Determination of PV Penetration in LV Networks Considering Stochastic Behavior of Loads and PVs

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Abstract— **In this paper, a method is proposed to determine the maximum possible PV installation in a low voltage feeder in distribution systems considering voltage profile constrains. The stochastic behavior of both PV and load is modeled and the effects of power curtailment, load management, and reactive power management on PV penetration are studied.**

Keywords- ***PV penetration; power curtailment; load management; reactive power.***

I. Introduction

Photovoltaic (PV) is amongst the most rapid growth renewable energy technologies worldwide. The annual growth rate of these systems has became more than 44% in the last decade and the installed capacity of them has increased from 1000 MW in 2000 to 18.2 GW by the end of 2010 [1]. Trends show that in the near future, the majority of new PV installations are grid-connected residential PVs [2-3]. Residential PVs are connected to distribution systems and their capacity is normally less than 10 kW [4].

Distribution systems are normally designed to operate in radial configuration. In these systems the power flow direction is from the upstream network toward the loads. Any change in power flow direction can cause problems in these systems especially in the area of power quality, operation of voltage control devices and the system protection [2], [4]. One of the main problems of high residential PV penetration is increasing the voltage at the point of connection and neighbor buses [5]-[11]. Besides, PVs are non-dispatchable active power sources and their output power is not controllable without adding some expensive equipment such as electric energy storage systems (EESS). In addition, the PV output is high at the time that the household consumption is usually low. The severity effect of residential PVs on distribution system is variable according to the size, location and network configuration and load condition as well [2], [4], [6].

Several methods can be proposed to increase the PV penetration at LV network. Reactive power absorption by PV inverter is amongst the solutions that can increase the PV penetration by means of decreasing the voltage at the point of connection [12]-[16]. However, according to some current standards this is not allowed [12]. Reducing the impedance of lines is other method to prevent the overvoltage; however the related cost is high and the effects on settings and operation of protection system have to be considered [5]. Output power curtailment of PV is amongst the efficient solutions [17]-[18]; however, a fair and suitable solution to determine the level of curtailment for different PVs in the system is required [5]. Another method could be load management. By using load management, the maximum consumption could be transfer to the high PV generation period and higher penetration of PV could be possible. Using EESS is another good but expensive solution [19].

In this paper, a method has been proposed in order to determine the maximum possible PV installation in a special feeder in distribution systems. The voltage increase at the point of connection is considered as the main constraint for the determination of PV penetration. The stochastic behavior of both PV and load is modeled by proposing a method which uses a new concept i.e. Photovoltaic Duration Curve (PVDC). By using the proposed method, the effect of Customer Self Management (CSM), which consists of power curtailment and using load management, and the effect of reactive power management on PV penetration can be studied. The structure of the paper is as the following: the problem regarding high PV penetration is illustrated at the first, the proposed method is discussed in the next section and finally the simulation results are shown.

II. Problem Discription

The distribution systems are normally designed to keep the voltage at an acceptable level in all load conditions. The concept usually is maintaining the voltage for all load conditions and all load points in the state that the maximum drop in the voltage is limited to an especial amount [20]. This condition may require the transformer with on load tap changer to be used. The traditional distribution systems are designed for mono-directional power flow; i.e. from the upstream network toward the load.

By increasing the penetration of low voltage customer-owned DGs, concerns regarding the reverse power flow are increasing. To clarify the problem, a simple electric circuit

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with an electric source, a line and a load is considered and shown in Fig. 1. The voltage at the load point is:

$$E = \frac{Z_L}{Z_L + Z_G} E_G \qquad (1)$$

The drop in the voltage of load depends on the grid and line impedance and the amount of load as well. Adding any active or reactive power source will change the (1) as the following:

$$E = \frac{Z_L}{Z_L + Z_G} (E_G + Z_G I_S) \qquad (2)$$

From this equation it is clear that if the added source acts as an active power source, the voltage will increase at the point of connection. PVs are usually active power sources and one of the main problems of adding them to the system is overvoltage occurrence especially in high PV and low load conditions. For more description, consider the distribution network of Fig. 2 where PV is assumed connected to each of the busses 2-6. The voltage of the buses at different load conditions and PV penetration are shown in this figure. It is clear that in some conditions, especially light load and high PV penetration the voltage at some buses such as bus 5 and 6 increases considerably.

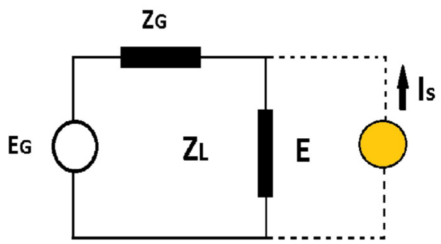

Figure 1. A simple network with load and PV

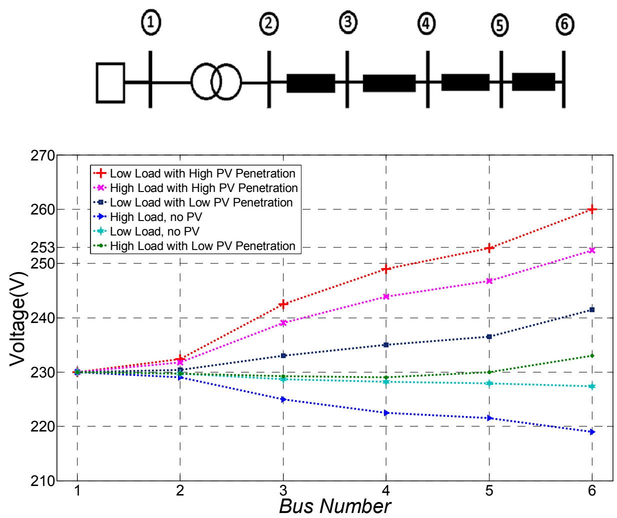

Figure 2. The voltage of the buses at different load conditions and PV penetration

Several papers have discussed different methods for decreasing the voltage at the point of connection by using PV inverter's reactive power absorption capability [12]-[16], [20]-[23]. Some of these methods need communication between different inverters to manage the amount of reactive power absorption of each PV. Implementing these methods is normally expensive and needs in-depth technical studies [21]-[22]. Other methods which don't need any communication can be divided into two different droop control methods; first the reactive power in the term of voltage of connection point (Q(U)) and second the power factor (PF) in the term of active power. Fig. 3 shows the droop curve of these methods.

Large scale generation such as wind farms, PV power plants or even large scale wind turbines usually have to support the grid with reactive power. For two different reasons the low scale PVs in distribution network have not been neither required nor even allowed in some standards to be active in the area of reactive power. The prior is that till now and in many cases the residential PV penetration in the system was low; therefore their impacts could not be considered on whole distribution system as effective as other traditional methods [4]. The second is that larger generators are normally connected to the transmission lines and high voltage distribution system rather than low voltage distribution systems. In LV distribution systems the X/R ratio is less than one while in transmission system the X/R ratio is usually larger than 1. In this condition, the effect of reactive power on the voltage of the system is not as effective as transmission system reactive power management.

The other problem regarding PV impact on the voltage is the voltage variations. The output of a PV is not fixed during a day and even during an hour. This matter is shown in Fig. 4. The grid in which PV is connected is a weak distribution network and the effect of output power fluctuations on the bus voltage is considerable.

As a result of increasing in the number of customer owned DGs especially residential PVs, the changes in the previous standards seem to take place and rules regarding the large scale generators are expected to be extended to the residential PVs [22]. Using the customer's inverters for reactive power support could be more effective and less price than traditional methods [22]. However, broad studies regarding PV inverter's reactive power management effects on distribution system are required to prevent lack of coordination among the different reactive power sources as well as the transformer tap positions.

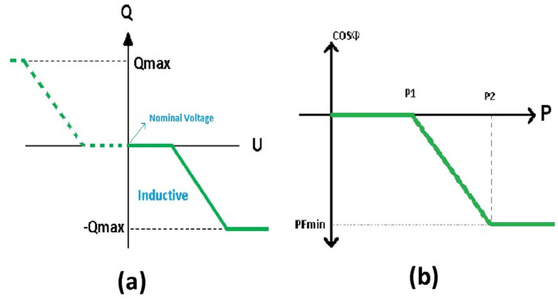

Figure 3. a) the reactive power in the term of voltage of connection point (Q(U)) b) the power factor (PF) in the term of active power

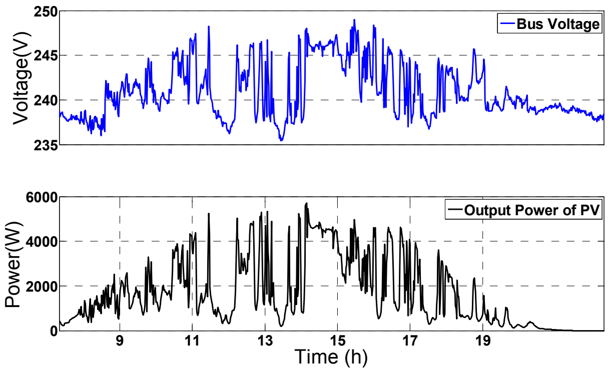

Figure 4. The voltage variations coused by a PV at a weak grid

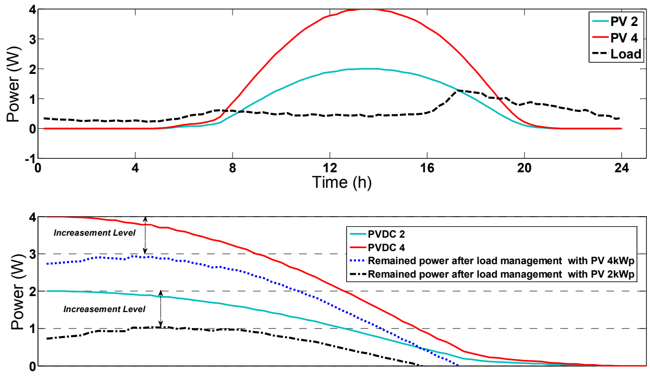

Figure 5. A perfect load management with two PVs

III. Proposed Method

A. Customer Self Management (CSM)

One of the methods which effectively can influence the PV penetration in the system is using the customer capability of controlling their consumption and generation. The maximum possible power injection for each customer can be determined according to pre-installation studies on the network. In this condition customers are not forced to manage their consumption or generation; yet they are not allowed to inject more power into the network than predetermined amount. If the customers inject more power than the determined value, they have to pay a penalty. However the customers can manage their generation and consumption in a way so they can install more PV without exceeding the maximum allowed power injected. The CSM can be done by power curtailment, using EESS or any sorts of load management tools and programs. In this paper, the effect of load management on PV penetration is studied by using a simple but effective method. In this method the Photovoltaic Duration Curve (PVDC) is introduced by using the actual PV output. The PVDC is extracted from PV output by arranging the output in descending order, rather than chronologically. By using a perfect load management, the load consumption is in highest amount in the condition of high PV generation. The maximum effect of load management on PV penetration can be determined by subtracting the Load Duration Curve (LDC) from PVDC. By using this method, the maximum possible load management of a customer for maximizing the PV installation could be determined. This is shown in Fig. 5. In this figure two PVs with different maximum peak capacities of 4 and 2 kWp have been considered with a typical household consumption and a perfect load management. The PV installed power with a perfect load management can be increased by the level which is shown in the figure. The amounts are around 1 kW and 0.9 kW for 4 kWp and 2 kWp PVs respectively.

One of the other effective solutions in CSM is to curtail the active power of PV at specific level. The percentage of the power lost by power curtailment is not equal to the level of curtailment. This is shown in Fig. 6. It can be seen from the PVDCs that by curtailment of the power at 70 % of nominal kWp, the energy loss is not equal to 30 %. The loss is less than 5 % in day A and 0 % in the day B.

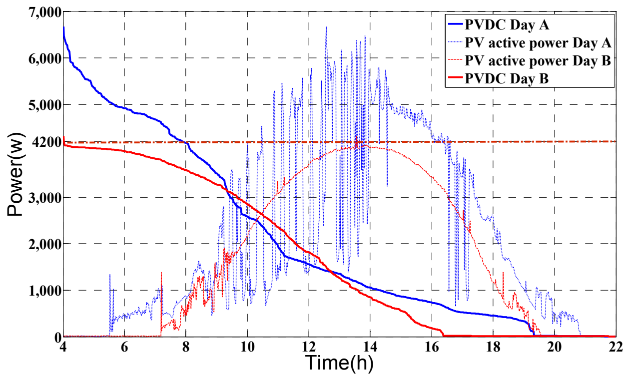

Figure 6. Active power curtailment of PV output

PV penetration can also be increased by using both power curtailment and load management. The extra capacity which can be added to the system depends on the PV capacity and level of load curtailment. Fig. 7 shows two PVs with 2 kWp and 6 kWp. Load management and power curtailment are applied by the customer. From the grid point of view, a 6 kWp PV with perfect load management and power curtailment at 70 % performs like as a DG with 3.7 kW capacity. This is 0.8 kW for a 2 kWp PV.

B. Reactive power management

As it is earlier mentioned, two different droop control methods i.e. the reactive power as function of voltage in the connection point (Q(U)) and power factor as function of injected active power cos□(*P*) can be used to decrease the voltage level. In the Q(U) method, the voltage of the connection points is considered as the reference for the droop control. The advantage of this method is that the inverters don't absorb the reactive power when the point of connection voltage is not high. This reduces the loss in the system caused by reactive power absorption. However, this method has two main drawbacks; first, the voltage is controlled only by means of local voltage and therefore cannot affect the whole system as much as possible. The second disadvantage is the lack of coordination between the PV inverter and other voltage controllers [4]. In the cos□(*P*) method, the amount of reactive power which is absorbed depends on the output active power of the PV panel. The implementation of this method is simple; however in some cases the reactive power is absorbed by the PV inverter without voltage problem in the network.

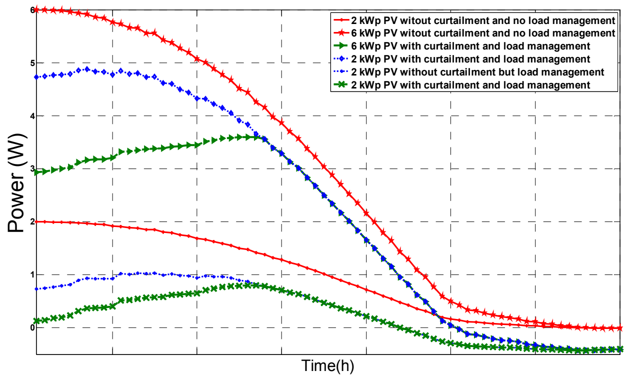

Figure 7. Using CSM to increase the PV penetration

In general, both methods have the drawback that they can increase the power loss and the line's congestion. In this paper the main purpose of reactive power absorption by PV inverters is considered to increase the PV penetration. By using a voltage related equation which is discussed in the next section some buses are selected for reactive power absorption according to the sensitivity analysis of the system. The main idea is not only to maintain the voltage in an acceptable value but also to reduce the power losses and congestion. The effects of the two different methods, selected customers or all customers, are simulated in the simulation results section.

C. *Voltage Analysis of the System*

In this paper we use the voltage sensitivity analysis equations to determine the amount of voltage increase caused by PV installation. The effect of reactive power absorption of PV inverters could be studied by the same way. The power flow equations for the system considering both inductive and resistive characteristics of the power lines are as follows:

$$P_k = \sum_{n=1}^{N} |V_k|.|V_n|.|Y_{kn}|.cos(\theta_{kn} + \delta_n - \delta_k) \tag{3}$$

$$Q_k = -\sum_{n=1}^{N} |V_k|.|V_n|.|Y_{kn}|.sin(\theta_{kn} + \delta_n - \delta_k) \tag{4}$$

where P, Q, V, δ, Y and θ are the active power, reactive power, magnitude of bus voltage phasor, angle of bus voltage phasor, magnitude of Ybus, and angle of Ybus respectively.

By expanding two previous equations in Taylor's series about the initial estimate and neglecting all higher order terms result in the following set of linear equations:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{vmatrix} \left[\frac{\partial P}{\partial \delta}\right] & \left[\frac{\partial P}{\partial V}\right] \\ \left[\frac{\partial Q}{\partial \delta}\right] & \left[\frac{\partial Q}{\partial V}\right] \end{vmatrix} . \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{5}$$

By solving the previous equation, the voltage sensitivity matrix can be extracted as the followings:

$$\begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = \begin{vmatrix} [S_{\delta P}] & [S_{\delta Q}] \\ [S_{VP}] & [S_{VQ}] \end{vmatrix} . \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{6}$$

From (6), the voltage variation due to active or reactive power variations is given by:

$$\Delta V = S_{VP}.\Delta P + S_{VQ}.\Delta Q \tag{7}$$

The proposed method is that by using (7) at weakest point of the network, the maximum possible installation of PV in the selected bus is determined. The voltage at the selected bus is different according to the PV penetration and load condition at the other buses. In this paper, three scenarios are considered; High PV penetration supposed that all other customers have installed PV, Medium PV penetration and low PV penetration. Equation (7) is updated according to the PV penetration of the system. By using this equation and the bus voltage before adding a new PV, the maximum possible PV installation is determined. The effect of CSM and reactive power management can be studied by changing in the amounts of active power and reactive power at each bus respectively. By using the sensitivity matrix, some buses are selected for reactive power absorption.

IV. SIMULATION RESULTS

To evaluate the impact of CSM and reactive power management on PV penetration, a LV network with 8 buses is considered and shown in Fig. 8. The number of customers in each bus is 0, 0, 3, 3, 4, 2, 3 and 2 customers in the order of bus numbers. The sensitivity matrixes of the system are as the followings:

$$S_{VP}(V/kW) = \begin{bmatrix} 0.019 & 0.021 & 0.022 & 0.023 & 0.023 & 0.024 & 0.023 \\ 0.020 & 0.240 & 0.242 & 0.247 & 0.249 & 0.251 & 0.248 \\ 0.020 & 0.241 & 0.539 & 0.249 & 0.250 & 0.252 & 0.250 \\ 0.020 & 0.243 & 0.245 & 0.476 & 0.479 & 0.482 & 0.478 \\ 0.020 & 0.244 & 0.246 & 0.477 & 0.591 & 0.595 & 0.479 \\ 0.020 & 0.244 & 0.247 & 0.479 & 0.593 & 0.822 & 0.481 \\ 0.020 & 0.243 & 0.246 & 0.477 & 0.480 & 0.484 & 0.669 \end{bmatrix} \tag{8}$$

$$S_{VQ}(V/kvar) = \begin{bmatrix} 0.139 & 0.140 & 0.139 & 0.139 & 0.139 & 0.139 & 0.139 \\ 0.142 & 0.196 & 0.196 & 0.196 & 0.196 & 0.196 & 0.196 \\ 0.143 & 0.197 & 0.235 & 0.197 & 0.197 & 0.197 & 0.197 \\ 0.144 & 0.198 & 0.198 & 0.255 & 0.255 & 0.255 & 0.255 \\ 0.145 & 0.199 & 0.199 & 0.255 & 0.270 & 0.270 & 0.255 \\ 0.145 & 0.200 & 0.200 & 0.256 & 0.271 & 0.314 & 0.256 \\ 0.144 & 0.200 & 0.199 & 0.255 & 0.255 & 0.255 & 0.280 \end{bmatrix} \tag{9}$$

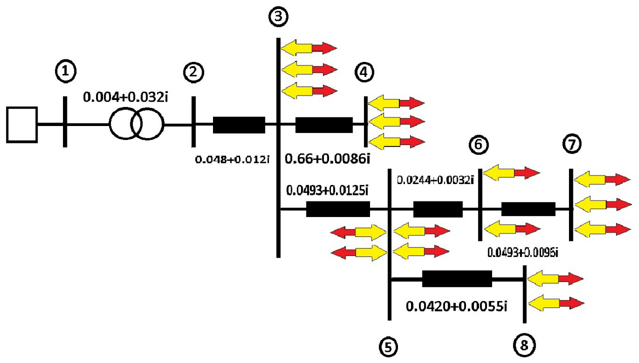

Figure 8. The case study

According to EN50160 [24], the maximum allowed increase in the voltage level is 10 percent; therefore 253 volt is used as the maximum voltage. It is assumed that the voltage of bus 1 is constant and is equal to 230 V. To consider the worst case scenario, the weakest point of the network is selected and the aim is to connect a 6 kWp PV to this point. Different conditions are simulated as the following:

Case1: there is no PV in the system.

Case 2: the PV penetration in the system is low, but there is neither load management nor power curtailment.

Case 3: the PV penetration in the system is low, load management is performed for all customers, but power curtailment is not performed.

Case 4: the PV penetration in the system is low, both load management and power curtailment are performed.

Case 5: the PV penetration in the system is medium, but there is neither load management nor power curtailment.

Case 6: the PV penetration in the system is medium, load management is performed for all customers, but power curtailment is not performed.

Case 7: the PV penetration in the system is medium, both load management and power curtailment are performed.

Case 8: the PV penetration in the system is high, but there is neither load management nor power curtailment.

Case 9: the PV penetration in the system is high, load management is performed, but power curtailment is not performed.

Case 10: the PV penetration in the system is high, both load management and power curtailment are performed.

To simulate the effect of reactive power absorption on PV penetration, the following cases has been considered and the effects on the mentioned bus voltage and power loss of the system are addressed:

Case11: the PV penetration in the system is low, there is neither load management nor power curtailment, and all PV inverters absorb the reactive power.

Case12: the PV penetration in the system is low, there is neither load management nor power curtailment, and selective buses absorb the reactive power.

Case13: the PV penetration in the system is medium, there is neither load management nor power curtailment, and all PV inverters absorb the reactive power.

Case14: the PV penetration in the system is medium, there is neither load management nor power curtailment, and selective buses absorb the reactive power.

Case15: the PV penetration in the system is high, there is neither load management nor power curtailment, and all PV inverters absorb the reactive power.

Case16: the PV penetration in the system is high, there is neither load management nor power curtailment, and selective buses absorb the reactive power.

Case17: the PV penetration in the system is high, there are both load management and power curtailment, and only inverters in the buses which PV is connected to it absorb the reactive power.

The results are shown in Table (I) and (II). The simulations show that in the condition of low PV penetration in the network, no problem will happen by adding the PV to the mentioned bus. However, by using CSM, the voltage will decrease by 10 Volt at the PV connection point and this allows more PV installation in the network. In the condition of medium PV penetration in the network, by adding a new PV to the mentioned bus, the voltage will exceed beyond the allowed band. By using load management, the voltage will decrease so that it will be in the allowed band. In high PV penetration, without CSM and even by reactive power absorption by all PV inverters, the voltage will increase more than the permitted amount. By using the CSM in high PV penetration, the voltage will be slightly more than allowed band. By reactive power absorption only by PV inverters which are selected, the voltage remains in the allowed band. Simulations also show that reactive power absorption in the conditions of low and medium PV penetration in the system is not necessary; yet performing reactive power absorption increases the power loss in the network by around 35 percent. By using the selective bus method, the power loss decrease to around 14 percent, yet the voltage decrease caused by PV inverter's reactive power absorption is still effective.

TABLE I. THE EFFECTS OF CSM ON THE VOLTAGE

	Voltage at different buses (V)						
Bus Number	***2***	***3***	***4***	***5***	***6***	***7***	***8***
Case1	229.6	225.2	224.1	222.25	221.6	220.8	221.8
Case2	230.8	249.6	254.3	261.9	264.6	267.9	263.8
Case3	230.8	246.1	249.9	256.2	258.4	261.1	257.7
Case4	230.7	242.8	245.8	250.7	252.5	254.6	251.9
Case5	230.7	243.3	246.5	251.5	253.6	256.3	252.2
Case6	230.6	240.3	242.7	246.5	248.1	250.2	247.0
Case7	230.5	238.0	239.9	242.9	244.1	245.8	243.3
Case8	230.5	238.0	239.7	243.2	244.6	246.6	243.9
Case9	230.3	234.5	235.5	237.5	238.3	239.4	237.9
Case10	230.2	233.3	234.0	235.5	236.1	236.9	235.8

TABLE II. THE LOSS IN THE SYSTEM WITH DIFFERENT REACTIVE POWER MANAGEMENT SCENARIOS

		Voltage at Bus 7	P Loss (W)
Low PV Penetration	***Case2***	246.6	2041
	Case11	241.7	2739
	Case12	243.8	2313
Medium PV Penetration	***Case5***	256.3	5463
	Case13	Case13	7346
	Case14	Case14	6260
High PV Penetration	***Case8***	267.9	12036
	Case15	256.7	16158
	Case16	261.4	13702
	Case17	247.8	6487

CONCLUSION

In this paper the stochastic behavior of both PV and load was modeled and the effects of load management, power curtailment and reactive power management on PV penetration were studied. In the condition of low PV penetration, no problem was happened by adding the PV to the selected bus. In the condition of medium PV penetration, the load management was required. By using the CSM in high PV penetration, the voltage will be slightly more than allowed band and the reactive power absorption was required. Simulations also showed that reactive power absorption in the conditions of low and medium PV penetration was not necessary, yet this work increased the power loss in the network by around 35 percent. By using the selective bus method, the power loss decreased to around 14 percent, yet the voltage decrease caused by PV inverter's reactive power absorption was still effective.

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