Reactive Power Considerations in Reliability Analysis of Photovoltaic Systems

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Abstract—**Reactive power is very essential in maintaining voltage stability of power systems. The voltage constraint at network nodes due to reactive power deficit or insufficiency of reactive power sources restricts active power delivery to the loads and could result in forced load curtailment. Limited attention has been given to reactive power aspect in reliability evaluation of power systems with penetration of renewable energy sources. The reactive power issues become more significant in distributed generation using renewable energy sources such as photovoltaic (PV) Cells, which operate mostly at unity power factor. This paper investigates the effect of reactive power shortage on reliability of power systems with significant penetration of PV cells. The IEEE 14-Bus system is utilized to perform this study. A measure of Expected Energy Not Supplied (EENS) on account of reactive power shortage and voltage violation in network is calculated. By using conventional Monte Carlo simulation, the results are compared with the case without taking into account reactive power and voltage violation constrains. This paper suggests that placement of the PV in the network can greatly reduce active and reactive power shortage during the contingencies. The reactive power is studied here from design and planning perspectives for reliable and stable power system operation when high penetrations of PV energy sources are present.**

Keywords – Renewable Energy, Photovoltaic Systems, Reactive Power, Power System Reliability, Load Curtailment.

I. INTRODUCTION

Renewable energy sources has gained significant attention in recent years because of economic and environmental concerns of fossil and nuclear fuel. The use of alternate sources such as wind and solar is continuously promoted by government policies by providing financial support and rewarding greenhouse emission reduction. Some governments have made renewable energy addition as an important target in their annual operating plan. For example, State of California has set target to have 33% renewable energy in total energy mix by 2020. As a result of such promotions, the penetration of solar and other renewable resources is increasing rapidly.

Although the renewable energy sources such as solar enhance the generation capability and address the environmental concerns [1], they could impose serious stability and reliability challenges in the case they are not equipped with adequate control mechanisms. This issue is more serious in small isolated power systems with high level of renewable energy penetration. Methods have been developed to evaluate reliability of power systems with renewable sources [2-5]. However, less attention has been given to reactive power aspects in conventional reliability evaluation techniques of such power systems.

Proper power systems modeling schemes assign limitations on the maximum and minimum reactive powers supplied by the synchronous generators and take into account the effect of reactive power shortage and voltage violations in the network for reliability analysis [6-7]. This paper focuses on reliability evaluation of power systems from the point of view of reactive power constraints of solar photovoltaic energy sources. Commercial PVs connected to grid through Grid-tie Inverters (GTI) operate at unity power factor and they are not usually a source of reactive power. During normal operation of power system the reactive power demand is majorly supplied by conventional generators and compensators in the system. In the contingency situations, reactive power flow changes significantly due to voltage variations as well as lines and shunt capacitors reactive power changes. Sufficient reactive power reserve is required to supply reactive power essential to maintain network voltage and system stability [9]. Reactive power delivery by network depends on location of reactive power sources, network configuration, etc. Adding distributed generation resources in the form of renewables such as PV cells improves the net available active power in the network during failure of network elements such as synchronous generators. However, the additional capacity from the renewables might not be utilized to fullest because of reactive power shortage during the contingency events. In this paper we calculate load curtailment during the failure events due to reactive power shortage and voltage violation.

A typical load flow program is used to calculate the node voltages following the contingency and the amount of load curtailment essential to restore voltages to acceptable levels is calculated. Reliability indices [7] are obtained for expected energy not supplied (EENS) because of real power shortage $EENS_P$ as well as expected energy not supplied because of

reactive power shortage $EENS_Q$. The system used for study is the IEEE-14 bus system, with conventional synchronous generators and solar PV Cells. PV output is time-varying as maximum power is produced during middle of the day and zero power is produced during night. Though PV generation apparently increases capacity of the system, the entire capacity of PV cannot be utilized to supply power in case of failure of conventional generators in the network due to reactive power limitations. In our case study, it is shown that active and reactive power demands during the normal operation and contingency situations vary greatly with the network configuration; that is, a proper configuration gives rise to increased reliability as opposed to an improper one. Proper placement of solar PV in the network is shown to reduce the active and reactive power losses to a large extent leading to reduced active and reactive power demand during the contingency situations. The rest of the paper is organized as follows. Discussions on reactive power requirements and reliability indices are introduced in sections II and III, respectively. In section IV, the system modeling is discussed. In section V, simulation results are presented followed by concluding remarks in section VI.

II. REACTIVE POWER REQUIREMENTS

The reactive power has a great impact on reliability as it plays an important role in maintaining power system voltage stability. Reactive power is often supplied locally as transfer of reactive power over long distances is not efficient. During the contingency situations sufficient reactive power reserve is required to meet the demand and maintain the voltage in the proper range. In order to maintain the voltage within the acceptable limits, different remedies are suggested in [7] and [14] such as reactive power injection at nodes with voltage violation or load shedding. Load shedding is not recommended and should be considered as the last option. Also, reactive power injection should be considered along with cost-benefit analysis as its use is limited by the cost of new compensators.

In this paper, the proper placement of the PV generators is considered as the solution of reactive power shortage in the power system. Our study suggests that even though the PV generator is not a source of reactive power but the proper placement of the solar PV in the network can significantly reduce reactive power demand through reduced reactive power losses in the transmission lines. Hence, the EENS due to the reactive power shortage is reduced to a large extent. Consequently, the additional active power availability due to PV generators can help balance both active and reactive powers.

III. RELIABILITY INDICES

The reliability indices defined in [7] are used to evaluate reliability of the considered network in different scenarios, which will be discussed later. Based on failure rate λ and repair rate μ, the Mean-Time-to-Failure (MTTF) and Mean-

Time-to-Repair (MTTR) can be defined as $1/\lambda$ =MTTF and $1/\mu$ =MTTR.

In order to calculate EENS, the real power load curtailment due to active and reactive power shortage are defined. Then, the expected energy not supplied is defined as $EENS_P$ and $EENS_Q$ as EENS due to active power shortage and EENS due to reactive power shortage, respectively. The above indices can be defined as

$$EENS_P = \sum_{i=1}^{8760} LC_{Pi} \tag{1}$$

$$EENS_Q = \sum_{i=1}^{8760} LC_{Qi} \tag{2}$$

Where, LC_{Pi} and LC_{Qi} are the real power load curtailment due to real power shortage and reactive power shortage for state i, respectively. In calculating the indices $EENS_P$ and $EENS_Q$, a two-step procedure is adopted; first the load curtailment is performed to reach a positive active power margin followed by further load curtailment to provide a positive reactive power margin.

IV. SYSTEM MODELING

This paper studies a network based on IEEE-14 Bus system consisting of two conventional synchronous and three solar PV generators. The load model is chosen from IEEE-reliability test system with a peak load of 285 MW [12]. The conventional generators are modeled as two-state models as shown in Fig.1. In order to consider the availability of the generators, (i.e., up or down states as shown in Fig. 1,) operating and repair times are chosen as exponentially distributed events. In Fig.1, MTTF and MTTR can be obtained from failure rate λ and repair rate μ, respectively. Then, time-to-failure (T_{up}) and time-to-repair (T_{down}) can be calculated by using equation (3) and (4) [11].
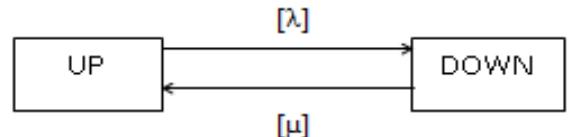

Fig.1 Two-state model for conventional generator

$$Tup = -MTTF \ln U_1 \tag{3}$$

$$Tdown = -MTTR \ln U_2 \tag{4}$$

where U_1 and U_2 are uniformly distributed random numbers in the range [0,1]. Figure 2 shows sample operating cycles of the generators with up and down states referred to 1 and 0, respectively, using equations (3) and (4). The PV four-stage generation model is adopted in this paper, which is based on hourly solar radiation data over a twenty four hour period. Thus, PV generators can be modeled as four-state generators

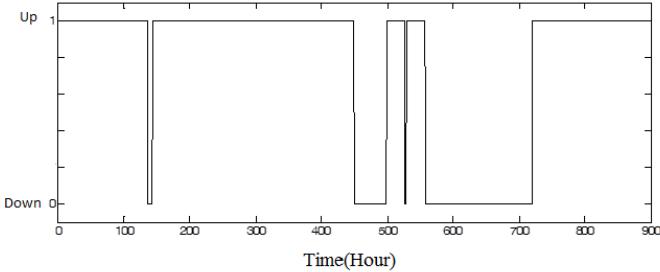with the states up, down, 50% de-rated, and 25% de-rated as shown in Fig. 3.

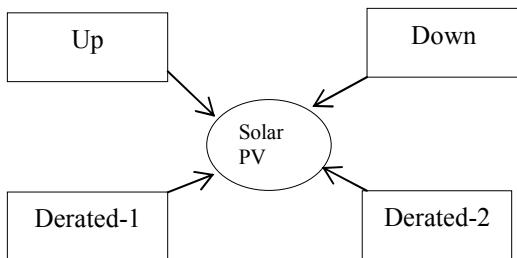Fig.2 Typical operating cycle of a generator

Fig.3 Four-state model of solar PV

The PV generation four-state model is developed based on solar irradiance received during different times of the day and are shown in Fig. 4. Here state 0 is the down state during night time, state 1 is 25% de-rated during early morning hours from 7.00am to 9.00am, state 2 is 50% de-rated state form 9.00am to 11.00am, and state 3 is full capacity from 11.00am to 1.00pm. A typical daily solar radiation profile is also shown in Fig. 4 to compare with the proposed four-state PV power profile.

In order to evaluate the reactive power constraints on the power system with high penetration of PV generation, the IEEE-14 bus system shown in Fig. 5 is utilized where the peak load in the network is 285 MW and two synchronous generators each capable of providing 150 MW are placed at buses 1 and 2. In addition, PV generators of 50 MW each are placed at buses 3, 4, and 5.
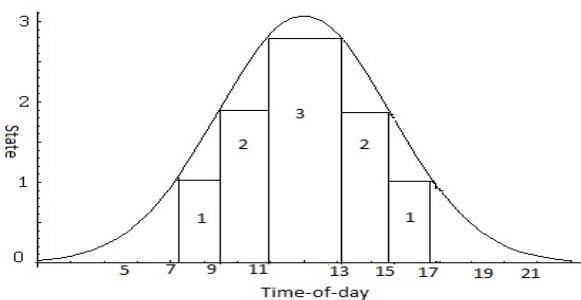

Fig.4 Daily solar radiation profile

In order to perform the reliability studies, three different cases are considered where all the generators (synchronous and PV) are subject to failure; a) only conventional synchronous generators supply the network; b) two conventional synchronous generators and three PV generators supply the network; however, no reactive power constraint is considered in reliability evaluation; and c) case b is repeated with reactive power constraint being considered. Monte Carlo simulations are performed to obtain the total expected energy not supplied. When performing case c, load flow is performed to obtain the maximum allowed load to the network that doesn't violate the reactive power limitations of the synchronous generators as well as the allowed voltage drop at network buses. Subsequently, active load curtailment due to reactive power shortage and/or voltage drop is considered and leads to an additional real power shortage. Different reliability indices for EENS due to real power shortage $EENS_P$ and EENS due to reactive power shortage $EENS_Q$, are obtained.

V. CASE STUDIES

Table 1 shows typical hours of healthy and failed operations for synchronous and PV generators. The MTTF and MTTR values for synchronous generators are obtained from IEEE reliability test system [12] whereas these values for solar PV generators are assumed to be the same as 50-MW synchronous generators' due to lack of data. Table II shows reliability indices for cases a, b, and c for the selected system. While it is expected that the presence of PV improves reliability but this assumption may not be true as the commercial PVs are designed to operate at unity power factor are not able to supply reactive power.

The Monte Carlo simulations are performed for cases a, b, and c where all the generators are subject to failure with the failure rates given in Table 1 and with the failure exponential distributions introduced in equations (3) and (4). In addition, the hourly load with the peak of 285 MW [12] as well as hourly PV generation from Fig. 4 is taken into account in cases b and c. Since the generator (synchronous and PV) failures are random, they might happen at night, when there is no PV generation to supply power, as well as in the middle of the day when there is maximum solar power available. Figures 7 and 8 show the active power margins for cases a and b, respectively. As the figures suggest the active power margin is improved by introducing PV generation as expected. Although sufficient active power capacity might be available during the contingency events, the failure of reactive power sources such as generators results in voltage violation at some buses due to shortage of reactive power. This is observed when case c is simulated. Figure 9 shows hourly reactive power margins in case b. By comparing Figs. 8 and 9, it can be observed that in some cases even though the active power margin is positive the reactive power margin is negative. Such cases result in voltage violation at power system buses. Though reactive power injection could provide the required reactive power [7],

it may not be an economically viable solution as it is utilized only for the contingency situation.
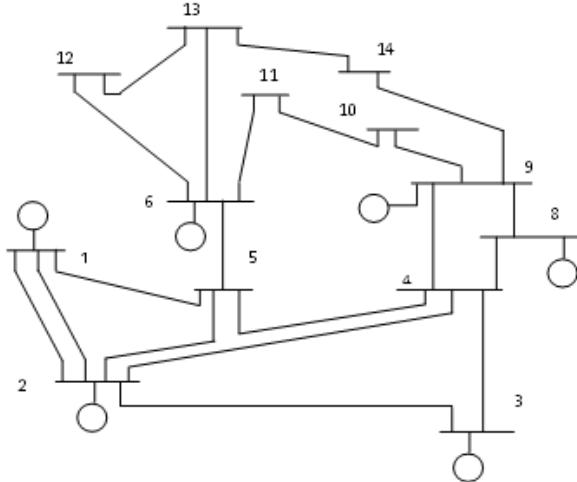

Fig.5 IEEE-14 Bus System

Our approach suggests that the network voltage violations can also be reduced by proper placement of PV generators across the network. It can be shown that the PV generators locations can significantly reduce reactive power demand leading to higher reactive power margins.
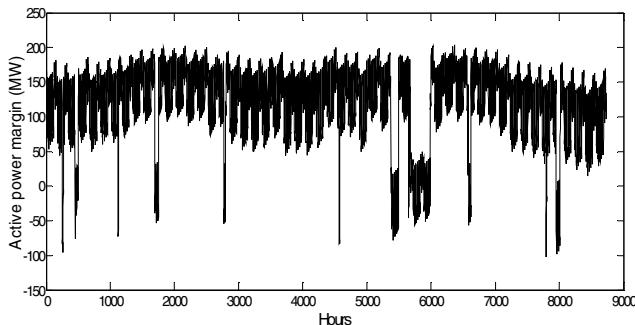

Fig.7 Active power margin without PV

The total EENS due to active and reactive power shortages are obtained hourly as the difference between the load demand and actual maximum active power supplied without reactive and voltage limits violations. This difference is calculated a systematic load shedding where the load is curtailed in small steps of 0.1% while maintaining the initial power factor. Next, by using equations (1) and (2) $EENS_P$ and $EENS_Q$ for the entire year are calculated. Power factors of 0.9 and 0.85 are considered in the study. Different power factors result in different reactive power requirement and network behavior following the contingency. The PV generators, each with 50MW maximum capacity, are placed in four arrangements in the network as follows: 1) at buses 3, 5, and 12, 2) at buses 6, 10, and 12, 3) at buses 5, 10, and 13, and 4) at buses 11, 12, and 13.
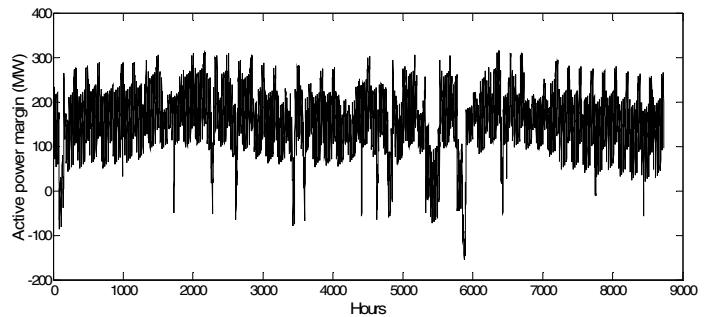

Fig.8 Reactive power margin with PV

TABLE I

GENERATOR RELIABILITY PARAMETER

	No.	Mean time to failure (1/λ) (Hours)	Mean time to repair (1/μ) (Hours)
Generator	1	960	40
	2	960	40
PV	3	1980	20
	4	1980	20
	5	1980	20

The simulation results show that even though PV generators do not supply any reactive power during contingencies, they can improve system reliability by reducing the reactive and active power demand due to reduced losses in the network.

A. Contingency Selection

In large practical power systems the total number of states of the network component is very high. Hence, here the most severe contingencies are selected; that is, the synchronous and solar PV generators failure. Load-flow determines the active and reactive power requirements in the network due to the active and reactive power demands based on the hourly load curve.

When the PV generators are placed at buses 5, 10 and 13 (case 3) Figs. 8 and 9 show active and reactive power margins using hourly load and total system capacity. The hourly generation is based on the synchronous generators active and reactive power limits and PV generators active power limits, according to Fig. 4 at different times of the day. Those contingencies, which violate the maximum generator active and reactive power capacities, are selected. Subsequently, loads are curtailed in very small steps maintaining the power factor till the synchronous generators active and reactive powers as well as PV generators active power limits are met. This load shedding program is utilized to calculate real power load curtailment LC_{Pi} and LC_{Qi} introduced in section III. This procedure is performed for different PV placements and load power factors.
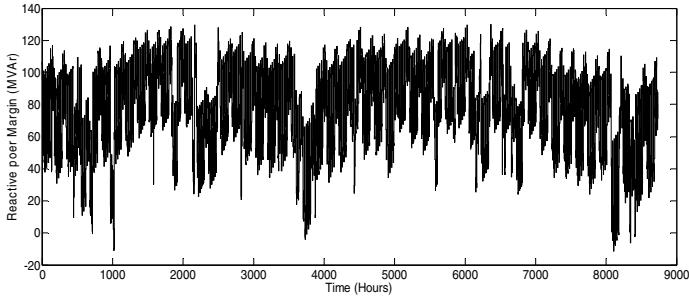
Fig.9 Hourly active and reactive power margin

B. Reliability evaluation procedure

The method explained above is described in a systematical way as shown below in order to calculate reliability indices explained in section III for the three different cases mentioned in section IV.

Step 1) Calculate the instantaneous load active and reactive power demand P_{Di} and Q_{Di} from hourly load curve,

Step 2) Calculate the total required generators active power P_{Gi} and reactive power Q_{Gi} for state i ,(note that PV generators do not supply reactive power) from load-flow,

Step 3) Check the generator active and reactive power limits and network voltages. If they are within the specified limits go to step 8.

Step 4) If there are active power limit violations (because of active shortage,) curtail the load proportionally at all buses till P_{Gi} fall below the generators limits, then update reliability index $EENS_P$,

Step 5) If there are reactive power or voltage violations (because of active or reactive power shortage,) curtail the load proportionally at all buses till P_{Gi} and Q_{Gi} fall below the generators limits, then update reliability indices $EENS_P$ and $EENS_Q$,

Step 6) If all the contingencies are checked, go to step 7; otherwise, go to step 3,

Step 7) Increment the time instant and repeat steps 1 through 6 till the time period under consideration is covered,

Step 8) Update reliability indices.

Table II shows reliability indices when PV generators are locate at buses 6, 10 and 12 (case 2) and under 0.9 power factor. Figure 10 shows the comparison of different PV generators placements where the network power factor is 0.9. It can be seen from Table II that the reliability has improved because of addition of solar PV generators in the system.

However, when we take into account reactive power shortage and voltage violations it is observed that just active power margin calculation does not provide accurate estimate of system reliability. Reactive power shortage results in additional real and reactive power load curtailment to maintain voltages, therefore the actual reliability is lower. Here, the

solution to this issue is proposed as proper location of solar PV generators in the network. It can be observed from Fig. 10 that placing PV generators at bus 3, 5 and 12 (case 1) offers best reliability. For lower power factors the network has higher active and reactive power losses; hence, contribution of PV generators will be even more significant as shown in Table III. For the power factor of 0.85, the best locations for solar PV generators are found to be at busses 5, 10, and 13 (case 3).It can be observed from Table .II and III, that the EENS because of reactive power shortage $EENS_Q$, has increased from 110.4 MWh/yr to 189.2 MWh/yr compared to the case with 0.9 power factor.

TABLE II
RELIABILITY INDICES POWER FACTOR 0.9

	Case A	Case B	Case C
$EENS_P$ (MWh/yr)	21939	9396	9449.2
$EENS_Q$ (MWh/yr)	-	-	110.4

TABLE III
RELIABILITY INDICES POWER FACTOR 0.85

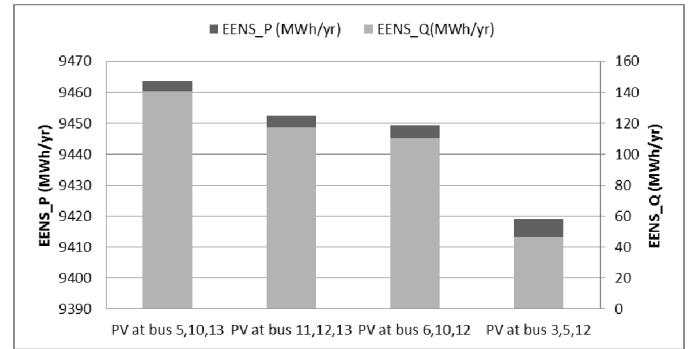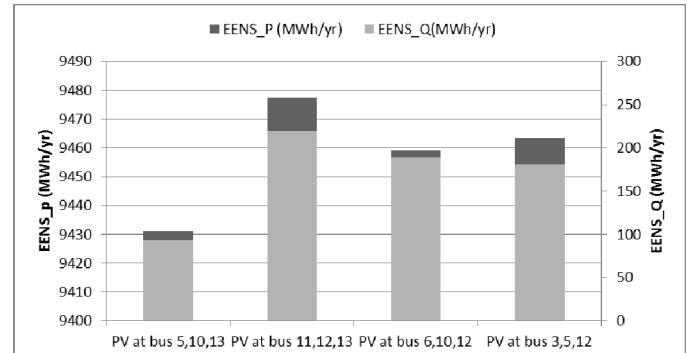|	Case A	Case B	Case C
$EENS_P$ (MWh/yr)	21939	9396	9459.1
$EENS_Q$ (MWh/yr)	-	-	189.2

Fig.10 PV locations and EENS for 0.9 Power factor.

Fig.11 PV locations and EENS for 0.85 Power factor.

C. PV Locations Selection

From Table II it is revealed that adding PV generators in the network improves reliability due to the extra active power available in the network. As discussed in the previous section if placed in proper locations, PV generators can significantly improve reliability by decreasing reactive power demand. Reduced reactive power requirement is the result of reduced reactive power losses in the network. Placement of the PV generators in the network is very important as buses far from the source tend to have voltage violations. Figure 10 shows that the PV generators at bus 3, 5 and 12 (case 1) provide better reliability for 0.9 power factor as EENS is lowest in this case. Also, if larger number of PV generators are utilized in the network, the reliability will further improve. We can observe from Fig.11, that $EENS_Q$ has increased due to more reactive power shortage in the network for the lower power factor of 0.85. As shown in Figs. 10 and 11, the minimum values of $EENS_P$ and $EENS_Q$ are higher with 0.85 power factor compared to 0.9 power factor case. Also, the best reliability in this case is offered by solar PV generators at buses 5,10 and 13 (case 3.) This is very important form the network design point of view and planning perspectives as improper PV locations in the network may not lead to the reliability improvement as expected. In addition, in placement of the PV solar generator, the normal operating power factor should be accounted for as different power factors require different PV locations.

VI. CONCLUSIONS

This paper investigates reliability evaluation of power networks with high penetration of PV generation. Most commercial PV generators do not supply reactive power. Consequently, in the case of failure of synchronous generator, a major source of reactive power, the network may not be provided with the required reactive power resulting in load reduction and reduced reliability. However, in spite of their inability to produce reactive power, PV generators may significantly help overcome load curtailment. Our study suggests that proper network configuration and PV location reduce the active and reactive power shortages by reducing active and reactive power losses. This technique is very simple and more economical to improve reliability of the systems with high PV penetration that does not require additional reactive power compensators.

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