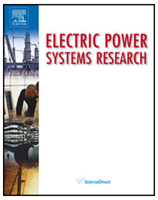
Electric Power Systems Research 141 (2016) 157–164

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



Coordinated two-stage volt/var management in distribution networks

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ARTICLE INFO

Article history:
Received 29 April 2015
Received in revised form 21 March 2016
Accepted 11 July 2016

Keywords:
Capacitor
Distribution network
Energy loss
On-load tap changer
Particle swarm optimisation
Volt/var control

ABSTRACT

This paper investigates daily volt/var control in distribution networks using feeder capacitors as well as substation capacitors paired with on-load tap changers. A two-stage coordinated approach is proposed. Firstly, the feeder capacitor dispatch schedule is determined based on reactive power heuristics. Then, an optimisation model is applied to determine the dispatch schedule of the substation devices taking into account the control actions of the feeder capacitors. The reference voltage of the substation secondary bus and the tap position limits of transformers are modified such that the model adapts to varying load conditions. The optimisation model is solved with a modified particle swarm optimisation algorithm. The proposed method is compared with conventional volt/var control strategies using a 14-bus system and its effectiveness is further illustrated on a 69-bus system. It is demonstrated that the proposed approach performs better than the conventional strategies in terms of voltage deviation and energy loss minimisation.

1. Introduction

Control of volt and var devices such as on-load tap changers (OLTC) and shunt capacitors affects the voltage profile and the total power loss in distribution networks [1]. Dispatch of the volt/var control (VVC) resources can be performed in a coordinated manner in constrained environments to meet specific operational objectives [2–17]. The complexity of the objective function, constraints, and computation is influenced by, among others: regulatory limits, switching limitations and available control devices. The focus of this paper is daily VVC with switching restrictions, which is usually applied to networks with widespread communication and control coverage [7–17]. The additional requirement of this VVC approach is a day-ahead forecast of load behaviour, which is made possible by the existence of load forecasting techniques that provide good accuracy [18,19].

Daily coordinated control of all distribution devices is computationally complex, but there are a number of ways to deal with this difficulty. One way to approach this is to simplify the solution space so as to reduce the computational burden. For instance, the requirements of dynamic programming can be eased according to [8,9,11], while a more efficient solver based on the interior-point method is presented in [17]. In [10] the number of possible states is decreased by combining artificial neural networks, a rule-based method and dynamic programming. Use of heuristic rules can also reduce the number of possible device operations, therefore simplifying the optimisation model [13]. These methods address the issue of computational complexity but the requirements for remote control infrastructure remain for network-wide implementation. Another alternative is to divide the scheduling problem into two sub-problems: one handling the dispatch of the substation capacitor (SC) and OLTC, and the other controlling the feeder capacitors (FCs) [12]. In particular, dispatch of the substation devices minimises reactive power-flow and the voltage deviation at the substation bus. FCs are then dispatched based on local bus voltage and power factor deviations using a fuzzy control scheme after the substation devices have been dispatched. The final states of the FCs are found when the bus voltage is within permissible limits. In [20] the total loss and voltage deviations at load buses are minimised through dispatch of all capacitors. The OLTC is controlled in real-time to keep the substation secondary bus voltage close to the set-point that incorporates the voltage change caused by the capacitors. In these previous approaches, the objectives specified for the substation control problem focus only on the secondary bus at the substation. The rest of the buses are considered in the control schemes for capacitors.

In this paper, a two-stage approach to daily VVC is presented with the devices controlled in a different manner. Firstly, a strategy to determine the FC dispatch schedule is developed using reactive power set-points. Then, with the FC schedule as input, coordination of the SC and OLTC is formulated as an optimisation problem.

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http://dx.doi.org/10.1016/j.epsr.2016.07.012
0378-7796/

The advantage of this approach is that the voltage deviations can be reduced further by adjusting the transformer tap ratio together with the capacitor on/off statuses. The reason is that, unlike capacitors, transformers equipped with OLTCs usually have a larger control range, smaller discrete steps and provide direct voltage adjustments. Hence the model can produce an improved voltage profile. Voltage magnitudes at all load buses are primarily controlled at the substation with the statuses of FCs given as input. Since the voltage constraint at each load bus is handled at the substation, the FC control problem focuses solely on loss reduction. This strategy facilitates the adoption of a technique relying only on reactive power-flows at the substation to determine the control actions for FCs. The FC control problem minimises the reactive power-flow through the distribution feeders at the substation bus, while the OLTC and SC problem minimises both the total loss and the voltage deviations at all distribution network buses. The decomposition of the VVC problem reduces the dimension of the optimisation model. Furthermore, the model can be applied to networks with extensive remote control capability and those with limited capability, i.e. coverage from the control centre to the substation but no coverage along medium voltage distribution lines.

The FC control problem is solved with a heuristic method while the OLTC and SC control problem is solved by particle swarm optimisation (PSO) with consideration of the discrete nature of the control variables. The performance of the proposed approach is analysed in relation to various implementations of conventional VVC. Simulation results show that the proposed approach minimises both the voltage deviations and the total energy loss while conventional control considers one objective at a time depending on specified settings.

The remainder of this paper is structured as follows. Section 2 gives a brief introduction of conventional VVC methods. Section 3 presents the proposed control strategy. A case study is described, followed by a discussion of results in Section 4. Section 5 concludes the study.

2. Conventional VVC

In traditional distribution networks, voltage regulation is realised through manual or automatic adjustments of transformer taps so that the voltage lies between the given upper and lower bounds. Automatic voltage regulation is achieved by using transformers equipped with OLTCs at distribution substations. Generally, automatic voltage regulation (AVR) settings comprise a voltage set-point and a deadband. The voltage set-point is the desired voltage at the bus controlled by the OLTC. The deadband is the allowed margin within which no tap changes are initiated; the controller sends out tap changes whenever the voltage falls outside the deadband. The steady-state tap position at time t is determined using [21]

$$u_{\mathrm{TAP}}^{t} = \begin{cases} u_{\mathrm{TAP}}^{t-1} + \Delta u_{\mathrm{TAP}}^{t}, & \text{if } V_{\mathrm{set}} - V^{t} > 0.5V_{\mathrm{db}}; \\ u_{\mathrm{TAP}}^{t-1} - \Delta u_{\mathrm{TAP}}^{t}, & \text{if } V_{\mathrm{set}} - V^{t} < -0.5V_{\mathrm{db}}; \\ u_{\mathrm{TAP}}^{t-1}, & \text{otherwise}; \end{cases}$$

where $\Delta u_{\mathrm{TAP}}^{t}$ is the number of tap movements required to bring the voltage V^t into the deadband, V_{db}; V_{set} is the voltage set-point. The deadband setting is, in general, selected in a way that avoids unnecessary operations [22]. The voltage set-point decision considers feeder losses and voltage regulation limits [23].

Capacitor control aims to reduce reactive power-flow through the substation transformer or the distribution feeder. In this way, the total loss is minimised. The use of capacitors also has the effect of raising voltage in addition to providing reactive power compensation. In this paper, a combination of automatic voltage regulation using OLTCs and time-based capacitor control is implemented. This method requires no remote control facilities because the OLTC and capacitors are controlled locally. It is henceforth referred to as conventional control.

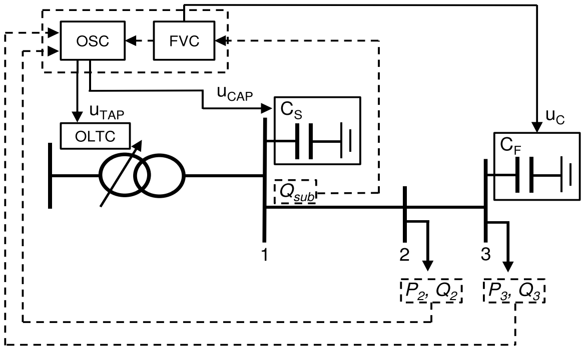

Fig. 1. Conceptual model of the proposed feeder var control and optimal substation control.

3. Feeder var control and optimal substation control (FVC–OSC)

The proposed method minimises the total loss and voltage deviations in distribution systems. The conceptual model of the method is illustrated in Fig. 1. The solution process comprises two stages. Firstly the FC schedules are determined. Then the SC and OLTC are coordinated optimally to complete the dispatch schedules. The FC on/off statuses are derived from reactive power variations on the feeder at the substation and supplied together with the forecasted active power and reactive power profiles of the loads to the SC and OLTC control model. Then, an optimisation algorithm is applied in which the switching sequences of the SC and OLTC are obtained.

The index t denotes a time interval, whose length is $\Delta t = 1$ h; $[t\Delta t, (t+1)\Delta t)$ denotes a single interval and N specifies the total number of intervals in the scheduling period, which in this study is 24. The time interval and bus indices satisfy $1 \le t \le N$, $1 \le d \le D$ and $1 \le j \le D$. D is the total number of buses in a given network. The transformer tap position (adjusted by an OLTC) is represented by the integer variable $u_{\mathrm{TAP}}^{t} \in [T^{\min}, T^{\max}]$ and related to the tap ratio a_r^t by $a_r^t = 1 - u_{st} u_{\mathrm{TAP}}^{t}$. u_{st} is the size of a single tap increment/decrement step. Capacitors are realised as shunt elements with on/off operations modeled as binary variables. $u_{\mathrm{CAP}}^{t} \in [0, 1]$ denotes the SC control action while the FC control actions are represented by $u_{\mathrm{C},d}^{t} \in [0, 1]$.

3.1. Feeder var control (FVC)

A heuristic scheduling technique based on the substation feeder reactive power profiles is proposed for FVC. The aim of this method is to minimise reactive power-flow through the transformer without SC and OLTC control. Furthermore, the total number of operations for the FCs during the scheduling period must not exceed the permissible limit.

The objective of FVC is to minimise feeder reactive power-flow as described below:

$$\sum_{t=1}^{N} \left| Q_{\mathrm{sub},n}^{t} \right|, \tag{1}$$

subject to