Volt/Var Control in Distribution Networks with High Penetration of PV Considering Inverter Utilization

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Abstract—In this paper, a Volt/Var control strategy in distribution networks with high PV penetration considering inverter thermal model is presented. This strategy considers a central distribution control to schedule active power and reactive power to deal with solar power generation intermittency. The objective is to provide voltage regulation control while solving for optimal power flow to minimize both distribution system losses and inverter losses. A radial distribution feeder with high PV penetration is considered for the analysis. Simulation results verify the effectiveness of the proposed strategy in regulating voltage within limits while allowing optimal reactive power allocation among distributed generation (DG) units to relieve the stress on some inverters especially those at the end of the feeder.

Index Terms--PV, Volt/Var, distribution feeder, PSO, inverter thermal model.

I. INTRODUCTION

Currently, most distribution networks are blind spots in the power system because of the lack of communication channels between its elements and the energy management center. The cost of adding communications is prohibitive due to the large number of distribution transformers that are geographically scattered and also because of the length of the feeders. In addition, the need for information exchange in the existing distribution networks is minimal due to the convenient configuration of the feeders that allow only unidirectional power flow, and the simplicity of forecasting local loads that follows seasonal patterns and the weather.

Migration from conventional centralized generation to renewable energy distributed generation (REDG) is challenging since the latter is intermittent and decentralized. Cloud passing causes significant voltage fluctuations especially when the PV penetration is high. Also, at high PV penetration levels, high feed-in and reverse power occur under light load conditions. This high reverse power could lead to overvoltage at the end of the distribution feeder resulting in voltage violation which is to be limited to within ±0.05p.u per ANSI C84.1 standard “Range A service voltage” [1]. Several approaches have been proposed to address the voltage rise issue such as using on-load tap changer (OLTC) and step voltage regulator in distribution networks, but these classical devices suffer from operational limitations in addition to its slow response [2,3].

Some research works have been proposed to upgrade the distribution system configuration by eliminating normally open sectionalizer or by replacing it with multi-terminal converters to improve voltage regulation [4,5]. These approaches are not suitable due to the increase of short-circuit level in distribution networks and the cost of upgrading the protection infrastructure.

On-line voltage regulation architectures can be classified into two main categories: centralized and decentralized. In the decentralized method, only local measurements are required to implement the control strategy. A droop-based active power curtailment technique for overvoltage prevention has been proposed in [6]. PV active power curtailment has a direct influence in controlling voltage throughout the distribution network due to the increase of R/X ratios in the distribution feeders. However, overuse of power curtailment eliminates the environmental and economic benefits of PV installations. A centralized reactive power compensation to regulate the voltage and reduce the power losses in distribution networks with PV appears in [7]. Model Predictive Control (MPC)-based Volt/Var has also been used to schedule the OLTC position, capacitor status, and output reactive power of DG depending on the load forecast, temperature, and clouds over the prediction horizon [8].

The centralized reactive power compensation strategies have considered solving the optimization problem to minimize the distribution network losses while regulating the feeder voltage. The advanced inverters are a key element in PV units that have the capability of supplying or absorbing reactive power that eventually results in better voltage regulation. However, overutilizing PV inverters for Volt/Var control causes additional losses in the inverter switches that results in junction temperature increase, thus leading to a faster depreciation of device. Thermal performance and reliability evaluation of PV inverter with extensive reactive power injection have been investigated in [9]. The study concludes that this extensive utilization of PV inverters could decrease its lifetime significantly. Therefore, junction temperature that is
associated with device losses can be an integral part of a REDG based distribution system control strategy that considers the impact of inverter utilization on its lifetime and reliability.

In this paper, a voltage regulation control strategy that includes solving for optimal power flow to minimize both distribution system losses and overutilization of inverters caused by Volt/Var control is presented. The main advantage of considering PV inverter utilization through inverter switching loss minimization is to reduce the stress on inverters especially for those located at the end of the feeder. This allows optimal reactive power allocation among DGs since owners of DGs are not compensated for their inverter overutilization. The proposed strategy considers scheduling output of PV active power for a specific period of time based on loads and solar radiation forecast to conform with the advanced metering infrastructure (AMI) that is designed to send and receive periodic signals every 15 mins. If voltage violations on one or more nodes are predicted, optimal power flow solver is enacted to allocate reactive power among DGs. Scheduling output real power for DGs is crucial in the economic dispatch of the distribution power system.

II. SYSTEM MODEL

A. Distribution System Model

A radial distribution feeder with \( n \) number of nodes is considered in this study as shown in Fig. 1. Node 1 represents the feeding substation whose voltage is assumed to be constant. To solve for power flow, a well-recognized power solver called DistFlow is used [10]. The power flow equations are given as follows:

\[
P_{i+1} = P_i - r_i \frac{P_i^2 + Q_i^2}{V_i^2} - P_{Li} + p_{DGi}
\]

\[
Q_{i+1} = Q_i - x_i \frac{P_i^2 + Q_i^2}{V_i^2} - Q_{Li} + q_{DGi}
\]

\[
V_{i+1}^2 = V_i^2 - 2 (r_i P_i + x_i Q_i) + \left( r_i^2 + x_i^2 \right) \frac{P_i^2 + Q_i^2}{V_i^2}
\]

where \( P_{DGi} \) and \( Q_{DGi} \) are the active power generation and load, and \( P_{Li} \) and \( Q_{Li} \) are the reactive power generation and load, respectively. \( V_i \) is the voltage magnitude at node \( i \). Feeder section between nodes \( i \) and \( i+1 \) is represented by impedance of \( r_i + jx_i \) and the complex power flow between these nodes with \( P_i + jQ_i \). Power losses in section \( i \) is given by

\[
P_{Lossi} = r_i \frac{P_i^2 + Q_i^2}{V_i^2}
\]

where \( P_{Li}, Q_{Li} \), and \( P_{DGi} \) are assumed to be previously known to perform power flow as will be explained later, and \( q_{DGi} \) is the main control variable. Reverse power occurs if \( \sum p_{DGi} > \sum P_{Li} \) making this feeder more vulnerable to voltage rise issues.

B. PV Inverter and its Thermal Model

There are different power electronics topologies that can be used as an interface PV to the grid. In this work a 2-level voltage source inverter (VSI) employing IGBT and diode devices is considered due to the ease of controllability. A typical PV power conversion module has two stages: The first stage includes PV cells and a DC converter to regulate the voltage across the DC-link. The second stage includes inverter to convert DC quantities to AC and an output LC filter to reduce harmonics. In the case of the grid-connected mode, the main grid provides the reference voltage and frequency to PV inverter controller. Therefore, the output inverter current can be controlled using a current regulation method. It is advantageous to transform the sinusoidal quantities in the controller to DC quantities using synchronous reference frame (SFR) or Park transformation such that there can be two separate compensators for active and reactive power output controller. Also, it is advantageous to use a Proportional Integrator (PI) compensator in the controller since it performs well when used to remove steady-state error of a DC quantity.

PV inverters are usually designed to generate the maximum active power with unity power factor under the normal condition with Maximum Power Point Tracking (MPPT). However, PV inverter’s controller provides the flexible capability to control the output real power by curtailing active power or exchanging reactive power with the grid. The PV inverter output power is limited by the rated apparent power \( S_{DGi} \). Therefore, the available reactive power capacity \( q_{DGi} \) can be found as

\[
q_{DGi} = \sqrt{S_{DGi}^2 - p_{DGi}^2}
\]

One of the objectives of this research is to incorporate the thermal model in the process of regulating the node voltages such that the overall power losses in the PV inverters can be minimized. The power losses in the inverter is affected by the thermal impedance between PV inverter switch junction and the ambient. The thermal model of PV inverter is shown in Fig. 2. The junction temperature \( T_j \) has a direct affect on the electrical performance and dissipated power of the power devices.
The thermal model provides an estimation of the junction temperature \(T_j\) that can be used in the PV inverter power loss calculation. \(T_j\) can be found from the thermal model as [9]

\[
T_j,s = P_s Z_{th,s(j-c)} + T_c 
\]

\[
T_j,d = P_d Z_{th,d(j-c)} + T_c 
\]

\[
T_c = T_a + [P_s + P_d] \times [Z_{th(c-h)} + Z_{th(h-a)}] 
\]  
(8)

where \(P_s\) and \(P_d\) are the losses in IGBT and diode, respectively; \(T_{j,s}\) and \(T_{j,d}\) are the junction temperatures in IGBT and diodes, respectively; \(Z_{th,s(j-c)}\) and \(Z_{th,d(j-c)}\) are the thermal impedances between junction and the case for IGBTs and diodes, respectively; and \(Z_{th(c-h)}\) and \(Z_{th(h-a)}\) are the thermal impedances from the case to heatsink and from heatsink to ambient, respectively. All of the thermal impedances can be obtained from device data sheets.

The instantaneous losses of the semiconductor power devices in the PV inverter that are controlled by pulse width modulation (PWM) vary based on the duty cycles. Therefore, an online simulation thermal model using PLECS-Simulink was developed to obtain the losses. The power losses in IGBTs and diodes can be divided into conduction and switching losses. Conduction losses in both devices can be expressed as

\[
P_{s\text{conduction}}(t) = i_c(t) \times v_{ce}(t) 
\]

\[
P_{d\text{conduction}}(t) = i_d(t) \times v_d(t) 
\]

(9)

(10)

where \(i_c(t)\) and \(i_d(t)\) are the instantaneous IGBT collector and diode currents, respectively; \(v_{ce}(t)\) and \(v_d(t)\) are the voltage across the IGBT and diode, respectively. The switching losses are associated with the turn-on and turn-off energy losses in the IGBTs and diodes.

\[
P_{s\text{switching}}(t) = (E_{s\text{on}} + E_{s\text{off}}) f_{sw} 
\]

\[
P_{d\text{switching}}(t) = (E_{d\text{on}} + E_{d\text{off}}) f_{sw} 
\]

(11)

(12)

where \(E_{on}\) and \(E_{off}\) are the switching energy during turn-on and turn-off, respectively. \(f_{sw}\) is the switching frequency of the inverter.

### III. CONTROL STRATEGY

A portion of conventional generation can be displaced with REDG without impacting system stability. Therefore, active and reactive power should be scheduled to maximize REDG utilization and to achieve an efficient economic dispatch. This would require a coordination between transmission energy control center (ECC) and distribution control units (DCU) in power substations. Depending on cyber and control resources, DCU performs power flow calculations based on the scheduled output power of DG and the load forecast for the next 10 or 15 minutes to find out the required complex power locally to avoid power congestion or shortage in the transmission network. In case of voltage violation in distribution feeder, solving for optimal power flow for reactive power allocation among DGs will be initiated. Multiple solutions exist that mitigate the voltage rise issue using \(q_{DG}\) available capacities. For this reason, an objective function is proposed to minimize distribution feeder power losses and the additional losses in PV inverter switches that result from voltage regulation due to overutilization of inverters. The additional inverter power losses of supplying reactive power \((P_{loss, add})\) can be obtained from

\[
P_{loss, add} = P_{loss, DG(p,q)} - P_{loss, DG(p)} 
\]

(13)

where \(P_{loss, DG(p,q)}\) is the total power loss in the inverter switches with active and reactive power supply, and \(P_{loss, DG(p)}\) is the total power loss in inverter switches with only active power supply. The proposed objective function can be expressed as follows:

\[
\text{minimize} \sum_{i=1}^{n} P_{loss, add}(i) + P_{Loss}(l) 
\]

Subject to \(V_{min} \leq V_i \leq V_{max}\) and (1)-(3), (5)

The problem can be solved using particle swarm optimization (PSO) method [11]. PSO works by initiating random particles \((x_i)\) within the search space, which are the control variables \((q_{DG})\). Then each particle will be evaluated by the objective function. PSO will search for the best candidate that allows the global minimum \((g_{best})\). In each iteration, particles modify its values or position and move toward \((g_{best})\) as given by

\[
v_{j+1} = w v_j + c_1 r_1 (P_{best} - x_j) + c_2 r_2 (g_{best} - x_j) 
\]

\[
x_{j+1} = x_j + v_{j+1} 
\]

(14)

(15)

(16)

where \(v_{j+1}\) and \(x_{j+1}\) are the new iteration velocity and position of the particles, respectively, \(w\) is the inertia weight set to 0.5, and \(r_1\) and \(r_2\) are random numbers between 0 and 1. \(c_1\) and \(c_2\) are the correction factors set to 1.5. The optimal solution can be achieved with 100 searching agents and less than 200 iterations. In each iteration, PSO will try to elect a candidate from particles that allows \(g_{best}\) and update \(P_{best}\) for each particle that allow the best personal solution. This will continue until a termination condition is met.

### IV. SIMULATION NETWORK

The analyzed distribution feeder is based on a 33-bus system described in [10]. It has been modified to include only nodes from 1 to 18 with the same impedances for each section similar to Fig.1. This 12.6kV feeder is connected to the main grid that is assumed to keep the voltage constant at node 1. The case study uses the solar radiation data from Solar Recourses and Meteorological Assessment Project (SOLRMAP) developed by National Renewable Energy Laboratory (NREL’s) [12]. The hourly load profile is extracted from Residential Energy Consumption Survey (RECS) for residential loads collected by U.S. Department of Energy (DOE) [13]. Both solar data and load are from Phoenix, Arizona collected in Nov. 21, 2011.

In practice, loads and PVs are connected to low voltage distribution laterals. However, the scope of this study is to investigate the impact of high PV penetration on main
distribution feeders. Therefore, each node is connected to 12.6 kV/0.24 kV three-phase transformer where PV inverters and loads are aggregated since they share the same profile. The peak load of this feeder is 3.4 MW which occurs in the summer season and the PV penetration is assumed to be 100% according to the summer peak. However, a voltage rise will typically occur when PV production is greater than local demand mainly in fall and spring seasons due to lower load power consumption. For this reason, a day from the fall season is considered; the intermittent nature of solar energy available is also evident which emphasizes the importance of short-time scheduling. Fig. 3 shows the total active power load and PV generation based on every 15 minute reading in the tested distribution network.

To incorporate the thermal model of PV inverter in the proposed control strategy, a three-phase inverter module from a leading manufacturer is selected. The inverter parameters and capacity are summarized in Table I. The lookup table of the aggregated inverter power losses for all possible input values is displayed in Fig. 4. It is obvious that exchanging reactive power with the grid whether it is positive or negative will lead to higher power losses in the inverter. Our objective is to minimize this additional loss incurred while delivering reactive power to relieve the stress on some inverters and encourage other inverters to engage in the Volt/Var control.

![Fig. 3. Daily load and PV generation profile of a distribution network.](image1)

![Fig. 4. PV inverter losses for the supply of active and reactive power.](image2)

In the current work, peak PV power production and voltage regulation during that time are considered for control strategy evaluation. Three cases are considered for the study which are:

- Case 1: Without Volt/Var from REDGs.
- Case 2: With Volt/Var from REDGs considering minimizing feeder losses.
- Case 3: With Volt/Var from REDGs considering minimizing feeder losses and additional inverter losses.

The voltage profile of node 18 which is located at the end of the feeder is obtained from the load flow simulation of the network during the selected day with and without Volt/Var control; the results are shown in Fig. 5. The voltage rises above the permissible value of 1.05 p.u at midday, and fluctuates significantly following PV production variations. When any voltage violation is detected, Volt/Var control in Case 3 is enabled to regulate the voltage throughout the feeder as shown in Fig 5. The proposed control strategy is capable of maintaining the voltage within limits by scheduling the available capacity of $Q_{DG}$ based on the optimal power flow solution.

Table II lists the distribution network loads, generations, and voltages for the three cases. $q_{DG,i}$'s at each node $i$ are the control variables for the controllers in Case 2 and Case 3. Case 1 shows the impact of high PV level presence on voltage profile throughout the feeder without reactive power injection. Voltages at nodes (13-18) are violated (>1.05 p.u) due to high reverse power without Volt/Var control. In case 2, Volt/Var control is enabled to mitigate the voltage rise while minimizing distribution feeder losses. It is obvious that utilizing the additional reactive power available capacity can help maintain voltage feeder within the permissible limit. However, this method yields an extensive reactive power exchange between the DGs and the grid with total $Q_{DG}$ of 1526 kVar as can be seen from Table III. In addition, it puts more stress on specific DGs at nodes 3, 8, 13, 14 and 17 where they reach almost the maximum inverter capacity of 200 kVA. Case 3 results show that the proposed method provides a good voltage regulation and improve reactive power allocation among the DGs when including the inverter losses in the objective function. The

### Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single inverter capacity</td>
<td>3.3 kVA</td>
</tr>
<tr>
<td>Aggregate inverter capacity</td>
<td>2000 kVA</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>500 V</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>240 V</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Output inverter filter</td>
<td></td>
</tr>
<tr>
<td>Inductor</td>
<td>5 mH</td>
</tr>
<tr>
<td>Capacitor</td>
<td>10 µF</td>
</tr>
<tr>
<td>IGBT</td>
<td></td>
</tr>
<tr>
<td>$V_{ce}$ (max)</td>
<td>600 V</td>
</tr>
<tr>
<td>$I_{c}$ (max) @ $T_c = 25°C$</td>
<td>40 A</td>
</tr>
<tr>
<td>$Z_{(d,v)}$</td>
<td>0.76°C/W</td>
</tr>
<tr>
<td>Diode</td>
<td></td>
</tr>
<tr>
<td>$V_U$</td>
<td>2 V</td>
</tr>
<tr>
<td>$Z_{(d,v)}$</td>
<td>2.51°C/W</td>
</tr>
<tr>
<td>$Z_{(b,c)}$</td>
<td>0.7°C/W</td>
</tr>
</tbody>
</table>
Fig. 5 Voltage profile of node 18.

exchanged reactive power between DGs and grid decreased to 954 kVar, and the total $P_{loss, DG}$ went down by 11 kW compared to case 2 as listed in Table III. However, Case 3 yields a higher distribution feeder power loss $P_{loss}$ by 4 kW due to the different $q_{DGi}$ allocation. It can be seen as a compromise between improved $q_{DGi}$ allocation and $P_{loss}$ in the distribution feeder. Both strategies require almost the same amount of reactive power from main grid. Therefore, it is important to coordinate between the DCU and ECC to make sure that reactive power is available. Otherwise, $q_{DGi}$ allocation will lead to higher power losses in both the distribution system and the PV inverters.

![Diagram](image_url)

### V. CONCLUSIONS

A new Volt/Var control strategy with power flow optimization for distribution networks with high PV penetration is presented. This method is based on scheduling available reactive power capacity of PV inverters to mitigate voltage rise in the distribution systems in a centralized manner. The simulation results show that the proposed method provides a good voltage regulation and improve reactive power allocation among DGs, which results in relieving the stress on some inverters. Estimation of power loss considering the junction temperature of power devices can be applied directly to assess the devices’ lifetime for given utilization of the PV inverters.

### REFERENCES


[12] https://www.nrel.gov/midc/sssp/