A Solar-assisted Voltage Optimization Method for Transmission Solar Network Power System

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***Abstract*—This paper proposes a new formulation and solution algorithm that uses transmission level solar inverters to address the security-constrained optimal power flow (SCOPF) problem. The goal is to stabilize voltage fluctuations in transmission networks in base case and contingency scenarios, by using bulk solar power plant with a minimal number of post-contingency corrections. To achieve this goal, a two-stage volt/var optimization method is proposed to first correct all voltage violations with the volt-var alternating current optimal power flow (ACOPF) algorithm for a base case. Then a linearized SCOPF volt-var control algorithm is proposed to identify the corrective actions for all potential voltage violations in all contingency scenarios. The proposed method was tested and validated on a modified IEEE 118-bus system with solar photovoltaic (PV) data.**

***Index Terms*—Photovoltaic, Volt/Var Control, Security-constrained AC optimal power flow**

I. Introduction

Reverse power flows and variable outputs from solar generation resources could cause temporal and spatial voltage variations in the power network. Such variations can lead to exceeding voltage limits established by the North American Electric Reliability Corporation in its voltage and reactive control standard VAR-001-4 at the sub-transmission level [1]. Voltage regulation devices currently deployed are operated to cope mainly with system load changes. Their settings are usually determined on a seasonal basis. The operation of these devices is not designed and coordinated for managing the real-time variations caused by integrated solar PV power. As a result, over- or under-voltage problems can occur more frequently, especially during the light load seasons in the spring and fall. Those phenomena have already been observed in high solar PV penetration areas, such as Hawaii and Southern California [5].

Volt/var control problem has been studied extensively. Most existing research formulates the reactive power/voltage optimization problem as an AC optimal power flow (OPF) problem that considers a full power flow solution within the network constraints [2-3]. Standard analyses such as contingency analysis are used to identify potential violations in both base case and contingency scenarios. Once the potential violations are identified, operators often take preventive actions based on expert knowledge of the system to ensure the system does not have voltage violations. The OPF problem with the contingency constraints is often referred to as the security-constrained optimal power flow (SCOPF) problem [4]. Though this has been a reliable method often practiced by system operators it may not be most efficient. The problems become more acute with increasing penetration of solar generation due to its variability and uncertainty.

The SCOPF problem has been widely classified into two classes: preventive and corrective [6] formulations. Preventive control is an action taken to move from the alert state to the normal state. However, the preventive security-constrained optimal power flow (PSCOPF) problems are usually large-scale power flow problems and are hard to solve directly. For a PSCOPF problem with C contingency scenarios, the size of the problem is approximately C+1 times larger than that of the conventional OPF formulation. As a result, many algorithms have been developed to handle this solving difficulty. In references [7–8], a series of iterative contingency filtering techniques or contingency ranking methods are proposed to minimize the number of contingency scenarios in the PSCOPF formulation. In references [9-10], different solution algorithms, such as sparse optimization techniques and benders decomposition, are proposed to solve the PSCOPF problem for reactive power/voltage control.

The second type of SCOPF model is the so-called corrective security constraint optimal power flow (CSCOPF), which allows the post-contingency control variables such as power generation outputs and transformer taps to be readjusted to remove any violations caused by the contingency. The scale of the CSCOPF formulation is often smaller than that of the preventive model. However, the model requires additional decision variables with respect to contingency scenarios, and more importantly it might need many different reschedules for each different contingency. The authors of reference [11] proposed one exact method to find the global algorithm and two fast local algorithms to find corrective actions for each contingency separately.

However, most research on SCOPF typically has focused on the optimization solution algorithm such as contingency filtering techniques [7-8]. Although, [2] and [16] have proposed ACOPF formulation with PV systems, none have utilized the utility-scale PV system for SCOPF formulation. These large-scale PV facilities will be interconnected to the grid via dedicated feeders or distribution feeders. At the transmission side, it is routinely required that interconnected PV provide grid support functions such as voltage regulation. Therefore, in this paper, we first propose our new formulation for SCOPF using pre- and post-contingency voltage requirements from the New York Independent Service Operator (NYISO) emergency operations manual [13].

To handle the computational difficulty from the SCOPF, we propose a two-stage CSCOPF algorithm in this paper. In the first stage, a full ACOPF based volt-var control algorithm is proposed. The purpose is to minimize the operational voltage violations for the base case normal scenario. After all voltage violations in the base case are cleared, we execute a linearized SCOPF volt-var control algorithm to identify corrective actions for all potential voltage violations in all contingency scenarios. The proposed methodology is the first of its kind, to guarantee minimized operational voltage violations in base case and contingency scenarios with significantly reduced problem scale and reduced calculation time. The main contributions of this paper are twofold:

- Different from the existing SCOPF methods, the proposed two-stage CSCOPF algorithm are OPF based algorithm with significantly reduced problem scale and linearized formulation. Therefore, it can be flexibly and effectively applicable to different power grid at different operation conditions.
- The proposed two-stage CSCOPF algorithm has been tested and validated on IEEE 118-bus system. And the results show the proposed algorithm can guarantee minimized operational voltage violations in both base case and contingency scenarios by utilizing the utility-scale PV system.

The remainder of this paper is as organized as follows. Section II provides the proposed volt-var SCOPF problem formulation. Then, the proposed solution method for the problem formulation is presented in Section III. In section IV, we present the modified 118-bus test system with time series solar PV and load data and the validated results of the proposed methodology on the modified 118-bus test system. Finally, we present our conclusions in Section V.

II. Proposed Methodology

A. Formulation of the Proposed Security Constrained Volt/Var Optimization Problem

We define here the SC-ACOPF problem. Let E be the set of lines and L be the set of load buses in grid. In each bus, let V_i^R and V_i^I be the real and imaginary parts of the voltage at bus *i*. In each line, let b_{ijc} and g_{ijc} ($i \neq j$) denote the susceptance and conductance at line *c* from bus *i* to bus *j* ($i, j = 1,..., N$), respectively.

The security-constraint volt/var AC OPF is developed on a current and voltage rectangular coordination basis as follows:

$$\text{Min}\, W_1 \sum_{(i,j,c)\in E} \frac{b_{ijc}}{b_{ijc}^2 + g_{ijc}^2} \left(\left(I_{ijc}^R + \frac{b_{ijc}^C V_i^I}{2} \right)^2 + \left(I_{ijc}^I - \frac{b_{ijc}^C V_i^R}{2} \right)^2 \right) + W_2 \sum_{i\in L} \left(V_i^I - v_i^I \right)^2 \quad (1)$$

Subject to the following constraints:

$$I_{ijc}^R = a_{ijc} \left(\frac{1}{\tau_{ijc}^2} (g_{ijc} V_i^R - (b_{ijc} + \frac{b_{ijc}^C}{2}) V_i^I) - \frac{1}{\tau_{ijc}} (g_{ijc} V_j^R - b_{ijc} V_j^I) \cos(\phi_{ijc}) + \frac{1}{\tau_{ijc}} (g_{ijc} V_j^I + b_{ijc} V_j^R) \sin(\phi_{ijc}) \right) \quad (2)$$

$$I_{ijc}^I = a_{ijc} \left(\frac{1}{\tau_{ijc}^2} (g_{ijc}^\varepsilon V_i^I + (b_{ijc}^\varepsilon + \frac{b_{ijc}^C}{2}) V_i^R) - \frac{1}{\tau_{ijc}} (g_{ijc}^\varepsilon V_i^I + b_{ijc}^\varepsilon V_i^R) \cos(\phi_{ijc}) - \frac{1}{\tau_{ijc}} (g_{ijc}^\varepsilon V_i^R - b_{ijc}^\varepsilon V_i^I) \sin(\phi_{ijc}) \right) \quad (3)$$

$$0 = \sum_{k\in G_i} P_k^g - d_i^P - V_i^R \left(\sum_{(jc):ijc\in\varepsilon} I_{ijc}^R + \sum_{(jc):jic\in\varepsilon} I_{ijc}^R \right) - V_i^I \left(\sum_{(jc):ijc\in\varepsilon} I_{ijc}^I + \sum_{(jc):jic\in\varepsilon} I_{ijc}^I \right) - \left[(V_i^R)^2 + (V_i^I)^2 \right] g_i^s \quad (4)$$

$$0 = \sum_{k\in G_i} Q_k^g - d_i^Q - V_i^R \left(\sum_{(jc):ijc\in\varepsilon} I_{ijc}^I + \sum_{(jc):jic\in\varepsilon} I_{ijc}^I \right) - V_i^I \left(\sum_{(jc):ijc\in\varepsilon} I_{ijc}^R + \sum_{(jc):jic\in\varepsilon} I_{ijc}^R \right) + \left[(V_i^R)^2 + (V_i^I)^2 \right] b_i^s \quad (5)$$

$$\underline{V}_i^2 \le \left(V_i^R \right)^2 + \left(V_i^I \right)^2 \le \overline{V}_i^2 \quad (6)$$

$$\left[\left(I_{ijc}^R \right)^2 + \left(I_{ijc}^I \right)^2 \right] \le \overline{I}_{cap}^2 \quad (7)$$

$$P_i^g = p_i^{sch} \quad (8)$$

$$q_i^{\min} \le Q_i^g \le q_i^{\max} \quad (9)$$

$$V_i^g = v_i^{sch} \quad (10)$$

$$\max(-\sqrt{\eta \cdot \left(s_i^{solar} \right)^2 - \left(p_i^{solar\_sch} \right)^2}, -0.328 \cdot p_i^{solar\_sch}) \le Q_i^{solar} \le \min(\sqrt{\eta \cdot \left(s_i^{solar} \right)^2 - \left(p_i^{solar\_sch} \right)^2}, 0.328 \cdot p_i^{solar\_sch}) \quad (11)$$

$$\sum_{(i,j,c)\in E} \left(1 - a_{ijc} \right) \le k \quad (12)$$

Equation (1) is the objective function of the volt/var AC OPF, which includes two parts. The first part is the system loss, which is computed by summing the losses of each line. The second part is the voltage deviation V_i^l of non-generator bus *i* from its bus voltage set point v_i^l. W_1 and W_2 are penalty coefficients on system real power losses and bus voltage deviations, respectively. The objective is to minimize the system loss, while regulating all the non-generator buses at scheduled voltage levels. The appropriate tradeoff between losses and voltage deviations are reflected by the values of the penalty parameters, which must be determined by the system operation requirements and offline testing results on a given power system. In the modified 118-bus system we are testing, we select the values of W_1 and W_2 as 1 and 15 based on our testing results.

Constraints (2) and (3), that is, I_{ijc}^{R} and I_{jic}^{I}, represent the real and imaginary parts of the current flowing from bus i to bus j through line circuit c. τ_{ijc} and ϕ_{ijc} represent the tap ratio and phase shift of the transformer c between buses i and j. The a_{ijc} is the binary variable representing the contingency of line i, j, if $a_{ijc}=0$ out of service and 1 otherwise. The sum number of contingencies is limited by (13) to k.

Constraints (4) and (5) represent the real and reactive power balance at bus i. P_k^g and Q_k^g represent the real and reactive power of generators at bus k, while d_i^P and d_i^Q represent the real and reactive load at bus i, and g_i^s is the shunt conductance at bus i.

Constraints (6) and (7) represent the current and voltage magnitude limitations for each bus and each transmission line.

Constraints (8) and (9) give the limits for the real and reactive power output from the generator. As can be seen from constraint (8), as in the proposed volt/var AC OPF solution, the generation dispatch should remain the same as in the case where the reactive compensation devices are not controlled. Note that this implies that in the OPF-based voltage control procedure, the original generation dispatch schedule will not be affected.

Constraint (10) requires the generation voltage set point to remain within the same limits as in the case where the reactive compensation devices are not controlled.

Constraints (11) gives the apparent power limit and the power factor limit for the reactive power output from the solar PV. The 0.328 in Constraint (11) represents the 95% power factor constraints at the solar inverter. It is noted that the both FERC Order 661-A and ERCOT generator interconnection requires a 0.95 power factor for renewable generator integration [12]. Constraint (12) guarantee the sum number of contingencies to be less than k.

B. Operational Voltage Limits

When the transmission system has its voltage violate the pre- or post-contingency voltage criteria, it is the Independent Service Operator's responsibility to apply relief measures to return the system voltage condition to within the normal range. For the NYISO, the so called "alert state criteria" is used to define the criteria for pre- and post-contingency voltage limits. The general rules for all NYISO members' operational voltage limits are summarized in Table I. The voltage limits in Table I are pre- and post-contingency voltage limitations from the NYISO emergency operations manual [13]. As shown in reference [13], the alert state criteria require the actual voltage on any bus listed in Table I be below its pre-contingency voltage limit for less than 15 minutes or be above its post-contingency voltage limit for less than 10 minutes. To satisfy the voltage requirements in Table I, an operational volt-var control tool is needed to control system voltages in both the pre- and post-contingency scenarios.

TABLE I. NYISO MEMBERS PRE-CONTINGENCY AND POST-CONTINGENCY VOLTAGE LIMITATIONS.

TO	Pre-Contingency		Post-Contingency	
	Low	High	Low	High
CH	0.95	1.05	0.90	1.05
ConEd	0.95	1.05	0.95	1.05
LIPA	0.95	1.05	0.90[1]/0.95[2]	1.05[2]/1.1[1]
NGRID	0.95[3]/0.98[4]	1.05	0.90[3]/0.95[4]	1.05
NYSEG/RG&E	0.90[5]/0.95[6]	1.05	0.90[5]/0.95[6]	1.05
O&R	0.95	1.05	0.95	1.05
NYPA	*	*	*	*

C. A Two Stage Volt/Var Optimization Method

ACOPF problem is of mixed integer non-linear type with the power balance equations causing the most difficulty in the optimization. The SCOPF-based optimization formulation minimizes voltage deviations for the normal case and for contingency scenarios, while minimizing mechanical switching of different reactive power devices such as shunt elements. Security constrained ACOPF problem is even more challenging due to the inclusion of additional constraints for each contingency. There are no commercially available tools to meaningfully perform SC-ACOPF optimizations. For example, computational solvers such as CPLEX takes hours to solve SC-ACOPF on a 1000 bus system with 20 contingencies. Even then, there is no guarantee of a solution.

To handle these solution difficulties, we describe our two-stage volt/var optimization method in this section. The flowchart of the proposed method is shown in Fig. 1. The two stages are the following: 1) solve the volt/var ACOPF formulation from the power flow base case received from system state estimator and 2) and then use the linearized algorithm to solve the security constraint volt/var ACOPF for all contingency scenarios.

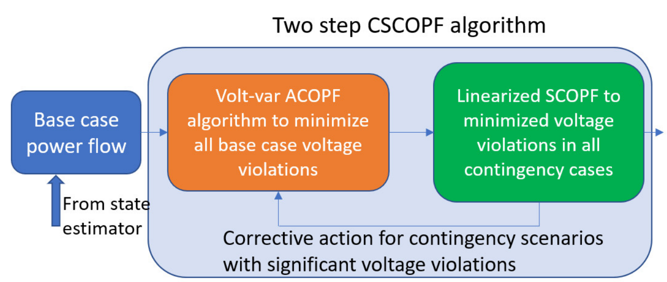

Fig. 1. Flow chart of the proposed two stage CSCOPF volt/var control method.

In the first stage, all voltage violations from the base case are solved with full volt/var ACOPF formulation as we shown in equations (1)-(13), with all binary variables a_{ijc} equals 1 in the formulation. It is noted that stage one will be solved in 5 min time intervals so all voltage violations in the base case will be corrected at each time step before we identify the corrective actions for all contingency scenarios.

In the second stage, the linearized algorithm is used to solve the security constraint volt/var ACOPF for all contingency cases. We use the linear PSCOPF function from PSS®E software in the second step [18]. When a huge number of contingency cases are considered, the PSCOPF problem becomes a large-scale optimization problem. Therefore, in the PSCOPF function from PSS®E, the master problem is set up with the base case condition and the cuts from the contingency cases, and a sub-optimization problem is modeled for each contingency to ensure the feasibility of the solution. A successive linear programming (SLP) is used, in which the system is linearized under current operating conditions and the violations are handled by an AC power flow. To keep the number of sub-problems small, a contingency filtering technique that is based on power flow solutions is applied. More detailed introduction on the PSCOPF function can be seen in [19].

III. Test System and Results

A. Modified 118-Bus System

We use the modified IEEE 118-bus test system shown in Fig. 2 to demonstrate proof-of-concept of the developed volt/var OPF algorithm. The current IEEE 118-bus test system [14] has only one snapshot power flow case. We modified the system to develop 5-min-resolution power flow cases for a 2-day period. Synthetic data has been generated to mimic 5-min load profiles as well as solar PV output at every bus for a full year.

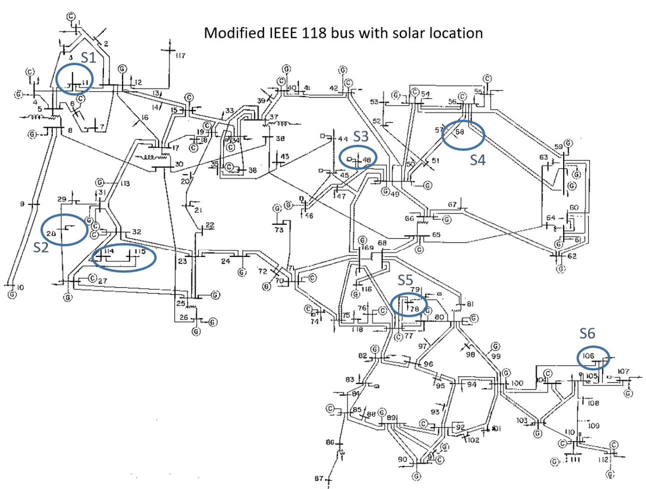

Fig. 2. Modified 118-bus test systemwith transmission level solar inverter.

The IEEE Reliable Test System hourly load shape [15] was used to develop hourly load values with the same participation factor as the original power flow case of the 118-bus system. Historical 1-min load data has been imposed on the hourly data to generate 1-min load data. These data were generated by taking the original-case load data as peak load for every bus in the system. The load profile was generated by assuming a constant load power factor at every bus, which was obtained from the original case.

Utility-scale PV plants are now being developed and interconnected to the grid at the transmission level, with maximum capacity ranging from a few MW to a few hundred MW [17]. A Western Electricity Coordinating Council Transmission Expansion Planning Policy Committee solar PV data set containing 1-min time series data for PV generation was leveraged to generate chronological solar data generation. Specifically, 5-min PV generation data equivalent to 30% penetration (30% of peak load) were extracted and placed at specific points in the 118-bus system. In total, 6 locations for PV placement were identified as shown in Fig. 2. The capacity of the selected PV are shown as: buses 11 with 252 MW, bus 28 with 98 MW, bus 48 with 302 MW, bus 58 with 130 MW, bus 78 with 311 MW, and bus 106 with 300 MW. The example of the power output from one of the selected utility-scale PV plant can be seen in Fig. 4. The buses selected for PV placement were non-generation buses, in order to prevent conflict voltage control by generators.

B. Simulation Results

The proposed two-stage volt-var ACOPF voltage control algorithm was implemented in the 118-bus test system for a full day, and the simulation results are compared for the following three cases:

Case 1: Base case with no control on solar inverter

Case 2: With volt-var ACOPF voltage control algorithm on the base case only

Case 3: Proposed two-stage volt-var ACOPF algorithm

Fig. 3 shows the bus voltage comparison of Case 1 and Case 2 on a randomly selected bus 22 for the 1-day simulation period (24 hours). As can be shown in Fig. 3, between 6:00 a.m. and 10:00 a.m. when a solar inverter starts to generate power to the system, there are obvious over-voltage issues at the selected bus. In comparison, the voltage level from the volt/var ACOPF algorithm can be maintained to its scheduled voltage range between 0.98 p.u and 1.02 p.u, which demonstrates the efficiency of the step-1 volt-var ACOPF algorithm we proposed in Section II.C. The real and reactive power output of one of the selected utility-scale PV plant at bus 48 is shown in Fig. 4. As can been seen in Fig. 4, the reactive power output of the PV is constrained by the apparent power limits of the solar inverter as well as the solar inverter power factor constraints in (12). It is also shown in Fig. 4, when solar is actively generating real power to the grid, it can also be used to provide volt-var support service.

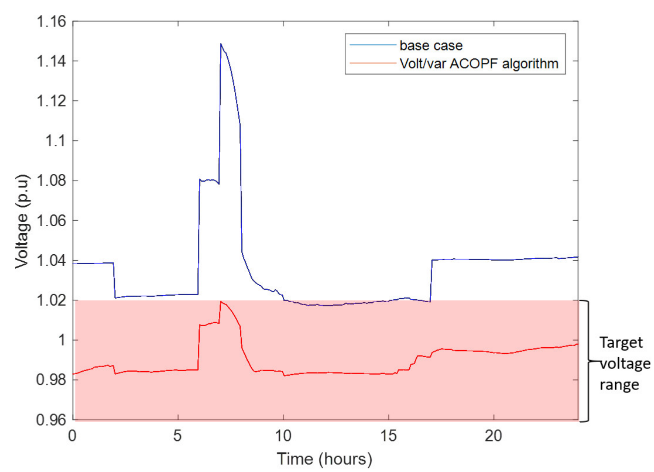

Fig. 3. Comparison of voltage profile on a randomly selected load bus.

Fig. 5 shows the comparison of cumulative bus voltage violations in p.u from Case 2 and Case 3 on all contingency scenarios for the 1-day simulation period (24 hours). As can be shown in Fig. 5, the second stage security constraint volt/var

ACOPF can effectively eliminate all voltage violations in contingency scenarios. Therefore, it is shown that the proposed two-stage volt-var ACOPF algorithm can eliminate the voltage violations in both base case and contingency scenarios.

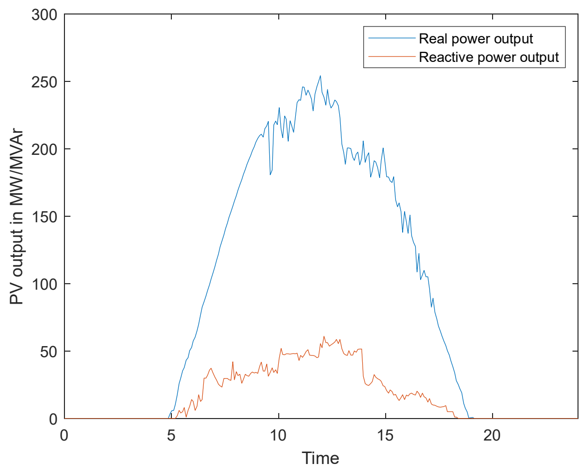

Fig. 4. Example of 1-day (24 hours) power output of utility-scale PV plant located at bus 48.

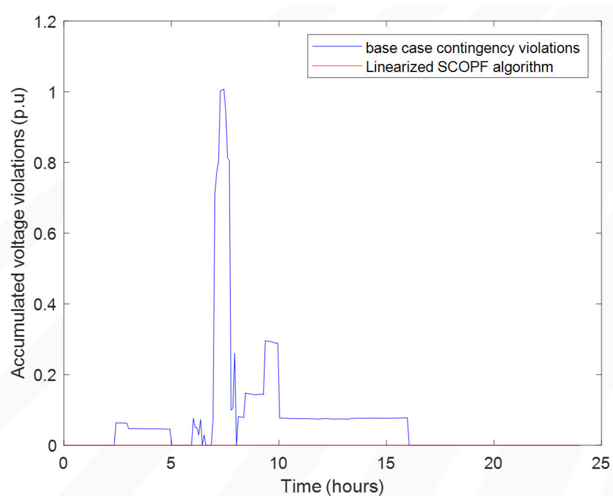

Fig. 5. Comparison of accumulated voltage violations on all contingency cases.

The simulation is conducted in GAMS 32.1.0, and KNITRO is used as the optimization engine in the volt-var ACOPF algorithm in stage 1. The proposed algorithm is executed on a laptop computer with an Intel Core i7-9850 CPU with 2.59 GHz clock frequency and 16 GB RAM on a Windows 10 operation system. The average solution time for each 5-minute time step is 6 seconds. In comparison of other existing SCOPF methods, the proposed two-stage CSCOPF algorithm have significantly reduced problem scale and solution time. In our next step, we will implement the proposed algorithm to the realistic NYISO grid.

IV. CONCLUSION

A new formulation for the SCOPF problem is proposed to utility transmission level solar PV inverter to minimize voltage fluctuations caused by intermittent PV outputs on the base case and contingency scenarios. To solve the SCOPF problem, a two-stage volt/var optimization method is proposed. The proposed algorithm first corrects all voltage violations for the base case by using a full volt-var ACOPF algorithm. Then a linearized SCOPF volt-var control algorithm is used to identify corrective actions for all voltage violations on all contingency scenarios. The proposed method was implemented and validated on a modified IEEE 118-bus system with PV data.

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