Fast Feeder Hosting Capacity using Swarm Based Intelligent Distribution Node Selection

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Abstract— **High penetration of renewable energy (RE) is highly expected for sustainable green power system. Photovoltaic (PV) is the most suitable form of renewable generation in present distribution system. However, in an existing feeder, the amount of PV accommodation is limited because of utility-established acceptable voltage limit, voltage unbalance, transformer rating, line thermal overloading limit, regulation equipment, protection co-ordination, feeder configuration, load profile and more. It is important for feeder operation and planning to calculate the amount of PV that can be hosted inside an existing feeder subject to satisfy voltage limit, thermal limit, and protection criteria – often referred to as feeder hosting capacity (FHC) or PV hosting capacity. PV has uncertainty due to inherent nature and further, PV ramp rate is much faster than regulator response time. Therefore, it is common practice to consider worst-case scenario. Usually FHC is a complex power system optimization problem using steady state calculations. It is not possible to explore all possible scenarios in a practical timeframe. Therefore, multiple pre-defined scenarios are generated from random Monte Carlo simulation. However, the authors propose a swarm based intelligent scenario (location) selection from local and global search experiences for faster and better solution. Simulation results show effectiveness of the proposed method.**

***Index Terms*— Feeder Hosting Capacity, Photovoltaic, PSO, Swarm Based Intelligent Selection, Local & Global Search, ETAP, Monte Carlo, PV Hosting Capacity, Distribution Feeder Hosting Capacity Analysis.**

NOMENCLATURE

ANSI	American National Standards Institute
Dmax	Max system load
EPRI	Electrical Power Research Institute
FHC	Feeder Hosting Capacity
Gbest	Global best
Pbest	Local best
Region C	More than 105% volt region in FHC [Fig. 2]
N_{pre}	Predefined number of trials at Region C
[$N1, N2, \ldots, Nn$]	State variable nodes for PV penetration
PSO	Particle Swarm Optimization
Vmax	Max system voltage after any PV penetration

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I. INTRODUCTION

RENEWABLE energy (RE) is mostly intermittent and non-dispatchable. Secondly, distributed RE back flows power to the grid and the grid was not designed for that. Therefore, high PV penetration brings technological challenges to the existing power grid, such as voltage rise, thermal overloading, protection malfunctions, power quality issues [1-10] and so on. Although rooftop small scale PV system is being continuously added in distribution system every day without through analysis of its impact. Most utilities accept a 15% PV penetration threshold [11] with respect to peak load. However, this criterion does not take into account PV locational impact or individual feeder characteristics.

High PV penetration induces voltage rise due to reverse power flow caused by PV power. However, ANSI C84.1-2011 recommends that the voltage of residential loads should remain within ±5% from its nominal value under normal operating conditions [12].

High penetration of distributed energy resources (DERs) has potential impact on distribution system. The amount of DER a feeder can accommodate depends upon many factors including DER characteristics, location of the DER along the feeder, feeder operating criteria and control mechanisms, and electrical proximity of DER to other DER systems [13]. A feeder response is checked to determine the total amount of DER that will cause an adverse impact to the feeder. . Feeder hosting capacity (FHC) or Hosting Capacity Analysis (HCA) is the amount of DER that can be accommodated at a given time and at a given location. The capacity must exist to 'host' DER without adversely affecting power quality or reliability under current configurations and without feeder upgrades or modifications. FHC is feeder specific, location dependent and time varying. For DER penetration, FHC does not allow voltage violations, thermal overloads, protection malfunctions and decreased quality/reliability. High penetration also needs excessive regulator operations. To calculate all those mentioned factors for FHC, a detailed and accurate model of entire distribution system is needed. FHC study helps utilities to make timely decisions for PV interconnection requests and ensure that distribution grids continue to operate reliably [14].

EPRI with collaborators is currently putting multiple efforts throughout the U.S. to assess how future high penetration DER integrates into distribution feeders of various types, load mixes, and solar characteristics [15-30]. FHC may dynamically change

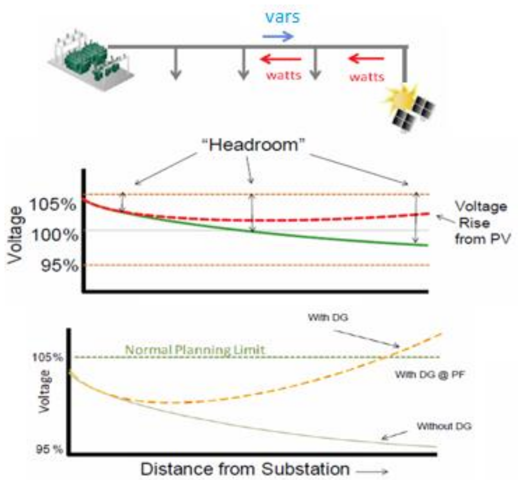

Fig. 1: Voltage profile along the feeder with and without PV [collected].

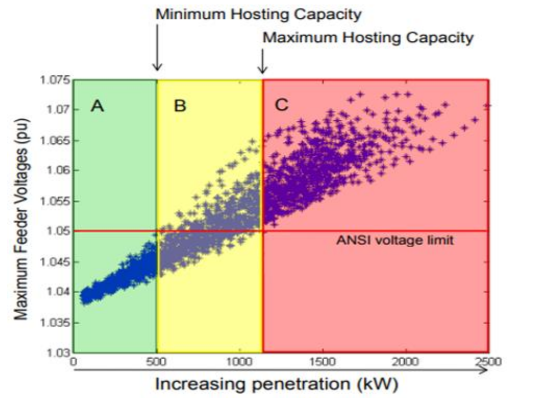

Fig. 2: Voltage spectrum for random PV penetrations [31].

over time due to normal feeder growth and reconfiguration. Though other forms of DER are available, the discussions in this paper are limited to PV hosting capacity only.

Different methods have been proposed to determine feeder hosting capacity. Some methods are stochastic [31-32]. In [33], feeder hosting capacity is calculated at the end of the feeder. Some runs selected scenarios of extreme cases [34].

On the other hand, swarm based methods, e.g., particle swarm optimization (PSO), has a guided search property for optimization and has already been used in engineering applications [35-40]. It is easy to implement and does not require gradient information of objective functions. It can explore more search spaces and can avoid local optima gradually. Complete AC load flow is solved for each scenario to obtain accurate analysis. Multi-core parallel processing is utilized in these calculations for faster execution.

The rest of the paper is organized as follows. In Section II, FHC is defined. The proposed FHC method using intelligent selection is described in Section III. Simulation data and results are reported and discussed in Section IV. Finally, conclusion is drawn in Section V.

II. Feeder Hosting Capacity

Feeder hosting capacity is the amount of DER and location that can be accommodated without adverse impact under current configurations and without feeder upgrades or modifications. FHC is not a straightforward process nor a single value for any given feeder [1]. FHC analysis depends on

- size of PV,
- location of PV,
- feeder characteristics,
- electrical proximity to other PV,
- unique solar resource characteristics in the area,
- PV control,
- protective coordination,
- regulation equipment (switch cap, voltage regulator, inverter) control and
- feeder configuration.

In this paper, PV locations and size are state variables and others are fixed.

Figure 1 shows voltage profile of a feeder with and without PV penetration. High PV penetration has the following impacts:

- voltage,
- protection,
- thermal loading,
- reliability and
- power quality.

Only voltage constraint is satisfied in this FHC paper and others are ignored for simplicity.

Typically, scenarios are generated randomly for each PV penetration. FHC is the worst case scenario. It takes many trials to reach the worst case or a near worst case scenario from random selection. For each scenario, a load flow is solved to find the maximum (worst) voltage of the system. Then maximum voltages of scenarios are plotted with respect to increasing penetration for visualization like Fig. 2. As thousands of random scenarios are possible, it takes long time for a large distribution system. Figure 2 shows a typical maximum voltage spectrum of a distribution system for FHC calculations.

III. Proposed Feeder Hosting Capacity

Instead of random, a swarm based intelligent scenario is explored for PV penetration in the proposed FHC method. It is inspired by particle swarm optimization [36]. The nodes where PV can be installed, is indicated as state variable nodes [*N*1, *N*2, …, *Nn*]. PV size at each state variable node is pre-defined or calculated from connected loads or PV inverters. For each penetration level, a local max voltage node (*Pbest*) and a global max voltage node (*Gbest*) are maintained to explore a new scenario. *Gbest* is the max voltage node of all previous scenarios. *Pbest* is the max voltage node of current scenario only. If *Pbest* is the same as *Gbest*, take next highest voltage node as *Pbest*. To generate scenarios for a specific amount of PV penetration, *Gbest and Pbest* nodes are always taken first with probability one. Then other are selected randomly from state variable nodes to fulfil the penetration. FHC mainly involves steady state power system calculations. In this study,

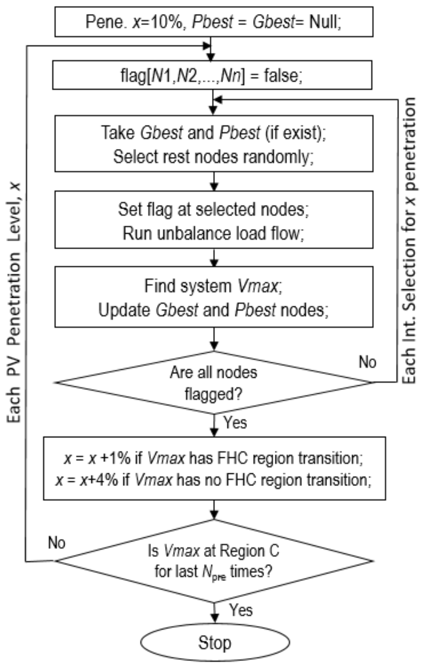

Fig. 3: Flowchart of FHC using swarm based intelligent selection.

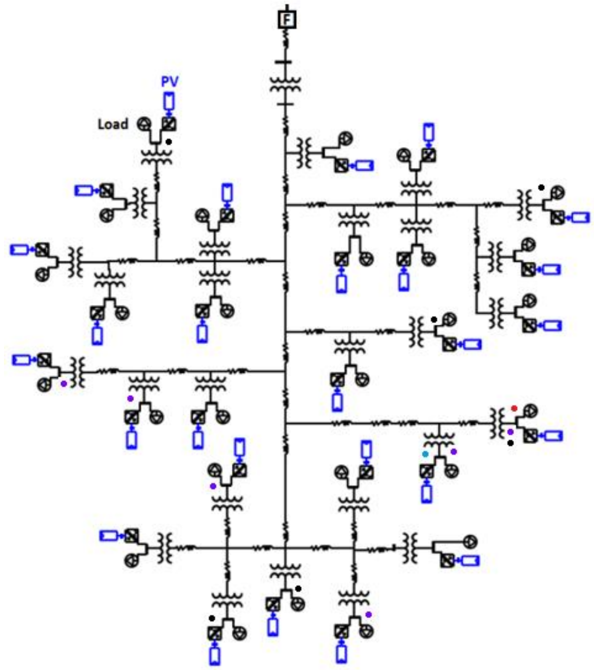

Fig. 4: ETAP one-line diagram of a distribution system with PV.

a complete unbalance AC load flow is run for the explored intelligent scenario for accurate results.

Pseudo-code for proposed FHC:

- Step 1 Calculate max system load *Dmax*. Get state variable nodes [*N*1,*N*2,…,*Nn*]. Penetration *x*=10% (of *Dmax*) PV. Assign *Pbest*= *Gbest* =Null.
- Step 2 flag[*N*1,*N*2,…,*N*n]=false.
- Step 3 Take always *Gbest* and *Pbest* nodes first. Then rest of the nodes will be selected randomly [*n*1,*n*2,…,*ni*] to fulfil *x* penetration.
- Step 4 Install PV at [*Gbest*,*Pbest*,*n*1,*n*2,…,*ni*] and set flag flag[*Gbest*,*Pbest*,*n*1,*n*2,…,*ni*]=true.
- Step 5 Run full AC load flow. Find max system voltage *Vmax* for current *x* PV penetration.
- Step 6 Depending on *Vmax*, update *Gbest* and *Pbest.*
- Step 7 Go to Step 3 if at least one node from [*N*1,*N*2,…,*Nn*] is not yet flagged (selected).
- Step 8 Increase penetration *x* by small (1%) step if *Vmax* is in region transition; otherwise, increase penetration *x* by large (4%) step.
- Step 9 If *Vmax* of all scenarios are at Region C for a predefined N_{pre} consecutive penetration levels then stop; otherwise, go back to Step 2.

Flowchart of the proposed method is shown in Fig. 3. Pseudo-code is also given with data structure for clear understanding. All the numerical values mentioned in flowchart and pseudo-code are chosen from previous experience. There is no hard and fast rule for those values. Instead of typical random selection, PSO inspired *Gbest* and *Pbest* are included in Steps 3 and 4. It takes less number of trials than random selection to find worst or near to worst case scenarios.

IV. Simulation Results And Discussions

Utility-established max voltage threshold plays an important role in FHC. According to ANSI standard, maximum 105% voltage is acceptable at customer end [12]. A residential distribution feeder of 1477 kW max unbalanced loading is investigated. The system is shown in Fig. 4. The feeder is modeled by 70 nodes in ETAP [41]. All loads are connected at secondary side of distribution transformers. GIS co-ordinates and branch impedances are not shown for simplicity. PVs are installed at rooftops behind the meters. Therefore, a system of DC PV with inverter is connected at each load node for simulation. However, the PV size is set to zero if the connected node of that PV is not selected for renewable energy penetration in simulation process. In this research, inverters operate at unity power factor. Smart inverters are still expensive and are not commonly used. Therefore, California Rule 21 is not considered here.

In the worst case scenario, PV can ramp from zero to full output instantly; however, voltage regulating devices, e.g., sub-station LTC, voltage regulator and switch capacitor, cannot react instantly. Moreover, to compare the proposed method with standard methods, voltage regulating devices are kept constant.

Please note that FHC searches for the worst case scenario, not the best case scenario. Selected penetrations from 28% to 116% are shown in Fig. 5 for FHC. At 40% PV penetration, the proposed swarm based intelligent method explores scenarios where system voltage varies from 104.11% to 104.79%. However, for the same 40% PV penetration, the typical random method explores scenarios where system voltage varies from 103.84% to 104.10%. At 100% PV penetration, system

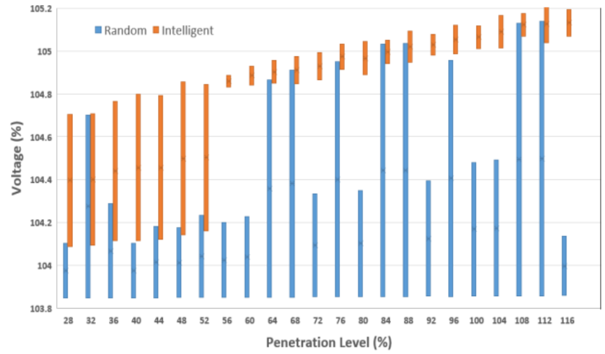

Fig. 5: Max system voltage for intelligent and random selections.

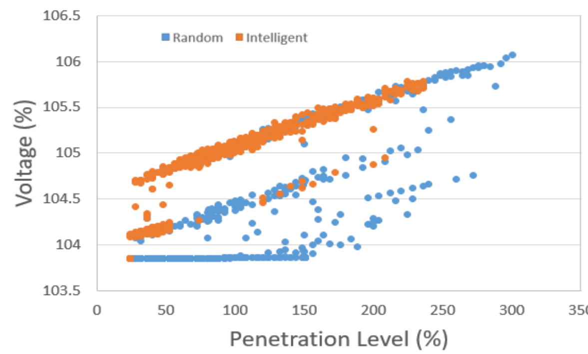

Fig. 6: Voltage spectrum for feeder hosting capacity.

maximum voltage varies from 105.01% to 105.11% and 103.85% to 104.48% for the proposed intelligent method and typical random method respectively. Table I shows results of some other PV penetrations. In random selection, system maximum voltage is completely random. Even though penetration is increasing, max voltage is randomly increasing and decreasing. On the other hand, system maximum voltage is continuously increasing with respect to increasing PV penetration in intelligent selection, which is expected. Therefore, the proposed method is directed and guided selection instead of typical random selection.

At the beginning of 60% penetration, *Gbest* and *Pbest* nodes are shown in red and green dots, respectively in Fig. 4. Usually *Gbest* node is the longest distance node from the feeder head with the maximum feedback voltage (104.84% here) over all previous penetration levels. However, *Gbest* and *Pbest* nodes are continuously updated. On top of *Gbest* and *Pbest* nodes, the proposed method selected other nodes randomly and are shown in purple color dots in Fig. 4 for the worst case scenario of 60% penetration. However, nodes with black dots are selected randomly by typical random method for the worst case scenario of 60% penetration. Fortunately, it randomly selects *Gbest* and thus that result contents the max voltage among other selections.

TABLE I: SYSTEM VOLTAGE (%) COMPARISON

	32% PV	40% PV	60% PV	80% PV	100% PV
Random Selection	103.84-104.70	103.84-104.10	103.85-104.22	103.85-104.34	103.85-104.48
Int. Selection	104.09-104.70	104.11-104.79	104.84-104.93	104.89-105.04	105.01-105.11

Table I shows system maximum voltage comparison for different penetration. Swarm based intelligent selection is very effective as it has both local and global best selection abilities. Therefore, the proposed swarm based intelligent method always explores expected higher voltage results than typical random method.

Figure 6 shows the spectrum of voltage with respect to PV penetration. Minimum FHC is 81% penetration of 1477kW load, i.e., 1196kW PV power using typical random selection where there is no voltage limit violation. However, minimum FHC is only 73% penetration of 1477kW load, i.e., 1078kW PV power using intelligent selection where there is no voltage limit violation up to 73% penetration but voltage violates at 81% penetration. FHC is 1196kW and 1078kW using random selection and intelligent selection respectively. Therefore, the proposed method calculated more conservative and accurate FHC than completely random method. FHC using random and intelligent selections is reported in Table II.

TABLE II: FEEDER HOSTING CAPACITY COMPARISON

	Loading (kW)	FHC (%)	FHC (kW)
Random Selection	1477	81	1196
Int. Selection	1477	73	1078

Figures 5 and 6 show how PV penetration affects FHC. Results of intelligent and random selections differ at each penetration level. Significant differences are reported for higher penetrations. Random selection cannot explore worse locations quickly. In limited number of trials, FHC results using random selection are less accurate as many important locations are not included in this process. However, the proposed intelligent selection method pays attention on worse locations. It explores more critical locations efficiently. Therefore, FHC using the proposed method is more accurate.

PV ramp rate is much faster than regulator response time. Large solar PV can change voltage faster than feeder regulation equipment can respond, thus resulting in potential over voltages. Duration and amount of voltage deviation is significant because in the worst case, PV can ramp from zero to full output instantly before regulation equipment operates (in a minute range). Therefore, minimum FHC is important for operation and planning of a utility.

V. CONCLUSION

Intelligent selection explores higher voltage worse case scenarios more than typical random selection. Considering recent high distributed renewable energy penetrations, feeder hosting capacity is an important tool to operate a feeder under utility-established thresholds without any adverse impact. A feeder should have sufficient feeder hosting capacity so that its customers can add their own PV in the system. Feeder hosting capacity should be re-calculated over time as feeder configuration, loading and equipment are changed. It indicates the feeder potential for maximum green power export to utility. Finally, FHC results are also used to make plan for required feeder update.

Smart inverters can increase FHC. In future, the authors will publish on FHC with smart inverter using swam based intelligent selection.

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