A Simplified Approach for Optimal Photovoltaic Generation Management to Avoid Voltage Violations

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***Abstract*—Voltage rise is known as one of the most significant technical impacts caused by photovoltaic (PV) generation. In this paper, a management approach is proposed to avoid voltage violations by properly curtailing the power injected by PV generators into the network. The proposed approach is formulated as a linear optimization problem since voltage variations due to PV connections are calculated using linear sensitivities. A responsibility index is also developed to quantify the contribution of each PV generator to the network voltage violation. This index can be used to reward the owners of those generators that have higher contribution on preserving network voltages within limits. Simulation studies have confirmed the effectiveness of this management strategy and the importance of the responsibility index.**

***Index Terms*—Optimization methods, photovoltaic generation, power distribution systems.**

I. Introduction

The increasing penetration of photovoltaic (PV) generation is a reality worldwide. Recently published statistics have revealed that the installed PV generation capacity exceeded 100 GW by the end of 2012, following an exponential trend [1]. This scenario raised utilities concern worldwide due to its technical impacts on distribution networks, such as: voltage magnitude rise, cable overload, and increase in voltage unbalance, harmonic distortion level and power losses. These impacts have been extensively discussed in previous works, with special attention to the voltage magnitude rise, which typically represents the most restrictive impact [2]-[5]. Thus, in the current scenario of rapid increase in PV penetration level, management techniques must be developed to assure that such penetration growth does not lead to a violation of voltage limits.

In this context, this paper proposes a PV generation management methodology to avoid network voltage violations due to excessive power injected by PVs. This method is formulated as an optimization problem, which targets the maximization of PV injected power without exceeding network voltage limits. A simple linear model is adopted to estimate voltage variations due to PV connection without the need of including the detailed power flow equations (which are nonlinear). Furthermore, a responsibility index is proposed to rank PV generators according to their energy reduction. As a result, PV owners can be fairly rewarded according to their contribution to network voltage regulation.

This paper is organized as follows. Section II describes the proposed PV management methodology. In this section, a practical index to quantify the responsibility of each PV generator to network voltage regulation is also proposed. The test system is described in Section III. Simulation results and analyses for different PV penetration scenarios are presented in Section IV.

II. Methodology for PV Generation Management

This section establishes a linear optimization strategy to manage the amount of active power injected by PVs at each instant of the day without violation network voltage limits.

A. Objective Function

The objective of this approach consists in maximizing the energy injected by PV generators into a distribution network within a 24-hour period. This may be achieved by maximizing the PV injected power at each instant of the day. Thus, at a given time instant *t*, objective function *F* that must be maximized is:

$$F = \sum_{i=1}^{N} \left(1 - \frac{V_i^t}{V_{\max}} \right) \cdot P_{PV_i}^t \cdot x_i \qquad (1)$$

where *N* is the number of customers in the network; V_i^t is the voltage magnitude at bus *i* at time instant *t* (disregarding PV generation); V_{max} is the maximum allowable voltage (1.05 pu);

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$P_{PV_i}^t$ is the power injected by a PV connected to bus i at time instant t (given in kW); and x_i is equal to one if there is a PV connected to bus i, and zero otherwise.

B. Constraints

Previous works have identified voltage rise as one of the main technical impacts of distributed generation [2]-[5]. Thus, the voltage at each network bus must be kept within statutory voltage limits (in Brazil, for secondary networks V_{min} = 0.91 pu and V_{max} = 1.05 pu) as shown in (2).

$$V_{min} \le V_i \le V_{max}, \qquad \forall i = 1,2,\cdots,N \tag{2}$$

The extent of voltage rise on a specific bus directly depends on several factors such as the number, power rating and location of PVs on the network. In this paper, bus voltage variations are calculated using voltage sensitivities, as explained in the next subsection.

Furthermore, at a particular time step, the power injected by each PV cannot exceed the limit imposed by its power rating and by the solar irradiance level. This constraint is mathematically expressed by (3), where $P\max_{PV_i}^t$ is the maximum power that can be injected by PV_i at time instant t.

$$0 \le P_{PV_i}^t \le P\max_{PV_i}^t, \qquad \forall i = 1,2,\cdots,N \tag{3}$$

C. Voltage Sensitivities

Usually, the bus voltages are calculated using power flow equations, which are nonlinear, increasing the complexity of the problem solution. However, in this paper, a very simple linear approach based on voltage sensitivities is adopted to estimate voltage rise due to PV power injection. This approach provides good results because, according to [6], the correlation between voltage rise and PV generation increase is approximately linear.

The variation of voltage at bus i with respect to the power injected at bus j is given by (4) [6]. In this equation, Z_{ij} represents the total branch impedance of the intersection among path "from the substation to bus i" and path "from the substation to bus j"; and V_j^0 is the voltage at bus j without any PV connected to the network.

$$\frac{\partial|V_i|}{\partial|P_j|} = -|Z_{ij}|\left[\frac{1}{|V_j^0|} + \frac{|P_j|}{|V_j^0|}\frac{|Z_{jj}|}{\left(|V_j^0|^2 - |Z_{jj}||P_j|\right)}\right] \tag{4}$$

$$V_i \cong V_i^0 + \frac{\partial|V_i|}{\partial|P_j|}\cdot P_{PV_j} \tag{5}$$

By replacing equation (5) into equation (2), the voltage constraint is given as follows.

$$V_{min} \le V_i^0 + \sum_{j=1}^{N}\frac{\partial|V_j|}{\partial|P_{PV_i}|}P_{PV_j} \le V_{max}, \quad \forall i = 1,2,\ldots,N \tag{6}$$

Such sensitivity based strategy is interesting because it demands very low computational effort. Only one 24-hour power flow calculation must be performed during the entire optimization process, to determine the initial voltages (V_j^0) for each time step.

D. Responsibility Index

Under a multiple PV scenario, it is useful to determine the relative contribution of each PV on avoiding voltage violations. This subsection proposes a responsibility index ($R\%$) that is capable of ranking PV owners according to the amount of energy curtailed to keep voltages within statutory limits. This index can be expressed for each PV_i as shown in (7), where T is the number of snapshots on a 24-hour simulation. The responsibility index is normalized, as in (8) to enable the comparison among multiple PVs.

$$R_i = \frac{\sum_{t=1}^{T}\left(P\,max_{PV_i}^t - P_{PV_i}^t\right)}{\sum_{t=1}^{T}P\,max_{PV_i}^t} \tag{7}$$

$$\overline{R\%}_i = 100\times\frac{R_i}{\sum_{j=1}^{N}R_j} \tag{8}$$

Larger $\overline{R\%}$ values indicate that the corresponding PV is more affected by the proposed management strategy and, therefore, contributes more to the avoidance of voltage violations. As a result, PV owners can be fairly rewarded according to their contribution to network voltage regulation.

E. Summary

A summary of the PV generation management methodology is presented in the flowchart of Figure 1. Firstly, a 24-hour power flow is performed to determine the state of the network without PV connections. This information will be used later to determine voltage sensitivities. Secondly, the 24-hour

PV generation profile is calculated for each generator considering its associated power rating and a typical solar irradiance curve provided by [7]. Then, for each time step, the optimum power injected by each PV is calculated using the proposed PV management formulation. Finally, the 24-hour optimum PV generation schedule becomes available to the Distribution Management System, and the contribution of each PV to network voltage regulation can be determined by using the responsibility index.

The overall algorithm has been developed using MATLAB optimization package and the OpenDSS software.

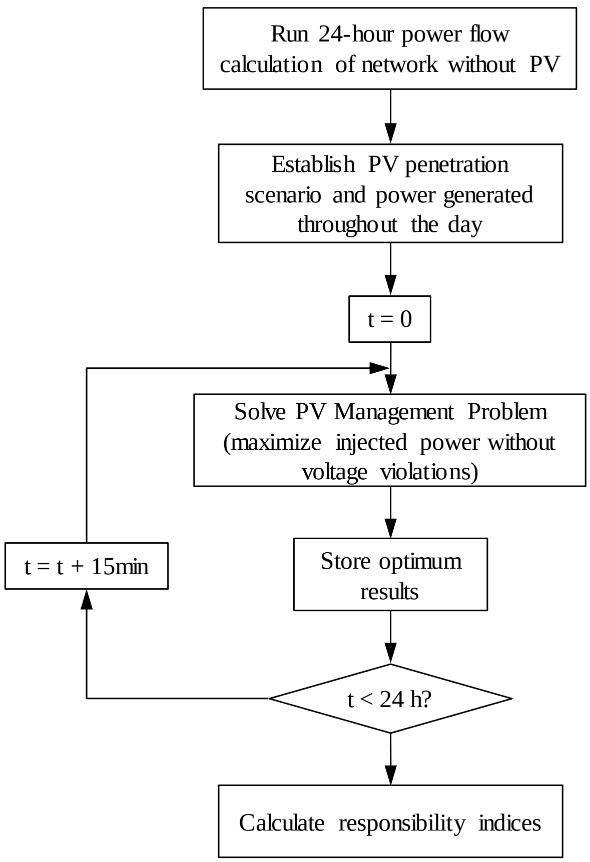


Figure 1. Overall flowchart of PV management methodology.

III. Description of the Test System

This section presents the description of the test system as well as the customer loads and PV generators models.

A. *Network Model*

A real Brazilian secondary network, whose topology is shown in Figure 2, has been selected for the studies performed in this paper. This secondary network is connected to a 13.8 kV system through a service transformer of 75 kVA, 13.8/0.22 kV (delta-grounded wye), and feeds 26 residential customers.

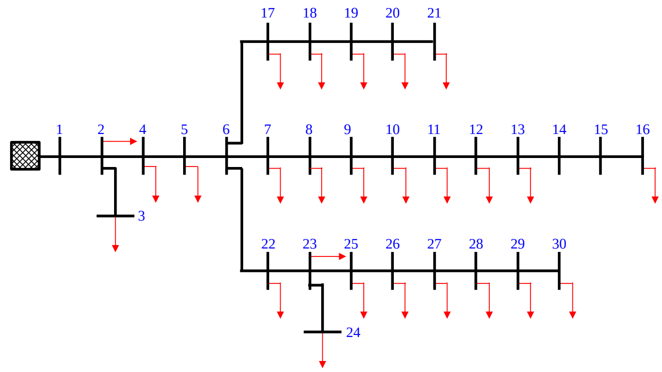


Figure 2. Test system single-phase diagram.

B. *Customer Load Model*

All network customers, which may be either single-phase or two-phase, are modelled as constant power loads of total peak demand of 34.4 kVA, (i.e., roughly 45% of transformer rating). In addition, their daily behavior follows load curves provided in [8], which are divided into 96 snapshots (each level corresponds to a 15-minute period).

Without any PV connected to the test system, the minimum and maximum daily voltages are 0.9178 pu and 1.00 pu, respectively. Both values are within normal operating range, which is 0.91-1.05 pu in Brazil.

C. *PV Generation Model*

Photovoltaic generators are modelled as negative loads (constant power injection) whose output power at each time snapshot is given by (9), where *Irr* is the solar irradiance level (in W/m^2), and P_{rated} is the PV power rating (in kW).

$$P = \frac{Irr}{1000\,W/m^2} \times P_{rated} \qquad (9)$$

IV. Simulation Studies and Results

A. *Studied Scenarios*

Three scenarios are considered in the simulations to verify whether the proposed technique can, in fact, avoid voltage violations or not. The selected scenarios are built as shown in Table I, where typical PV power ratings for Brazilian networks (0.0-4.0 kW) are considered.

One shall notice that, at this stage, only deterministic scenarios were selected because the main idea is to illustrate the proposed method. However, since this is an ongoing project, randomly generated scenarios will also be tested where PV penetration level, PV location, and PV power rating will be included as problem uncertainties.

TABLE I. PV CONNECTION SCENARIOS

Scenario 1		Scenario 2		Scenario 3	
Bus	Power rating (kW)	Bus	Power rating (kW)	Bus	Power rating (kW)
2	2.0	2	2.0	2	2.0
7	3.0	7	3.0	7	3.0
24	4.0	24	4.0	24	4.0
		20	3.0	20	3.0
		28	2.0	28	2.0
		13	4.0	13	4.0
				16	2.0
				19	3.0
				8	3.0

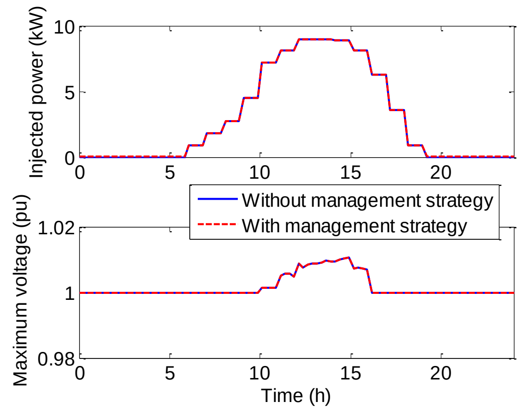
B. *Results and Analyses*

Simulation results for the three scenarios are summarized in Figure 3 and in Table II. For the purpose of comparison, detailed power flow calculations have been performed considering maximum PV generation (labeled as "Without management strategy") and limited PV generation (labeled as "With management strategy") to verify network voltages behavior. Only the network maximum voltage is shown in Figure 3 because this is the critical parameter (minimum voltage is not violated by the PV penetration). As shown, in Scenario 1, no control action is necessary since the total power injected by PVs (9.0 kW at peak) is not sufficient to violate voltage limits. For the penetration level considered in Scenario 2, even though control actions are required around 12:00 pm, only 2.26% of PV generated power should be prevented from being injected into the network. Finally, in the third scenario, the PV management scheme must act during an extended period of about 7 hours, reducing 12.7% of the total PV generation.

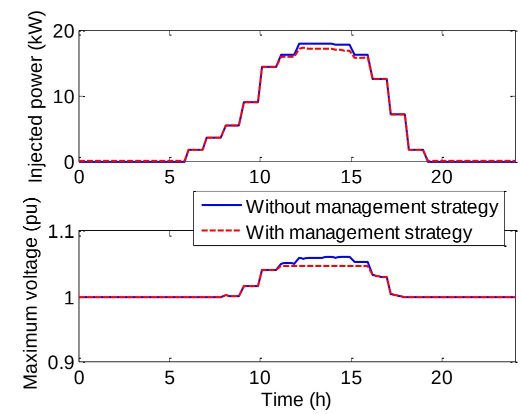
TABLE II. EFFECT OF PV MANAGEMENT ALGORITHM ON PV POWER GENERATION

Scenario	Reduction on generated energy (%)
1	0.00
2	2.26
3	12.7

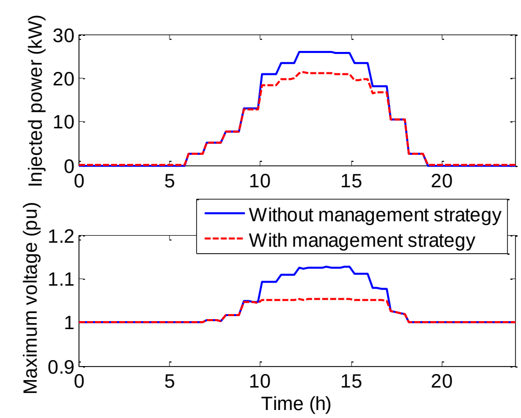
When management strategy is included, the network voltages for Scenarios 2 and 3 remain below 1.05 pu, which indicates that the proposed strategy based on linear voltage sensitivities was effective in preserving network voltages within limits.



(a) Scenario 1: 3 PV generators



(b) Scenario 2: 6 PV generators



(c) Scenario 3: 9 PV generators

Figure 3. Impact of the proposed PV management strategy on the total injected power and peak network voltage.

V. RESPONSIBILITY INDEX

To illustrate the applicability of the responsibility index, it is calculated for the three PV penetration scenarios previously studied, and results are shown in Table III. In Scenario 2, only PV connected to bus 13 is affected by the proposed management approach, while, in Scenario 3, three PVs are affected. The responsibility index further indicates that, for the third scenario, the PV connected to bus 16 is the most affected unit as less than 50% of its capacity is effectively used.

TABLE III. NORMALIZED PERCENTAGE CONTRIBUTION OF EACH PV TO RESPECT VOLTAGE LIMITS

Scenario 1		Scenario 2		Scenario 3	
Bus	$\overline{R\%}$	Bus	$\overline{R\%}$	Bus	$\overline{R\%}$
2	0.00	**13**	**100.0**	**16**	**63.4**
7	0.00	2	0.00	**13**	**28.1**
24	0.00	7	0.00	**20**	**8.50**
		24	0.00	2	0.00
		20	0.00	7	0.00
		28	0.00	24	0.00
				28	0.00
				19	0.00
				8	0.00

This index can be adopted to proportionally reward those PV owners affected by the PV management technique. However, further investigations are still necessary to establish adequate reward policies, which is beyond the scope of this paper.

VI. CONCLUSIONS

This paper has proposed a PV management methodology to avoid violations of network voltage limits. The proposed strategy consists in maximizing the energy injected by PVs without the occurrence of voltage violations. An interesting feature of this approach is the use of sensitivities to calculate voltage variations without the need of including power balance equations, which would greatly complicate the problem since these, are nonlinear equations. Simulation studies have confirmed that this sensitivity-based method has good accuracy and, therefore, is effective in avoiding the voltage violations.

A responsibility index was also proposed to identify the contribution of each generator to preserve voltages within limits. This index shall be used by utilities to reward (proportionally) those customers which generation was affected by the proposed management strategy.

The future developments of this work include:

- Consider other technical impacts (such as network losses and cable overload) as constraints to the optimization model;
- Develop attractive reward policies to draw customer interest to participate in the management strategy;
- Consider more realistic PV penetration scenarios, which should include uncertainties on PV location, PV power rating, number of PVs on the network etc.

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