A Multi-Objective Voltage Optimization Technique in Distribution Feeders with High Photovoltaic Penetration

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1 Introduction

For environmental reasons, there has been a consistent increase in global installation of photovoltaic (PV) systems. This is further facilitated by the declining cost of PV modules over the years. The increase in PV installations is evident as the financial investments in PV installation globally is also on the rise. The increase in levels of PV penetration have lead to several challenges which include reverse power flow, voltage control issues, power quality issues (voltage and current harmonics, flicker, momentaries), protection coordination problems, and possible increase in system losses. Of these issues, voltage control is one of the most important and of concern to utility companies. Traditionally, utility companies uses the legacy devices such as reactors, voltage regulators (VR), ON/OFF load tap changers (OLTC), and switched capacitor banks for voltage control. With the integration of intermittent renewable energy resources such as PV systems, the need for fast and more effective voltage control becomes imperative. According to IEEE 1547-2018, inverter-based DERs such as PVs are allowed to participate in feeder voltage regulation. According to [11,17,18], the use of smart inverters (SIs) could provide a more effective and economical way of voltage control especially at high levels of penetration of inverter-based DERs. Voltage optimization can be carried out with the use of several components in a distribution network. Several devices such as voltage regulators, OLTC, switched capacitor banks, reactors, energy storages and recently smart inverters (SI). SIs can be used to make significant impact on the voltage profile of the distribution system using the power factor control mode or the Volt-VAR/Watt control mode. With all these devices simultaneously present in the distribution network, there is an obvious need for optimizing their operation and also their interaction in the system. Therefore the optimal coordination of the control operations of the smart inverter and these existing legacy devices becomes necessary. This paper presents a multi-objective voltage control optimization algorithm which is an extension of a previous work done by the authors in [19]. In order to take the advantage of the reactive power injection by the smart inverter, the reactive power injection by the switched capacitor banks are minimized as one of the optimization objectives. The smart inverters are set to constant power factor mode with the optimal value selected...
between 0.6 – 1 to allow for reactive power injection. The VR and OLTC switching constraints are set within ±16. The other objective functions are to flatten the nodal voltage profile towards the lower threshold of 0.95pu and minimize the overall active power losses in the network. The rest of the paper is organized as follows: Section 2 presents a brief review of existing voltage control and optimization techniques; the proposed optimization algorithm and its formulation is presented in Section 3; Section 4 describes the feeder used as case study and the simulation set up; Section 5 presents the simulation results and their analyses; while Section 6 concludes the paper.

2 Voltage Control and Optimization Methods

Several voltage control techniques have been proposed and reported in literature. Active distribution networks allow for bidirectional flow of active and reactive power due to the integration of distributed renewable energy generators. An evolutionary-based algorithm for LTC and shunt capacitor Scheduling was proposed by authors of [20]. The study was done to minimize the active power loss of the system while keeping the operation of the voltage control devices and the total harmonic distortion within limits. An NREL report and publication by Ding et al [21, 22] developed an iterative optimization algorithm that coordinates the use of SI, LTCs and capacitor banks for optimal voltage regulation while implementing conservative voltage reduction technique as a means of minimizing the total system losses. The impact of the proposed optimization algorithm on the system’s power quality was also analyzed. Reference [23] developed three fuzzy logic controllers that control the OLTC switching, the reactive power sharing (to enable a relaxation of the OLTC switching operation) and reduce the active power curtailment from the integrated distributed generation. Similar to [23], authors of [24] proposed a Volt-VAR optimization (VVO) algorithm that relax the voltage regulators and LTC operations as well as minimizing the amount of PV generation curtailed. The proposed VVO multistage algorithm was compared to the multi-objective VVO. Most of the previously published papers did not optimally choose the SI setting such as its power factor, minimization of reactive power injection by the shunt capacitor banks by allowing more reactive power injection by the SIs, and flattening the system’s voltage profile and implementing conservation voltage reduction by pushing the nodal values to 0.95 pu. To address these research gaps, this paper proposes a multi-objective optimization algorithm that flattens the node voltage profile, minimizes the power loss in the network as well as minimizing the reactive power injection by the capacitor banks by optimally selecting the power factors of the SIs, the tap position of the voltage regulators and LTC as and the amount of reactive power to be injected by the capacitor banks.

3 Formulation of Proposed Optimization Algorithm

**Objective functions**

The first objective $OF_1$ of the proposed optimization algorithm is to flatten the voltage profile of the network as much as possible and also to make the nodal voltages close to the lower boundary of the ANSI C84.1 voltage range of 0.95pu. The benefit of this approach is to take the advantage of conservative voltage reduction which allows the total load on the network to be reduced by simply lowering the nodal voltages.

$$OF_1 = \min \sum_{j=1}^{N} \left( (V_{j} - V_j^\text{min}) + \alpha (V_j^\text{max} - V_j^\text{min}) \right)$$

where $V_j^\text{min}$ and $V_j^\text{max}$ are the minimum and maximum allowable nodal voltages respectively as expressed in equation (4), while $\alpha$ is a factor which is used to make the nodal voltage $V_j$ close to $V_j^\text{min}$.

Objective 2 ($OF_2$) is minimizes the total active power losses in the network.

$$OF_2 = \min \frac{P_{\text{total loss}}}{P_{\text{loss}} + P_{\text{trans}} + P_{\text{lines}}}$$

where $P_{\text{loss}}$ is the sum of the active power loss in the transformers and $P_{\text{lines}}$ is the sum of the active power loss in the lines.

The third objective ($OF_3$) of this work is to minimize the total amount of reactive power injected by the two capacitor banks connected to buses 844 and 848.

$$OF_3 = \min \sum_{cb=1}^{N} Q_{cb}$$

Where $Q_{cb}$ is the capacitor bank reactive power injection and $N_c$ is the total number of capacitor banks in the network.

**Constraints Formulation**

Bus voltage constrains is set to be within the ANSI C84.1 standards.

$$V_j^\text{max} \geq V_j \geq V_j^\text{min}$$

$$1.05pu \geq V_j \geq 0.95pu$$

Capacitor bank VAR and switching constraints is given as equation (5). The maximum reactive power injection by these capacitors are 300kVAR and 450kVAR according to the values in the feeder parameters.

$$|Q_{cb}^j| \leq |Q_{cb}^i|$$

Typical VRs and OLTCs have 32 tap steps. For each tap step, the change in voltage is typically 0.625%.

$$-16 \leq \text{Tap}_{\text{vr}} \leq +16$$

To enable the SIs inject some reactive power into the network in order to allow for some voltage control by the SI, the PF values of the SI are set as variable for the optimization in other to get their optimal values.

$$0.6 \leq PV_{PF} \leq 1$$
Table 1: PV Specifications

| PVs          | Maximum Power (kW) | Inverter (kVA) | Phases | Default PF |
|--------------|--------------------|----------------|--------|------------|
| PV1 and PV5  | 300                | 400            | 1      | 0.8        |
| PV2, PV3, PV4 and PV6 | 300                | 400            | 3      | 0.8        |

4 Feeder Test Case and Simulation

In order to validate the effectiveness of the proposed multi-objective optimization technique, six PVs with specifications as shown in Table 1 are integrated to an IEEE 34 node distribution feeder (as shown in figure 1). For each of the PVs, a minute resolution actual global horizontal irradiance and temperature data (as shown in figures 2 and 3 respectively) are used as input to estimate the power output of the six PVs. The PV locations were selected a little farther from the substation transformer where there is a potential for some voltage regulation issues.

Figure 1: IEEE 34 node test feeder with PV locations

Figure 2: 1-minute resolution global horizontal irradiance profile of the location used for the simulation

5 Simulation results and Analysis

The PV integrated IEEE feeder was modelled using the OpenDSS software with the optimization algorithm developed with MATLAB. A time series simulation with a total time step of 1440 minutes was carried out. Based on the three objective functions formulated, the Pareto fronts for the 24 hour optimization are plotted as shown in figures 4, 5, and 6. The Pareto fronts show the several optimal solutions available for the multi-objective optimization.

Based on the objective of highest priority, the values of the variables which are the tap settings of the LTCs, power factor of the PVs, reactive power injection of the capacitor banks, can be selected. For example, if the objective of highest priority is to have the minimum amount of losses ($OF_2$) in the network the Pareto optimal values with their corresponding decision variables is as presented in tables 2 and 3. The loss minimization objective presented in tables 2 and 3 show the optimal values of the tap settings of the LTCs, power factor of the PVs, reactive power injection of the capacitor banks that will achieve the minimum amount of losses in the network. Using the optimal values acquired from the optimization algorithm, the nodal voltages of the network were simulated. The nodal voltages of buses (single phase buses) 822 and 864 are as shown in figures 9a and 9b respectively while the nodal voltage for buses 840, 846, 848 and 890 are as shown figures 7, 8, 10 and 11 respectively.

The voltage profile on these buses clearly show the effectiveness of the proposed optimization algorithm. The bus voltage profiles were adequately reduced without going below the ANSI C84.1 standard voltage level of 0.95pu. As mentioned earlier, this was done to implement the benefits of Conservative voltage reduction which can be effectively used to reduce the total load on the network as well as minimize the total system power loss. Also, as shown in figure 11 the un-optimized voltage profile of bus 890 was increased from less than the minimum 0.95pu to values above the minimum 0.95pu.

Figure 12 show the un-optimized and optimized total system losses. The figure clearly shows there is consistent reduction in the overall system losses after optimization. Figure 13 shows the capacitor reactive power with and without the use of the proposed optimization algorithm. The value of the $kVAR$ injection by the capacitor banks were consistently reduced which further shows the effectiveness of the proposed optimization algorithm.

6 Conclusions

With the consistent rise in PV penetration on distribution feeders, effective voltage regulation and optimization using Volt-VAR control becomes very important. This paper presented a multi-objective optimization using the existing network legacy devices (switched...
Figure 4: Hourly Pareto optimization curve for the optimized objective functions

Figure 5: Hourly Pareto optimization curve for the optimized objective functions
Figure 6: Hourly Pareto optimization curve for the optimized objective functions

Figure 7: Voltage Profile of Node 840

Figure 8: Voltage Profile of Node 846
Figure 9: Voltage profiles of Nodes 822 and 864

Figure 10: Voltage Profile of Node 848

Figure 11: Voltage Profile of Node 890
Figure 12: Hourly losses in the system

Figure 13: kVAR injection on nodes 844 and 848 by shunt capacitors

Table 2: Hourly Pareto optimal values with minimum system looses

| Hour | $OF_1$ (kW) | $OF_2$ (kVAR) | $OF_3$ (kVAR) | $VR_1$(pu) | $VR_2$(pu) |
|------|-------------|---------------|---------------|------------|------------|
| 1    | 29.2225     | 77.8766       | 483.3489      | 0.9250     | 0.9500     |
| 2    | 29.2225     | 77.8766       | 483.3489      | 0.9250     | 0.9500     |
| 3    | 29.2225     | 77.8766       | 483.3489      | 0.9250     | 0.9500     |
| 4    | 30.5524     | 76.6284       | 458.7750      | 0.9250     | 0.9500     |
| 5    | 2.6370      | 42.8064       | 26.2413       | 1.0063     | 0.9625     |
| 6    | 32.0493     | 75.6853       | 560.9548      | 0.9000     | 0.9438     |
| 7    | 30.4924     | 78.3439       | 540.5442      | 0.9125     | 0.9125     |
| 8    | 31.9572     | 46.2742       | 228.2742      | 0.9125     | 0.9188     |
| 9    | 6.9547      | 23.7373       | 109.9043      | 0.9938     | 1.0063     |
| 10   | 5.5729      | 17.0715       | 282.4728      | 0.9875     | 0.975      |
| 11   | 6.2144      | 26.3293       | 291.0744      | 0.9750     | 0.9938     |
| 12   | 5.4538      | 14.4402       | 208.2059      | 1.0500     | 1.0000     |
| 13   | 5.9157      | 38.1515       | 275.5213      | 0.9831     | 0.9398     |
| 14   | 3.6769      | 23.0707       | 109.9043      | 1.0188     | 0.9563     |
| 15   | 5.1211      | 15.9318       | 245.9954      | 1.0000     | 1.0000     |
| 16   | 5.797       | 12.5233       | 228.1546      | 1.0688     | 0.9688     |
| 17   | 6.4897      | 25.0358       | 299.8358      | 0.9813     | 1.0250     |
| 18   | 33.58       | 66.7876       | 466.7909      | 0.9000     | 0.9000     |
| 19   | 33.5301     | 75.1029       | 540.5442      | 0.9125     | 0.9188     |
| 20   | 32.9089     | 74.3735       | 494.4018      | 0.9063     | 0.9250     |
| 21   | 32.3954     | 77.4375       | 566.4084      | 0.9188     | 0.9063     |
| 22   | 29.8817     | 79.9226       | 576.6802      | 0.9063     | 0.9398     |
| 23   | 33.4353     | 73.2124       | 496.9962      | 0.9000     | 0.9188     |
| 24   |             |               |               |            |            |
capacitor banks, voltage regulators and LTCs) and respective power injection from smart inverters. The proposed algorithm minimizes the voltage fluctuation (by implementing conservative voltage reduction), the total system losses, and the amount of reactive power injection by the switched capacitor banks. The Pareto optimization results showed that by selecting the objective of highest priority, the values of the voltage regulators’ tap position, reactive power injection from the capacitor banks and the power factor value of the smart inverters can be effectively selected. Using one of the Pareto optimal solutions, the bus voltage profiles, system power loss and the capacitor bank reactive power injection were simulated. The results showed the effectiveness of the proposed multi-objective algorithm.

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