

# Distribution Network Reconfiguration to Increase Photovoltaic Hosting Capacity

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**Abstract**—A stochastic model is developed for analyzing the impact of network reconfiguration on improving photovoltaic hosting capacity (PVHC) of distribution networks. System voltage is used as the criterion to determine the PVHC of the network. The distribution network reconfiguration is modeled as an optimization problem to minimize voltage violations associated with increasing solar penetration in the network. The proposed methodology is evaluated in a three-phase, unbalanced, IEEE 37-node distribution test system. The effect of optimal reconfiguration on PV deployments in specific locations is also investigated. Results show that network reconfiguration could significantly improve PVHC, especially when PV units are located nearer to feeder ends and tie switches.

**Index Terms**—Distribution network, distributed solar, hosting capacity, network reconfiguration.

## I. INTRODUCTION

The power system has been undergoing a dramatic transformation in the last few decades because of the increasing penetration of distributed energy resources (DERs). Among DERs, photovoltaic (PV) devices have become extremely popular over the years. However, the continually increasing presence of PV in the power grid, particularly in the distribution system, is raising concerns regarding the capacity of the current infrastructure to facilitate more of such generating units. Reinforcing the distribution network might become a necessity in the not too distant future. Meanwhile, distribution network reconfiguration (DNR), using manual and remote-controlled switches, can be used as an interim solution to house more DERs in the distribution network.

The main issues associated with the increasing penetration of PV include overvoltage, overloading of the network, and malfunctioning of the system protection and control equipment. The level up to which PV penetration can be increased without affecting the performance of the network is called its PV hosting capacity (PVHC). This index is dependent on the characteristics of the distribution feeder and also on the performance criterion for PVHC evaluation. Different network parameters have been evaluated to assess the impact of DERs on the system, including voltage, thermal loading, and power quality [1], [2]. Violation of these indices is undesirable as it can be detrimental to stable and reliable operations of the network.

Several works in the literature, such as [3], have adopted an optimization-based approach to determine the location and maximum amount of PV to be integrated in the network.

However, this type of approach provides little information on the system-wide capability to accommodate PV. In 2012, the Electric Power Research Institute (EPRI) developed a comprehensive framework to assess the PVHC of a distribution network based on a number of performance indicators [4]. A stochastic analysis method was used in [4], where a number of scenarios of PV deployment were generated and the performance of the network was evaluated.

Following this, several researchers such as those in [5], [6] have used the stochastic model to analyze the PVHC of various distribution feeders. Although different performance indicators can be used to mark the PVHC of a network, voltage violation is often used, as in [7], since it is the most limiting factor for increasing PV penetration. Some works, for example [8], have extended EPRI's framework to derive signature maps demarcating a feeder into different regions based on the risk of violating performance parameter limits.

The stochastic analysis tool has set forth a new wave of research activities focusing on methods to improve the PVHC of feeders. In [9], [10], volt-var compensation has been used to improve the PVHC using the smart inverter associated with PV units. Besides this, tap changing transformers and voltage regulators were also used to maximize the PV penetration in the network as in [11].

Another viable alternative is to exploit the network reconfiguration technology to expand the PV accommodation capability of distribution networks. Some works such as [12] have used DNR to maximize PVHC. However, these studies have focused on PV installation at predefined sites in the network. The uncertainty in the number and location of PV plants in the network are not considered. Therefore, the PVHC derived is solely based on the knowledge of potential locations and does not account for the capacity of the system as a whole.

To this end, this paper seeks to explore how network reconfiguration could affect PVHC in distribution networks using a stochastic model. We first begin with the stochastic analysis of the PVHC of a distribution network. Further, the effectiveness of using network reconfiguration for increasing the PVHC in the feeder is studied. Finally, the analysis is narrowed down to specific scenarios to exhibit the reconfiguration scheme and its accompanying benefits. The hypothesis in this work is that whenever a distribution system operator is presented with any potential locations for PV deployment, there exists a mechanism to alter the topology of the network to the best-

suited configuration for the scenario.

The remainder of the paper is organized as follows: Section II describes the methodology of using network reconfiguration to improve PV hosting capacity. Case studies and results on the IEEE 37-node test feeder are discussed in Section III. Conclusion and potential future work are discussed in Section IV.

## II. PROBLEM FORMULATION

### A. Scenario-based PVHC Analysis of Distribution Network

The PVHC of a distribution feeder is defined as the maximum amount of PV that can be accommodated without adversely affecting the network performance during operation. This index, however, is not singular and is usually characterized as a range extending from the minimum feasible HC to the maximum possible penetration which the system can withstand. The PVHC limits are unique to each feeder and correspond to the feeder topology, voltage level, loading, and presence of power conversion elements such as capacitors and regulators in the network. Although different parameters can be used as the HC evaluation criteria, voltage is the most significant one and is commonly used to gauge the capacity of the network.

A modified version of the algorithm derived from [4] is adopted in this paper for analyzing the PVHC of a feeder. Algorithm 1 describes the methodology used in the study. This procedure, although time-consuming, is quite capable of capturing the uncertainty in location and rating of PV generation employed in the network.

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#### Algorithm 1 Stochastic analysis of PVHC using the Voltage criterion

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- 1: Randomly generate scenarios: number and locations of PV
  - 2: **for** Every scenario generated **do**
  - 3:   **for**  $step = 0, 0.2, 0.4 \dots, 1$  **do**
  - 4:      $PV_{penetration} \leftarrow maxLoadLevel * step$
  - 5:     Assign penetration level to PV units
  - 6:     Run system power flow with PV integration
  - 7:     Collect computed voltage at all nodes
  - 8:     Store the maximum node voltage
  - 9:     Calculate percentage of nodes with overvoltage
  - 10:   **end for**
  - 11: **end for**
  - 12: Identify the acceptable, feasible, and unacceptable PV penetration levels based on the voltage threshold.
  - 13: Determine the minimum, maximum, and median PVHC of the network.
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### B. Reconfiguration of Distribution Network

Despite being introduced as a mechanism for loss minimization, DNR is slowly gaining momentum in other domains as well. One such area of interest is in the enhancement of PVHC of distribution networks.

Reconfiguration is essentially a Mixed-Integer Nonlinear Programming problem with complex constraints. The aim is

to determine the status of different switches in the network. The switches can either be a sectionalizing (status=1) or tie (status=0) switch. Hence, the problem is binary in nature. The Binary Particle Swarm Optimization (BPSO) with selective search space [13], [14], has proved to be efficient over the years and is therefore adopted for DNR in the current work. The flow chart of the network reconfiguration scheme is described in Fig. 1.

1) *Objective*: Reconfiguration is employed in this work to curb the voltage violations when DERs (particularly PV) are integrated into the feeder. Therefore, for each scenario of PV deployment, the optimal configuration that minimizes the percentage of overvoltage in the network is to be determined. This involves the calculation of feeder exposure to overvoltage, given by:

$$OV_{exposure}\% = \frac{N_{node_{violations}}}{N_{nodes}} * 100 \quad (1)$$

where,  $N_{node_{violations}}$  is the number of nodes in the network that violate the voltage threshold;  $N_{nodes}$  is the total number of nodes in the network.

2) *Power Flow Constraints*: For a configuration to be feasible, there must exist both active and reactive power balance at each node. This can be represented in a vector form as:

$$BP = N_D \quad (2)$$

where,  $B$  is the Branch Node Incidence Matrix;  $P$  is the vector of branch power flows;  $N_D$  is the net load at all nodes in the network.

3) *Radiality Constraint*: The topology of the distribution network must have a radial structure. This requires that the tie switch combinations do not form any loops in the network. This constraint can be implemented in the algorithm by using a technique known as loop breaking which is described in [14]. Mathematically, the constraint is expressed as:

$$N_{branches} - N_{buses} + 1 = 0 \quad (3)$$

where,  $N_{branches}$  is the number of branches and  $N_{buses}$  is the number of buses in the network.

4) *Connectivity Constraint*: There must exist at least one path from each node to the source, i.e., no node should be left unconnected to the main network structure, which is represented by its equivalent graph.

### C. Increasing PVHC with Network Reconfiguration

Reconfiguration is used as an enhancement technique in the PVHC analysis of the network. This implies that whenever there is a violation of the limit set on the performance parameter, an optimal topology management by altering the status of switches will be performed. A stochastic analysis approach is used to manage the uncertainty in the locations and sizes of PV units by considering a large number of potential scenarios. In each scenario, the voltage limit of the network is tested and in case of violation, DNR is utilized to alleviate the stress on the network.

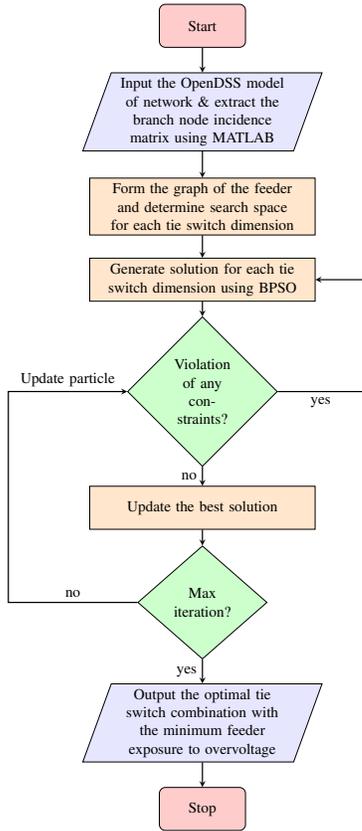


Fig. 1. Flowchart for optimal network reconfiguration

Algorithm 2 describes the methodology to evaluate PVHC of a network when reconfiguration is used as an enhancement technique.

**Algorithm 2** Scenario-based evaluation of network PVHC with reconfiguration

- 1: Random generation of scenarios
- 2: **for** Every scenario generated **do**
- 3: Incremental increase in PV penetration
- 4: Run system power flow with PV integration
- 5: Determine the maximum of computed voltage at all nodes:  $V_{max}$
- 6: **if**  $V_{max} > V_{threshold}$  **then**
- 7: Perform optimal network reconfiguration
- 8: Determine  $V_{max}$  and  $OV_{exposure}$  as in Eq. 1 for the new topology
- 9: **else**
- 10: Determine  $V_{max}$  and  $OV_{exposure}$  for the current configuration
- 11: **end if**
- 12: **end for**
- 13: Determine the minimum, maximum, and median PVHC based on  $V_{threshold}$

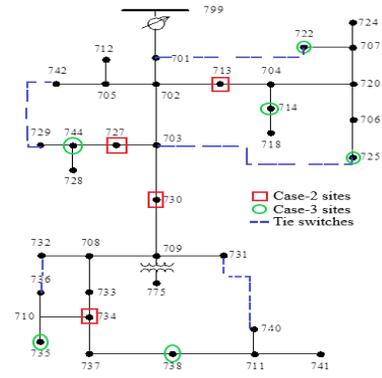


Fig. 2. Modified IEEE 37-node test feeder

III. CASE STUDIES

The proposed PVHC enhancement methodology is tested on the modified IEEE 37-node distribution test feeder which is an unbalanced system with an operating voltage of 4.8 kV and a rated load of 2.6 MW. The network is modified to accommodate five normally open tie switches as illustrated in Fig. 2, and sectionalizing switches are presumed to exist on the normally closed lines. Further, the network performance with PV integration is evaluated using the OpenDSS software developed by EPRI [15]. Four case studies are performed to evaluate the benefit of DNR in PVHC improvement.

A. Case 1: Impact of DNR on System PVHC

The PVHC of the IEEE 37-node test feeder is evaluated using the stochastic approach described in Section II, and the result is presented in Fig. 3. The minimum, median, and maximum PVHC of the network are 1,120 kW, 6,260 kW and 11,400 kW, respectively. When incorporating the optimal reconfiguration strategy at scenarios generated in this model, an increase in the network PVHC is observed. The minimum, median, and maximum PVHC, in this case, are 2,136 kW, 7,208 kW and 12,280 kW, respectively. Fig. 4 shows the evaluation result of network PVHC with DNR as an enhancement tool.

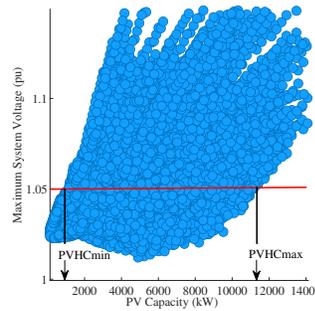


Fig. 3. Scenario-based PVHC analysis without reconfiguration

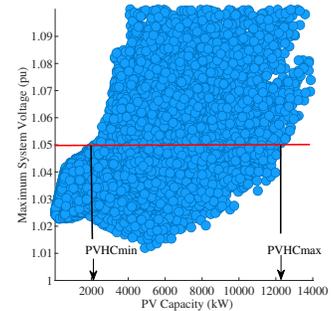


Fig. 4. Scenario-based PVHC analysis with reconfiguration

### B. Case 2: Integration of PV at Four Locations

In this case, one particular potential scenario is considered where PV units are deployed at four sites as marked in Fig. 2. The PV sites are concentrated towards the center of the feeder in the normal layout and away from the normally open tie switches. Fig. 5 shows the rise in the maximum system voltage with increasing PV penetration. It is observed that the maximum system voltage is reduced by network reconfiguration and the PV capacity limit at the voltage threshold (1.05 pu) is increased from 4,318 kW to 4,820 kW. It is also seen from Fig. 6 that DNR reduces the percentage of feeder exposure to overvoltage.

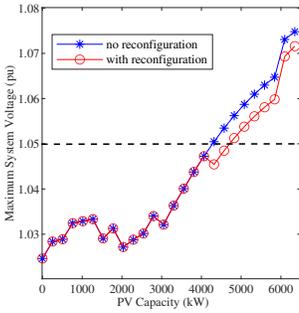


Fig. 5. Maximum Voltage in the feeder with increasing PV capacity for case 2

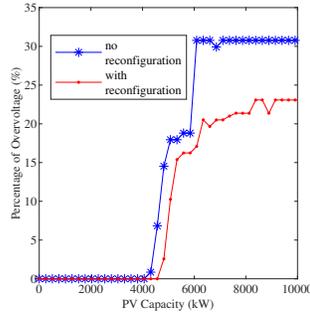


Fig. 6. The percentage of overvoltage in the feeder with increasing PV capacity for case 2

### C. Case 3: Integration of PV at Six Locations

In Case 3, the PV units are deployed at six locations as depicted in Fig. 2. These units are situated closer to the feeder ends and tie switches in the normal topology of the network. The effect of DNR in reducing the maximum system voltage with increasing PV penetration is presented in Fig. 7. It is observed that the network reconfiguration is able to reduce the maximum system voltage, thereby increasing the PV capacity limit at the voltage threshold (1.05 pu) from 4,850 kW to 5,650 kW. Also, the benefit of DNR in reducing the feeder exposure to overvoltage is more pronounced in this case as illustrated in Fig. 8.

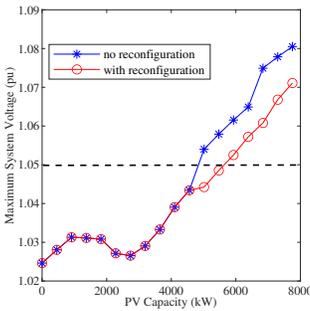


Fig. 7. Maximum Voltage in the feeder with increasing PV capacity for case 3

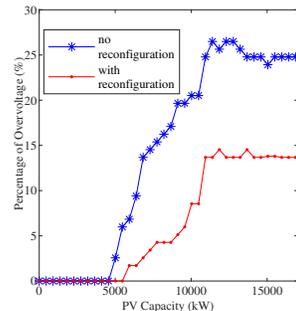


Fig. 8. The percentage of overvoltage in the feeder with increasing PV capacity for case 3

It is observed that in case 3, when the PV plants are located nearer to feeder ends and normally open tie switches, the percentage increase in the PV capacity limit by network reconfiguration is 16.5%. Whereas in case 2, when the PV units are concentrated away from the feeder ends, reconfiguration results in 11.6% increase in the PV capacity limit.

The switching decisions which resulted from the optimal network reconfiguration algorithm (i.e., BPSO) for the cases 2 and 3 are summarized in Table I. For the first case, the reconfiguration strategy is dependent on individual scenarios and hence is not provided in Table I. Each switch dimension in the decision table corresponds to a tie switch (status=0) for the configuration.

TABLE I  
SWITCHING DECISION

	Tie switches with nodes
Case 2	704-720 , 705-742 , 733-734 , 710-734 , 703-725
Case 3	705-742 , 708-732 , 704-713 , 731-740 , 703-725

### D. Case 4: Impact of DNR on Locational PVHC

The PVHC discussed so far involves the presence of more than one PV units. Although it is evident from the previous cases that PVHC is highly location-dependent, to further explore this characteristic, the impact of PV integration on individual system nodes is analyzed. Initially, a PV sweep analysis is performed whereby a PV unit of 2 MW is connected to one node at a time and the corresponding maximum system voltage is noted. The resulting voltage map of the feeder is represented in Fig. 9. It is observed that the nodes at the feeder end are subjected to overvoltage.

In Fig. 10, the system nodes are clustered based on the maximum PV capacity that can be installed at each individual node without violation of voltage criterion. As evident from the figure, the nodes at the end of the feeder have a limited capacity to accommodate PV. However, this limitation can be alleviated by exploiting the reconfiguration technology. The percentage increase in PVHC of each node by employing DNR

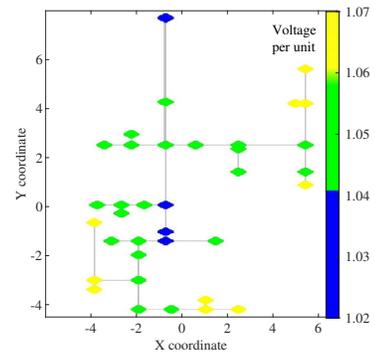


Fig. 9. The circuit plot with nodes marked to represent the maximum system voltage variation with PV integration

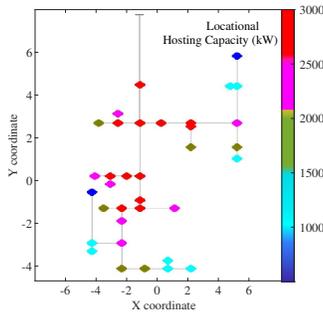


Fig. 10. Circuit plot with nodes marked to represent locational PVHC

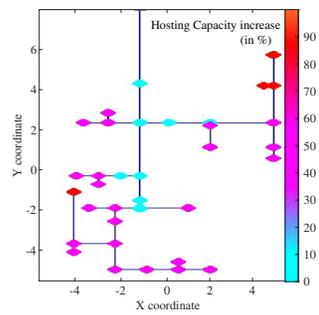


Fig. 11. Circuit plot with nodes marked to represent increase in PVHC with reconfiguration

is represented in Fig. 11. It is seen that DNR aids in increasing the node-based PVHC to an extent particularly for those at the end of the feeder.

During the analysis, the nodes in close vicinity often relied on the same topology for attaining the maximum PVHC. As a result, the nodes are classified into different sets. The resulting switching decision along with the set of nodes is presented in Table II. It is noted that the extreme end nodes have unique switching decisions. The table does not include nodes such as 701, 702, 775, since their PVHC cannot be increased with DNR.

TABLE II  
SWITCHING DECISION FOR LOCATIONAL PVHC ANALYSIS

Set	Nodes	Tie switches
1	703, 727, 730, 709	705-742, 710-734, 701-722, 706-725, 709-731
2	713, 704, 714	727-744, 710-734, 707-722, 703-730, 737-738
3	706, 720, 725	703-727, 733-734, 707-722, 703-730, 711-740
4	712, 742	702-703, 710-736, 707-722, 706-720, 711-738
5	707, 722, 724	729-742, 710-734, 701-702, 703-725, 734-737
6	708, 732, 733	729-742, 708-732, 701-722, 706-725, 738-711
7	710, 735	705-742, 732-736, 701-702, 706-725, 709-731
8	711, 738, 740, 741	729-744, 708-732, 701-722, 703-725, 708-709
9	734, 737	702-705, 710-734, 704-720, 706-725, 731-740
10	728, 729, 744	702-705, 732-736, 707-722, 706-720, 734-737
11	718	702-705, 710-736, 707-722, 703-730, 709-731
12	731	705-742, 708-733, 707-722, 706-725, 734-737
13	736	729-744, 733-734, 707-722, 706-720, 709-731

#### IV. CONCLUSION

This paper studied the capability of distribution network reconfiguration to enhance the PV hosting capacity. A stochas-

tic approach was used to account for the uncertainty in the number, location, and size of PV plants. We found that network reconfiguration was able to reduce system voltage violations, thereby improving the network capacity to host PV generation. Different PV deployment scenarios and the associated impacts on system voltage were also investigated. It was interesting to find that reconfiguring the topology of the network could significantly improve the PV hosting capacity, especially when PV units are located nearer to feeder ends. The reconfiguration scheme used in this model, however, is static in nature and based on the potential PV deployment scenario. This could be further extended by considering dynamic and real-time network reconfiguration to improve system performance during system operations.

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