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Distributed PV Hosting Capacity Estimation and Improvement: 33kV Distribution System Case Study

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Abstract— Solar power generation, mainly from photovoltaic (PV) systems, has been rapidly growing in Jordan. However, increased PV penetration in distribution systems can cause multiple technical issues; namely, overvoltage at grid buses and overloading at the substation transformers in case of excessive reverse power flow. Thus, it is vital to be able to estimate the capacity of distribution systems for distributed generation (DG); and gradually find methods to increase it to allow for more integration of on-grid PV systems. In this paper, a simple deterministic method to estimate the PV capacity of distribution systems is presented, utilizing incremental increase in PV power injection. This method, which does not require detailed knowledge of the distribution grid's load profile, can be used to estimate how much installed PV power can be incorporated into the distribution system without violating certain power quality constraints. The proposed method is applied to a 73-node 33 kV distribution system located in the town of Al-Qatraneh in Jordan. Additionally, two operational methods for increasing the PV capacity are proposed to improve the ability of the system to incorporate more solar energy without the need for expensive upgrading of the distribution.

Keywords— Capacity, Distributed generation, Distribution system, Energy in Jordan, Photovoltaic.

I. INTRODUCTION

Jordan does not hold significant reserves of conventional energy resources, forcing the government to import more than 96% of its aggregate energy needs [1]. Yet, the lack of conventional energy reserves is more than compensated for by the abundance in solar energy. On a typical day, Jordan receives a solar radiation of up to 8kWh/m^2 [2]. This, combined with the fact that the cost of solar panels has been consistently declining, makes PV sources one of the most viable energy investment options for both the government and the private sector.

The main scope of this paper is on-grid PV systems feeding power directly into the distribution system, i.e., distributed generation (DG) from PV. High amounts of on-grid PV integration can have many undesired effects on the distribution system, most important of which is overvoltage [3]. Such negative effects happen when the power generated from DG sources exceeds the distribution system load and feeds the surplus power back to the transmission system.

In this paper, a simple deterministic method is presented to estimate the capacity of distribution systems to incorporate PV power (PV capacity). This method is subsequently tested under various loading conditions. In addition to testing the PV capacity, this paper proposes two operational methods to improve PV capacity.

The existing voltage control methods help stabilize the voltage profile of radial distribution systems [4], like On-load Tap Changing (OLTC) [5, 6] and cable/overhead line reinforcement. Since the majority of distribution transformers in Jordan is incapable of OLTC, and reinforcement is very costly, the method proven to be the most effective is the reactive power control, or what is simply referred to as the Q-methods [7], [8]. This can be done by modifying the power factor of the PV panels, making them either generate or consume

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reactive power in such a way that could help improve the system's capacity for PV energy. Modern solar inverters can generate (or consume) reactive power to eliminate the need to install new reactive power control equipment like mechanical SVCs or STATCOMs. The method proposed in this paper is called the solar matching of reactive power method. This method is a modified version of the Fixed Power Factor reactive power control method [9] used for voltage rise mitigation.

The remainder of this paper is organized as follows. The following section provides a theoretical background for the algorithms presented in the paper. Section 3 describes the algorithm used for determining the PV capacity for the distribution system; and Section 4 provides an analysis of the methods used to improve the PV capacity. Section 5 describes the distribution system that was used as a case study. It further describes the simulation setup used. Section 6 summarizes and analyzes the results obtained from the simulation; and section 7 considers an additional scenario and analyzes the effect of relaxing some of the conditions in the previous sections. Section 8 concludes the paper.

II. THEORY

A) PV Capacity

The PV capacity of distribution systems refers to the maximum installed PV power that can be incorporated within the distribution system without violating any performance indicators. These performance indicators are satisfied as long as certain technical constraints, such as bus voltages and transformer power ratings, are not exceeded.

To determine the maximum PV capacity, all PV plants are assumed to generate at peak capacity in order to simulate the maximum impact of the distributed PV on the distribution grid. The impact of the PV system on the following grid parameters is observed [10]:

- Voltage; that is, the voltage at each bus must be limited to a certain maximum value with respect to the nominal voltage on that bus.
- Power; that is, power going through the substation transformer is limited by a certain maximum value related to the transformer rating.

In this paper, bus voltage is chosen as the main performance indicator. According to the Jordanian Performance Standards Code, the limit of the long duration voltage variation at any connection point is six percent of the nominal value for medium voltage distribution systems [11]. However, a more conservative limit of four percent was chosen for this paper.

Regarding the power at the substation transformer, overloading transformers for long periods of time causes their depreciation and leads in extreme overloading cases to their failure. Nevertheless, some references allow for an overload of up to 200% under certain conditions, and for a limited duration [12]. For the purposes of this paper, the overload limit of 150% is the maximum allowable loading. This limit can be considered high if it lasts for more than an hour; therefore, towards the end of this paper, we consider relaxing the constraint on the transformer power rating by allowing the use of the transformers that can handle a higher rated power than what is currently used.

Another impact of the increase in PV capacity could be the overload of transmission lines. For the purposes of this study, transmission lines will be assumed to have enough capacity to carry the added load from the PV generation. This will not be considered as a limiting factor in the determination of the PV capacity.

To quantify the PV capacity of different systems, the following definition for PV capacity is used: "The PV capacity of the distribution system is the maximum amount of PV power injected into the grid, before the voltages at the buses or the power fed back to the substation exceed their maximum allowed values."

B) Overvoltage Caused by PV Power Injection

Understanding the factors affecting overvoltage helps power engineers to choose the option that best mitigates its effects. Fig. 1 demonstrates a single line diagram of a two-bus power system to which distributed generation is added at the load bus.

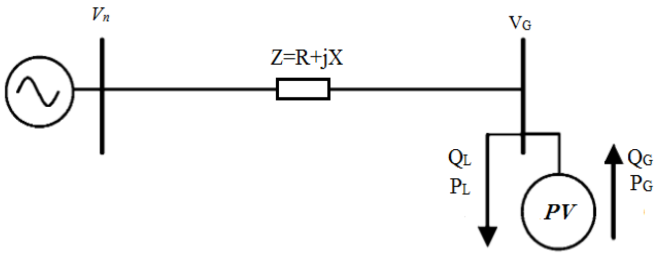

Fig. 1. Single line diagram of a two-bus system including distributed PV generation

Consider V_n to be the nominal voltage at the slack bus with a reference angle of 0°. V_G represents the voltage level at the distribution bus. $Z=R+jX$, is the impedance of the transmission line connecting the two buses. The change in voltage (ΔV) is defined as:

$$\Delta V \equiv V_G - V_n \tag{1}$$

The amount of the complex power injected by the DG sources connected to the load bus, S, is given by (2), where P_G and Q_G represent the active and reactive power injected to the grid by the PV source, respectively; and P_L and Q_L represent the amount of the real and reactive power consumed by the load connected to the same bus.

$$S \equiv (P_G - P_L) + j(Q_G - Q_L) = P + jQ \tag{2}$$

ΔV can now be found as follows:

$$\Delta V = I.Z = I.(R + jX) \tag{3}$$

where I represents the current flowing in the direction from the load bus towards the slack bus. The current I can also be found using:

$$I = \left(\frac{S}{V_G}\right)^* = \frac{P - jQ}{V_G^*} \tag{4}$$

Combining (3) and (4), we get:

$$\Delta V = \left(\frac{P - jQ}{V_G^*}\right).(R + jX) = \frac{P.R + Q.X}{V_G^*} + j\frac{P.X - Q.R}{V_G^*} = \Delta V_d + j\Delta V_q \tag{5}$$

In general, the imaginary part of the equation is much smaller than the real part; therefore, (5) can be approximated as shown in (6):

$$|\Delta V| \cong \frac{|P.R + Q.X|}{|V_G|} \tag{6}$$

Note that based on (6), and given that V_G is generally kept within a maximum of 10% of the nominal value, the voltage rise can be controlled by altering any of the remaining four variables.

Various methods have been proposed in the literature. Different methods are presented to improve the PV capacity based on modifying one or more of the parameters in (6). For instance, [13] and [6] use reactive power control to make the value of Q less than zero, whereas cable reinforcement is used to decrease the values of R and X.

III. INCREMENTAL POWER INJECTION TO TEST PV CAPACITY

It is difficult to obtain the daily load profile for many distribution systems in Jordan. This lack of data prevents BOTH design engineers and researchers from being able to measure or estimate the PV capacity of some distribution systems. Therefore, a deterministic method was developed to help estimate the PV capacity of distribution systems. This method only requires knowledge of the grid's topology and parameters.

The method proposed in this paper is to gradually increase the level of PV penetration on the grid, such that a small amount of power is added in each step. PV power is injected equally into all buses except for the slack bus. After the increase, a number of performance indices is measured using the voltage on each bus and the power fed back through the substation transformer. The moment one of the performance indicators is violated, the algorithm stops increasing the generated power. The last value of the distributed generation power represents the PV capacity. In this method, all PV sources are assumed to produce the same amount of power. Bus voltages and power flow through the transformer can be calculated using a power flow analysis method such as the Newton-Raphson or Gauss-Seidel methods [14]. The flowchart in Fig. 2 depicts the algorithm used. Simulation was carried out using the MATPOWER software package which works in a MATLAB environment [15].

IV. METHODS TO INCREASE PV CAPACITY

A) Reactive Power Control-Solar Matching of Reactive Power

Several methods have been developed for controlling reactive power [16,17]. These methods have generally been targeted at limiting overvoltage caused by the injection of DG power into medium voltage (MV) and low voltage (LV) systems. The most common methods for reactive power control (the *Q-methods*) include: fixed reactive power method (fixed *Q-method*), where a fixed amount of reactive power is consumed at each bus; fixed power factor (fixed $\cos\phi$ method), where the inverter is set to a constant power factor; and $\cos\phi$ *P-characteristic* method, where the inverter has either a lagging or leading power factor depending on the voltage level at the bus [8], [18].

The proposed reactive power control method is the fixed power factor method. In this case, the inverters at the buses farthest away from the transformer substation will be set to consume reactive power; that is, they will have a lagging power factor. This would cause the voltage at the said buses to drop.

Given a constant power factor, the reactive power will increase with the increase of real power generation. The tendency of the voltage to increase due to the increase in real power generation will be limited by a corresponding increase in reactive power consumption.

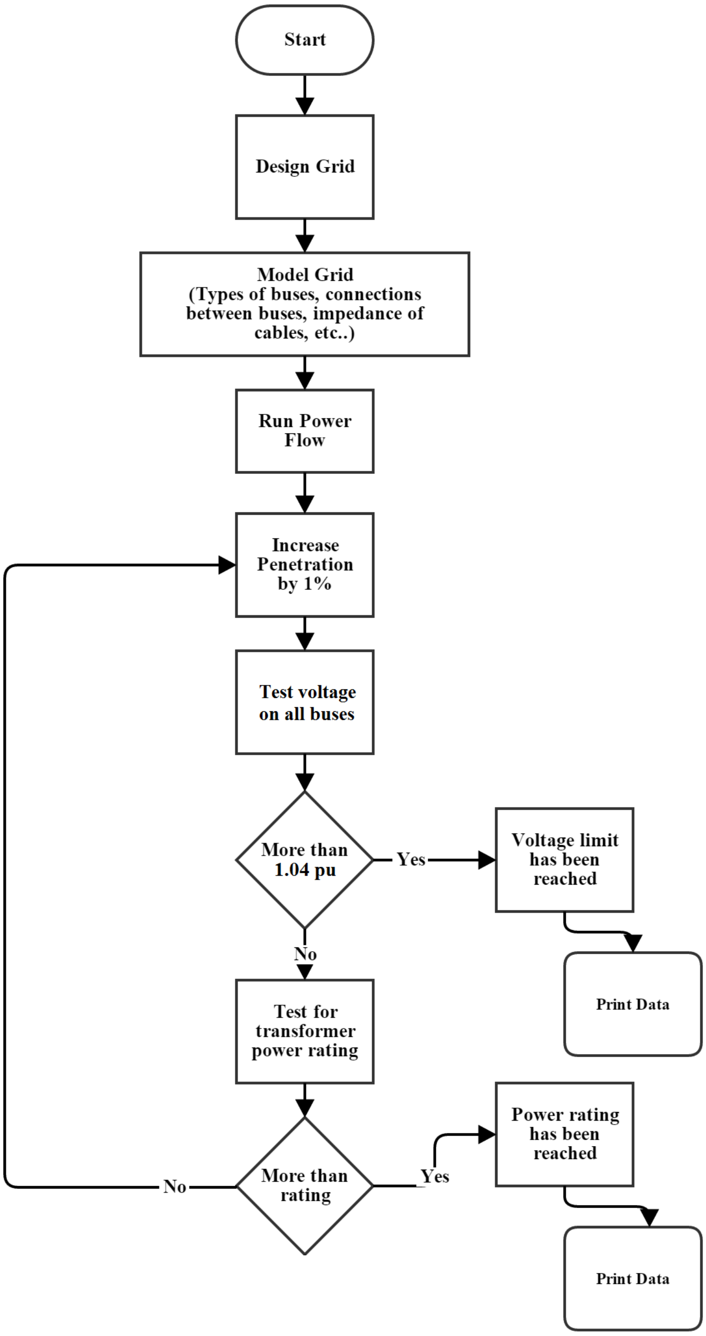

Fig. 2. Flowchart illustrating the proposed method to test the PV capacity

However, for the PV sources that consume reactive power, there must be also a provider of such power. The distribution system can get this power from the transmission grid, but that would cause an additional burden on the substation transformer, as more power will have to pass through it. A better idea is to set some of the PV sources, namely, the sources closer to the substation transformer, to generate the required reactive power; thus eliminating the need to obtain it from the transmission network. Some of the PV sources will be set to generate reactive power and increase their voltage. Choosing the PV sources at the buses closest to the substation, for this purpose, is acceptable, since the voltage at those buses generally does not exceed the 4% limit.

The distribution system under study covers a relatively small area; therefore, it can be assumed that solar irradiance over the entire system is uniform. Consequently, it can be assumed that the amount of the real power produced by each PV plant is approximately the same in all plants in the area. Furthermore, if about of half the PV plants is set to consume reactive power, and the other half is set to generate it, the power will be balanced with no need to obtain more power from the transmission network. The greatest benefit of this method is that it requires no communication between different plants, and therefore, no extra cost. Basically, the power factor of each solar inverter is set to a constant value during installation. This method will be referred to as the 'Solar matching of reactive power'; and will be tested in Section 5 on Al-Qatraneh distribution network in Jordan.

B) Gradual Power Curtailment

It is possible to curtail the power generated by some PV systems when the generated power causes high levels of overvoltage at nearby buses. This method can be highly beneficial in reducing the voltage level of the selected buses. However, power curtailment has the disadvantage of requiring communication and control systems in order to control the amount of power generated by each PV system. In this paper, an additional method to control the amount of power generated at each bus is proposed to keep the voltage level of all buses within the voltage constraint of 1.04 p.u. Allowing for more solar power to be generated at some of the buses helps increase the overall power generation of the system and the system's PV capacity.

To implement this method, two voltage limits are set. The first one, a hard limit, is set to 1.04 per unit (p.u.), which is a limit that cannot be violated. The second limit, a soft lower limit of 1.035 p.u., is set to be used for some of the buses in the system. When the voltage at any of the buses reaches the soft limit (i.e., the lower limit), the control system prevents the PVs connected to that bus from further increasing their power generation. This is done in order to reduce the amount of voltage rise at that particular bus. This does not necessarily prevent further voltage increase on that bus, as the increase in power injection at other nearby buses can still contribute to a change in this bus's voltage though it can limit the voltage increase to relatively smaller amounts. In all cases, once a hard limit is reached anywhere in the system, simulation stops; and the new PV capacity is determined. Fig. 3 presents the modified algorithm for increasing the PV capacity.

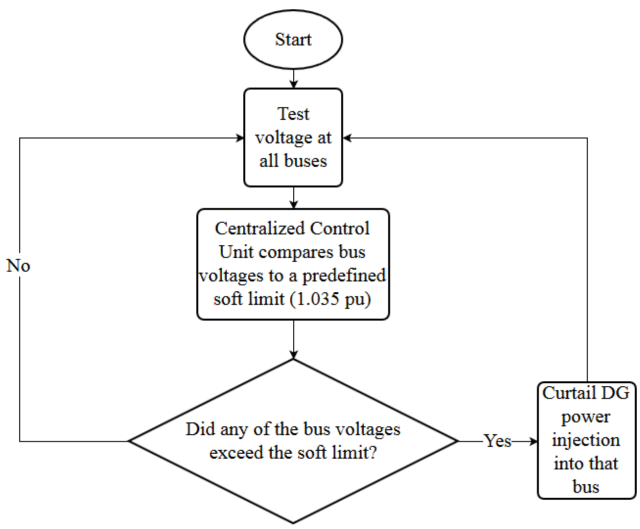

Fig. 3. Algorithm describing the gradual power curtailment process

V. SIMULATION SETUP

A) Al-Qatraneh Distribution System

Solar matching of reactive power was applied to a medium voltage (MV) distribution system in Al-Qatraneh, Jordan [19]. The aim is to test the effectiveness of the proposed method in increasing the PV capacity in local power systems. It is important to note that since Al-Qatraneh grid has been used, the proposed methodology is for the improvement of the operation of an existing system rather than the design of a new system.

Fig. 4 shows Al-Qatraneh distribution network used in this paper with the proposed locations for adding PV sources. At the right side of the diagram, the distribution network starts at the substation transformer, rated at 15 MVA, to reduce the voltage from 132kV to 33kV. After that, several feeders are connected to the loads of the system. Each load is represented in this diagram by another transformer, which reduces the voltage further to the level required by the load. The ratings of the transformers in kVA are shown in the diagram.

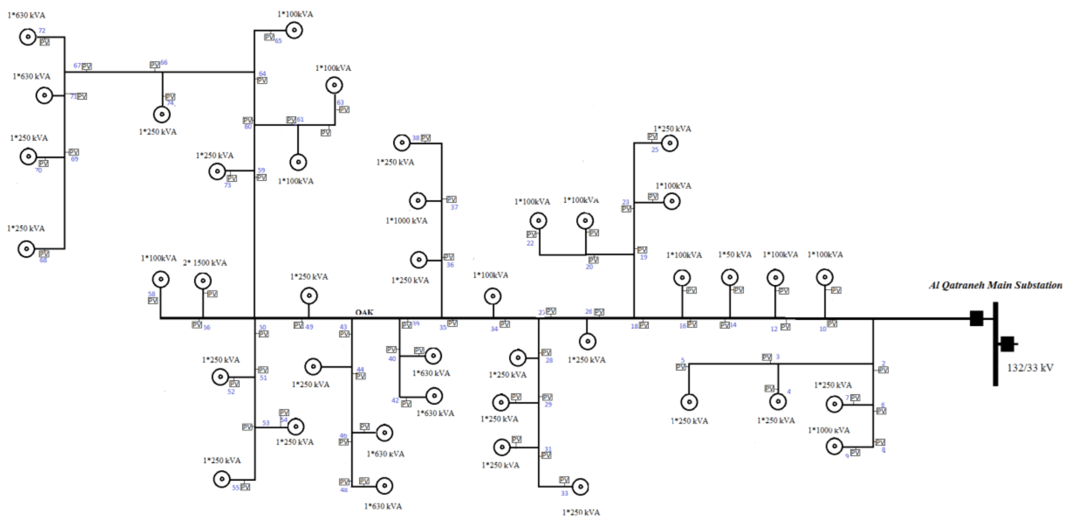

Fig. 4. Al-Qatraneh distribution system

B) Load Profile

For simulation purposes, PV power injected was tested under three load conditions; that is, 50% loading (light), 70% loading (moderate), and 120% loading (high), where the percentage is calculated with respect to the rating of the transformer connected to the load. The PV capacity is then tested for the three loading conditions. All loads were set to have a power factor of 0.95 lagging.

VI. RESULTS AND DISCUSSION

Table 1 summarizes the limits set for bus voltages and the substation transformer power, respectively. Al-Qatraneh system was modeled using MATLAB; and the initial PV capacity of the grid was tested. The results for the initial test are shown in Table 2 where, in both cases, the parameter violated was the voltage limit at the buses.

TABLE 1
VOLTAGE AND TRANSFORMER LIMITS FOR THE DISTRIBUTED SYSTEM

Substation transformer Apparent Power	22.5MVA
Bus Voltage Hard Limit	1.04 per unit

TABLE 2
HOSTING CAPACITIES OF AL-QATRANEH SYSTEM UNDER THREE DIFFERENT LOADING CONDITIONS

Load Value	PV Power	Power Fed Back to the Transformer	Limit Exceeded
50%	22.12 MW	14.90 MVA	Voltage at Bus 64
70%	26.82 MW	16.86 MVA	Voltage at Bus 64
120%	38.55 MW	21.76 MVA	Voltage at Bus 64

After determining the initial PV capacity of the system, we tested the first method, i.e., solar matching of PV reactive power, on Al-Qatraneh test feeder. The power factor (PF) at PV inverters was set at 0.97 with half of the buses (the ones close to the substation transformer) set to leading PF, and the other half (the buses farther away from the transformer) set to lagging PF. A simulation was run on Al-Qatraneh Model as shown in Fig. 4 to measure the voltage at all buses in the process to ensure the voltage limit was not violated. Table 3 presents the improvement on the PV capacity of Al-Qatraneh grid.

Based on Table 3, we can see that consuming reactive power by PV inverters is effective in decreasing overvoltage. This is sufficient to increase the PV capacity of the grid when consumption is low (50-70%). Nonetheless, the method, on its own, seems insufficient in increasing the PV capacity at high consumption scenarios. Solar matching of reactive power is highly effective at limiting overvoltage. This is why the method is highly effective when consumption is low; at low consumption levels, overpowering the transformer is not an issue. However, for the method to be effective at high consumption scenarios substation transformers need to be upgraded to counteract the increased amounts of power injected into the system.

TABLE 3
PV CAPACITY OF AL-QATRANEH DISTRIBUTION SYSTEM WITH REACTIVE POWER CONTROL USING INVERTER POWER FACTOR CONTROL

Load Value	PV Power, MW	Power Fed Back to the Transformer, MVA	Limit Exceeded	Percentage Increase in PV Capacity, %
50%	28.6	20.81	Voltage at Bus 55	29.29
70%	33.04	22.5	Power Substation Transformer	22.82

Testing the second method, i.e., the gradual power curtailment method, showed even better results for the lower (50% and 70%) loading conditions as can be seen in Table 4. A percentage increase of 35.156% and 23.182% was achieved for those loading conditions, respectively. However, it can be seen that this method does not provide much improvement for high loading conditions. The 120% loading was almost the same as the first method.

TABLE 4
PV CAPACITY OF AL-QATRANEH DISTRIBUTION SYSTEM WITH GRADUAL PV POWER CURTAILMENT

Load Value	PV Power, MW	Power Fed Back to the Transformer, MVA	Limit Exceeded	Percentage Increase in PV Capacity, %
50%	29.9	20.279	Voltage at Bus 55	35.156
70%	33.04	22.5	Power Substation Transformer	23.182
120%	39.56	22.5	Power Substation Transformer	2.621

The results show that the constraint in the power rating of the substation transformer at the substation can affect the amount of improvement we can achieve in the PV capacity of the system. This leads us to consider the effect of relaxing that constraint to study whether or not it is worth our efforts to replace this transformer with one that has a higher power rating, and determine the appropriate power rating required. Increasing the PV capacity of the distribution system is not affected by the performance of the transformer. In addition, the choice of the soft limit as 1.035 p.u. was rather arbitrary. While it seemed to work well, the question remains as to whether this choice is ideal, or if there is a more optimal value for that. The following section investigates those two issues.

VII. FURTHER IMPROVEMENTS OF THE GRADUAL POWER CURTAILMENT METHOD

As shown in the previous section, the efficacy of the second method, i.e., the gradual power curtailment method, in improving the PV capacity of Al-Qatraneh distribution system was largely limited by the power rating of the substation transformer. In addition, the choice of soft voltage limit was rather arbitrary. While it did prove useful, there is a better more optimal value for this limit. In this section, we investigate the effect of relaxing the power rating limit on the transformer, and varying the value of the soft voltage limit.

We performed a parametric study in which we gradually reduced the soft voltage limit in steps of 0.001 per unit, and ran the simulation to see if we could achieve any further increase in the PV capacity. Like in the previous simulations, the loading conditions considered were 50%, 70%, and 120%. In addition, the transformer limit was relaxed to estimate the highest possible PV capacity that can be achieved if power is allowed to be fed back to the grid. The results of this simulation are presented in Fig. 5.

The graphs in Fig. 5 show that a great improvement in the results can be achieved if the substation transformer has a higher power rating. A big increase in the PV capacity was noted in all three loading conditions, with the lowest (50%) loading condition achieving the highest increase in PV capacity. A more detailed description of the best values that were achieved is presented in Table 5.

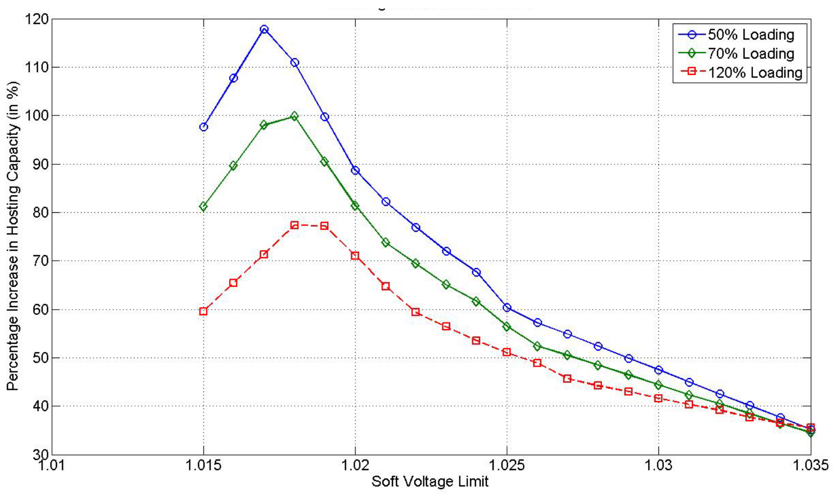

Fig. 5. Effect of varying the soft voltage limit on increasing the PV capacity for various loading conditions and relaxing the transformer limit

Note that an increase in PV capacity of up to 117.8% can be achieved for the 50% loading condition, while for the higher loading condition, an increase in PV capacity of about 77% is achieved.

This would require an increase in the rating of the substation transformer used in the system. While the cost of using such a transformer might be high, it allows a bigger increase in the PV capacity considering the upgrade in the transformer.

TABLE 5
RESULTS SUMMARY FOR VARYING THE SOFT LIMIT AND REMOVING THE LIMIT ON THE TRANSFORMER RATING

Percent Loading	Soft Limit	DG Power Injected (MW)	Power Fed Back to Transformer (MVA)	Percent Increase in PV Capacity	Voltage Limit Exceeded
50%	1.017	48.1914	40.103	117.863%	No voltage was exceeded
70%	1.018	53.5909	42.26537	99.817%	Voltage at bus 55
120%	1.018	68.3613	48.96908	77.332%	No voltage was exceeded

Furthermore, it can be noted that at the optimal value of the soft voltage limit, for two out of the three loading cases considered, none of the hard voltage limits on any of the buses was reached. Simulation simply stopped as the voltage on all buses reached the soft limit; and there was no further need to put a hard limit on the buses to maximize the PV capacity.

VIII. CONCLUSION

The injection of high amounts of PV power into distribution systems could lead to undesirable effects on the grid. It is, therefore, important to measure the PV capacity of distribution systems before planning large-scale integration of photovoltaic modules. A simple deterministic method to estimate the PV capacity that does not require detailed data is proposed. Additionally, two methods to increase the PV capacity are introduced and studied, namely solar matching of reactive power, and gradual PV power curtailment, which were both tested on Al-Qatraneh distribution network in Jordan. Both methods proved to be effective at low to normal load levels. They were, however, shown to be insufficient at high consumption levels. Further analysis showed that better results can be obtained by relaxing the constraint on the size of the substation transformer in the grid, as large amounts of power need to be fed back to the transmission system, when the PV capacity is increased.

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