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A new approach based on ant colony optimization for daily Volt/Var control in distribution networks considering distributed generators

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ABSTRACT

This paper presents a new approach to daily Volt/Var control in distribution systems with regard to distributed generators (DGs). Due to the small *X*/*R* ratio and radial configuration of distribution systems, DGs have much impact on this problem. A cost-based compensation methodology is proposed as a proper signal to encourage owners of DGs in active and reactive power generation. An evolutionary method based on ant colony optimization (ACO) is used to determine the active and reactive power values of DGs, reactive power values of capacitors and tap positions of transformers for the next day. The results indicate that the proposed encouraging factor has improved the performance of distribution networks on a large scale.

1. Introduction

Nowadays, numerous factors, such as significant advances in several generation technologies, environmental impacts of electric power generation, deregulation of power systems and tight constraints over the construction of new transmission lines for long distance power transmission, actively encourage consumers and distribution companies to more uses of generation, called distributed generators (DGs) [1–3]. Studies carried out by research centers show that DGs participation in energy production will increase to even more than 25% in the near future [1]. Therefore, it is necessary to study the impact of DGs on power systems, especially on distribution networks.

Since the *X*/*R* ratio of distribution lines is small and the configuration of distribution network is radial, the daily Volt/Var control is one of the most important control schemes in the distribution networks, which can be affected by DGs.

The daily Volt/Var control is defined as regulation of voltage over the feeders and reactive power (or power factor) at the substation bus [4]. The control is achieved by adjusting the Load Tap Changer transformers (LTCs), Voltage Regulators (VRs) and capacitor banks as control variables to minimize the objective function considering the constraints. Many researchers have investigated reactive power and voltage control in distribution networks. For instance, Baran et al. presented a supervisory Volt/Var control scheme, based on the new measurements and computer resources; which were available at the substation bus. They obtained the new measurements based on this fact that the voltage drop on the feeder varies linearly with the total feeder load current measured at the substation [4]. Roytelman, et al. presented a centralized Volt/Var control algorithm for the distribution system management. They considered summation of power losses and power demands as the objective function [5]. The supervisory control schemes for integrated Volt/Var control at the substation and feeders were presented in [6]. The supervisory controller, located at substation, coordinates the control of local regulating devices based on dynamically changing system conditions. An approach for modeling local controllers and coordinating the local and centralized controllers at the distribution system management was presented by Roytelman and Ganesan [7,8]. A heuristic and algorithmic combined approach for reactive power optimization with time varying load demand in distribution systems was presented in [9]. Volt/Var control in distribution systems using a time-interval was described by Hu et al. [10]. The aim is to determine optimum dispatch schedules for on-load tap changer (OLTC) settings at substations and all shunt capacitors switching based on the day-ahead load forecast. A genetic algorithm based procedure is used to determine both the load level partitioning and the dispatch scheduling. An improved evolutionary programming and its hybrid version combined with the nonlinear interior point technique to solve the optimal reactive power dispatch problems was proposed in [11]. Niknam et al. presented methods for the Volt/Var control in radial distribution networks considering Distributed Generations [12–15]. They considered electrical power losses as the objective function and used the genetic algorithm and hybrid ACO evolutionary algorithm for minimizing the objective function. Also they have not considered the impact of active power of DGs on the Volt/Var control problem. A daily Volt/Var control in distribution networks with regard to DGs is the main purpose of this article. The objective function includes the cost of electrical energy generated by DGs and

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distribution companies during the next day. The control variables are the active power of DGs, reactive power of capacitors and tap of transformers and VRs in the next day.

Due to the equipment in distribution systems, such as Static Var Compensators (SVCs), DGs, load tap changers and VRs, the daily Volt/Var control problem is usually modeled as a mixed integer nonlinear programming problem. Conventional and classical methods such as linear programming, mixed integer programming, and quadratic programming, can be applied to solve the mentioned problem. However, these methods finally reach a local minimum and some of them cannot handle the integer problems [16]. Evolutionary methods, owing to independence on the type of objective function and constraints, can be used for solving these sorts of problems [16]. In this paper, an evolutionary optimization method based on ACO has been put into use to solve the daily Volt/Var control, which not only has a better response but also converges more quickly than ordinary evolutionary methods like genetic algorithm [15,17].

The main contributions of this paper are as follows: (i) present a new approach for daily Volt/Var control in distribution networks considering DGs, (ii) consider the active power of DGs as a control variable, (iii) present a cost based compensation methodology for control of DGs, (iv) present an evolutionary optimization based on ACO algorithm to solve the Volt/Var control.

Following this section, the proposed Volt/Var control problem is formulated in Section 2. A cost evaluation method applicable to DGs is presented in Section 3. The effect of DGs on the voltage profile of distribution networks is shown in Section 4. In Sections 5–7, the basic mechanism of the ant colony system and implementing the used ACO to Volt/Var control problem are recommended, respectively. Finally, in Section 8, the feasibility of the proposed approach is demonstrated and compared with methods based on particle swarm optimization, Tabu Search, differential evolution and genetic algorithm for two distribution test feeders.

2. Daily Volt/Var control in distribution networks including DGs

The daily Volt/Var control in distribution networks considering DGs is a nonlinear optimization problem with continuous and discrete parameters and variables. The objective function and constraints are presented as follows:

2.1. Objective function

In this paper, the proposed objective function includes the following two parts:

1. Cost of electrical energy generated by distribution companies.
2. Cost of electrical energy generated by DGs.

The objective function of daily Volt/Var control is defined as

$$\begin{aligned}
f(\overline{X}) &= \sum_{t=1}^{Nd}\left(Price^t * P^t_{Sub} * \Delta t_t + \sum_{i=1}^{N_g} C_{Pgi}(P^t_{gi}) * \Delta t_t\right)\\
\overline{X} &= [\overline{Tap}, \overline{Q_G}, \overline{U_C}, \overline{P_G}]\\
\overline{Tap} &= [\overline{Tap_1}, \overline{Tap_2}, \ldots, \overline{Tap_{Nt}}]\\
\overline{Tap_i} &= [Tap_i^1, Tap_i^2, \ldots, Tap_i^{Nd}]; \quad i = 1,2,3,\ldots,N_t\\
\overline{Q_G} &= [\overline{Q_{g1}}, \overline{Q_{g2}}, \ldots, \overline{Q_{gNg}}]\\
\overline{Q_{gi}} &= [Q^1_{gi}, Q^2_{gi}, \ldots, Q^{Nd}_{gi}]; \quad i = 1,2,3,\ldots,N_g\\
\overline{P_G} &= [\overline{P_{g1}}, \overline{P_{g2}}, \ldots, \overline{P_{gNg}}]\\
\overline{P_{gi}} &= \left[P^1_{gi}, P^2_{gi}, \ldots, P^{Nd}_{gi}\right]; \quad i = 1,2,3,\ldots,N_g\\
\overline{U_C} &= [\overline{U_{c1}}, \overline{U_{c2}}, \ldots, \overline{U_{cNc}}]\\
\overline{U_{ci}} &= \left[U^1_{ci}, U^2_{ci}, \ldots, U^{Nd}_{ci}\right]; \quad i = 1,2,3,\ldots,N_c
\end{aligned} \tag{1}$$

where N_c is number of capacitors, N_g is number of DGs, N_d is number of load variation steps, N_t is number of transformers, t is an index which represents time steps of load level $\overline{X}$ is state variables vector $\overline{Tap}$ is tap vector representing tap position of all transformers in the next day, $\overline{Tap_i}$ is tap vector including tap position of the ith transformer in the next day, Tap_i^t is tap position of the ith transformer for the tth load level step, $\overline{Q_G}$ is DGs reactive power vector including reactive power of all DGs in the next day, $\overline{Q_{gi}}$ is DGs reactive power vector including reactive power of the ith DG in the next day, Q^t_{gi} is reactive power of the ith DG for the tth load level step, $\overline{P_G}$ is DGs active power vector including active power of all DGs in the next day, $\overline{P_{gi}}$ is DGs active power vector including active power of the ith DG in the next day, P^t_{gi} is active power of the ith DG for the tth load level step, U^t_{ci} is state of the ith capacitor in the light of turning on and off during time "t", which equals 0 or 1, $\overline{U_{ci}}$ is capacitors switching vector including state of the ith capacitor in the next day, $\overline{U_C}$ is capacitors switching state vector including state of all capacitors in the next day, Δt_t is time interval, $Price^t$ is electrical energy price generated by the distribution company for the tth load level step, P^t_{Sub} is active power of distribution company for the tth load level step.

In this problem, it is assumed that tap position of transformers changes stepwise.

In the objective function formula, P^t_{Sub} is considered as a slag bus and calculated based on state variables for the tth load level step.

2.2. Constraints

Constraints are defined as follows:

- Active and reactive power constraints of DGs:

$$(P^t_{gi})^2 + (Q^t_{gi})^2 \leqslant S^2_{gi,\max} \tag{2}$$

$S_{gi,\max}$ is the apparent power of the ith DGs.

- Distribution line limits:

$$|P^{\text{Line}}_{ij}|^t < P^{Line}_{ij,\max} \tag{3}$$

$|P^{\text{Line}}_{ij}|^t$ and $P^{\text{Line}}_{ij,\max}$ are the absolute power flowing over distribution lines and maximum transmission power between the nodes i and j, respectively.

- Tap of transformers:

$$Tap_i^{\min} < Tap_i^t < Tap_i^{\max} \tag{4}$$

$Tap_i^{\min}, Tap_i^{\max}$ and Tap_i^t are the minimum, maximum and current tap positions of the ith transformer, respectively.

- Unbalanced three-phase power flow equations.
- Maximum allowable daily operating times of transformers:

$$DOT_i^{\text{Trans}} \leqslant MADOT_i^{\text{Trans}} \tag{5}$$

DOT_i^{Trans} and $MADOT_i^{\text{Trans}}$ are the daily operating times and maximum allowable daily operating times of the ith transformer, respectively.

- Maximum allowable daily operating times of capacitors:

$$\sum_{t=1}^{Nd} U^t_{ci} \leqslant MADOT_i^{Cap} \quad i = 1,2,3,\ldots,Nc \tag{6}$$

$MADOT_i^{\text{Cap}}$ is the maximum allowable daily operating times of the ith capacitor.

- Substation power factor

$$Pf_{\min} \leqslant Pf^t \leqslant Pf_{\max} \tag{7}$$

$Pf_{\min}$, $Pf_{\max}$ and Pf^t are the minimum, maximum and current power factor at the substation bus during time t.

- Bus voltage magnitude

$$V_{\min} \leqslant V_i^t \leqslant V_{\max} \tag{8}$$