배전계통 전압/무효전력조정을 위한 새로운 전압/무효전력제어 방식

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A New Volt/Var Control of Substation for Distribution Volt/Var Regulation

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Abstract - In this paper, we proposed the on line volt/var control schemes of the *Load Tap Changer* (LTC) transformer and shunt capacitor bank for distribution volt/var regulation. In the existing volt/var control of the distribution substation, the voltage of feeders and var of distribution systems is mainly controlled by the LTC transformer tap position and on/off status of the shunt capacitor. The LTC and shunt capacitor bank has discrete operation characteristics and therefore it is very difficult to control volt/var at the distribution networks within the satisfactory levels. Also there is limitation of the operation times of the LTC and shunt capacitor bank because it is affects on their functional lifetime. The proposed volt/var control algorithm determine an optimal tap position of LTC and on/off status of shunt capacitors at a distribution network with the multiple feeders. The mathematical equations of the proposed method are introduced. Simple case study was performed to verify the effectiveness of the proposed method.

Nomenclature

K	: Total tap number of the LTC
$\Delta V_k(t)$	: Voltage error
a_k	: Tap interval of the LTC
db	: Dead band of the LTC
dt	: Time delay of the LTC
$T_k(t)$	: Tap position of the LTC
$c_k(t)$, $g_k(t)$	: The counter of the voltage regulator
$f_k(t)$	: Tap changing of the LTC
$e_k(t)$	: Error of the voltage regulator.
$V_{ser}(t)$	: Sending-End Reference voltage
V_{ce}	: Reference voltage of LDC
Z_{eq}	: Compensating impedance of the LDC
$I(t)$	: Bank (load) current
$V_{se}(t)$	: Sending-End Voltage
$V_{tap.k}(t)$	: Secondary voltage of MTR when a tap is located in the k-th position
$Z_{MTR.k}(t)$	: Impedance of the MTR when a tap is located in the k-th position.
N	: Number of feeders
$V_{n.max}$	: Maximum customers voltage at the feeder n
$V_{n.min}$	: Minimum customers voltage at the feeder n
V_{min}	: Lower permissible voltage limit (0.94 [p.u.])
V_{max}	: Upper permissible voltage limit (1.06 [p.u.])
V_{nom}	: Nominal voltage
$CAP(t)$	: Capacitor On/Off status at the time t

1. Introduction

The purpose of volt/var control in a distribution substation is to control the reactive power flow over the main transformer and the voltage on the low-voltage bus [1-5]. *Shunt Capacitors* (SC) are widely used and installed at the low-voltage bus of the substation to control the reactive power. The secondary bus voltage of a main transformer at a distribution substation is regulated by the tap changing operation of the *Load Tap Changing* (LTC) transformers. In addition, modern distribution substations monitoring and recording the bus voltages, real and reactive powers of the feeders, on/off status of the capacitors, tap position of the LTC transformer, etc. for *Energy Management Systems* (EMS). In previous work in this issue, the combined artificial neural network-fuzzy dynamic programming method [1] and the heuristic supervisor control method [2,5] are proposed to achieve the volt/var control of distribution network. However, the unbalanced load diversity of the multiple feeders at the distribution substations are not considered in their work.

In this paper, volt/var control algorithms are proposed which determine an optimal tap position of LTC and on/off status of capacitor banks at a distribution network with the multiple feeders. In the proposed method, the LTC tap positions are determined by the method in [2-3] and on/off status of shunt capacitors are determined by the reactive power flows at the substations in an on-line manners.

2. Proposed Volt/Var control method

2.1 LTC transformer and shunt capacitor

model

In a typical control of the LTC transformer, the tap position is changed discretely. The tap position is changed by the tap interval of the LTC when the voltage error deviates from the specified dead band during the specified time delay. The tap changing operation depends on the dead band and the time delay. The dead band and the time delay element is adopted to reduce the effect of transient voltage variation and avoid unnecessary tap changing operations.

The simplified discrete equations of LTC model are given by [3-4]:

$$T_k(t+1)=T_k(t)-a_k f_k(e_k(t),c_k(t)) \tag{1}$$

$$c_k(t+1)=g_k(e_k(t),c_k(t)) \tag{2}$$

$$f_k(e_k,c_k)=\left[\begin{array}{l} 1 \quad if\ e_k=1\ and\ c_k>dt \\ -1\ \ if\ e_k=-1\ and\ c_k<-dt \\ 0 \quad otherwise \end{array}\right. \tag{3}$$

$$g_k(e_k,c_k)=\left[\begin{array}{ll} c_k+1 & if\ e_k=1\ and\ c_k\geq 0 \\ c_k-1 & if\ e_k=-1\ and\ c_k\leq 0 \\ 0 & otherwise \end{array}\right. \tag{4}$$

$$e_k(\Delta V_k,db)=\left[\begin{array}{ll} e_k=1 & if\ \ \Delta V_k>db \\ e_k=-1 & if\ \Delta V_k<db \\ 0 & \quad otherwise \end{array}\right. \tag{5}$$

The simplified discrete equation of shunt capacitor model is given by:

$$CAP(t)=\left[\begin{array}{l} 1,\ \text{when capacitor is on at the time t} \\ 0,\ \text{when capacitor is off at the time t} \end{array}\right. \tag{6}$$

2.2 LTC transformer controller

In practice, the modern distribution substation is equipped with a current transformer at the each feeder. In addition, load diversity of each of the feeders is recorded for EMS. However, the load diversity information of each of the feeders is not used for voltage regulation. The proposed method has an additional information flow that is the load diversity information of each feeder.

Voltage regulation in the conventional *Line Drop Compensation* (LDC) method is performed by bank current and bus voltage. The SERV (Sending-End Reference Voltage) and the SEV (Sending-End Voltage) in the conventional LDC method are given by [3-4]:

$$V_{ser}(t)=V_{ce}+Z_{eq}\times I(t) \tag{7}$$

$$V_{se}(t)=V_{tap,k}(t)-Z_{MTR,k}(t)\times I(t) \tag{8}$$

The LTC and voltage regulator is used to keep the SEV at the SERV. Therefore, the SEV is controlled within V_{ser} ± db (dead band of voltage regulator). Hence, determining LDC setting values with the hypothetical standard distribution feeder is not proper due to the unbalanced load diversity on multiple feeders and its seasonal variation [3-4].

In the proposed method, at the time t, the desired tap position of LTC and error of LTC are determined by solving an integer optimization problem. The objective function is defined as how close the maximum and minimum customers voltages of each feeder are close to the nominal voltage. The SEV and desired tap position is determined by:

$$\underset{V_{se}}{Min}\,J=\sum_{n=1}^{N}\left\{(V_{nom}-V_{n,max})^2+(V_{nom}-V_{n,min})^2\right. \tag{9}$$

Subject to.

$$V_{n,min}\geq V_{min}$$
$$V_{n,max}\leq V_{max}$$
$$V_{n,min}=Min(F(V_{se}))$$
$$V_{n,max}=Max(F(V_{se}))$$

Thus, in Eq. (8), desired tap position in accordance with the desired SEV is determined. Then, the $e_k\ (t)$ in the proposed method is adjusted as:

$$e_k(T_k(t),T_k(t-1))=\left[\begin{array}{ll} e_k=1 & if\ T_k(t)>T_k(t-1) \\ e_k=-1 & if\ T_k(t)<T_k(t-1) \\ 0 & otherwise \end{array}\right. \tag{10}$$

Hence, the major concerns of conventional method are to find the LDC setting values over a study period because it is off-line method. It requires frequently and periodic changes of the LDC setting values to maintain the voltage regulation quality because the load diversity of multiple feeders has timely and seasonal variations. But in contrast, the major concerns of proposed method are to find the LTC tap position in real time because it is online method. It requires more computational efforts than conventional method.

The inverse time delay of LTC transformer can be implemented by:

$$dt(t)=\left[\begin{array}{ll} \left|\dfrac{dt}{\alpha(T_k(t)-T_k(t-1))}\right| & if\ T_k(t)\neq T_k(t-1) \\ dt & otherwise \end{array}\right. \tag{11}$$

Where, α is a coefficient.

It is proper that a relatively large time delay (*dt*) is applied in inverse time delay of the proposed method to reduce the unnecessary tap changing operation of the LTC transformer.

2.3 Shunt Capacitor controller

Capacitor banks are usually installed at the substations to reduce the reactive power demand from the transmission systems during the heavy load conditions. These capacitors need to be switched out, however, during the light load conditions. Since capacitor banks change the reactive power and low voltage bus voltage, we developed the following simple control stragety based on the reactive power measurement whcih is available in most of the modern substations. The shunt capacitor

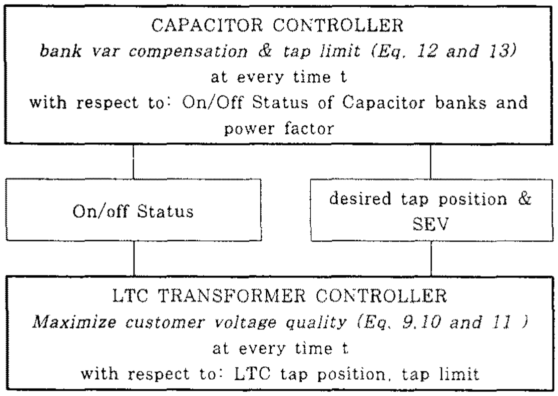


Fig. 1 Functional block diagram of the proposed control schemes

operation is determined by

$$CAP(t)=\begin{cases}1, \text{ Bank PF} > 0.7\,Q_c \\ 0, \text{ Bank PF} < 0.5\,Q_c\end{cases} \qquad (12)$$

where Qc is the Kvar rating of the substation capacitor.

2.4 Cooperation control schemes

The main purpose of this paper is the development of a new cooperation control schemes for two substation devices - LTC transformer and capacitor banks - in order to optimize their effectiveness. The functional block diagram of the proposed Volt/Var control is shown in Fig. 1. The LTC transformer and shunt capacitor controller is decoupled because the substation capacitor bank operate only a few times a day and also relatively smaller than LTC, this interaction does not seem to be an important factor in the performance of these cooperation. The disadvantages of the MLDC method are frequent tap changing operation [3-4]. Therefore, the changing operation is limited by the predefined upper and lower tap position which is determined by the statistical analysis from real load profiles of the substation.

Therefore, the following operation strategy are added in the capacitor controller as

$$CAP(t)=\begin{cases}1, \text{ Desired tap position} > \text{Upper tap and bank PF} > 0.6\,Q_c \\ 0, \text{ Desired tap position} > \text{Lower tap and bank PF} < 0.5\,Q_c\end{cases} \qquad (13)$$

3. Case Study

3.1 Test systems

The sample distribution systems and their actual real and reactive power are shown in Fig. 2 and 3, respectively. Table 1 shows the specification of the test systems. In Fig. 3, the load profiles of the feeders real and reactive power flows of the bank are taken from the real substations in Korea at summer season.

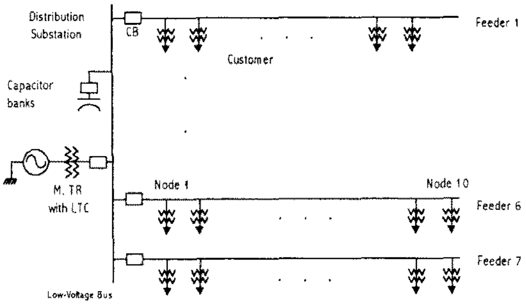
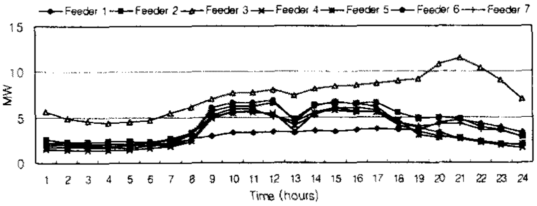
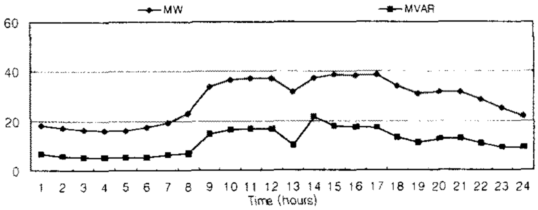


Fig. 2 A sample distribution systems



(a) Active power of the feeders



(b) Active and reactive power of the bank

Fig. 3. Real and reactive power of the sample distribution systems

Table 1. A specifications of the sample distribution systems

M. TR	Impedance(self base)	0.0042+j0.15 (p.u.)
	Rated capacity	45/60 (MVA)
	Tap interval of LTC	0.0125 (p.u.)
Feeder	Impedance	0.0347+j0.0746 (p.u./km)
	Number	6
	Number of node	10
	Node interval	1 (km)

3.2 Simulation results

Table 2 shows the results of the case study. It can be seen that the number of LTC tap changing operation is dramatically reduced and PF of the bank is improved by the proposed method. In addition, it can be seen that the proposed Volt/Var method are efficient for the real distribution systems which have a unbalanced load diversity.

Table 2. Results of case study from the proposed method

hour	capacitor	LTC tap	PF	customer voltage	
t	*CAP*	*k*		maximum	minimum
1	0	-1	0.942	1.007	0.953
2	0	-1	0.948	1.009	0.962
3	0	-1	0.951	1.010	0.967
4	0	-1	0.954	1.010	0.969
5	0	-1	0.953	1.010	0.968
6	0	-1	0.958	1.008	0.964
7	0	0	0.952	1.018	0.968
8	0	0	0.956	1.009	0.953
9	1	1	0.988	1.031	0.968
10	1	1	0.995	1.025	0.957
11	1	1	0.996	1.024	0.956
12	1	1	0.997	1.024	0.953
13	1	0	0.956	1.022	0.956
14	1	1	0.999	1.024	0.952
15	1	2	0.998	1.036	0.961
16	1	2	0.998	1.036	0.961
17	1	1	0.997	1.022	0.944
18	1	1	0.980	1.030	0.949
19	1	1	0.962	1.036	0.951
20	1	2	0.975	1.049	0.947
21	1	2	0.976	1.055	0.945
22	1	1	0.951	1.043	0.942
23	0	2	0.943	1.034	0.946
24	0	0	0.923	1.014	0.944

4. Conclusion

In this paper, we proposed a new control schemes for main transformer with LTC and substation capacitor banks for distribution Volt/Var regulation. The proposed control schemes of the LTC transformer improve the voltage regulation over the multiple feeders at the distribution substation and that of the capacitor to improve the PF at the substation and reduce the tap changing operation of LTC transformer. Their cooperation schemes are introduced. The proposed control schemes are easily adopted in the existing substation Volt/Var controllers. The main features of the proposed scheme is the Volt/Var regulation for the multiple feeders with the unbalanced load diversity which is common in distribution network. Test results shows that the proposed cooperative schemes are very efficient for substation with LTC transformer and capacitor banks to regulate the distribution Volt/Var.

[References]

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