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Real-Time Volt/VAr Control Based on the Difference between the Measured and Forecasted Loads in Distribution Systems

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Abstract – This paper proposes a method for real-time control of both capacitors and ULTC in a distribution system to reduce the total power loss and to improve the voltage profile over the course of a day. The multi-stage consists of the off-line stage to determine dispatch schedule based on a load forecast and the on-line stage generates the time and control sequences at each sampling time. It is then determined whether one of the control actions in the control sequence is performed at the present sampling time. The proposed method is presented for a typical radial distribution system with a single ULTC and capacitors.

Keywords: Capacitor, Load forecast, Real-time control, Under-load tap changer (ULTC)

1. Introduction

Volt/VAr control is important to the daily operation of distribution systems because the proper dispatch of volt/VAr devices not only reduces the total power loss, but also improves the voltage profile for distribution feeders. With the development of communication and power electronic technologies, integrated control of all the available Volt/VAr devices, including the under-load tap changer (ULTC) and capacitor banks installed at substations or distribution feeders, becomes available for distribution systems.

Over the last two decades, several techniques have been proposed to deal with the volt/VAr control problems in distribution systems. Most of the previous techniques have been accomplished in the off-line environment by finding dispatch schedules for capacitors and ULTCs based on the load forecast for the day ahead. Some papers have proposed a dynamic programming approach for volt/VAr control problems [1−3]. Some researchers have used neural-net-based methods to control the volt/VAr devices [4-6]. In [7], a time-interval base volt/VAr control method used a genetic algorithm to divide the daily load into several load levels and to find the optimal tap positions for each load level and the dispatch schedule of capacitors.

Since the loads in real distribution systems are subject to non-simultaneous variation, the control of volt/VAr devices should follow the often changing load conditions to reduce total power loss and to improve the voltage profile. For this purpose, this paper proposes a real-time volt/VAr control method based on the difference between the measured and forecasted loads.

In the off-line stage, a dispatch schedule is determined using the hourly load profile available from load forecasting and then the load profile at each sampling time is calculated by applying a cubic spline interpolation to the hourly data. In the on-line stage, the time and control sequences at each sampling time are generated based on the off-line dispatch schedule. To reflect the power system conditions at each sampling time, the generated time sequence is adjusted based on the difference between the measured and forecasted loads. It is then determined whether one of the control actions in the control sequence should be moved up to the present sampling time. The proposed algorithm is demonstrated in a typical radial distribution system and compared with the off-line control method.

2. Problem Formulation

The distribution system under study is shown in Fig. 1. The main transformer is installed with a ULTC to keep its secondary bus voltage close to the preset value under changing load conditions. Since the primary bus voltage changes slightly over a day compared to the secondary bus and feeder voltages, the primary bus voltage is assumed to be constant. Two shunt capacitors are installed at the secondary bus to compensate the reactive power flow through the main transformer. In addition, some capacitors are installed at feeder buses to maintain the voltage profile within the acceptable limits and to minimize the power loss.

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In this paper, it is assumed that the proposed algorithm will be applied to this central unit.

To minimize the total power loss in a distribution system and bus voltage deviation from the desired value, the dispatch problem can be formulated as follows:

$$J = [w_1 \sum_{h=1}^{24} L_h + w_2 \sum_{h=1}^{24} \sum_{n=1}^{N} D_{n,h}], \tag{1}$$

where w_1 and w_2 are weighting factors for the power loss and voltage profile, N is total number of nodes in the distribution system, L_h is total percent loss in the distribution system at hour h, and $D_{n,h}$ is voltage deviation of node n from 1.0 pu at hour h.

The objective function of (1) is subject to the following inequality constraints:

$$V_{\min} < V_{n,h} < V_{\max} \tag{2}$$

$$\sum_{h=2}^{24} \left| TAP_h - TAP_{h-1} \right| \le MK_T \tag{3}$$

$$\sum_{h=2}^{24} \left| C_{m,h} \oplus C_{m,h-1} \right| \le MK_{C_m}, \tag{4}$$

where $V_{n,h}$ is voltage of node n at hour h, V_{min} and V_{max} are nodal voltage limits, TAP_h is tap position at hour h, MK_T is maximum operating number of the ULTC, $C_{m,h}$ is status of capacitor m (on or off) at hour h, and MK_{Cm} is maximum operating numbers of capacitor m.

3. Off-line Stage

3.1 Off-line Dispatch Schedule

With the day-ahead load profile available from a load forecast, the off-line dispatch schedule of the volt/VAr devices is determined from minimizing J in (1). For this minimization, this paper uses the time-interval based volt/VAr control algorithm presented in [7]. During the minimization, the voltage profile at hour h, V_h, is obtained by solving the following equation:

$$\mathbf{V}_h \text{ such that } f_n(\mathbf{V}_h, P_{n,h}, Q_{n,h}) = 0, \tag{5}$$

where $P_{n,h}$, $Q_{n,h}$ are forecasted active and reactive loads of node n at hour h and f_n is load flow equation of node n including the consideration of the operation of volt/VAr devices.

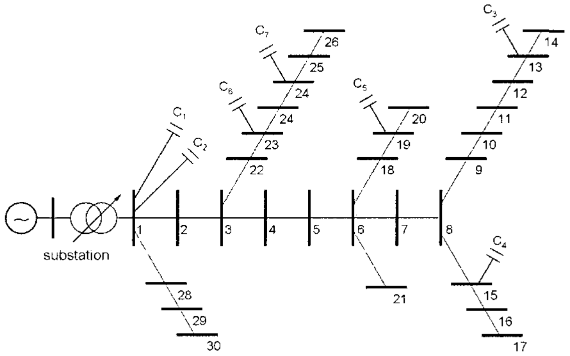

Fig. 1. Distribution system under study

3.2 Interpolation of the Forecasted Load Data

Although the proposed algorithm requires load data at each sampling time, only hourly data are available from the load forecast. In order to determine the load data at each sampling time, a cubic spline interpolation is applied to the hourly data and then the interpolated load data are discretized with the sampling interval Δt_s:

$$P_n[i] = P_n(t)\,|_{t=i\Delta t_s} \tag{6}$$

$$Q_n[i] = Q_n(t)\,|_{t=i\Delta t_s}, \tag{7}$$

where $P_n(t)$ and $Q_n(t)$ are interpolated active and reactive loads of node n at time t.

Then, the forecasted voltage profile without any voltage control during a day, $\mathbf{V}[i]$, is obtained by solving the following equation:

$$\mathbf{V}[i] \text{ such that } f_n^0(\mathbf{V}[i], P_n[i], Q_n[i]) = 0, \tag{9}$$

where f_n^0 is load flow equation of node n without considering the operation of volt/VAr devices.

4. On-line Stage

At sampling time i_0, the future dispatch schedule can be divided into time sequence $T_0[i_0]$ and control sequence $C_0[i_0]$, as shown in the equation

$$\begin{aligned} T_0[i_0] &= \{j_1, \cdots, j_k, \cdots, j_K\} \\ C_0[i_0] &= \{c_1, \cdots, c_k \cdots, c_K\} \\ c_k &= \{(d_k, o_k) \mid d_k \in \{ULTC, C_m\}, o_k \in \{up, down, on, off\}\}, \end{aligned} \tag{10}$$

where j_k is k-th scheduled time, c_k is k-th scheduled control action, and K is total operating number of all volt/VAr devices after i_0.

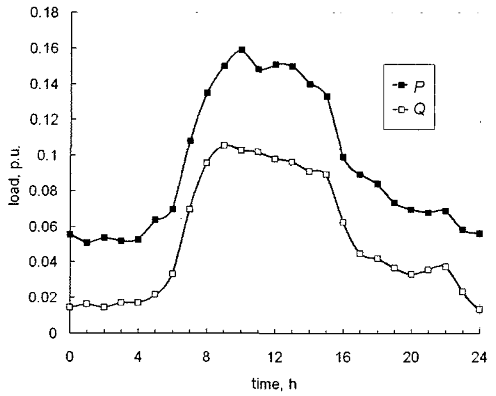

Fig. 4. Forecasted and interpolated daily load curves

In this step, it is important to reduce computational burdens to perform the proposed method in real-time. For this purpose, the following assumption is made:

Load assumption: The future difference between the measured and interpolated loads is the same as the present difference.

This assumption originates from the fact that when the measured load exceeds the forecasted one, the load in the future is more likely to also be larger than the forecasted load.

In addition to the time sequence in (10), the control sequence is also adjusted for on-line control. Considering the computational burden, the following constraint is used in this step:

Control constraint: only one element of the control sequence can be moved up to the present sampling time and the order of the others should be preserved without any change.

When the p-th control action, c_p, is moved up to i_0, the schedule of (10) is changed to

$$\begin{aligned} \hat{T}_p[i] &= \{\hat{j}_0,\ \hat{j}_1,\ \cdots,\ \hat{j}_{p-1},\ \hat{j}_{p+1},\ \cdots,\ \hat{j}_K\} \\ \hat{C}_p[i] &= \{c_p,\ c_1,\ \cdots,\ c_{p-1},\ c_{p+1},\ \cdots,\ c_K\} \end{aligned}, \quad (11)$$

where $\hat{j}_0 = i_0$.

According to the schedule of (11), the voltage profile at the sampling time $\hat{j}_k$, $\hat{\mathbf{V}}[\hat{j}_k]$, which corresponds to the voltage profile just after c_k is performed at $\hat{j}_k$, is obtained by solving the following equation:

$$\begin{gathered} \hat{\mathbf{V}}[\hat{j}_k] \text{ such that} \\ f_n(\mathbf{V}[\hat{j}_k], P_n[\hat{j}_k] + \Delta P_n[i_0], Q_n[\hat{j}_k] + \Delta Q_n[i_0]) = 0 \\ \Delta P_n[i_0] = \tilde{P}_n[i_0] - P_n[i_0], \\ \Delta Q_n[i_0] = \tilde{Q}_n[i_0] - Q_n[i_0], \end{gathered} \quad (12)$$

where $P_n[\hat{j}_k]$ and $Q_n[\hat{j}_k]$ are forecasted active and reactive loads of node n at $\hat{j}_k$, $\tilde{P}_n[i_0]$ and $\tilde{Q}_n[i_0]$ are measured active and reactive loads at node n where device d_k is installed.

With the obtained $\hat{\mathbf{V}}[\hat{j}_k]$ and the load assumption, the voltage of node n can be re-forecasted as

$$\begin{aligned} \hat{V}_n[m] &= V_n[m] + \Delta V_n[\hat{j}_k] \\ &= V_n[m] + (V_n[\hat{j}_k] - \hat{V}_n[\hat{j}_k]) \end{aligned} \quad \hat{j}_k \le m < \hat{j}_{k+1}, \quad (13)$$

where $V_n[m]$ is interpolated voltage at node n at the sampling time $m > i_0$ given by (9). Fig. 2 shows an example of the re-forecasted voltage. Using the re-forecasted voltage $\hat{V}_n[m]$ of (13), the value of the following objective function $J_p(i_0)$ is calculated:

$$J_p(i_0) = \left[w_1 \sum_{m=i_0}^{M} \hat{L}[m] + w_2 \sum_{m=i_0}^{M} \sum_{n=1}^{N} \hat{D}_n[m] \right], \quad (14)$$

where M is total sampling number in a day, $\hat{L}[m]$ is total percent loss at the sampling time m, and $\hat{D}_n[m]$ is voltage deviation of node n from 1.0 pu at the sampling time m.

The objective function $J_p(i_0)$ of (14) represents the total power loss and voltage deviation when c_p is performed at i_0. As shown in Fig. 3, repeating the procedure from (11) to (14) yields $J_p(i_0)$ for p=0,…,K. Note that $J_0(i_0)$ corresponds to the objective function when no control action is performed at i_0.

If $J_p(i_0)$ has a minimum value at $k = p$, the p-th control action, c_p, is performed at i_0 and the future dispatch schedule at the next sampling time becomes

$$\begin{aligned} T_0[i_0+1] &= \{j_1,\ \cdots,\ j_{p-1},\ j_{p+1},\ \cdots,\ j_K\} \\ C_0[i_0+1] &= \{c_1,\ \cdots,\ c_{p-1},\ c_{p+1},\ \cdots,\ c_K\} \end{aligned} \quad (15)$$

If $J_k(i_0)$ has a minimum value at $k = 0$, no control action is performed at i_0 and the future dispatch schedule at the next sampling time becomes the same as (10).

5. Simulation Results

The distribution system presented in Fig. 1 is used to evaluate the performance of the proposed algorithm. Two capacitors (C1 and C2) are installed at node 1 and the ULTC is placed between nodes 0 and 1. The ULTC can change the voltage from –5% to +5% with 17 tap positions ([–8, –7, …, 0, 1, …, 7, 8]). Table 1 describes the detailed data for the capacitors. The impedance of the substation transformer is (0.0178+j0.3471) pu and the maximum operating number of the ULTC, MK_T, is set to 30 assuming that the voltage at the primary bus is 1.0 pu, and the voltage at each bus is limited to between 0.95 and 1.05 pu.

Table 1. Capacitor data for test distribution system

Capacitor number	Location (bus no.)	Size [kVAr]	Maximum operating number
C_1	1	900	6
C_2	1	600	6
C_3	13	600	2
C_4	15	600	2
C_5	19	300	2
C_6	23	900	2
C_7	25	900	2

In the simulations, the load at each bus consists of 50% constant-power and 50% constant-impedance. It is assumed that the load at each bus changes during the day according to the daily load curve indicated in Fig. 4, but that it varies randomly by 15% around the nominal level, in both real and reactive parts. In this way, loads for all 24 hours are obtained.

With the coefficients w_1 and w_2 of (1) set to 0.5 and 0.5, respectively, the dispatch schedule is obtained from the time-interval base volt/VAr control algorithm in [7]. Following the procedure described in Section 3.1, we generated the off-line dispatch schedule given in Table 2. Using this off-line dispatch schedule, the distribution system is simulated with the sampling interval set to 30 s. Table 3 shows the operation records of volt/VAr devices. In the proposed method, the real-time control action for each device is performed within the maximum operating number in the off-line dispatch schedule, because the proposed method only adjusts the scheduled times and changes the order of control actions using the difference between the measured and forecasted loads. Table 4 summarizes the simulation results for the proposed method.

6. Conclusions

This paper proposes a real-time volt/VAr control method based on the difference between the measured and forecasted loads to reduce total power loss and to improve the voltage profile over the course of a day. To reduce computational time, the proposed method is divided into two stages. In the off-line stage, the dispatch schedule is determined using the hourly load profile available from a load forecast and then the load profile at each sampling time is calculated by applying an interpolation technique to the hourly data. In the on-line stage, the time and control sequences at each sampling time are generated based on the off-line dispatch schedule. Using the control sequence and the interpolated load profile, it is determined whether one of the control actions in the control sequence is performed at the present sampling time. The performance of the proposed method was evaluated for a typical radial distribution system with a single ULTC and capacitors.

Table 2. Off-line dispatch schedule generated at the off-line stage

device	time	move	device	time	move	device	time	move
C6	5:00:00	1	C2	9:00:00	1			
TAP	6:23:00	+2	C2	11:00:00	0	C1	19:00:00	0
TAP	6:44:00	+3	C2	13:00:00	1	C2	20:00:00	0
TAP	7:05:00	+4	C1	14:00:00	0	C5	23:00:00	0
TAP	7:27:00	+5	TAP	15:18:30	+6	C5	24:00:00	1
TAP	7:52:00	+6	TAP	15:46:30	+5	C6	24:00:00	0
C1	8:00:00	0	C1	16:00:00	1	C1	24:00:00	1
C2	8:00:00	0	TAP	16:14:30	+4	C2	24:00:00	1
TAP	8:17:00	+7	TAP	16:42:30	+3	TAP	24:00:00	+1
C1	9:00:00	1	TAP	17:10:30	+2			

Table 3. Operation record of volt/VAr devices in real-time control

device	time	move	device	time	move	device	time	move
TAP	4:29:30	+2	TAP	7:39:00	+7	C5	15:54:30	0
C1	4:30:30	0	C1	7:40:00	1	TAP	16:13:30	+3
C2	4:31:30	0	C2	7:41:00	1	TAP	16:44:30	+2
TAP	5:30:00	+3	C2	8:18:00	0	C5	16:45:30	1
TAP	6:06:00	+4	C1	10:51:30	0	C1	20:01:00	1
C6	6:21:00	1	C1	11:22:30	1	TAP	22:16:00	+1
C2	6:27:30	1	C1	11:53:30	0	C2	22:73:00	1
TAP	7:06:37	+5	TAP	14:40:30	+6			
C2	6:58:30	0	TAP	15:11:30	+5			
TAP	7:08:00	+6	TAP	15:42:30	+4			

Simulation results demonstrated that the proposed method performs better than the off-line control method with the same operating numbers of volt/VAr control devices.

Table 4. Simulation results

	Off-line dispatch schedule	Proposed method
Total loss [kWh]	2134.57	1881.45
Average voltage deviation [pu]	0.01392	0.01321

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