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Optimal PV Inverter Reactive Power Control and Real Power Curtailment to Improve the Performance of Low Voltage Distribution System

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Abstract
The connection and use of renewable energy sources such as grid connected photovoltaic (GCPV) systems in distribution networks have been increasing over the last few decades. The grid connected PV system is one of the most promising renewable energy solutions which could offer many benefits to both the end user and the utility network. Such systems may cover the consumer's own power demand and reduce electricity bills, while feeding any surplus power into the grid or use the grid as a backup system in times of insufficient PV generation. However, integrating a high penetration level of small-scale grid connected PV systems into the low voltage distribution system (LVDS) could cause operational problems. One of the technical issues is a possible voltage rise along distribution network as a result of reverse power flow, especially at low demand and high generation conditions that are restricting the ability of networks to accommodate further connections. And another issue is a possible voltage drop along the network during no PV generation, especially at high demand and no PV generation conditions. Based on the latent reactive power capability and real power curtailment of single phase inverters, this paper has proposed a new comprehensive PV operational optimization strategy to improve the performance of significantly LVDS with residential GCPV penetrations. Optimal PV inverter reactive power control and real power curtailment to improve the performance of low voltage distribution system is studied on the configuration of IEEE 33 bus system. The node data (Load and PV generation) for each hour of the day is taken from the load and PV generation pattern for the domestic consumer of urban area. Three scenarios of PV penetration level are considered during the study. The proposed algorithms are coded using MATLAB. As a result of optimal reactive power control and real power curtailment (if necessary), voltage profile of the network has improved, ensuring the benefit of PV installation.

Keywords
Grid Connected Photovoltaic(GCPV) power system, Distribution system load flow, Voltage profile, Optimal reactive power control, Real power curtailment

1. Introduction

In recent years, both demand for electricity and fossil fuel costs have grown rapidly and energy security concerns and global warming issues are becoming more important. These concerns are directing energy research attention towards renewable energy sources, such as solar and wind energy in order to contribute to the growing energy demands and reduce the need for fossil fuels. Moreover, cost reduction of PV panels and technical progress in power electronic conversion and semiconductor devices make photovoltaic (PV) systems one of the most promising renewable energy sources. Grid connected PV systems have many technical advantages such as flexibility, simplicity to install in any area where the solar irradiation is available, being non polluting, emitting no noise and requiring little maintenance. Therefore, many countries are encouraging households to install PV systems in order to generate their own power, to reduce electricity bills and to increase the contribution of renewable energy to limit carbon dioxide (CO_2) emissions [1]. So, photovoltaic (PV) systems are being increasingly installed in low voltage (LV) distribution networks by consumers to reduce the cost of electricity supply. However, the expanding scale of residential PV connections leads to detrimental impacts on the network operation. Two of the foremost issues are voltage deviation and voltage unbalance [2]. During high PV generation periods, there is a possibility of significant reverse power flow and consequent voltage rises on the LV feeder. On the other hand, serious voltage drops may occur due to the intermittent loss of PV generation during cloudy days or no PV generation period. Furthermore, the increasing installation of single-phase rooftop PV units at random locations with various ratings is further worsening the already poor network profile of distribution system. Traditional approaches to address voltage regulation and unbalance problems are utilizing secondary LV transformer on load tap changer (OLTC), autotransformers, voltage regulators, and switched capacitors. However, tap positions cannot be changed frequently, autotransformers, voltage regulators, and switched capacitors introduce additional failure points into the system with expensive approaches that are usually not justified due to low cost benefit ratios [3]. The more recent approaches to overcome the voltage deviation problem in LV networks with high PV generation penetration involve inverter-based reactive power control. Compared with the above-mentioned traditional approaches, PV inverter reactive power control is more effective, has superior transient performance, and does not require extra investments [4]-[5]. In order to increase the utilization of grid-tie PV inverters, they can be operated in reactive power compensation mode when PV power is unavailable. As the number of grid-tied inverters increases, their usage as VAR compensators will help in grid voltage regulation and reduce the need of expensive capacitor banks [6].

2. PV Control Strategy

Traditionally, PV inverters were designed to feed as much active power as was available from the solar array at unity power factor into the point of common coupling. More recently, utilities and independent power providers have shown tremendous interest in the inverter's capability to also absorb and provide reactive power from and to the grid. Over 95% of the time a PV inverter is running below its rated output current when converting DC solar power to AC active power. The unused capacity of the inverter can then be put to use to produce reactive power. The output of a smart PV inverter has both reactive and active AC currents that add geometrically to the apparent power, which will be limited by the current rating of the inverter.

2.1 Reactive power capability of PV inverter

The inverter's capacity and real power are represented by vectors with magnitudes S and P as shown in Figure 1. The semicircle with radius denotes the boundary of the inverter's operating range in PQ space [4]. The amount of reactive power (Q) available from the inverter is constrained by

$$-\sqrt{S^2 - P^2} \leq Q \leq \sqrt{S^2 - P^2} \tag{1}$$

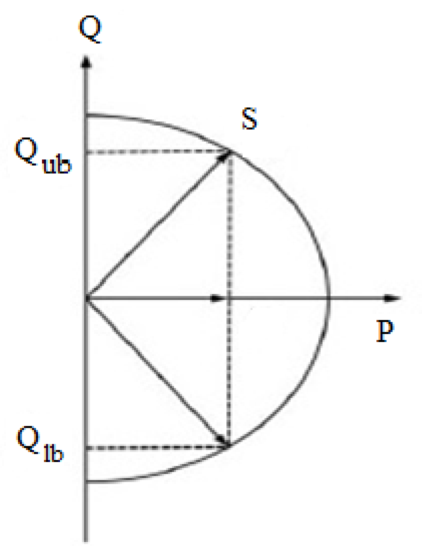

Figure 1: Reactive power capability of PV inverter

2.2 Proposed PV inverter control strategy

Based on the reactive power capability and real power curtailment of the PV inverters [7]- [8], one of the following proposed three control options is selected for the desired network performance as shown in Figure 2. Control option1 (Optimal Q-control with rated inverter power factor capacity): This option is selected for normal operating conditions. As the inverter real power generation is usually below its rating, the inverter has the capability to supply/absorb reactive power, at a cost

of incremental inverter losses.
Control option2 (Optimal Q-control with rated inverter capacity): This option is selected if the network performance is still not within the limit with option1. This is due to the limited effect of reactive power of inverter. Then a comprehensive control can be implemented where the reactive power is controlled with rated inverter capacity.
Control option3 (Optimal Q-control with real power curtailment of Inverter): This option is selected if the network performance is still not within the limit with option2. In this option real power curtailment is available to each inverter to allow both reactive power and real power controls. Curtailment incurs a relatively higher cost in the optimization process and partial curtailment allows all the users to share the network resources when constraints exist.

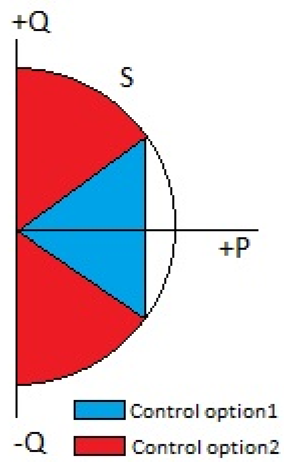

Figure 2: Proposed PV inverter control strategy

3. Methodology

In rooftop PV penetration to low voltage system, reactive power control and real power curtailment from PV inverter is very important function to improve the performance of the distribution system. The solution involves selecting the optimal reactive power control and real power control that results the smallest voltage deviation to all the nodes of the networks, minimum power loss of the network, minimum real power curtailment of PV system and that satisfies a group of operation constraints.

1. Objective functions

   (a) Minimization of voltage deviation

$$V_{dev}(i) \tag{2}$$

   $\forall$ i, i$\in$ All node of the network
   Voltage deviation limit for the study is $\pm 5\%$ of rated voltage [9]

   (b) Minimization of power losses

$$P_{loss} = \sum_{i=1}^{N_{br}} {I_i}^2 R_i \tag{3}$$

   where,
   i is the any branch of the network
   N_{br} is the total no of branch in the network
   I_i is the magnitude of the current flowing through the branch i
   R_i is the resistance of branch i

   (c) Minimization of total real power curtailment

$$PV_{\text{P(curt)}} = \sum_{i=1}^{n} (\text{Real power curt. of the PV})_i \tag{4}$$

   where,
   i is the any number of the PV
   n is the total number of the PV in the network

2. Constraints

   (a) Capacity limit of the PV inverter

$$P_{PV}^2 + Q_{PV}^2 \leq S_{PV}^2 \tag{5}$$

   where,
   P_{PV} is the real power of the PV
   Q_{PV} is the reactive power of the PV
   S_{PV} is the apparent power of the PV

   (b) Power loss before and after control

$$P_{loss}(\text{After control}) \leq P_{loss}(\text{Before control}) \tag{6}$$

So, mathematically this multi-objective optimization problem can be represented as,

$$\min \mathrm{F} = [V_{dev}(x), P_{loss}(x), PV_{\mathrm{P(curt)}}(x)] \tag{7}$$

where, x is the optimal reactive power control and real power curtailment of the PV inverter.
Optimal control is obtained by repeated load flow for the distribution system for different proposed control options.
The Gauss-Seidel method for load flow requires large computation time as the number of bus increases. And the Newton-Raphson method for load flow converges only for low R/X ratio. In general a distribution system has large R/X ratio with large number of buses, so above methods are not suitable for distribution system load flow as it has poor convergence characteristics. Because of above problem, backward-forward fashion method of load flow used in this study work [10]. PVs generations are represented as negative PQ load for the load flow. MATLAB code is developed for the optimization of reactive power control and real power curtailment.

4. Result and Discussion

IEEE 33 bus distribution system, which is taken as model configuration for the study is shown in Figure 3 [11]. The distribution transformer of 11/0.4 kV is represented by S/S and which is considered as a grid in the study. The node data (Load and PV generation) for each hour of the day for three scenarios (LPPL, HPPL and EPPL) is taken from the load and generation of PV pattern for the domestic consumer of urban area. Each node is considered as 30 meter of span and the conductor used is Dog (0.1 sq inch ACSR). This network is considered as low voltage three phase four wire distribution systems. The base for load and PV generation is taken as 5 kVA and 0.23 kV. The results of the study for phase C of the network is only shown in this paper.

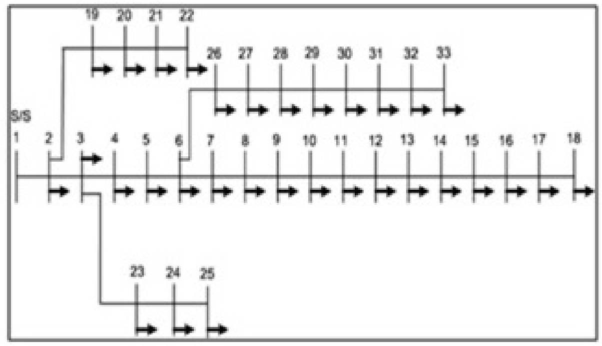

Figure 3: Single line diagram of the IEEE 33 bus system

4.1 Simulation results of Low Penetration w.r.t Peak Load(LPPL) case

The proposed algorithm is implemented for LPPL case and the test results for the real power, reactive power, intial voltage and optimal condition voltage profile of the network are shown in Figure 4, 5 , 6 and 7 respectively. Results for phase C of the network are presented based on the combination of line type and color. As demonstrated in Figure 4 to 7, originally the network load was much higher than the PV generation, especially between 18:00 to 21:00 hour, causing dramatic voltage drop to 0.845 pu at node 18; 20:00 hour. After applying the proposed inverter control strategy, the network performance is improved i.e voltage increased from 0.845 to 0.893 pu and power loss decreased from 6.35 kW to 4.072 kW at node 18; 20:00 hour. The network performance cannot be improved further during (18:00 to 21:00) due to low PV penetration, as PV penetration was not coincident with the peak load.

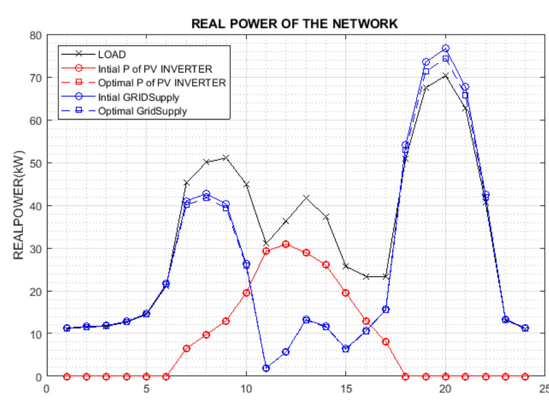

Figure 4: Real Power of load, PV inverter and grid

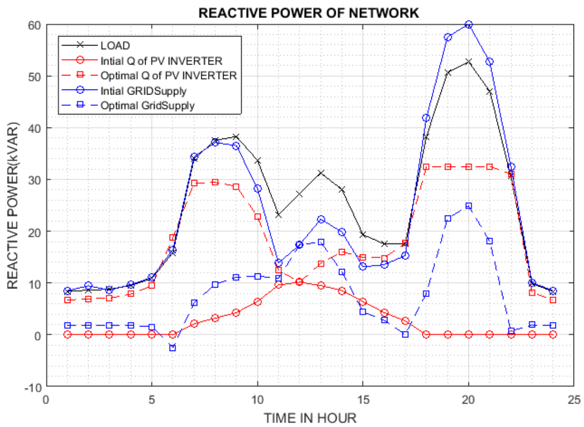

Figure 5: Reactive Power of load, PV inverter and grid

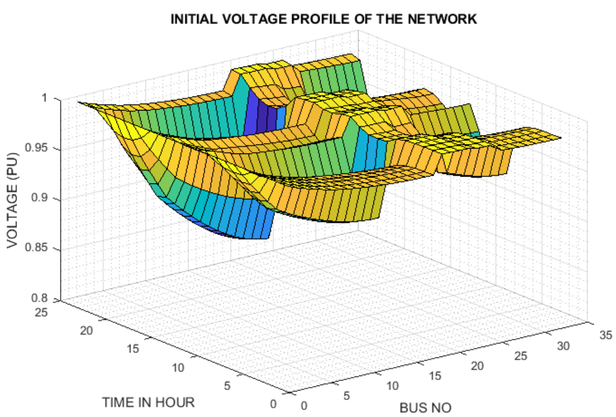

Figure 6: Initial voltage profile of the network

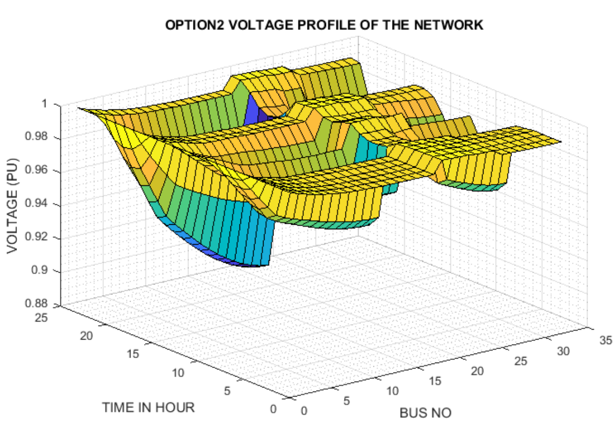

Figure 7: Optimal condition voltage profile of the network

4.2 Simulation results of High Penetration w.r.t. Peak Load(HPPL) case

The proposed algorithm is implemented for HPPL case and the test results for the real power, reactive power, intial voltage and optimal condition voltage profile of the network are shown in Figure 8, 9, 10 and 11 respectively. Results for phase C of the network are presented based on the combination of line type and color. As demonstrated in Figure 8 to 11, the scenario of high PV penetration is formed to simulate the projected increased PV connections. Originally, as the generation is much higher than the load, especially between 11:00 and 15:00 hour, poor network performance, characterized by a significant reverse power flow, dramatic voltage rise to 1.112 pu. To mitigate the voltage rise and improve the overall network quality, inductive reactive power is injected optimally by the PV inverters. However, the network performance has not been improved more due to power loss constraints, which is due to the limited effect of reactive power control on networks with high R/X ratio. Thus, real power curtailment is used to work with reactive power control as explained in option3. After applying the option3, the real power curtailed during the peak generation time and then the network performance is improved i.e voltage decreased from 1.112 to 1.05 pu and power loss decreased from 5.65 kW to 2.29 kW.

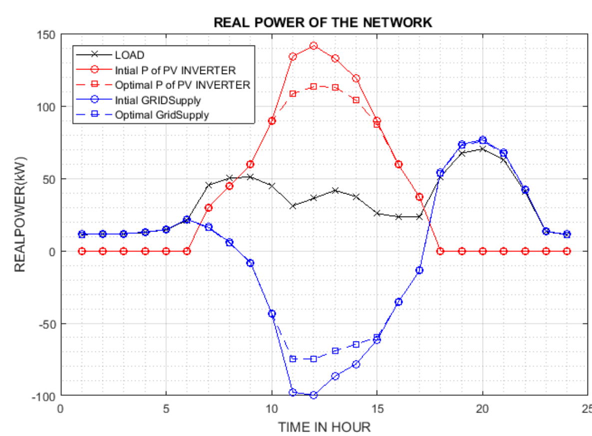

Figure 8: Real Power of load, PV inverter and grid

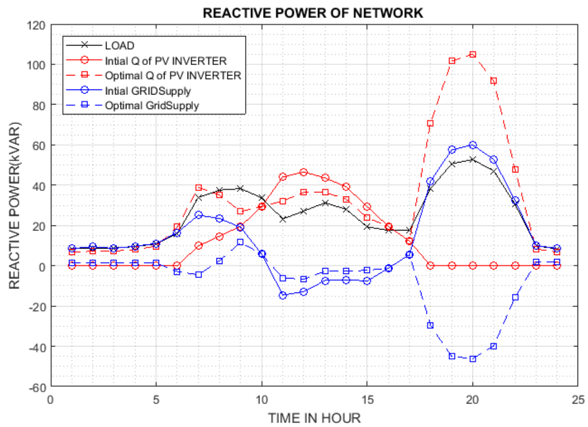

Figure 9: Reactive Power of load, PV inverter and grid

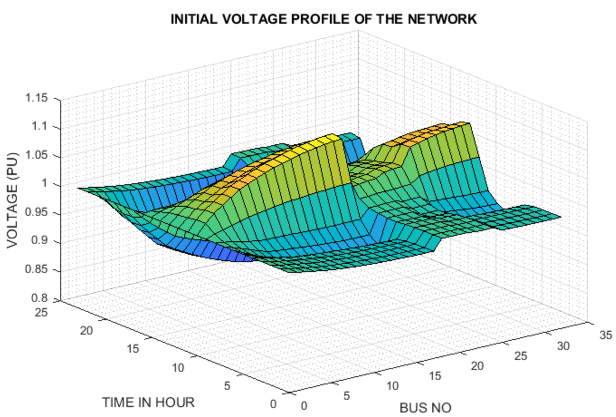

Figure 10: Initial voltage profile of the network

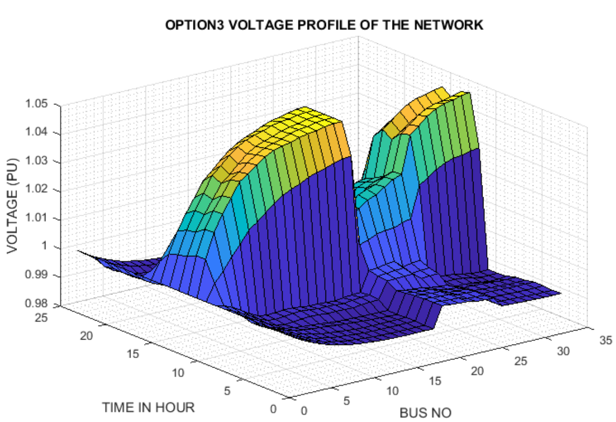

Figure 11: Optimal condition voltage profile of the network

4.3 Simulation results of Equal Penetration w.r.t. Peak Load(EPPL) case

The proposed algorithm is implemented for EPPL case and the test results for the real power, reactive power, intial voltage and optimal condition voltage profile of the network are shown in Figure 12, 13, 14 and 15 respectively. Results for phase C of the network are presented based on the combination of line type and color. As demonstrated in Figure 12 to 15, the scenario of equal PV penetration w.r.t to peak load(kVA) is observed. Originally, as network voltage was very poor during peak load and no PV generation time due to no any control. After, applying the reactive power control, the network performance during entire hour of the day stay within the limit of $\pm 5\%$ of rated voltage.

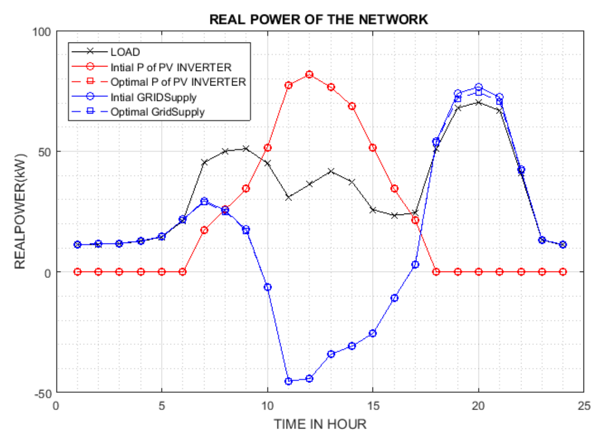

Figure 12: Real power of load, PV inverter and grid

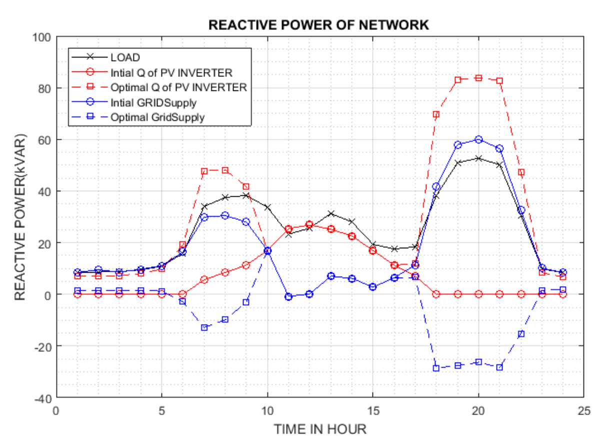

Figure 13: Reactive power of load, PV inverter and grid.

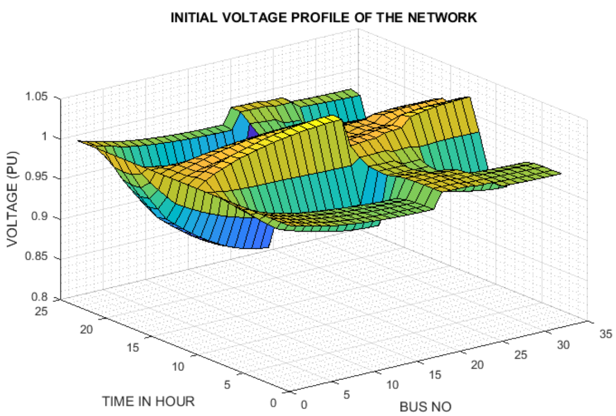

Figure 14: Initial voltage profile of the network

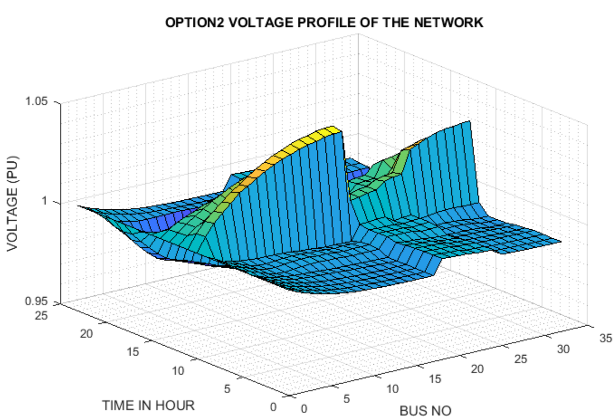

Figure 15: Optimal condition voltage profile of the network

5. Conclusion and Recommendation

This paper has introduced an algorithm on PV inverter control to utilize the reactive power capability of PV inverter. A PV control options assessment strategy is proposed based on the reactive power capability and real power curtailment of single phase inverters and its effectiveness under three different PV penetration scenarios are studied. LPPL has low PV generation w.r.t. load during entire hours of the day and simulation results have shown that reactive power capability limit of PV inverters are insufficient to maintain the desire voltage limit during peak load time (18:00 to 21:00). So, it requires increasing the PV penetration in the network. HPPL has high PV generation w.r.t. load during 9:00 to 17:00 hour and the simulation results have shown that reactive power capability limits of PV inverters are insufficient to maintain the desired voltage limit during 11:00 to 15:00 hour due to power loss constraints. So, it requires real power curtailment to the PVs. To overcome this real power curtailment, PV having large capacity have to be installed the energy storage device, like battery. In last scenario, EPPL has high PV generation during 10:00 to 16:00 but lower than HPPL and the simulation results shows that reactive power capability limits of PV inverter are sufficient to maintain the desired voltage limit during entire hours of the day without real power curtailment.

To implement the proposed PV control strategy in low voltage distribution networks, the following factors should be considered.

- PV reactive power is controlled in this study to provide grid support. Thus, in a way similar to the existing real power feed-in tariff, feed-in policies on the inverter reactive power generation should be proposed and provide financial benefits for the consumers involved.
- Each residential premise can be equipped with advanced metering system such as home area network interfaced with PV inverter controlled by smart meters. In fact, some latest advanced metering infrastructures already have the capability of collecting data from and sending control signals to inverters.
- The control procedure: Network information (e.g., loads and generations at each house) is collected and passed to the centralized network controller, where according to the network status, one of the three proposed control options is selected and the optimal set points of each controlled PV inverter are determined. Then, the set points will be sent to each inverter and implemented.

So, considering the limitation of the smart PV inverter and reactive power feed in policies, this work can be enlarged extended.

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