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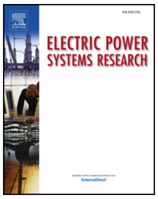

Feeder Voltage Profile Design for Energy Conservation and PV Hosting Capacity Enhancement

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ABSTRACT

Distribution system voltage drop can affect conservation voltage reduction efforts and also photovoltaic hosting capacity. This paper presents a voltage profile design algorithm, which employs a time-series analysis to place the necessary number of voltage control devices at appropriate locations for maintaining a feeder's voltage profile over time. With a flatter voltage profile, the feeder operating voltage can be lowered to conserve energy, and the photovoltaic (PV) hosting capacity will also increase. A key feature of the algorithm is the selective evaluation of practical constraints relevant to the design of the type of voltage control device considered. To obtain statistically relevant results for the control benefits, feeders selected for testing the algorithm are based on results from a feeder taxonomy study. Through case studies on detailed, statistically selected feeder models, both energy conversation and photovoltaic generation hosting capacity benefits are demonstrated. The effects of advanced inverter control functions are also considered.

1. Introduction

Conservation voltage reduction (CVR) aims at reducing the real power consumption of voltage-dependent loads, and also the peak demand of the system, by reducing the voltage magnitude at the consumer end. Lowering the voltage also increases the margin for a feeder to host more renewable energy sources, like PV generators. One of the important reasons why utilities cannot lower the voltage is the voltage drop across feeders. In distribution systems voltage must be maintained within the ANSI standard limits at customer loads [1]. Feeders experience voltage drops due to a combination of feeder length, load distribution, and other factors. One solution to voltage problems is line reinforcement. Although this solution can effectively reduce feeder losses while mitigating over voltage problems introduced by PV generators, it is very expensive [2]. In order to maintain customer voltages within acceptable limits, voltage control solutions like load tap changing transformers, voltage regulators, switched capacitor banks, and/or fixed capacitor banks are traditionally used. Smart inverter control is also a possible option in the future.

Voltage control systems use either local or centralized control. Some research has investigated centralized control [3–5], but centralized control requires communications, which comes with additional security issues. This adds to the operation overhead, and can be deemed impractical for very remote locations. This paper focuses on local control.

Within all the voltage control options, capacitor banks are generally considered the least expensive upfront investment for providing voltage control. Much research has focused on the optimal sizing and placement of capacitors. In recent years, optimization methods based on artificial intelligence have been applied, such as particle swarm optimization [6,7], fuzzy logic [8] and genetic algorithm. Other optimization algorithms employed include differential evolution and pattern searches [9]. Applying capacitor banks alone does not always completely solve voltage problems. In some cases voltage regulators may be more effective than pure reactive power control in solving voltage problems. Optimal capacitor and voltage regulator placement and sizing is considered in References [10–12]. However, an approximate power flow method is used in these studies. The approximation limited the accuracy of the results. This was improved upon in Reference [13], minimizing the number of required regulators to optimize a cost function, but the philosophy for initial voltage regulator selection, placement, and tap setting is similar to that of References [10–12].

With the large, ongoing increase in distributed generation interconnections, especially PV generation, more and more research is devoted to voltage control by smart inverters. Smart inverters can be set to operate at desired phase angles between voltage and current, and thus

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Nomenclature

$t \in [0, T]$	0 and T represent the time indices for the 'From' time and 'To' time of the period for analysis, respectively
L	Number of load buses in a distribution feeder
V_{ru}, V_{rl}	Upper (V_{ru}) and lower (V_{rl}) voltage limits
V_{sp}	Voltage set point
n_{fc}, n_{sc}, n_{vr}	Total number of fixed capacitors, switched shunt capacitors and voltage regulators installed by VPD per feeder, respectively
N_{fc}, N_{sc}, N_{vr}	Maximum number of fixed shunt capacitors, switched shunt capacitors and voltage regulators allowed per feeder, respectively
Q_t	Average reactive flow per phase at the beginning of a feeder at time point t ($t \epsilon [0,T]$)
t_{Lmin},t_{Lmax}	Time points of minimum and maximum load within the interval [0,T]
C_F	Fixed capacitor kVar per phase (*Fixed Cap Size*)
C_S	Switched capacitor kVar per phase (*Switched Cap Size*)
Q_i	Average inductive load per phase at customer i
N	Total number of customers downstream from a given location
Q_{Lossj}	kVar loss of component j
K	Total number of components downstream from a given location
C_k	kVar output per phase of the capacitor k
Y	Total number of capacitors downstream from a given location already installed by VPD
GTA Operators: →	Set element operator
select(oper)	Returns one or more components for which *oper* is true
obj(objective function, constraints)	Evaluates objective function subject to constraints, and returns the value of objective function if constraints are satisfied for all *t*, and null (i.e., φ) if constraints are not satisfied
after(p,pc)	Inserts component p_c after component p in model being operated on, and returns new model
min(oper)	Returns component p that results in minimum value of *oper*

the inverters may either source or sink reactive power. However, under current restrictions established by IEEE 1547, active voltage control by inverters is not permitted. Even if the voltage control restriction on smart inverters is altered in the future, there are still concerns with using smart inverters. One concern is the large number of smart meters and associated controllers required. Based upon current technology, it has been demonstrated that covering as few as 25% of renewable generation points of common coupling with smart meters would not be economical, even over 10 years [14]. A second concern involves issues of islanding where UL 1741 listed inverters operate alongside non-certified equipment or synchronous generators [15].

References [3–13] all have objectives of minimizing power losses or maximizing savings (power loss reduction multiplied by the unit cost of energy production). The voltage control device placement is achieved by solving the minimized or maximized objective functions. In this paper we introduce a design algorithm that allocates capacitor banks and voltage regulators from a different perspective — to control the voltage profile throughout a feeder. Rather than minimizing the power losses, the goal here is to flatten the voltage profile, resulting in improved CVR benefits and an increased PV hosting capacity. Depending on the voltage reduction magnitude and the load voltage-dependency factor, CVR can slightly increase feeder losses. However, in the experience of the authors, total energy savings due to CVR significantly outweigh any increase in feeder losses.

None of the voltage design solutions of References [3–13] take into account the time varying load patterns of the feeder and its individual loads. The ability to control the feeder voltage profile within ANSI limits over time affects both conservation voltage reduction and PV hosting capacity benefits. Here we investigate performance and economic advantages derived from maintaining a feeder's voltage profile within ANSI limits over time. A new design algorithm for accomplishing this is presented. It is referred to as Voltage Profile Design (VPD) and uses Graph Trace Analysis (GTA) [16]. The effectiveness of the VPD algorithm has been validated on a set of test feeders. The test feeders were chosen based on the results obtained from a feeder taxonomy study [17,18].

The paper is organized as follows. Section 2 presents the problem that the VPD algorithm solves. Section 3 provides the GTA based approach used by VPD for solving the problem. Here design for radial feeders is considered. Section 4 presents the basis for selection of feeders and the test feeder set. Section 5 includes a case study and a comparison of the cost benefits, energy conservation, and PV hosting capacity improvements obtained on application of the VPD algorithm to the feeders. Conclusions are presented in Section 6.

2. Problem Formulation

Maintaining a flat voltage profile, within ANSI standard limits at all customer locations, is essential in distribution systems. An objective function for minimizing the voltage deviations of all load bus voltages (V_l) from a voltage set point (V_{sp}) across a set of time points is given by (1).

$$\sum_{t=0}^{T} \sum_{l=1}^{L} |V_l - V_{sp}| \tag{1}$$

The voltage deviations may be minimized by suitably placing voltage control devices, like fixed shunt capacitors, switched shunt capacitors, and voltage regulators, at those locations where (1) is minimum. A voltage profile design (VPD) algorithm is proposed here to identify such locations. In this algorithm the minimum value of the objective function is obtained with a graph trace search (explained in Section 3), rather than calculating a point where the derivative is zero in a quadratic function. To the authors the use of the absolute value in (1) is more intuitive than the use of squared values. A squared value shrinks when the deviation is less than 1, and is magnified when the deviation is greater than 1. The VPD algorithm works for radial distribution feeders with renewable generators located on either the primary or secondary of the feeder. The algorithm seeks to determine appropriate locations to place voltage control devices, and the necessary number of devices. However, this objective function alone is not sufficient for maintaining voltages within limits. The VPD algorithm also considers additional constraints associated with the desired voltage profile.

Most optimization approaches for determining the number and locations of voltage control devices give a single optimal solution. Placing these optimal number of devices at their optimal locations may not be feasible for a utility. This could be a reason why many utilities still use a manual approach for designing the voltage profile of feeders. The approach employed here is to utilize a detailed feeder model, and limit the maximum number of devices and the voltage limits to defined values. Eqs. (2) and (3) ensure that the voltage set points of all voltage control devices, and the voltage at each load bus, are within the specified voltage limits. Eqs. (4)–(6) ensure that the number of each type of voltage control device installed is less than or equal to the maximum number of such devices to be used. Constraints [4–6] can be set out of the way by making the maximum allowed number of devices very large, or in the presence of capital investment limits, can be used to develop a feasible solution.

$$V_{rl} \le V_{sp} \le V_{ru} \tag{2}$$