



Formulation and solution of distribution system voltage and VAR control with distributed generation as a mixed integer non-linear programming problem



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ABSTRACT

Coordinated voltage and VAR control (VVC) can provide major economic benefits for distribution utilities. Incorporating distributed generations (DG) for VVC can improve the efficiency and reliability of distribution systems. This paper presents an approach to formulate and solve distribution system VVC with DG units as a mixed integer non-linear programming (MINLP) problem. The method can be utilized to create an effective control scheme for both the traditional VVC devices and DG units. The MINLP formulation is based on three-phase power flow formulation, and is solved with an open-source BONMIN optimization solver with outer approximation (OA) algorithm. BONMIN is interfaced with Matlab via a third-party optimization toolbox. The proposed approach is applied to several distribution feeder models with promising results.

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1. Introduction

Power factor (PF) correction and conservation voltage reduction (CVR) can reduce distribution losses and overall power demand. PF correction is performed with fixed and switchable capacitor banks in traditional feeders. PF correction reduces line losses by limiting the amount of current drawn by reactive power (VAR) loads. The traditional voltage control devices include load tap changer (LTC) transformers and voltage regulators (VRs). In North America, the node voltages have to be kept within the ANSI specified operational range [1], between 114 V and 126 V for all secondary buses on a 120 V voltage base. Studies have shown that reducing feeder voltage can noticeably reduce feeder power demand in real utility systems if a large portion of the loads are constant impedance and constant current loads [2,3]. Applying PF correction and voltage control together is commonly referred to as voltage and VAR control or optimization (VVC or VVO).

There are several existing methods for VVC and VVO. References [4–7] present local control approaches for capacitor banks and VR devices. The local control methods are generally simple, provide no coordination between devices, and are often limited to a single directional power flow. Supervisory control and data acquisition (SCADA) based VVC usually provides coordination of control

devices, as described in [8–11]. These approaches are based on complicated rule structures. They consider VAR and voltage decisions separately, and generally do not yield optimal solutions. Analytical approaches, like the one presented in this paper, consider VVC as an analytical problem. Existing analytical techniques include non-linear programming (NLP) with interior point algorithm [12], sensitivity based approaches [13], dynamic programming [14], discrete coordinated descent method [15], and mixed integer linear programming (MILP) [16,17].

Artificial intelligence (AI) methods, such as artificial neural networks [18], fuzzy systems [19] and genetic algorithms [20], could be useful tools for VVC. With increasing DG penetration into distribution feeders, DG units could participate in VVO. Inverter coupled DG units can provide real and reactive power to offset some of the system power demand, as described in [21–23].

Direct MINLP formulation and solution has been difficult due to the fact that commercial optimization solvers cannot generally solve MINLP problems. With advances in open-source MINLP algorithms, a direct MINLP formulation of VVO can be presented and solved. The MINLP approach can provide value to VVO since it reduces the need for linearization in problem formulation and the need to transform continuous values into discrete values. This paper proposes a new formulation method for VVO problem with DGs as a direct MINLP problem. The proposed approach solves VVO for all three phases, works for different load types, incorporates integer decisions, and allows for non-linear voltage, current and

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control equations. The method has shown promises to yield optimal solutions effectively.

2. Description of the voltage and VAR optimization problem

The purpose of VVO is to operate distribution feeders at the most efficient operating conditions. Distribution system control variables to be optimized are the capacitor bank switch positions, VR tap positions, and reactive power outputs of DG units. The optimization approach is described in the following sections.

2.1. MINLP solution approach

Distribution system VVO is formulated as an MINLP problem. Commercial optimization solvers, such as IBM ILOG CPLEX, are known to be unable to solve MINLP problems. However, there is great academic interest in new MINLP solvers. Basic Open-source Mixed Integer (BONMIN) solver is an open-source state-of-the-art optimization solver, developed for solving general MINLP problems [24]. BONMIN has several optimization algorithms, including branch-bound, outer approximation (OA), Quesada Grossman branch-cut, and Hybrid OA based branch-cut. OPTI Toolbox is a third-party toolbox developed to interface Matlab with open-source solvers, including BONMIN [25]. The proposed approach in this paper uses OPTI Toolbox to describe VVO as an MINLP problem in Matlab and to solve it with BONMIN.

In the present study of BONMIN algorithms, the OA algorithm showed the most promise for fast convergence for VVO problem formulation described in this paper. It has been noted in [24] that it is not uncommon that one algorithm outperforms the others. The general idea of the OA approach is to relax the MINLP problem into MILP and NLP sub-problems and iteratively solve these problems until an optimal solution is reached. The OA algorithm used in BONMIN code is described in detail in [26,27].

2.2. Objective function

The objective function considered in the proposed approach is to minimize the real power drawn from the substation, constrained by node voltage and branch current limits.

2.3. Power flow constraints

The distribution power flow constraints are developed with the help of the ladder iterative power flow approach [28]. The idea of ladder iterative power flow approach is to perform a series of node voltage determining forward sweeps and use the calculated voltages for current determining backward sweeps, until the solution converges. The approach has been shown to have fast convergence and work well for balanced and unbalanced three-phase feeders [28]. The power flow constraint used in the MINLP formulation is written the same way as the voltage and current equations of the ladder iterative power flow approach. However, the optimization solver cannot use complex numbers; therefore, all complex numbers have been decoupled into their Cartesian forms.

Three-phase voltage drop equations describe the relationship between node voltage phasors, branch current phasors and branch impedances. The distribution lines are modeled as three-phase Π -equivalent circuits. The transformer model includes series impedances as well as impedances of magnetizing branches. Variable tap-position is also incorporated into the transformer for VRs. The substation connection is presented as an ideal source; three phases have the rated voltage magnitude and abc phase sequence.

The loads for the system are represented as a weighted combination of constant impedance, constant current, and constant power loads. Load level at the rated voltage is assumed to be known. For

each load type, Cartesian load currents are presented as functions of Cartesian power and voltage components. Distributed loads are modeled as spot loads at the midpoint of the branches. The DG units are presented as negative loads, with a specified real and controllable reactive power outputs. The inverter reactive power output is limited by the apparent power rating and the DG real power generation. Capacitor banks are modeled as negative reactive power loads with controllable switch settings.

2.4. Voltage and current constraints

The node voltages are limited by the ANSI standard in the US. The voltage limits are enforced by non-linear inequality constraints by determining voltage magnitude from Cartesian representations of the voltage phasor. Distribution lines also have maximum allowed current limits. The Cartesian coordinate representations of current phasor are used to find current magnitude, which is limited by the maximum line current.

3. MINLP model

The general MINLP formulation is presented as follows:

$$\min\{F(x) : Ax \leq b, A_{eq}x = b_{eq}, l_b \leq x \leq u_b, C(x) \leq d, C_{eq}(x) = d_{eq}, x_i \in Z\}$$

where $F(x)$ is the objective function to be minimized, A and b define linear inequality constraints, A_{eq} and b_{eq} define linear equality constraints, l_b and u_b are the bounds that constrain x , $C(x)$ and d define non-linear inequality constraints, $C_{eq}(x)$ and d_{eq} define the non-linear equality constraints, Z is the integer set, and x_i is the subset of x restricted to be integers. The solution approach, described in Section 2, is implemented in this section for the MINLP model.

3.1. Objective function

The objective function, the real power drawn from the substation, is written as

$$F = \sum_{g \in P} \sum_{k \in B_r} (V_s^x(g) I_{sk}^x(g) + V_s^y(g) I_{sk}^y(g)) \quad (1)$$

where B_r is the set of branches connected to the substation, $I_{sk}^x(g)$ and $I_{sk}^y(g)$ are the Cartesian presentations of g -phase current in branch k , $V_s^x(g)$, $V_s^y(g)$ are Cartesian representations of source voltage of phase g at substation, p is the set of phases that the branch currents are drawn from.

3.2. Power flow constraints

The branch voltage equations are written as voltage equations in ladder iterative power flow process [28]. The downstream voltage is written as a function of the upstream voltage and the voltage drop in the branch. For example, if the node n has a voltage V_n , and it is connected to node m through branch with impedance of Z_{nm} and branch current I_{nm} , the constraint for voltage V_m at node m would be formed as follows:

$$V_m = V_n - Z_{nm} I_{nm} \quad (2)$$

$$V_m^x + jV_m^y = V_n^x + jV_n^y - (R_{nm} + jX_{nm})(I_{nm}^x + jI_{nm}^y) \quad (3)$$

$$V_m^x - V_n^x + R_{nm} I_{nm}^x - X_{nm} I_{nm}^y = 0 \quad \text{and} \quad V_m^y - V_n^y + R_{nm} I_{nm}^y + X_{nm} I_{nm}^x = 0 \quad (4)$$

where R_{nm} is branch resistance, X_{nm} is branch reactance, V_n^x , V_n^y , V_m^x and V_m^y are Cartesian representations of the node voltages at nodes n and m , respectively, and I_{nm}^x and I_{nm}^y are Cartesian representations of the branch current between nodes n and m . Eq. (4) is extended to

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