell, M McCarty, K Atef, A Nagarajan, P Gotseff, 2016, "Voltage support study of smart PV inverters on a high-photovoltaic penetration utility distribution feeder", *Proceedings IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 1375-1380.