Distributed Generation Hosting Capacity

Solar PV Integration Issues - Review

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***Abstract* — Distributed generation (DG), specifically, solar photovoltaic (PV) systems have dramatically increased during last decade and still continue to increase. While the addition of distributed renewable generation into power systems helps to meet increasing demand and decrease dependency on fossil fuel, there are number of challenges that needs to be considered for planning and integration of distributed renewables into power systems. Integration of large scale solar PV into power systems has several impacts on voltage profile, power quality, and reliability of the power system. One of the important tools for analyzing of these issues is using a hosting capacity approach which will define maximum amount of DG for the given power distribution network.**

Keywords — Distributed generation, curtailment, hosting capacity, harmonic distortion, dynamic loading, power quality, grid reliability, solar PV, voltage profile

I. INTRODUCTION

Power systems structure has been changing from integrated to decentralized generation. Generation units are to being owned by small entities and to the added bulk power distribution network which creates a competition among power producers. Transmission and distribution networks are still naturally monopolized [1]. Also, the electricity generated from renewable resources is replacing the electricity generated from fossil fuels. Small generation units are increasing at distribution level. These changes in power systems will bring challenges and have several other impacts to the operation, protection, and planning of the on power system. The amount of DG that can be connected to the distribution network depends on several factors, parameters such as characteristics of the generation units, configuration and operation of the network, the requirements of the existing load, and regional normative grid requirements [2]. There are different indicators in power systems which might be restrictive for increasing hosting capacity of the DG. These indicators include over/under voltages, overloading and losses, power quality issues, harmonics, protection and current quality issues [3]. The performance indicators such as power quality measurements like voltage variations and risk of overload can be used to measure the possible impacts from DG in distribution network. Thus, the hosting capacity can be defined as the maximum amount of generation that can be integrated until the performance becomes unacceptable [2]. Integrating distributed renewable generation like solar PV has even more challenges comparing the traditional DG systems. The intermittency and difficulty of prediction which occur different timescales make it difficult to control and planning of the power system. Integration of distributed PV systems into distribution network has potential impacts on distribution system performance. Introducing large amounts of solar PV has several impacts and depends on the feeder size, location of the PV along the feeder, feeder electrical characteristics, control equipment, number and size of the other PV systems installed nearby [4]. Other concerns of PV integration could be steady state overvoltage and line loading violations. Besides impacts, the increasing PV integration has several benefits such as improving systems losses and voltage profiles [5]. In this review paper, the integration of DG into power system and hosting capacity is presented from recent studies. Increasing of PV system impacts on distribution network and PV hosting capacity calculations depending on the feeder characteristics is also provided in detail. First, the increasing of the hosting capacity of DG by curtailment of renewable energy resources presented considering two limit settings: overvoltage and overcurrent [2]. Next, the methodology for determining the hosting capacity based on harmonic distortions presented [3]. Finally, the locational dependence of the PV hosting capacity based on feeder load and voltage impacts of PV on two selected distribution feeders are discussed from resent publications [5], [4].

II. HOSTING CAPACITY IMPROVEMENT

The potential increase of the renewable integration hosting capacity into existing regional distribution network is studied in ref [2]. The network is located in Sweden which has 1TWh annual capacity with 10-130 kV voltage level. Approximately 10% of the consumption in this network comes from installed 40MW wind power and 20 MW hydropower. The measurement data is collected from two complete calendar years. The parameters for the voltage limits and transformer tap changer settings were chosen close to utility practice. Load flow calculations were done by using commercially available power system simulation software [2].

Several considerations are taken into account for hosting capacity limits such as power quality parameters, equipment specifications, and customer service specifications. In order to define the hosting capacity limits. The first consideration is transformer rating limit which was between 30 and 60MVA for this network. Voltage limit was chosen from operated voltage as 132kV and from the new generation should not increase by +/- 5%. So the hosting capacity voltage limit taken as +/-5%. The line currents are calculated and compared maximum allowable currents that line cable handle, and the resulted current limits for overhead lines were defined as 290 and 480 amperes [2].

During the simulation, various renewable generations sources are considered in the system such as: Bio energy from CHP plant, wind power, hydropower, solar PV.

The hosting capacity of the network was studied with different scenarios of mixed combinations of following renewable generation: constant production (bio), existing wind and hydropower, wind (100%), wind (50%) + hydro (25%) + Solar (25%), wind (50%) + solar (50%).

The results of the hosting capacity calculations show that transformer's rating power is one of the limiting factor for the hosting capacity. If the transformer's capacity increased then the overcurrents will be limiting factor for hosting capacity comparing to overvoltages because tap changers of the transformers will maintain the voltages at desired values. Installed capacity of renewable resources may be increased, but the total energy produced will decrease due to availability of energy resources [2].

A. Curtailment Method

Sometimes, the power output from energy resources are reduced when they reach the hosting capacity limit. This is known as curtailment. For example, we may control the wind power generation by pitching the blades. The curtailment was carried out by 2% and 5% for each generation and then out powers were compared with generated power with no curtailment. The results show that small curtailment of the renewable generation will increase the hosting capacity and total generated power. Further increasing the curtailment after a certain percentage is not effective, so the curtailment has also limits. In this study following results obtained after curtailment [2]:

1) *wind (85%)+hydro(15%)*
   - *a) with no curtailment - 130MW, (350GWh produced)*
   - *b) with curtailment of 2% - 154MW (410GWh)*
   - *c) with curtailment of 5% - 171MW (455GWh)*
2) *wind (100%)*
   - *a) with no curtailment - 75MW, (190GWh)*
   - *b) with curtailment of 2% - 84MW (210GWh)*
   - *c) with curtailment of 5% - 90MW (230GWh)*

B. Dynamic loading method

In order to accommodate large amount of DG, the network lines should handle to carry the large amount of currents. Dynamic line ratings provide the operator with the overhead transmission and distribution line's actual ability to carry power at any moment in time while keeping design limits such as conductor temperature, wind speed, conductor size and resistance. Static ratings assumes constant weather conditions. In this study, the amount of additional energy production with dynamic rating is used [2]:

1) *wind (85%)+hydro(15%)*
   - *a) without dynamic line rating - 130MW, (350GWh)*
   - *b) with dynamic line rating - 260MW (700GWh)*
2) *wind (100%)*
   - *a) without dynamic line rating - 75MW, (190GWh)*
   - *b) with dynamic line rating - 120MW, (350GWh)*

The results show that dynamic line rating gives much larger increase in hosting capacity than the generation curtailment method. Two methods can be combined to increase the hosting capacity even more. The combinations of two methods was simulated and following result obtained:

3) *wind 68MW (50%)+hydro 25MW(25%) + soalr 87MW (25%) - with curtailment (0.5%) dynamic line rating - 180MW, (350GWh)*

When there is a need for costly grid improvements in order to integrate large DG into given network, the curtailment option can be used by increasing the capacity of the generation without upgrading the grid. In this case the clear forecasting and communication between production unit and network unit are essential [2].

Another method for improving the hosting capacity regarding harmonic distortions is provided in ref [3]. Majority of the distributed renewable generation like wind turbines and solar PV systems use power electronics conversion technologies which are the potential sources of harmonic currents. Nonlinearity content of the injected current will have negative effects to the voltage quality of the network. The paper examines harmonic hosting capacity which can be defined as the maximum amount of DG connected to the network without exceeding the harmonic distortion limit for each harmonic component [3]. There has been number of studied about estimating the number of DG with power-electronic interface that can be connected to the grid without exceeding acceptable distortion limits, but they were not able to calculate the hosting capacity. In this paper, the methodology to calculate the harmonic hosting capacity is presented.

For the calculation of harmonic capacity the information about quality indicators are obtained and chosen as requirements on voltage distortion set by regulator and consequences of exceeding the threshold the amount of risk the network operator willing to take. It is defined that the harmonic hosting capacity is a maximum value of the harmonic current of order *h* that will drive the harmonic voltage as the maximum harmonic voltage value. The capacity of the *h* order calculated [3].

The worst case scenario is obtained when the injected current into network has the same angle as harmonic distortion from the utility system, which is also defined as minimum hosting capacity and the phase angle difference will be 0^0. So, any new harmonic current injected to the network will increase the magnitude of voltage harmonic for the harmonic order at given point. The maximum harmonic hosting capacity occurs when the phase angle difference will be 180^0. The magnitude of maximum and minimum harmonic hosting capacity can be calculated with following equations (1), (2) respectively [3].

$$I_{HC-h} = -I_{u-h} + \frac{V_{limit-h}}{Z_{u\text{-}h}} \tag{1}$$

$$I_{HC\text{-}h} = I_{u\text{-}h} + \frac{V_{limit-h}}{Z_{u\text{-}h}} \tag{2}$$

It is also important to know that approximate value of equivalent harmonic impedance of the utility system. In order to assess the worst and best case scenarios the following procedures should be applied for each harmonic order:

- define the maximum voltage distortion or margin of the voltage distortion from local grid codes and standards;
- determine the equivalent harmonic impedance of the given utility system;
- measure the harmonic distortion of the network
- Calculate the equivalent harmonic current of order h produced by utility system side.
- From the source impedance and the background distortion, calculate the magnitude of harmonic hosting capacity of order *h* for worst situation and for best situation using the equations (1) and (2) respectively [3].

It is also noted that dynamic behavior of the power systems due to factors like load variations, capacitor and transformer switching, and changes of harmonic injection from nonlinear loads should be considered. Following considerations must be taken into account:

- Existing values of the voltage magnitude and phase angle. Daily, weekly, seasonal variations and expected changes in the future.
- Emission from new installed equipment: harmonic current, daily, weekly, seasonal variations.
- Source impedance as function of frequency, and any variations in source impedance.

The procedure above is evaluated by simple case study by using real Brazilian power system. In the methodology section, the equivalent line, transformer, generator, load parameters and voltage harmonic limits, harmonic impedances are provided Harmonic voltage distortion is obtained by simulation. For the given network (138 kV busbar) considering harmonic orders 2nd, 3rd, 5th, 7th, 11th, and 13th, the hosting capacity for the worst case scenario is 37MW and for the best scenario is 160MW obtained [3].

Additional considerations have to be taken into account such as the impact of the harmonic current summation and the influence of generation profile. Analyzing the aggregation of the harmonic current for individual equipment is important. Also, the intermittency of the renewable generations needs to be considered. Effect of the voltage distortion and THD limits are also points need to be considered [3].

III. INCREASING PV IMPACTS AND PV HOSTING CAPACITY

Voltage impacts from distributed PV on two distribution feeders are analyzed in ref [4]. The paper discusses about two similar feeders with similar characteristics which has different responses to distributed PV systems. It is noted that no two feeders are identical, therefore, the response from distributed PV will always be unique. For example, two feeders have same conductor type, voltage class, and amount of demand served can have different response to the distributed PV. Examined feeder one is in the 15kV class with 8MW total load. The feeder has no line regulators and the half of the customers are located close to the end of the feeder. The total area is about $5km^2$. The second feeder is also in the 15kV class and serves 6MW load and the distance is about 58miles long. This feeder utilizes three banks of single phase line regulators for voltage support and 1.7MW solar PV. The second feeder is not stiff as first feeder. The electrical impedance characteristics of the feeder defines its stiffness. First feeder has higher transfer capability than second one [4].

The voltage profiles are provided for both feeders, and it is noted that the available margin (headroom) for voltage rise from PV is nominally the difference between the actual feeder voltage and the maximum allowable voltage. Because the system is electrically weaker at the ends of the feeder which can accommodate less PV capacity to rise the voltage. If the PV is closer to the substation it would rise the voltage much easier. Of course load tap changers set point should be taken into account which gives us voltage size at the head of the feeder. So, the voltage margin (headroom), usually 0.96-1.04 p.u. depends on feeder impedance, regulators, and capacitor banks. We mentioned earlier that the second feeder uses line regulators and it has long mileage. That means PV impact on this feeder would be different than the first feeder. The longer distribution lines, the weaker the system [4].

Based on the voltage analysis the hosting capacity is less than the amount of the installed PV on the second feeder for the given conditions. During the sunny day the PV systems generate more power and the voltage levels exceeds from ANSI limits. This results overvoltage issues in the system. EPRI (Electric Power Research Institute) conducted analysis high penetration impact of PV on more than 30 feeders. The feeder impact depends on *feeder characteristics, PV size, PV location, feeder monitoring criteria, and load size*. The criteria for monitoring incudes measuring and observing all kinds of impacts like *voltage, power quality, protection, loading, control, and losses*. Depending the monitoring criteria the size of the PV hosting capacity could be limited [4].

According to the paper, PV hosting capacity is defined as the maximum amount of PV that feeder can accommodate before adverse impacts occur, and this depends on PV penetration, monitoring criteria, load, and feeder characteristics. The hosting capacity can be labeled as maximum or minimum levels and it depends on the level of impact. The simulation results show that there are three regions of the operating margins. Up to 500kW capacity there PV deployments do not cause adverse impacts (voltage levels). So, all regardless of PV size and locations there would be no problem with this system unless the size exceeds the threshold. When the hosting capacity exceeds 500kW then there could be some violations, so we may call the 500kW is the minimum hosting capacity. When we reach to 100kW capacity we will start to see violations on voltage level regardless of size or location of the PV, so the 100kW is the maximum hosting capacity. So the network can accept as large as 1000kW PV system which is highest hosting capacity [4].

PV deployment characteristics related based on the weighted average impedance of the system. It is simply relating the sum of the individual PV sizes to the short circuit impedance. If the ratio of the weighted average impedance to highest primary impedance is lower, the feeder is stiffer and the PV systems can be optimally integrated. The voltage based minimum hosting capacities for different load levels were created for small and large scale PV systems for both feeders. In Table I. the large scale PV minimum hosting capacity is provided (feeder 2), and all other tables could be found in ref [4]. According to this table the voltage-based hosting capacity limit would be approximately 500kW.

TABLE I. LARGE SCALE PV MINIMUM HOSTING CAPACITY (KW) [4]

	Maximum Load	***Minimum Load***
Primary Overvoltage	500	500
Secondary Overvoltage	1500	500
Primary Volatge Deviation	1500	1500
Regulator Voltage deviation	500	500

It is also noted that the in addition to the PV size/location, the inverter's power factor also play an important role in determining hosting capacity limits. In examined second feeder the PV hosting capacity exceeds the limit, so the inverter is operated off unity power factor (0.97 inductive) to absorb reactive power [4]. Currently, significant research going on about advanced solar inverters which could help to increase PV hosting capacity.

The following study is also presented to determine and visualize the maximum hosting capacity of PV systems for distribution feeders based on location of the PV systems and resistance to the substation. The research is funded by Sandia National Labs. The study investigated the effect of the increasing PV to the maximum feeder voltage, line loading and feeder violations. Different than the previous study the research investigates individual areas of the feeder to determine the local maximum level.

For the analysis the short feeder with 4km, 12.47kV, 288busses, chosen. 200of the busses are three phase which serves mostly industrial customers. There are two switching capacitors and no other voltage regulating equipment. The PV systems were sized up to 10MW in 100kW increments. Unbalanced three-phase power flow is solved using OpenDSS with GridPV and analysis performed using MATLAB.

For the analysis the minimum load considered 50% and the maximum load is considered 100% the feeder peak load. For each increments from 100kW to 10,000kW, there are 200 scenarios with power flow solutions obtained, and maximum bus voltage on the feeder obtained at each scenario.

The maximum line loading for each of the interconnection locations (200) was determined for each PV system sizes. There wasn't over-loading when considering 3.5MW system, but considering 3.9MW more than half of the scenarios result in overloading. This is because of different cable types used throughout the network.

Using the same data the locational analysis are also obtained. In this case distance of the PV interconnection to the substation is taken as an independent variable. Increase of the system size close to the substation has small effect on PCC bus voltage. Increasing the distance of the connection further away from substation increases the resistance which causes impact of system size on PCC voltage to increase. Same data was analyzed using the impedance and PV system size as an independent variables and their impact on maximum feeder voltage.

The effects of increasing PV system size on line loading and for maximum bus voltage is also observed for both 50% and 100% load case. The line connected to PCC becomes the most heavily loaded line. It is noted that the larger peak load causes the PCC voltage to be slightly lower, and in this case the current output pf the PV is slightly higher to maintain the same power output.

Several measurement parameters were considered to measure voltage variations in different scenarios of PV sizes. Maximum line loading vs. PV size, max bus voltage vs. PV size, maximum voltage vs. PV distance, PV size vs. PV resistance, maximum line loading vs. PV size, maximum voltage vs. PV size graphs are provided to visualize how the maximum capacity and impact of the PV hosting in a given network.

The results showed that the studied feeder the size of the PV system is mostly impacted by thermal limits as opposed to the voltage limits. On allowed system size the feeder load has less impact before thermal violations occur because impedance from PCC to the substation is the main factor.

IV. CONCLUSION

Major changes in power systems and the impact of these changes are discussed. Increasing hosting capacity methods for DG are provided. Hosting capacity of DG, specifically, solar PV depends on several factors such as feeder size, location, control equipment, and other DG installed along the feeder. It is possible to increase PV hosting capacity by curtailing, optimization of dynamic line ratings, and increasing control equipment. Consideration of limiting factors like harmonic distortion, power quality, voltage variations, and protection the hosting capacity can be calculated. In conclusion, the hosting capacity of DG depends on number of power system performance factors, and there is no single specific rule to evaluate hosting capacity for all network because distribution networks are not same.

V. REFERENCES

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