Overvoltage Issues due to Solar Photovoltaic (PV) Integration at Low Voltage (LV) Side

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Abstract — In Sri Lanka, due to the current power suspense, solar power harnessing intends to increase significantly with the support from the government renewable energy policy. As a result, deployment of Photovoltaic (PV) systems integrated with Low Voltage (LV) system has been increasing rapidly over the past years. However, the penetration of grid connected PV systems without proper regulatory framework by the power distribution authorities has led to number of issues such as voltage fluctuations, voltage rise, over voltage issues and increase power dissipations. Abnormal voltage rises have been observed in solar inverters at different locations of the country. Several complaints regarding inverter tripping and incidents related to damages to electrical appliances have been reported to solar companies and power distribution authorities.

In this research, a selected, real distribution system with an abnormal voltage rise was studied and simulated with MATLAB (Matrix Laboratory) Simulink. A detailed analysis of the feeder was carried out with the aid of the simulation to find the causes for the abnormal behavior. A software tool was developed to check whether a request to install an additional solar PV system of a given capacity at a given location on the feeder can be accommodated, and advice on the changes that may be required.

***Keywords*—Solar PV, voltage rise, Low Voltage distribution, Solar inverters**

I. INTRODUCTION

Solar power is developing in popularity as it is adaptable with several advantages to people and also to the environment [1]. Also, solar power is a very safe substitute for gases and fossil fuels which produce many byproducts unsafe for the environment. However, problems such as voltage fluctuations, voltage rise, over voltage issues, reverse power floor and increase power dissipations were observed with the implementation of the grid connected PV systems, especially on the LV network without proper regulations. Thus, to mitigate this over voltage issue grid stability, reliability and power quality must be improved by maintaining grid connected inverters in proper standards [2].

The main problem focused in this paper is the issue of overvoltage which is common in many feeders with high PV penetrations. Over voltage conditions lead to unintended tripping of inverters at times the PV owners need them most, and damages to the electrical appliances live on the system. It is observed that the voltage at some inverters is rising beyond 255V despite the recommended upper limit of 6% above the nominal (230 V) as per the prevailing standards.

In this research, a particular feeder with abnormal voltage rise was selected for a detailed study. The selected feeder and the connected PV inverters were modelled using MATLAB simulation software. The factors contributing to the aforementioned problems were identified, investigated and solutions proposed. The software system that was developed can also be used to check if a request for a prospective PV connection of a given capacity at a given location in the feeder can be permitted without causing overvoltage and other issues in the feeder.

II. MODELLING OF THE FEEDER

Diyawanna Garden Feeder of Sri Jayawardanapura, Colombo was selected for this study as it experienced abnormal overvoltage issues and inverter tripping during peak hours of solar-generation. Parameters of this feeder obtained from the utility electric supplier and the relevant solar power installation companies are given in Table 1.

Table 1: Parameters of the feeder

Area: Sri Jayawardenapura ,Colombo (feeder 5)
Substation name: Diyawanna Garden
Distance: 1050m
Number of residential loads selected for the study: 89
Number of houses with solar PV integrations: 9
Number of houses with inverter tipping issues: 3
Substation transformer: 160 kVA, 33kV/400V, 50 Hz, Dyn11
Conductor type: Aerial Bundle Conductor (ABC)
Line conductor: 70 mm^2
Neutral Conductor: 56.4mm^2
Conductor resistance: 0.44 Ω/km
Conductor inductance: 0.36 mH/km
Conductor capacitance: 12.74 nF

Modelling of the feeder and the transformer was done in MATLAB simulation software. Here, each section of the feeder between service poles was modeled using respective values of inductance, resistance and capacitance of the line. The phase conductors and the neutral conductor were modeled individually as the loading on individual phases are different. The consumers without solar inverters were lumped together at each service pole but the consumers with solar inverters (net metered consumers) were added separately. Fig. 1 shows the model of the feeder so developed. Solar PV inverters were modeled considering their functionalities in a grid-tied environment as described in section II. Load of each consumer was estimated in terms of their monthly energy consumptions and typical daily load patterns. Entire feeder was modeled phase by phase, ensuring the loading on each phase (red, yellow and blue lines) is matched with the loading data available for the transformer. A greater emphasis regarding the loading was placed around the mid-day (noon) as the focus of study was on overvoltage conditions which occur around this time when the solar generation is at their peaks.

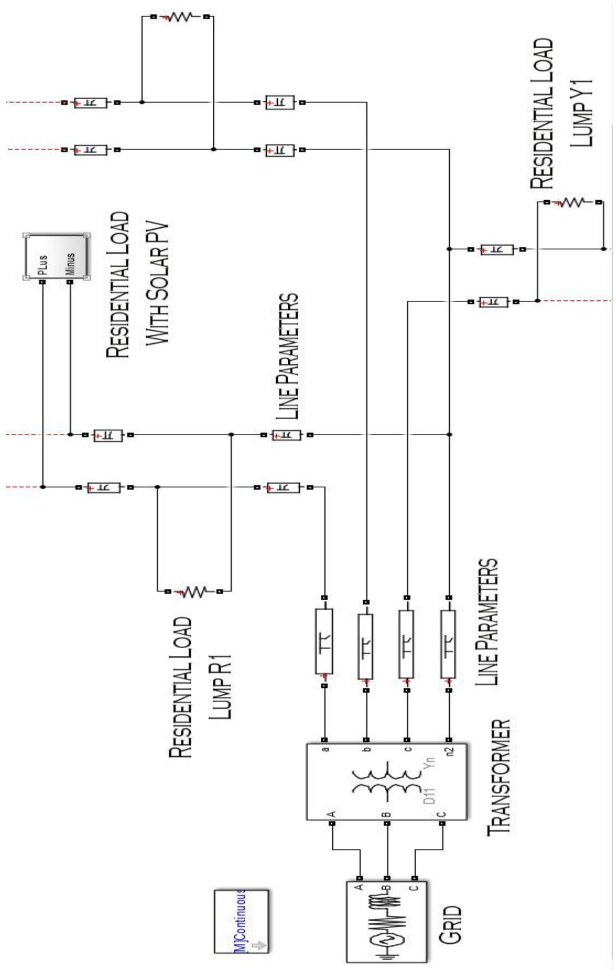

Fig. 1. Model of the Feeder

III. MODELLING OF THE INVERTER

A grid connected inverter converts DC power generated by the PV arrays into AC power, synchronized with the grid voltage and frequency [3]. The DC power is controlled by a

MPPT (Maximum Power Point tracking) subsystem to produce the maximum power that the array is capable of producing at a given time. This power is then channeled through the inverter to the grid with appropriate matching of voltage and frequency. The inverter model developed for this particular study, however, did not incorporate the MPPT subsystem because the object of this study is investigating overvoltage occurrences and the inverter should therefore be a source of variable output power.The maximum output power can be taken as rated power, occurring at noon with maximum solar irradiance.

So, the inverter was modelled as a subsystem of injecting sinusoidal AC current in to the grid at the same frequency, against the grid-voltage.The amount of injected current is determined by the amount of power delivered to the grid, subjected to the limit of inverter capacity. The Total Harmonic Distortion of the injected current was held below 5% to comply with regulations and the real conditions in practice. Fig. 2 shows the arrangement of the inverter, which is a single-phase H-bridge, operated with hysteresis current control. Input to the inverter was a fixed DC voltage source, sufficient to force the relevant maximum current in to the grid.Output is having an inductor to facilitate a controlled injection of current against the grid voltage.

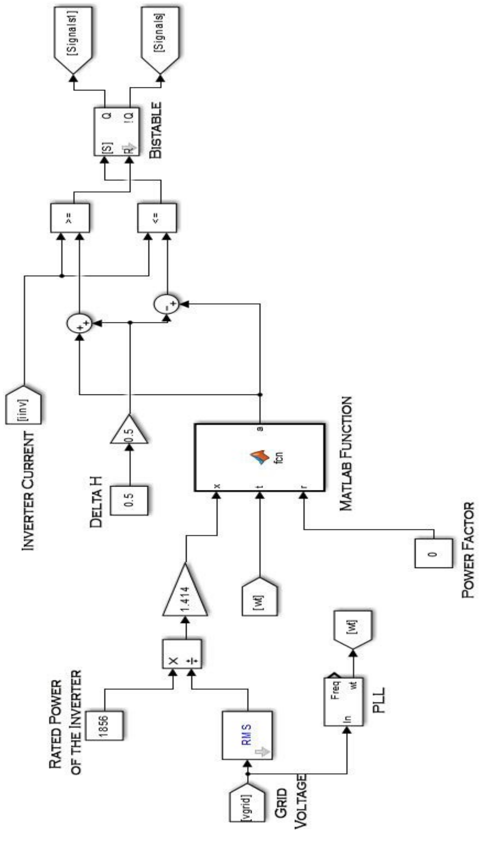

Fig. 2. Circuit of inverter (H-bridge)

Hysteresis current control delivers desired current at the inverter output within a preset narrow tolerance-band, called Hysteresis (ΔH). The waveform of desired current, also called reference current, is given as an input to the controller along with other two inputs of Hysteresis (ΔH) and the feedback of output current, The switching is done in such a way that when the inverter current is falling ΔH/2 below the reference current the IGBT 1 and 2 are switched on and when the inverter current is rising ΔH/2 above the reference current the IGBT 3 and 4 are switched on. Thus, simply the inverter current tracks the reference current within ±ΔH/2 tolerance. The controller generates switching signals S_1, S_2, S_3 and S_4 for the 4 IGBTs in the H-bridge to effect the above action[4]. Fig. 3 shows the generation of switching signals by the current controller. Magnitude of the reference current determined by the amount of power that the solar array is generating as described before is used with the profile of supply voltage waveform obtained through a Phase Locked Loop (PLL) to derive the sinusoidal reference current waveform. An adjustable phase shift between the injected current and the supply voltage was given to simulate the effects of inverter power factor. Equation 1 gives the mathematical form of the reference current waveform.

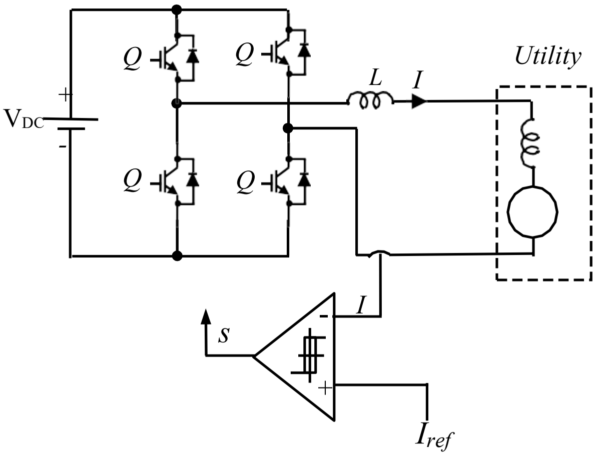

Fig. 3. Controller Model for the inverter

$$I_{ref} = I_m \sin(\omega t + \alpha) \text{..} (1)$$

Where,

I_{ref} = reference current
I_m = amplitude of reference current
α = leading power factor angle
ωt = phase angle of the supply voltage waveform obtained by the PLL

Normally, and also as per the prevailing regulations the inverters are set to deliver power to the grid at at unity power factor (α = 0). This makes the best use of the inverter's kVA capacity to deliver a given power resulting in perhaps the lowest cost per Watt of the inverter. The provision of variable parameter α, however, enables the investigation of the possibilities of using inverter power factor to mitigate the overvoltage conditions in the feeder.

IV. SIMULATION OF THE FEEDER

The complete model of the feeder with its connected loads and the solar PV inverters were simulated in MATLAB. The case of mid-day operation was considered for the simulation by assuming each inverter to deliver respective rated power and the consumers to consume mid-day loads estimated beforehand for a typical day using collected data.

A. *Simulation of the inverter*

In order to have meaningful interpretations of the results of simulation it is important to verify that the solar inverter model is producing the anticipated current in to the grid having acceptable THD levels as the real inverters do in practice. To check this aspect the model of solar inverter (single phase) was simulated with its output tied to the 230V, 50 Hz, AC supply and power output set to 2kW at unity power factor. Fig. 4 shows the waveforms of voltage and current at the inverter output and they verify the anticipated operation. The injected current is inphase with the voltage and the THD of the current is 3.82% which is below the 5% upper limit [5].

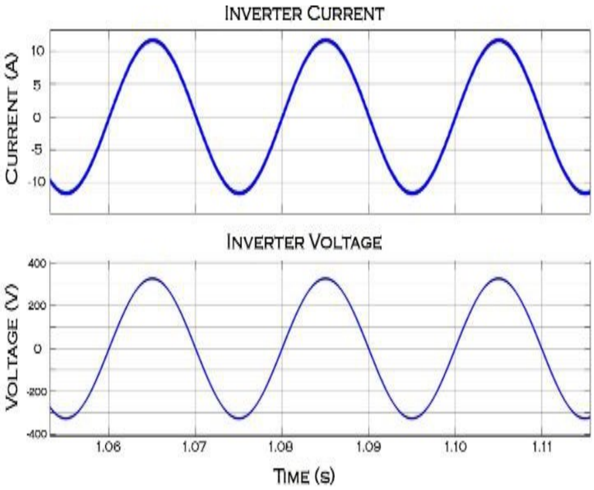

Fig. 4. Voltage and current profile of the inverter

B. *Simulation of the complete inverter*

The complete feeder comprising transformer, lines, solar inverters and consumer loads was simulated with generation and consumption data as of mid-day as described before. Fig. 5 shows the variation of rms voltages of the three phases along the feeder from the location of the transformer. Clearly, the Blue phase shows an overvoltage condition towards the end of the feeder, which is exactly what experienced by the actual feeder. This overvoltage is exceeding the 6% limit of 243.8V indicating an undesirable power quality condition. The reason for the frequent tripping of inverters connected to the end of the Blue phase of the feeder is now understood by the result of this simulation.

Fig. 5. Voltage variation along the feeder on three phases (Distance measured from the transformer)

C. *Sensitivity Analysis*

A comprehensive analysis was done through simulations to find out the factors that affect the voltage rise of the feeder. First a sensitivity analysis was carried out with respect to changes in resistance, inductance and capacitance of the feeder, taking one at a time. It was found that reductions in resistance have a higher effect in lowering the voltage rise than the reductions in inductance and capacitance. This is mainly due to the dominancy of real power flow along the feeder. Changes in residential loads and changes in the inverter capacities were also investigated. The growth of power demand is forecasted as 5% per annum and it was observed that the increase in residential load will lower the rise of voltage, but the percentage of increase was not sufficient enough to bring the voltage back to the desired range. Increase in the solar inverter capacities would lead to further elevation of the voltage rise problem, especially given the trend of upgrading the panels by solar consumers without informing the authorities. The effects of power factor of inverters on the voltage rise were also investigated. It was found that by altering the power factor of the inverters at the end of Blue phase from unity to 0.90 leading, that is making them consume lagging reactive power, the overvoltage condition at the end of Blue phase could be eliminated. Although the inductance of distribution feeders is generally small, the net inductance of Blue phase over its nearly 1 km long distance has been sufficient to create an adequate voltage drop with the reactive power flowing in to the inverter to bring the voltage back to normal range. Technically and economically this appears to be the preferred option as far as this particular feeder is concerned at this state of operation. The voltage in Blue phase along the feeder after the inverters at the end of Blue phase only set to operate at 0.90 leading power factor is shown in Fig. 6. It clearly indicates that the overvoltage condition that previously occurred in Blue phase is now eliminated.

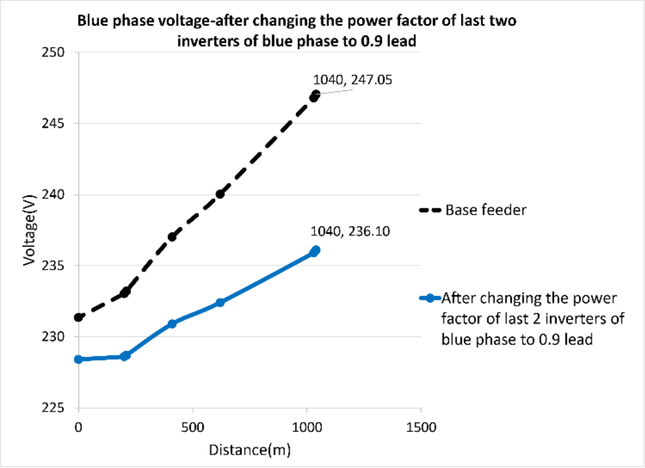

Fig. 6. Voltage variation along the feeder on Blue Phase after the inverters at the end of Blue Phase set to 0.90 leading

With the additional loading by the reactive power of the inverters, the line losses went up but it could be observed that the increase of line losses is very small. Fig. 7 shows the line losses in the Blue phase before and after changing the power factor of its end inverters and it indicates that the net increase of line losses is only 56 W, which is negligible as this increase is limited to a shorter duration of the day.

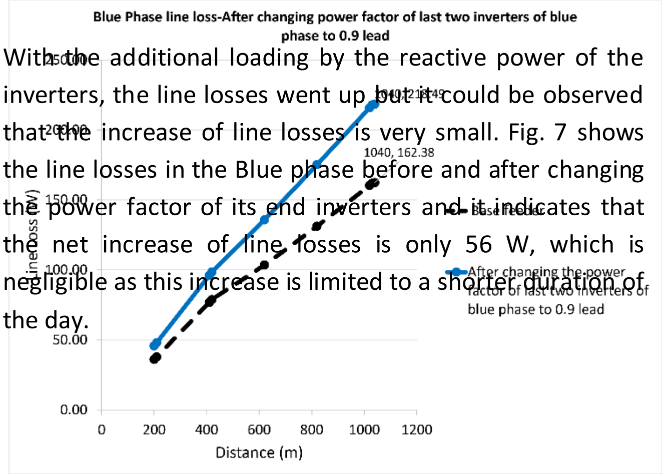

Fig 7. Line losses with the distance in Blue-phase after Power Factor of the Last Inverters changed to 0.90 lead

V. MITIGATION OF OVERVOLTAGE

According to the investigations in section III C, the most economical solution to mitigate the overvoltage issue in the feeder is to draw out reactive power from strategic locations of the feeder, specifically towards the end of the feeder. This option will increase the current in the feeder and the corresponding line losses but a way out to cost this additional losses should be possible as the consumers are now guaranteed their maximum generation without an unintended tripping.[6-8]. This reactive power drawing or loading can be done in two ways:

1. Changing the Power factor of solar inverters
2. Using fixed reactors at different locations

The first option is to set all solar PV inverters to operate (deliver power in to the feeder) at a leading power factor, e.g. 0.90, so that each inverter consumes a reactive power in proportional to the real power it generates. In fact, setting the power factor of the inverters operating towards the end of the feeder alone is adequate to solve the issue but as a general policy each inverter can be made to operate at this power factor. The feeder was simulated with each solar inverter on it set to power factor 0.90 leading. Fig. 8 shows the voltage variation along the feeder on the Blue phase which indicates that the overvoltage conditions are now eliminated. Fig. 9 shows the variation of line losses along the feeder on the Blue phase. The net increase of line losses in the Blue phase is now 84 W which is not that hard as this loss lasts only for limited no. of hours during the day. Currently, all solar PV inverters are operated at unity power factor to keep the kVA rating of the inverter at its lowest value for a given real power and also to comply with prevailing regulations. A new policy in this regard is necessary to implement this option.

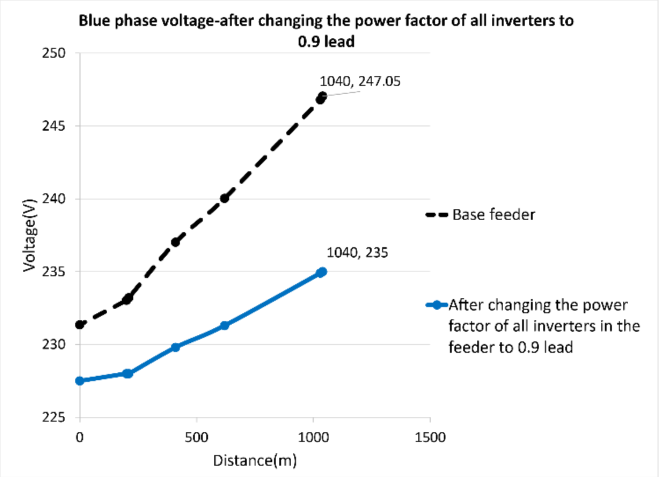

Fig. 8. Voltage variation along the feeder on Blue Phase after all inverters on the feeder set to 0.90 leading

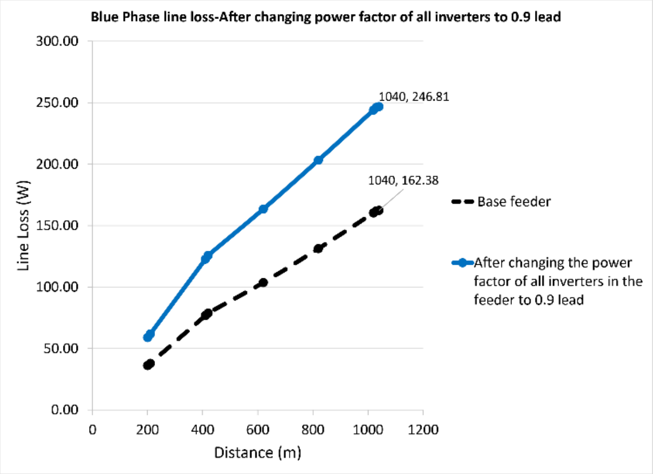

Fig. 9. Line losses with the distance in Blue-phase after Power Factor of the Last Inverters changed to 0.90 lead

The second option is to add reactors to the feeder at pre-identified locations supported with control to alter the reactive power to regulate voltage, adaptively. Alternatively, properly sized fixed reactors may be placed at selected locations to keep the voltage within range but they need to be cutoff after the solar generation falls low in order to avoid under-voltage conditions during night peak. It was found that a 4 kVAR reactor connected at the mid-point of Blue phase could solve the overvoltage problem in that phase with a negligible increase of line losses, just by10 W. Fig. 10 shows the voltage at the end of the Blue phase after the 4 kVAR reactor is connected at the middle of the same phase, at a time of peak solar PV generation. It is seen that the voltage is now limited at 243.2 V which is within the safe range.

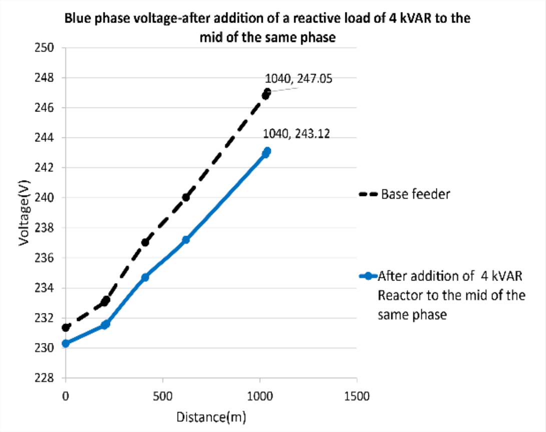

Fig 10. Voltage variation along the feeder on Blue Phase with a 4 kVAR reactor at the middle of same phase

VI. ACCEPTABILITY FOR CHECKING NEW CONNECTIONS

The decision to grant approval for a new connection of a solar PV inverter to a feeder, which is already having PV inverters, should be made after careful checking on whether the new connection would create overvoltage conditions forcing even some existing inverters to trip out. The system model developed in this study can be readily used to check such conditions by adding the model for new inverter at respective location in the feeder and simulating to see if it creates overvoltage conditions. This will be a valuable tool for the distribution system operators to check up different scenarios of the feeder operation with solar connections.

VII. CONCLUSION

This paper has described a study done on overvoltage issues on LV distribution lines, caused by the operation of solar PV inverters and the ways of mitigating the same. A representative feeder that experienced overvoltage conditions was used for the study. The entire feeder including transformer, connected loads and solar PV inverters was modelled in that a separate model for solar PV inverters was developed from the feeder’s point of view with the possibility to adjust power. The simulation of the feeder showed generation of overvoltage towards the end of the feeder during peak of solar generation, exactly as the way it was witnessed in the real feeder.

The study revealed that the easiest and the most economical way to mitigate the overvoltage situation in the feeder is to change the operating power factor of the solar inverters at the end of the feeder to about 0.90 leading from its present default value of unity. The line losses then went up by 56 W, which is small. Alternatively, and also as a general policy, all solar inverters connected to the feeder may be set to operate at 0.90 leading to mitigate the issue of overvoltage . The line losses then rise up little further up to 84 W which is still not hard as this lasts only for few hours of the day. On the other hand, if a proper policy framework is established, the cost of increased losses can be shared with the solar PV customers as their inverters are then guaranteed uninterrupted generation without unexpected tripping. To operate at 0.90 leading power factor the solar PV inverters need little more rated kVA capacity, and this additional cost has to be borne by the customers. The other option found from the study is to connect fixed reactors towards the middle of the feeder to draw out reactive power without asking customers to change their power factor. For the particular feeder a 4 kVAR reactor could remove the overvoltage conditions during peak hours of solar generation with only 10 W of negligible rise in the line losses. However, this reactor needs to be cutoff after the solar generation falls low as it would otherwise cause under-voltage conditions during night peak. An alternative would be to equip the reactor with appropriate control to adjust reactive power as appropriate to keep the voltage within the range.

An important other outcome of the study is that the developed simulation model can be used as a valuable tool for testing any residential feeder with appropriate adaptation of parameters, especially to check if a prospective PV connection could be permitted without causing overvoltage conditions in the feeder.

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