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Probabilistic Approach for Hosting High PV Penetration in Distribution Systems Via Optimal Oversized Inverter with Watt-Var Functions

Abdelfatah Ali, Karar Mahmoud, David Raisz, *Senior Member, IEEE*, and Matti Lehtonen

***Abstract*— Accommodating a high penetration of intermittent photovoltaic (PV) in distribution systems can potentially cause several operational problems, most importantly the voltage violations. An optimal probabilistic approach is proposed in this paper to optimally host high penetrations of PV units considering their stochastic nature. A benefit of the proposed approach is that it provides wider planning options since it optimizes the interfacing inverter oversize with smart watt-var functionalities. These smart functionalities include 1) active power curtailment, and 2) inverter reactive power. The utilization of these functionalities in the optimization model yields an optimal PV hosting that maximizes the benefits to distribution systems. The optimal probabilistic model of PV incorporates the probabilities of the PV power output and load while optimizing the inverter oversize and the two functionalities simultaneously. The proposed approach complies with the recently released IEEE 1547:2018 standard which regulates the reactive power support via the interfacing PV inverters. The efficacy of the proposed approach is demonstrated by comparisons with existing approaches. The results confirm the superiority of the proposed approach to optimally accommodate high PV penetration at single or multiple locations while minimizing voltage violations. The proposed approach is also applied to maximize the hosting capacity of PV.**

***Index Terms*--Distribution systems; photovoltaic; voltage violations; optimal accommodation.**

I. Introduction

WORLDWIDE, the integration of various renewable energy sources (RES) to medium-voltage (MV) distribution systems has outstandingly increased. It is a fact that distributed RES could have positive impacts on distribution systems, such as improving the supply reliability, enhancing power quality, and minimizing losses [1]–[3]. One of the most widespread RES types is photovoltaic (PV). Since most power distribution systems are originally designed based on centralized generation schemes and unidirectional power flows, the interconnection of PV can degrade their normal operating conditions [4]–[6]. These consequences have significant effects on limiting the allowed penetration of PV in distribution systems.

The smart functionalities of the interface inverter of PV could beneficially mitigate the technical problems associated with high PV penetrations [4]–[8]. Active power curtailment (APC) of the PV generation is considered an effective functionality, but it wastes energy and it should as rarely as possible. Another option is reactive power control which is constrained by the spare capacity of the PV inverter. It is important to note that the spare capacity is minimum during the highest PV generation, and so this latter option could be not available. To allow further reactive power support, the PV inverter could be oversized considering the flexible modular structure of PV systems [9]–[11]. Indeed, the consideration of these smart functionalities, i.e., APC and inverter oversizing, during the planning stage of PV could have pronounced impacts on facilitating the accommodation of PV.

Different methods in the literature have focused on the accommodation of PV in power distribution systems. Analytical expressions have been introduced in [12]–[14] for the optimal allocation of RES to minimize the power losses. These analytical expressions are efficient, accurate, and fast, but they ignore the stochastic nature of PV. The authors of [15] have proposed a planning approach of multi-type RESs including PV to maximize the energy loss reduction in distribution systems. In [16], a method was proposed to place one PV unit in distribution systems considering load variations. The authors of [17] have considered vital aspects related to RES planning, including cost minimization, carbon emission reduction, and the uncertainty of load demand. Great interest has been directed to apply various metaheuristic optimizers for the PV accommodation problem, such as 1) ant colony optimizer [18], tabu search [19], genetic algorithms [20], developed two-layer gravitational search algorithm [21], and simulated annealing [22]. Different probabilistic hosting capacity enhancement strategies of microgrids and unbalanced distribution systems have been proposed in [23]–[25]. In [26], an optimal sizing and siting scheme for the PV has been presented to improve power system resilience. The authors of

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[27] have introduced various probabilistic indices to assess the operational problems with high PV penetrations based on technical benefits and risks tradeoffs.

As stated in the abovementioned literature review, considerable work and studies are oriented to the optimal accommodation of PV in distribution systems. Nevertheless, several of the existing approaches simplify the complexity of the PV planning model by following assumptions. Some of the approaches consider either one location of PV or utilize deterministic PV and loads models. More importantly, most of the existing approaches ignore the smart functionalities of the PV inverter during the planning stage of PV. Hence, this optimal PV accommodation problem considering the smart functionalities still needs further investigations and developments, which is the main scope of this work. Another vital motivation to investigate the reactive power capability of PV inverters is the recently released IEEE 1547:2018 standard [28] which regulates reactive power support via the interfacing inverters.

An optimization-based probabilistic approach is introduced in this work to optimally accommodate a high PV penetration in power distribution systems. The proposed approach considers the stochastic nature of PV and loads. In addition, it provides an optimal inverter oversize enabled with smart watt-var functionalities which are considered as planning variables to be optimally determined considering utility preference for minimizing voltage violations while handling system constraints. The accommodation PV model is solved using a nonlinear interior point method. To reveal the efficacy of the proposed approach, it has been evaluated against the traditional approach that ignores the smart functionalities of PV inverters. The proposed approach is compared with an extended approach that minimizes energy losses. Furthermore, to simulate the practical condition, the proposed approach has been tested under preset utility regulations in terms of permissible APC and inverter oversize limits. The mathematical formulation of the proposed approach is general and applicable to include other objectives, constraints, and/or variables. The major contributions of this paper can be itemized as follows:

- A probabilistic approach for hosting high PV penetration in distribution systems is proposed.
- The proposed approach considers the intermittency of the PV generation and load variations.
- The active power curtailment of PV and the inverter reactive power capability are incorporated in the proposed planning approach.
- The proposed approach can optimize the interfacing inverter size considering smart watt-var functionalities.
- Comprehensive simulations considering different practical scenarios are performed.
- The proposed approach can maximize the hosting capacity of PV.

II. Problem Description

A. Impact of PV on Voltage Regulation

The voltage regulation problem is considered as the main drawback and limitation for the integration of a large amount of PV into low voltage and MV distribution systems. Fig. 1

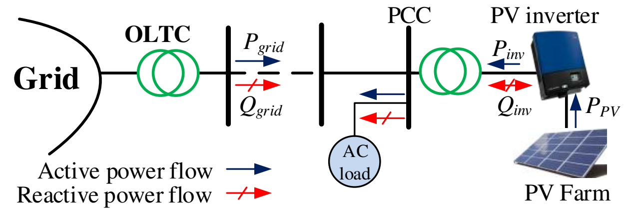

Fig. 1. Schematic diagram of a conventional distribution feeder with PV system.

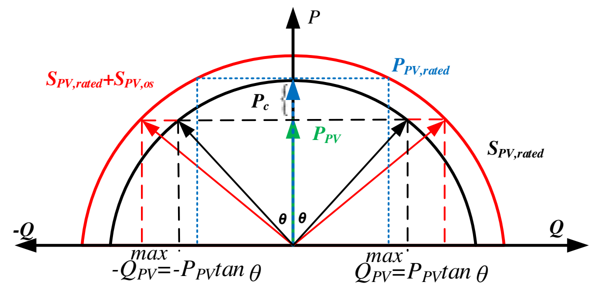

Fig. 2. Capability curve of the PV inverter considering the oversizing and APC options.

shows a schematic diagram of a conventional distribution feeder with the PV system (point of common coupling (PCC)). A load is connected to the same bus as PV. The maximum efficiency of the PV unit can be drawn by its operation at the maximum power point tracking mode. In another meaning, the generated power of PV depends on the conditions of the energy source instead of the power balance between loads and supply in the feeder. Hence, the required power should be supplemented from the main grid.

Due to the high penetration of PV, the output power overrides the local load and reverse power flow can take place due to this surplus active power generation of PV into the distribution network. This reverse power flow leads to voltage deviation as the conventional distribution feeders are designed for one-direction power flows. By increasing the reverse power flow in the distribution feeder, the voltage violates the upper voltage limit (i.e. voltage rise) which leads to negative impacts on equipment. Therefore, the voltage deviation problem is a serious issue to be considered for distribution systems with excessive PV penetration.

B. Smart Functionalities of PV Inverter

The PCC voltage is regulated by managing active and reactive power injected by PV inverters. The reactive power of PV inverter can be continuously controlled, depending on the active power generation of the PV. The capability curve of a voltage source inverter (VSI) is shown in Fig. 2. In this Figure, the inverter's operating range is represented by a black semicircle in which its radius denotes the size rating of the PV inverter ($S_{PV,rated}$), P_{PV} is the PV active power output, and Q_{PV}^{max} is the maximum reactive power of the PV. During the mid-day time, PV inverter operates to its full capacity for active power injection (i.e. P_{PV}=$P_{PV,rated}$), where $P_{PV,rated}$ is the rated active power that can be generated by the PV. But, the reactive power capability of PV inverters should satisfy the capacity constraints. The maximum reactive power limits of the PV inverter can be defined as follows:

$$Q_{PV}^{max} = \pm\sqrt{S_{PV,rated}^2 - P_{PV}^2} \qquad (1)$$

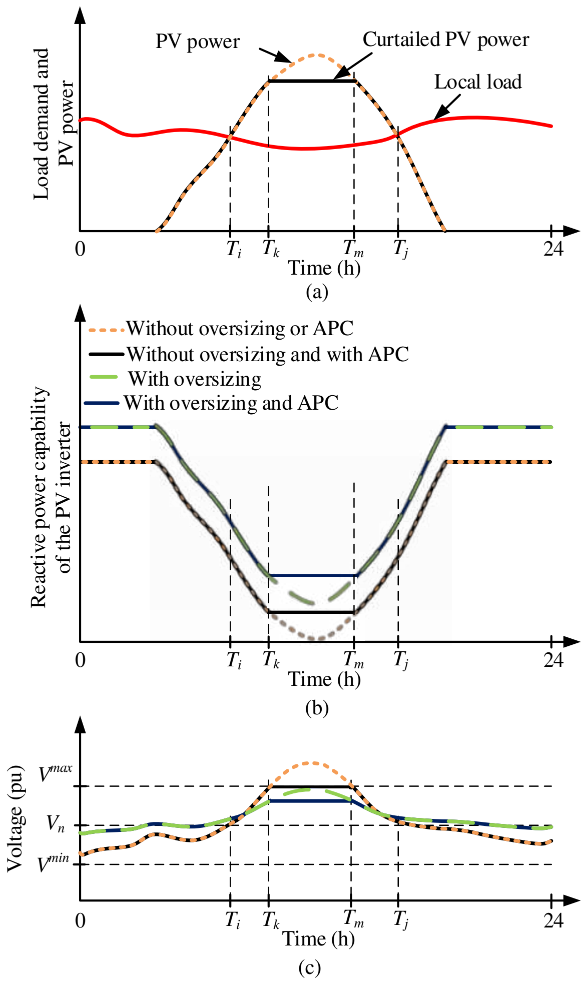

Fig. 3. Description of the smart functionalities of the PV inverter. (a) Local load and PV power profiles, (b) Reactive power of the PV inverter, and (c) Voltage profiles.

Therefore, when P_{PV}=$P_{PV,rated}$, the spare capacity for reactive power injection/absorption to regulate the voltage is zero. Hence, to get further reactive power capability from the PV inverter for voltage regulation, it should be oversized by a certain percentage from its normal rating.

C. Designing of Inverter Oversizing considering APC

The reactive power capability of the PV inverters is constrained by the active power generation of the PV given on the normal rating. Therefore, the capacity of the PV inverters can be oversized to provide further reactive power capability for voltage support. However, employing the oversizing feature in practice would require additional capital investment. Therefore, to maximize the benefits of the investors, the capacity of the inverter should be optimally computed. In this paper, the optimal oversize ($S_{PV,os}$) of the PV inverters is determined considering the option of APC to regulate the voltages in the distribution system. The capability curve of the PV inverter considering the options of oversizing and APC is shows in Fig. 2 (red semicircle).

In Fig. 3, the role of the smart functionalities of PV inverters for voltage regulation at PCC is demonstrated. As illustrated in Fig. 3 (a), due to the high penetration of PV, the output power is not only responsible for load compensation in which it overrides the load during the period T_{ij}. The surplus power flows back into the distribution system. Hence, the voltage at PCC deviates from the nominal voltage (V_n). Because of the continuous increasing of PV output power, the PCC voltage violates the upper boundary (V^{max}) during the period T_{km}, as described in Fig. 3 (c).

To solve the voltage rise problem during T_{km}, three possible options are available as described in Fig. 3 (b): 1) APC, 2) inverter oversizing, and 3) both APC and inverter oversizing. The corresponding voltage profiles of these options are given in Fig. 3 (c). In this work, we utilize the latter option which offers wider design variables to optimally accommodate the high PV penetration with minimum voltage deviation in the distribution system.

III. Problem Formulation

Here, the optimal accommodation of high PV penetration by utilizing smart inverter functionalities of the interfacing inverter to regulate voltage in power distribution systems is intended to be determined. The voltage magnitude deviation for all probabilities of PV power output and load is used as an objective function to be reduced. For this purpose, for each state (each time segment has several states for the PV power and load), the total voltage magnitude deviation should be determined and weighted based on the occurrence probability of this state during the planning period. The objective function can be mathematically expressed by:

$$Minimize\ VD = \sum_{t=1}^{n_t}\sum_{s=1}^{n_s}\sum_{i=2}^{n_b}\left(\frac{V_{i,s}^t - V_n}{V_n}\right)^2 \times P_{com}^t(\chi_s) \quad (2)$$

where VD is the total voltage deviation in the distribution system; $P_{com}^t(\chi_s)$ is the PV power output and load demand combined probability during state s; n_s, n_b, and n_t are the state number every time segment (i.e., the product of PV output power and load states (6×7)), number of nodes, number of the time segments, respectively; $V_{i,s}^t$ is the voltage magnitude at bus i for time segment t and state s; V_n is the normal voltage of the buses (e.g. V_n=1 pu); χ is a matrix which has two columns includes the feasible combinations of the PV output power and load states.

The constraints (equality and inequality) that have been considered in the optimization problem can be given by:

$$P_{G,1,g}^t + \chi(s,1)P_{PV,i}^t - \chi(s,2)P_{d,i}^t - V_{i,s}^t\sum_{j=1}^{n_b} V_{j,s}^t \begin{bmatrix} G_{ij}\cos\delta_{ij,s}^t \\ +B_{ij}\sin\delta_{ij,s}^t \end{bmatrix} = 0 \quad (3)$$

$$Q_{G,1,s}^t - \chi(s,2)Q_{d,i}^t - V_{i,s}^t\sum_{j=1}^{n_b} V_{j,s}^t \begin{bmatrix} G_{ij}\ \sin\ \delta_{ij,s}^t \\ +B_{ij}\cos\ \delta_{ij,s}^t \end{bmatrix} = 0 \quad (4)$$

$$V^{\min} \le V_{i,s}^t \le V^{\max}, \qquad \forall i \in \phi_b, s, t \quad (5)$$

$$\begin{cases} V_{1,s}^t = 1.0 \\ \delta_{1,s}^t = 0.0 \end{cases} \quad (6)$$

$$Q_{PV,k,s}^{min} \le Q_{PV,k,s} \le Q_{PV,k,s}^{max}, \quad \forall k \in \phi_{PV}, s \quad (7)$$

$$\sum_{k=1}^{n_{PV}} P_{PV,k} \le \sum_{i=1}^{n_l} P_{d,i,s}^t + P_{loss,s}^t, \quad \forall i \in \phi_b, k \in \phi_{PV}, s, t \tag{8}$$

$$S_{PV,os,k}^{min} \le S_{PV,os,k,s} \le S_{PV,os,k}^{max}, \qquad \forall k \in \phi_{PV}, s \tag{9}$$

$$P_{c,k}^{min} \le P_{c,k,s} \le P_{c,k}^{max}, \qquad \forall k \in \phi_{PV}, s \tag{10}$$

where G_{ij} and B_{ij} are the conductance and susceptance of line ij, respectively; $\delta_{ij,s}^t$ is the voltage angle difference at bus i and j during state s, respectively; $V_{1,s}^t$ and $\delta_{1,s}^t$ are the voltage and angle at bus 1(slack bus), respectively; $P_{G,1,s}^t$ and $P_{d,i}^t$ are the grid active power and demand active power, respectively; $Q_{G,1,s}^t$ and $Q_{d,i}^t$ are, respectively, the reactive power of the grid and load reactive power; $P_{PV,k}$ is the active power output of PV at bus k. $Q_{PV,k,s}$, $Q_{PV,k,s}^{min}$, and $Q_{PV,k,s}^{max}$ are the reactive power, minimum reactive power, and maximum reactive power of PV at bus k during state s and time instant t, respectively; V^{min} and V^{max} are the minimum and maximum voltage limits, respectively; $P_{loss,s}^t$ is the active power loss; $S_{PV,os,k,s}$, $S_{PV,os,k}^{min}$, and $S_{PV,os,k}^{max}$ are the inverter oversize, minimum inverter oversize, and maximum inverter oversize at bus k during state s, respectively; $P_{c,k,s}$, $P_{c,k}^{min}$, and $P_{c,k}^{min}$ are the APC variable, minimum APC limit, and maximum APC limit of PV at bus k during state s, respectively; n_{PV} and n_l are, respectively, the number of PV nodes and number of loads, respectively; ϕ_b and ϕ_{PV} is set nodes and set of the PV nodes.

IV. Solar Irradiance and Load Modeling

Here, the models of the probability generation for the load demand and the PV are described. Beta and normal probability density functions (pdf) are utilized to represent solar radiation and load demand, respectively [10], [15].

Hourly historic data of solar irradiance and load for three years have been considered here. Each year has been divided into four seasons and each season is represented by a day within that season. The day which represents the season is subdivided into 24-h in which each hour represents a time segment. Each time segment represents a specific hourly interval for the entire season. Therefore, there are 96-time segments for the whole year (24-h each season). These data are used to calculate the mean and standard deviation of the solar irradiance and load for each time segment. Then, the Beta pdf and normal pdf are generated for each time segment, as described below.

A. Modeling of Solar Irradiance

For each time segment t, the probabilistic nature of solar irradiance can be formulated using Beta pdf as follows [10], [15]:

$$f_b^t(R) = \begin{cases} \dfrac{\Gamma(\alpha^t + \beta^t)}{\Gamma(\alpha^t)\Gamma(\beta^t)} \times (R^t)^{(\alpha^t - 1)} \times (1 - R^t)^{(\beta^t - 1)}, \\ \qquad\qquad 0 \le R^t \le 1, \alpha^t, \beta^t \ge 0 \\ 0, \qquad\qquad otherwise \end{cases} \tag{11}$$

Where Γ is the gamma function; α^t and β^t are the Beta parameters (shape parameters).

The mean (μ^t) and standard deviation (σ^t) of the arbitrary solar radiation R are used to determine α^t and β^t every time segment as given in (12) and (13):

$$\beta^t = (1 - \mu^t) \times \left(\frac{\mu^t \times (1 + \mu^t)}{(\sigma^t)^2} - 1 \right) \tag{12}$$

$$\alpha^t = \frac{\mu^t \times \beta^t}{1 - \mu^t} \tag{13}$$

Then, for each state, the probability of solar radiation can be computed by:

$$prob_R^t(G_x) = \int_{R_{x1}}^{R_{x2}} f_b^t(R).dR \tag{14}$$

where $prob_R^t(G_x)$ is the probability of solar radiation in state x; R_{x1} and R_{x2} are the solar radiation bounds of state x.

From the generated Beta pdf for a time segment, the PV output power for the states of this segment can be computed by:

$$P_{PV_x} = N \times \frac{V_{MPP} \times I_{MPP}}{V_{OC} \times I_{SC}} \times V_{cell_x} \times I_{cell_x} \tag{15}$$

in which

$$T_{cell_x} = T_A + R_{avs}\left(\frac{N_{OT} - 20}{0.8} \right) \tag{16}$$

$$I_{cell_x} = R_{avs}\left(I_{SC} + K_i \left(T_{cell_x} - 25 \right) \right) \tag{17}$$

$$V_{cell_x} = V_{OC} - K_v T_{cell_x} \tag{18}$$

where V_{MPP} is the voltage at maximum power point; I_{MPP} is the current at maximum power point; V_{OC} is the open-circuit voltage; I_{SC} is the short circuit current; V_{cells} and I_{cells} are the cell voltage and cell current, respectively; N is the number of PV modules. T_A is the ambient temperature; T_{cells} is the cell temperature; R_{avs} is the average solar irradiance; K_i, K_v, and N_{OT}, respectively, are the current temperature coefficient, voltage temperature coefficient, and nominal operating temperature of the cell [10], [15].

B. Modeling of the Load Demand

As the load is uncertain, the distribution of the load can be modeled utilizing a normal pdf [29], as follows:

$$f_n^t(l) = \frac{1}{\sigma_l^t \sqrt{2\pi}} \times \exp\left[-\left(\frac{(l - \mu_l^t)^2}{2(\sigma_l^t)^2} \right) \right] \tag{19}$$

Hence, for each state, the probability of the load demand can be given as follows:

$$prob_l^t(G_y) = \int_{l_{y1}}^{l_{y2}} f_n^t(l).dl \tag{20}$$

where l_{y1} and l_{y2} are the load demand bounds of state y; $prob_l^t(G_y)$ is the load demand probability in state y.

C. Combined PV-load model

The modeling of PV solar irradiance and the load demand given in (14) and (20), are utilized to compute the combined model of PV and load. In this paper, the load states and the solar irradiance states are supposed to be autonomous. Therefore, the combined probability of the load and solar radiation for each time segment t ($P^t_{com}(\chi_s)$), can be determined by using the two probabilities, as follows [15]:

$$P^t_{com}(\chi_s) = prob^t_R(G_x) \times prob^t_l(G_y) \quad (21)$$

Then, a PV–load model can be determined by considering all possible PV power and load combinations. The complete model of PV–load is expressed as follows:

$$\psi = \left[\left\{\chi_s, P^t_{com}(\chi_s)\right\} : \chi = 1 : n_S\right] \quad (22)$$

where $P^t_{com}(\chi_s)$ and ψ are a vector (one column) that represents the combined probability based on matrix χ, and the complete PV-load model, respectively.

V. Interior Point Optimization Method

Interior point methods are an effective class of algorithms that are extensively used to solve linear and nonlinear convex optimization problems. Different areas have utilized the interior point methods; one of these areas is the electric power systems. The primal-dual interior-point method is the commonly applied class of the interior point method due to its efficiency [30]. To use the interior point method for solving nonlinear optimization problems, a perturbation parameter is presented in the complementarily Karush-Kuhn-Tucker (KKT) condition [31]. The general optimization problem can be described by:

$$Minimize\ f(x) \quad (23)$$

subject to

$$\begin{cases} h(x) = 0 \\ g(x) \le 0 \end{cases} \quad (24)$$

where *f(**x**)* and ***x*** are the objective function to be optimized and vector of decision variables, respectively; *h(**x**)* is the equality constraint; *g(**x**)* is the inequality constraint.

By applying the optimality conditions of KKT in the optimization problem given in (23) and (24), the following formula can be obtained:

$$\begin{cases} \nabla_x L(x, \lambda_h, \lambda_g) \\ h(x) = 0 \\ g(x) \le 0 \\ \left[\lambda_g\right] g(x) = 0 \\ \lambda_g \ge 0 \end{cases} \quad (25)$$

where $\nabla_x L(x,\lambda_h,\lambda_g) = \nabla_x f(x) + \nabla_x h(x)\lambda_h + \nabla_x g(x)\lambda_g$ is the vector of first derivatives of the Lagrange function with respect to the decision variables ***x***; λ_g and λ_h are the Lagrange multipliers of the inequality and equality constraints, respectively; and a diagonal matrix with the considered variables is denoted by [..].

The optimality conditions of the KKT through the convergence process should be modified to determine the optimization problem solution. The inequality constraints given in (25) can be converted into equalities constraints by using slack variables *SV* > 0, and the strict combinatory problem of the complementary equations is concerned through

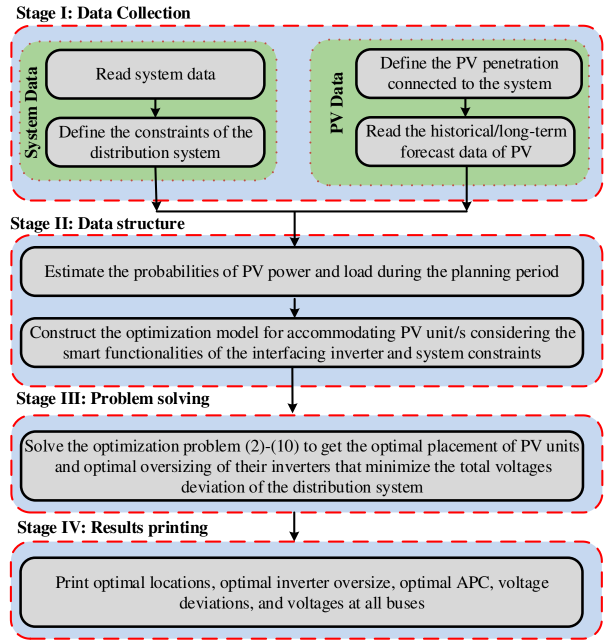

Fig. 4. Solution process of the proposed method.

the perturbation parameter $\mu \ge 0$. Hence, equation (25) can be reformulated as follows:

$$\begin{cases} \nabla_x L(x, \lambda_h, \lambda_g) = 0 \\ h(x) = 0 \\ g(x) + SV = 0 \\ \left[\lambda_g\right] SV - \mu[1, \cdots, 1] = 0 \\ (SV, \lambda_g, \mu) \ge 0 \end{cases} \quad (26)$$

The equations in (26) are iteratively solved by Newton's method.

VI. Solution Process

The solution process of the suggested approach is shown in Fig. 4. As shown, the solution of the proposed method needs four sequential stages (i.e. Stage I, Stage II, Stage III, and Stage IV). The data collection is the first stage (Stage I), where all needed data from the distribution system and PV units are collected by the algorithm. In the second stage (Stage II), the collected data are structured to estimate the probabilities of the PV generation and the load during the planning time, and the optimization problem is created. The constructed optimization model is solved in Stage III. To determine the initial setpoints of the control system, several robust power flow algorithms have been introduced in [23]–[25], [32]. In this work, a robust backward/forward sweep power flow method is used for this purpose [33]. The reactive power of the PV inverter and the APC have been optimally computed in the optimization problem. The results are saved in Stage IV. The interior-point nonlinear convex optimization method is used to solve the objective function in (2-10).

VII. Results and Discussions

A. Test System

A 33-bus test distribution system is used to test the performance of the proposed approach as shown in Fig. 5.

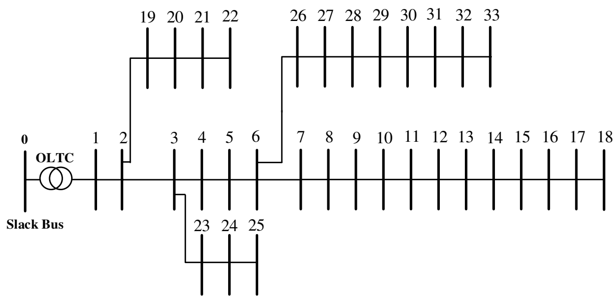

Fig. 5. Single line diagram of 33-bus distribution system.

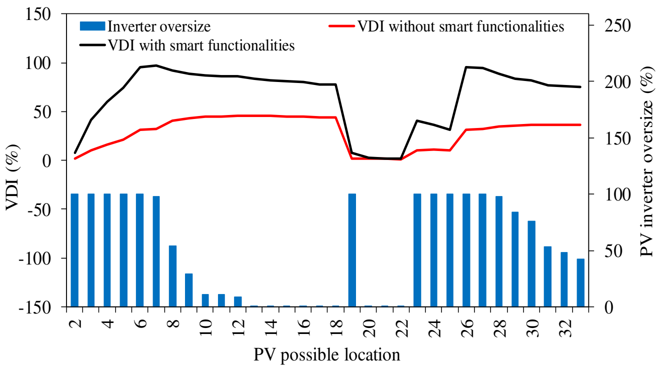

Fig. 6. VDI with the two approaches and optimal inverter oversizing computed by Approach II (one PV location).

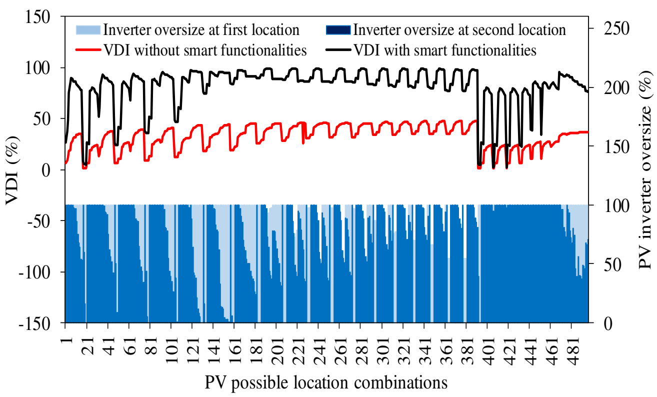

Fig. 7. VDI with the two approaches and optimal inverter oversizing computed by Approach II (two PV locations).

This system has been commonly used the literature for PV allocation studies. The complete data of that system (line and bus data) are given in [34]. 80% PV penetration is selected to be optimally accommodated in the case of single location and two locations. The PV penetration is defined as the percentage of the total PV capacity with respect to the total load demand. The parameters of the PV module are given in [15]. According to standard in [35], the lower and upper voltage limits are 0.95 p.u. and 1.05 p.u., respectively. Hourly historic data of solar irradiance and load for three years which are used in this paper are given in [36] and [37], respectively.

B. Performance Evaluation of the Proposed Approach

To reveal the effectiveness of the suggested approach, it is compared with an approach that ignores the smart functionalities of PV inverters. Fig. 6 shows the voltage deviation improvement (VDI) with the two approaches: 1) Approach I (without considering the smart functionalities of the PV inverter) and 2) Approach II (with considering the smart functionalities of the PV inverter) with respect to the base case (without PV). VDI is computed by the corresponding VD values, where it is $100\times(VD_{base}-VD_{Approach})/VD_{base}$. In addition, it shows the optimal PV inverter oversize (OS) computed by Approach II, where the whole PV penetration is accommodated at one location in the distribution system. It is clear from the figure that the VDI values by Approach II are significantly higher than those of Approach I. This improvement implies that the consideration of the smart functionalities can guarantee an optimal accommodation of the high PV penetration with respect to the minimum voltage deviation.

Fig. 7 illustrates the results for the cases of accommodating the PV penetration at multiple locations (two locations) in the distribution system. In this case, we have assumed that the total PV penetration is divided into two even parts (i.e. 40% penetration at each location). The results confirm the validity of the proposed approach for optimally accommodating the high PV penetration at multiple locations while maximizing the VDI.

TABLE I
RESULTS OF THE BASE CASE, APPROACH I, AND APPROACH II WITH SINGLE AND MULTIPLE PV LOCATIONS

PV No.	Applied method	Optimal location	VD (pu)	VDI (%)	APC (kW)	Inverter OS (%)
0	Base case	-	7.99	-	-	-
1	Approach I	bus 13	4.36	45.46	-	-
	Approach II	bus 7	0.26	96.74	73.26	98
2	Approach I	bus 18	4.17	47.75	-	-
		bus 33				
	Approach II	bus 12	0.09	98.90	0.00	32
		bus 29			0.00	95

Table I compares the results of Approach I and Approach II for the accommodation of a single PV unit and two PV units. The comparison is performed with respect to the determined PV locations, total VD, VDI, APC, and inverter oversize. As seen from the table, Approach II provides optimal PV locations and so VD is significantly improved compared to the base case and Approach I. For instance, the VDI values are 96.74% and 98.90% for Approach II which are much higher than those of Approach I for single and multiple PV accommodation, respectively. It worth to note that the determined PV locations vary according to the utilized approach.

Regarding APC values computed by Approach II (Table I), they are 73.26 kW and 0.00 kW in the cases of single and multiple locations, respectively. The reason for increasing the APC value in the case of a single location is that the total PV penetration is focused at one location causing voltage rise which requires high APC to be mitigated. However, the PV penetration is distributed in the case of multiple PV locations and so the APC is small. The inverter oversize computed by Approach II is 98% for single PV accommodation, and 32% and 95% in the case of multiple PV accommodation. Note that the maximum limit of oversizing is set to be 100% of the inverter rating (in order to investigate practically unlimited oversizing).

Figs. 8 and 9 compare the voltage profile at PCCs in the case of Approaches I and II for single and multiple PV accommodation. It is obvious the superiority of the proposed approach (Approach II) for flatting the voltage and keeping it

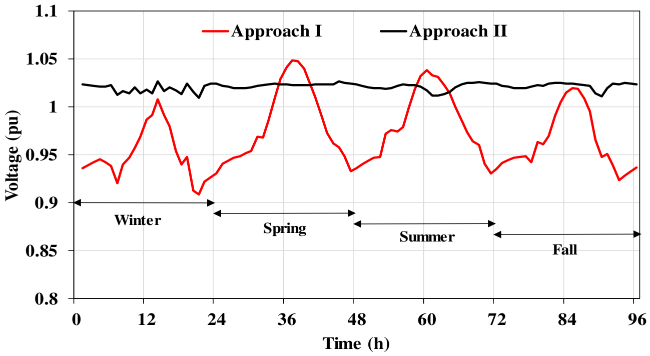

Fig. 8. Hourly voltage profile at PCCs with the two approaches (I and II) in the case of one PV location.

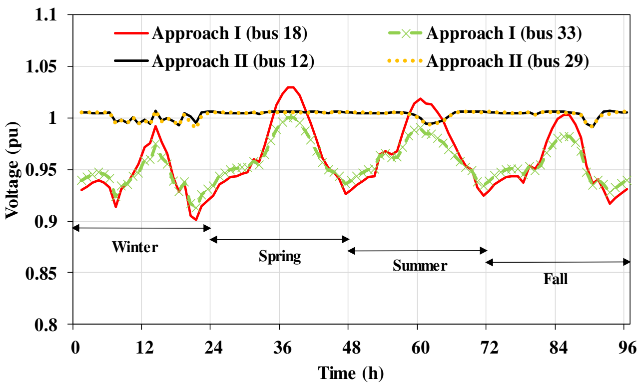

Fig. 9. Hourly voltage profile at PCCs with the two approaches (I and II) in the case of two PV locations.

within limits compared to Approach I. These benefits of Approach II are accomplished by the consideration of the smart functionalities including optimal reactive power dispatch and APC of the optimally oversized PV inverters (Fig. 10). Note that the maximum APC for the single PV location is 17 kW which is small.

C. Effect of Oversizing Limit on VD

To simulate the real situation that there is a limitation in the allowed oversize of the PV inverter, we have tested Approach II with setting the maximum limit of oversizing to be 30% of the inverter rating. As shown in Table II, the VD values have been significantly reduced compared to the base case, but they are slightly higher than the case of 100% oversize limit. Therefore, the proposed approach is fixable for accommodating PV according to the available standard of the utility.

D. Loss-based Approach

In this subsection, we have studied the performance of the proposed method by considering the total active losses (instead of total VD) as an objective function to be minimized. As shown in Table III, the determined locations vary from those obtained by Approach II (Table I). In addition, much higher values of APC are noticed in this approach (Loss-based Approach) compared to Approach II. For instance, the values of APC in the case of a single location are 73.26 kW and 16488 kW for Approach II and Loss-based Approach, respectively. As the APC is high in Loss-based Approach, the in inverters do not oversize. Another benefit of Approach II is the lower total VD implying that the voltage profile has been optimally improved. This analysis demonstrates that the

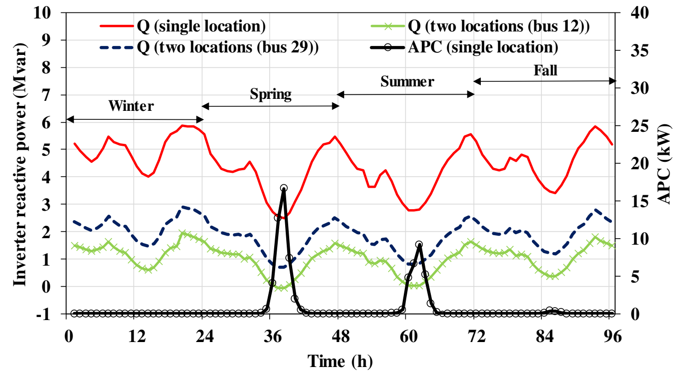

Fig. 10. Reactive power (Q) and APC of the oversized PV inverter in the case of Approach II.

TABLE II
RESULTS OF 30% INVERTER OVERSIZING LIMIT

PV No.	Optimal location	VD (pu)	VDI (%)	APC (kW)	Inverter OS (%)
1	7	0.56	93.04	73.41	30.00
2	12	0.12	98.53	1.00	28.82
	29			0.00	30.00

TABLE III
RESULTS OF THE LOSS-BASED APPROACH

PV No.	Optimal location	VD (pu)	VDI (%)	APC (kW)	Inverter OS (%)
1	bus 30	3.32	58.46	16488	0.00
2	bus 14	1.79	77.65	7042	0.00
	bus 30			2393	0.00

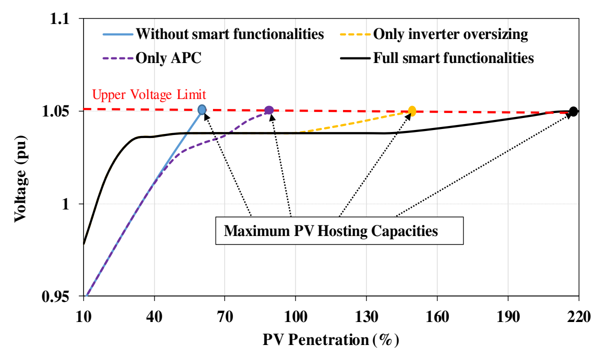

Fig. 11. Voltage variation with the PV penetration.

utilization of total VD as an objective function could have pronounced positive impacts on maximizing the accommodation of the PV penetration with respect to the operation voltage limits.

E. Application of the proposed approach for maximizing the hosting PV capacity

Here, we demonstrate the applicability of the proposed approach to maximize the hosting capacity of PV. For this purpose, in Fig. 11, the variations of the maximum voltage at PCC are shown with four scenarios: 1) without smart functionalities, 2) with APC only, 3) with inverter oversizing only, and 4) with full smart functionalities. The maximum limits of APC and inverter oversizing are set to be 30%. As noticed in Fig. 11, for all scenarios, the voltages increase with the PV penetration and they reach the upper voltage limit (red dashed line) at different PV penetrations in which the maximum hosting capacity is attained. For instance, the maximum PV hosting capacities when considering full smart functionalities is 220% which is much higher than of the base scenario (only 60%). It is also obvious that the consideration of inverter oversizing only achieves higher PV hosting capacity than considering APC only, where the corresponding figures are 150% and 90%, respectively.

F. PV Hosting Capacity Variation with Inverter Oversizing

In this subsection, we investigate the effect of oversizing limit on the PV hosting capacity. For this purpose, we have compared the hosting capacity with 10% inverter oversize limit (complies with the recently released IEEE 1547:2018 standard) with that in the case of 30% inverter oversize limit. Fig. 12 compare the voltage profile at PCCs in the case of 30% and 10% inverter oversize limits which are labeled as Case 1 and Case 2, respectively. It is clear that the proposed approach can maximize the PV hosting capacity while keeping the voltage within the lower and maximum limits for the both cases. It is important to note that the computed hosting capacity is 220% for Case 1 which is much higher than that for Case 2 (160%). This implies that a wider oversizing limit of the interfacing inverter can provide further benefits in terms of maximizing the hosting capacity of PV. This improvement is accomplished by the extended watt-var functions of the inverter in Case 1. To demonstrate this feature, we compare the hourly PV reactive power and APC for Case 1 and Case 2 as shown in Fig. 13. From this figure, it can be noticed that the APC for Case 1 is higher than that for Case 2, allowing to increase the hosting capacity for Case 1.

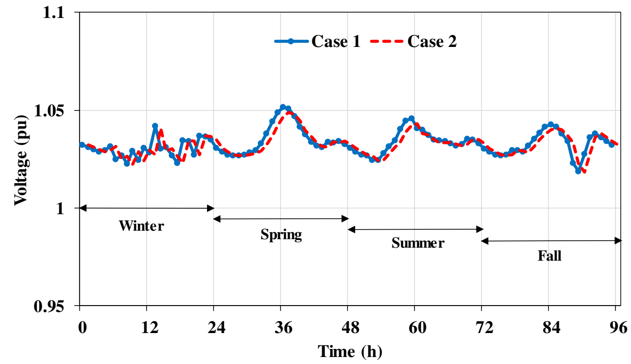

Fig. 12. Hourly voltage profile at PCCs with Case 1 and Case 2.

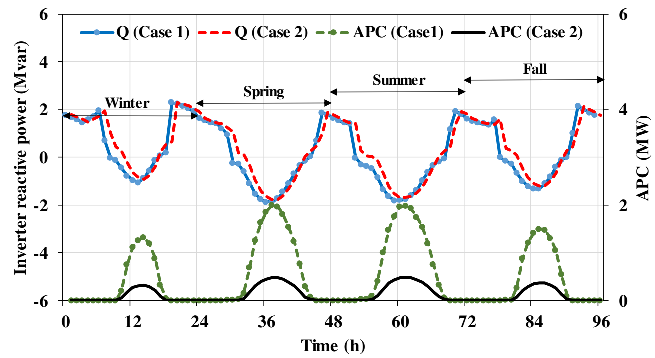

Fig. 13. Reactive power (Q) and APC of the oversized PV inverter for Case 1 and Case 2.

G. Discussions

Based on the calculated results, the effectiveness of the proposed approach is demonstrated compared with existing approaches that ignore the smart functionalities of PV inverters. Specifically, the proposed approach can optimally host high PV penetrations considering their stochastic generation. The proposed approach provides extended planning options as it optimizes the interfacing inverter oversize with smart watt-var functionalities. This improvement implies that considering the smart functionalities can ensure an optimal accommodation of the high PV penetration with respect to a low VD rate. The proposed approach is a helpful tool for distribution system planners for computing the optimal PV inverter oversize for hosting high PV penetrations considering voltage regulation of utilities.

Note that PV units can be integrated with battery energy storage systems (BESSs) which can contribute to increasing the hosting capacity of PVs. To consider such BESSs, a detailed model of them, e.g. state of charge and charging/discharging limits, could be integrated into the mathematical model of the proposed approach. Another note is that the cost of active power curtailment, the cost of oversizing, and the cost of these combined smart watt-var functionalities, are not considered in this work and left for a future study. Furthermore, similar to the consideration of the PV inverter control, the hierarchical droop-based control implemented in [38] can be considered in the planning phase of PV.

VIII. CONCLUSIONS

An optimal approach for calculating the optimal accommodation of high PV penetration has been proposed considering the stochastic nature of PV and load variations. The proposed approach can precisely determine the best places of PV units to minimize the voltage deviations in the entire distribution system taking into consideration various constraints. Besides, it yields an optimized APC and PV inverter oversize in a simultaneous manner. The smart functionalities of the interfacing inverter of PV have been incorporated in the optimization model solved by a nonlinear interior point method. Intensive simulations have been performed on the 33-bus distribution systems. Unlike the traditional approach, the proposed approach can optimally accommodate high PV penetration at single or multiple locations for minimizing voltage violations, thanks to the consideration of the smart functionalities. In addition, the utilization of VD as an objective function can greatly maximize the accommodation rate of PV at single or multiple locations compared with the Loss-based Approach. The applicability of the proposed approach to maximize the hosting capacity of PV has been verified.

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