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Cooperation Schemes of the LTC and SC for Distribution Volt/Var Compensation

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Abstract - In this paper, the on-line volt/var control algorithms of the *Load Tap Changer* (LTC) transformer and *Shunt Capacitor* (SC) are proposed for distribution volt/var compensation. In the existing volt/var control of the distribution substation, the feeder voltage and reactive power demand of the distribution are mainly controlled by the LTC transformer tap position and on/off operation of the SC. It is very difficult to maintain volt/var at the distribution networks within the satisfactory levels due to the discrete operation characteristics of the LTC and SC. In addition, there is the limitation of the LTC and SC operation times, which affects their functional lifetimes. The proposed volt/var control algorithm determines an optimal tap position of the LTC and on/off status of the SC at a distribution substation with multiple connected feeders. The mathematical equations of the proposed method are introduced. A simple case study is performed to verify the effectiveness of the proposed method.

Keywords: SC, Distribution system, LTC transformer, SC, Var compensation, Voltage regulation

1. Introduction

It is critical to maintain a suitable voltage level at the customer terminals in a power distribution system. The *Load Tap Changing* (LTC) transformer and *Shunt Capacitor* (SC) banks at the substation, *Series Voltage Regulator* (SVR) at the feeder, as well as the capacitors are integrated to regulate distribution volt/var in the distribution voltage regulation practices. The applications of these equipments differ from utility systems in regards to their volt/var regulation practices. The purpose of volt/var control in a distribution substation is to control the reactive power flow over the main transformer and the voltages on the low-voltage network [1-5]. The SC is widely installed at the low-voltage bus of the substation to control the reactive power flow. The secondary bus voltage of a main transformer at a distribution substation is regulated by the tap changing operation of the LTC transformers. In addition, modern distribution substations monitor and record 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 works in this issue, the combined artificial neural network-fuzzy dynamic programming method [1] and the heuristic supervisory control method [2, 5] are proposed to achieve the volt/var control of a distribution network. However, the unbalanced load diversity on the multiple feeders at the distribution substations are not considered in their works.

In this paper, volt/var control algorithms are proposed that determine an optimal tap position for the LTC and on/off status of capacitor banks at a distribution network with multiple feeders. In the proposed method, the LTC tap positions are determined by the method in [3-4] and on/off status of the SC is fixed by the reactive power flows at the substation and the LTC tap position in an on-line manner.

2. Representation of the LTC and the SC model

In a typical control of the LTC transformer, the tap position is changed discretely. The functional diagram of the LTC control is shown in Fig. 1. The simplified discrete equations of the LTC model are given by

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

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

$$f_k(e_k, c_k) = \begin{cases} 1 & \text{if } e_k = 1 \text{ and } c_k > dt \\ -1 & \text{if } e_k = -1 \text{ and } c_k < -dt \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

$$g_k(e_k, c_k) = \begin{cases} c_k + 1 & \text{if } e_k = 1 \text{ and } c_k \geq 0 \\ c_k - 1 & \text{if } e_k = -1 \text{ and } c_k \leq 0 \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

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$$e_k(\Delta V_k, db) = \begin{cases} e_k = 1 & \text{if } \Delta V_k > db \\ e_k = -1 & \text{if } \Delta V_k < -db \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

Where,

$T_k(t)$: tap position of LTC

$c_k(t)$, $g_k(t)$: time delay element of LDC

$f_k(t)$: tap changing element of LDC

$e_k(t)$: measuring element of LDC

a_k : tap interval of LTC

$\Delta V_k(t)$: voltage error of LDC

db : dead band

dt : time delay

k : number of LTC taps.

From (1)-(5), the tap position is changed by the tap interval of LTC (a_k) when the voltage error deviated from the specified dead band (db) during the specified time delay (dt). Thus, the tap changing operation depends on the dead band and the time delay. The dead band and the time delay element are adopted to reduce the effect of transient voltage variation and to avoid unnecessary tap changing operations.

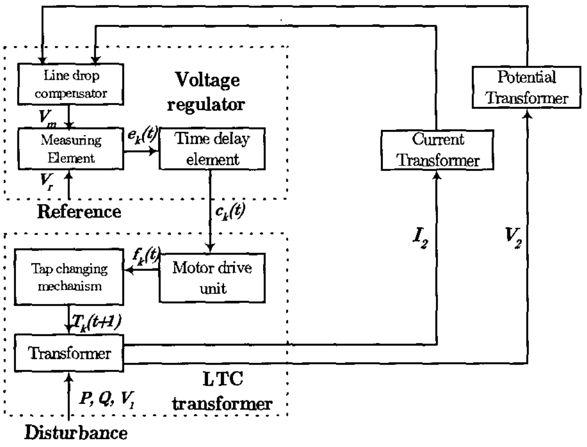


Fig. 1 Functional diagram of the conventional LTC control

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

$$CAP(t) = \begin{cases} 1, & \text{if capacitor is on at the time t} \\ 0, & \text{if capacitor is off at the time t} \end{cases} \tag{6}$$

3. Proposed Volt/Var Control Method

In the proposed method, the LTC tap positions are determined by the method in [3, 4], called the *Multiple Line Drop Compensation* (MLDC) method, and on/off status of the shunt capacitors is determined by the reactive power flows at the substations and the LTC tap position in an on-line manner.

3.1 Line Drop Compensation Method

Generally, voltage regulation practices in a distribution system are based on radial power flow from the substation to the loads, e.g. *Line Drop Compensation* (LDC) method of LTC transformer. The primary control of distribution voltage is a LTC transformer control and the LDC method is widely adopted.

The *Sending End Voltage* (SEV) and *Sending End Reference Voltage* (SERV) in the LDC method are given by

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

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

Where,

$V_{ser}(t)$: SERV

V_{ce} : reference voltage of LDC

Z_{eq} : compensating impedance of LDC

$I(t)$: load current at bank

$V_{se}(t)$: SEV

$V_{tap,k}(t)$: voltage of LTC transformer when tap is located on k-th tap position

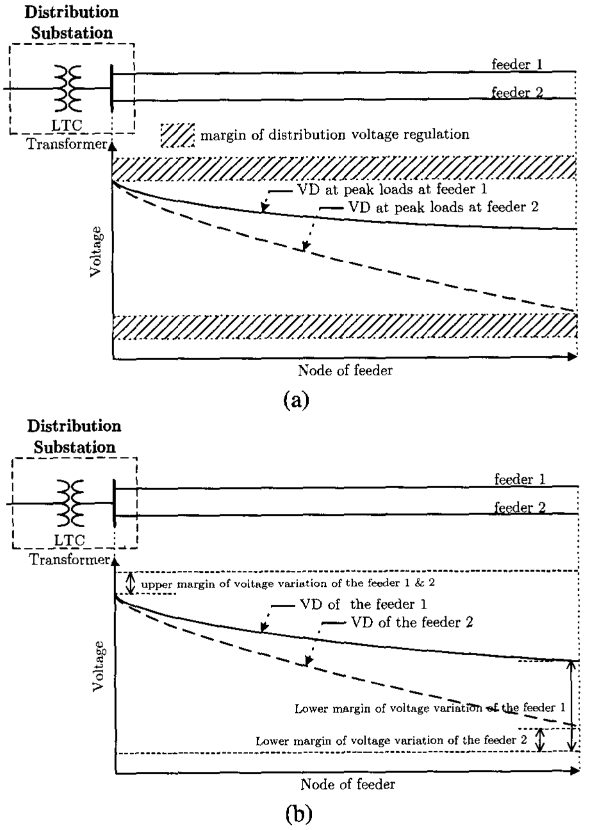
$Z_{MTR,k}(t)$: internal impedance of LTC transformer when tap is located on k-th tap position

From Eqs. (7) and (8), voltage regulation in the LDC method is performed by the information of the load current and the bus voltage and the customer voltages are reliant on the SEV. The LTC and voltage regulator is used to keep the SEV at the SERV. Hence the SEV is controlled within $V_{ser} \pm db$ (dead band of voltage regulator). The relationship between the SERV and the SEV has the hysteretical behavior due to the dead band of the ULTC control mechanism [3-4].

Therefore it can be seen that determining LDC setting values with the multiple distribution feeders is not accurate because of the dissimilar load diversity (voltage drop: VD) on different feeders (see Fig. 2). It is obvious that the conventional LDC method could not maintain the customer's voltages within the permissible limits when the power distribution systems have unbalanced load diversity on multiple feeders.

3.2 LTC Transformer Control Method

In practice, the modern distribution substation is equipped with a current transformer at each feeder. In addition, the load diversity of each of the feeders is recorded for EMS. However, the load diversity information of multiple feeders is not used for voltage regulation practice. The MLDC method [3-4] has an additional information flow, which is the load diversity information of multiple feeders as shown in Fig. 3.



(a)

(b)

Fig. 2 Illustration of the voltage variation margin: (a) margin of distribution system, (b) margin of feeders

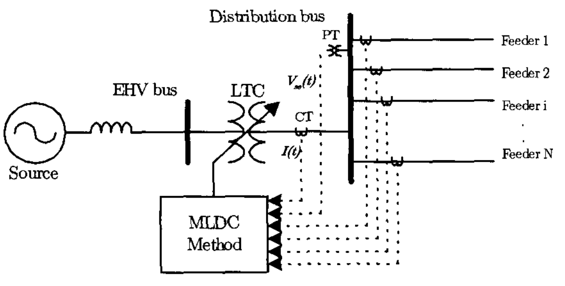


Fig. 3 Functional diagram of the MLDC method

Voltage regulation in the conventional LDC method is performed by bank current and bus voltage. The SERV and the SEV in the conventional LDC method are given by Eqs. (7) and (8).

In the MLDC method, at time t, the desired tap position of the LTC and error of the LTC are determined by solving an integer optimization problem. The objective function is defined as how close the maximum and minimum customer's voltages of each feeder are to the nominal voltage. The SEV and desired tap position are determined by the minimizing objective function as

$$\underset{V_{se}}{Minimize} \quad J = \sum_{n=1}^{N} \{(V_{nom} - V_{n,\max})^2 + (V_{nom} - V_{n,\min})^2\} \quad (9)$$

Subject to

$V_{n,\min} \geq V_{\min}$

$V_{n,\max} \leq V_{\max}$

Where

V_{nom} : nominal voltage

$V_{n,\max}$: maximum customer's voltages of feeders by the SEV

$V_{n,\min}$: maximum customer's voltages of feeders by the SEV

n : number of feeders.

Eq. (9) is an integer optimization problem. To solve such problems, we could simply solve the *Linear Problems* (LP), ignoring the integer restriction, and then either round off or truncate the fractional values of the LP optimal solution to get feasible integer solution. However, for large problems the procedure can become computationally expensive. Furthermore, even after examining all combinations, we cannot guarantee that one of them is an optimal integer solution to the problems. Fortunately, all optimal integer solution candidates of the problems in Eq. (9) are identical to the number of ULTC taps (*k*), which does not contribute to the computational burden of the problems. In this paper, we first solve the problem using the Quasi-NR method, which finds an optimal SEV, then locates the two ULTC tap positions that are fit to the optimal SEV. Finally, one of these candidate tap positions could be selected as an optimal tap position.

Thus, in Eq. (9), the desired tap position in accordance with the desired SEV is determined. Then, the $e_k(t)$ in the proposed method is adjusted as:

$$e_k(\hat{T}_k(t), T_k(t-1)) = \begin{cases} e_k = 1 & \text{if } \hat{T}_k(t) > T_k(t-1) \\ e_k = -1 & \text{if } \hat{T}_k(t) < T_k(t-1) \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

Note that the major concerns of the conventional method are to find the LDC setting values over a particular study period since it is an off-line method. This requires frequent and periodic changes of the LDC setting values to maintain the voltage regulation quality because the load diversity of multiple feeders has both timely and seasonal variations. But in contrast, the major concerns of the MLDC method are to locate the LTC tap position in real time because it is an online method. This requires greater computational efforts than the conventional method.

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

$$dt(t) = \begin{cases} \left| \dfrac{dt}{\alpha(\hat{T}_k(t) - T_k(t-1))} \right| & \text{if } \hat{T}_k(t) \neq T_k(t-1) \\ dt & \text{otherwise} \end{cases} \tag{11}$$

Where, α : 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.

3.3 SC Control Method

A shunt capacitor is usually installed at the distribution substation to reduce the reactive power demand from the transmission systems during the heavy load conditions. However, during light load conditions, these capacitors need to be switched out. Since capacitor banks change the reactive power and low voltage bus voltage, a simple control strategy method is introduced based on the reactive power measurement that is available in most modern distribution substations [2]. The SC operation is determined by

$$CAP(t) = \begin{cases} 1 & \text{if } Q_s > \alpha_1 Q_c \text{ during } dt_c \\ 0 & \text{if } Q_s < \alpha_2 Q_c \text{ during } dt_c \end{cases} \tag{12}$$

Where

Q_s : kvar demand of distribution system

Q_c : kvar rating of the substation capacitor

dt_c : time delay of SC

α_1, α_2 : upper and lower threshold coefficient.

3.4 Proposed Cooperation Schemes

The main purpose of the proposed volt/var control method of the distribution network is the development of new cooperation control schemes for two substation devices – the LTC transformer and capacitor banks - in order to optimize their effectiveness. The functional diagram of the cooperation schemes of the proposed volt/var control is shown in Fig. 4.

The LTC transformer and the SC controller are decoupled because the substation capacitor bank operates only a few times a day and is also relatively smaller than the LTC. This interaction does not seem to be an important factor in the performance of this cooperation. The disadvantage of the MLDC method is the frequent tap changing operation. Therefore, the tap changing operation could be limited by the predefined upper and lower tap positions (T_u, T_l) that are determined by the statistical analysis from real load profiles of the substation. And then SC is switched on to compensate the reactive power flow and bus voltage.

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

$$CAP(t) = \begin{cases} 1 & \text{if } \hat{T}_k(t) > T_u \text{ and } Q_s > \alpha_1' Q_c \text{ during } dt \\ 0 & \text{if } \hat{T}_k(t) > T_l \text{ and } Q_s < \alpha_2' Q_c \text{ during } dt \end{cases} \tag{13}$$

Where,

α_1', α_2' : adjusted upper and lower threshold coefficient

T_u, T_l : tap limits

In the proposed cooperation schemes, the time delay of the SC is equal to the time delay of the LTC to synchronize the operation of the two devices. In Eq. (13), threshold coefficients (α_1', α_2') and tap limits (T_u, T_l) can be obtained by the statistical analysis of bank/feeder load demand.

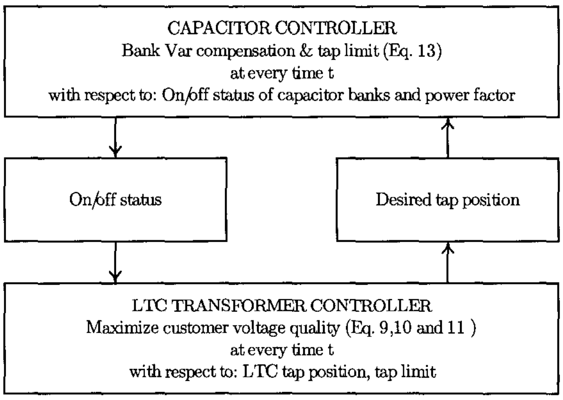


Fig. 4 Functional diagram of the proposed cooperation control schemes

4. Case Study

4.1 Test System Model

A test system used in volt/var control simulation is shown in Fig. 5. The test system is based on the 22.9 kV distribution systems and its' specification is shown in Table 1. The sample load curves of the test system are taken from the real operation data of substation B in Korea during July and September and are shown in Fig. 6.

The LTC transformer and control parameters of the existing and proposed method that are used in the case study are shown in Table 2.

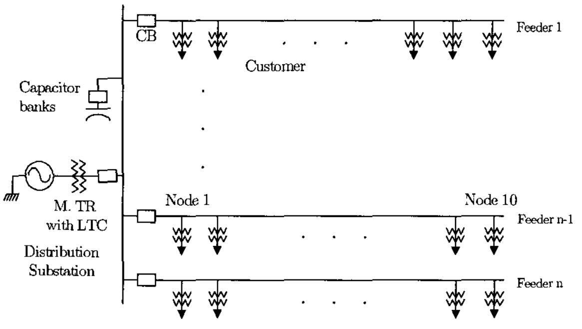
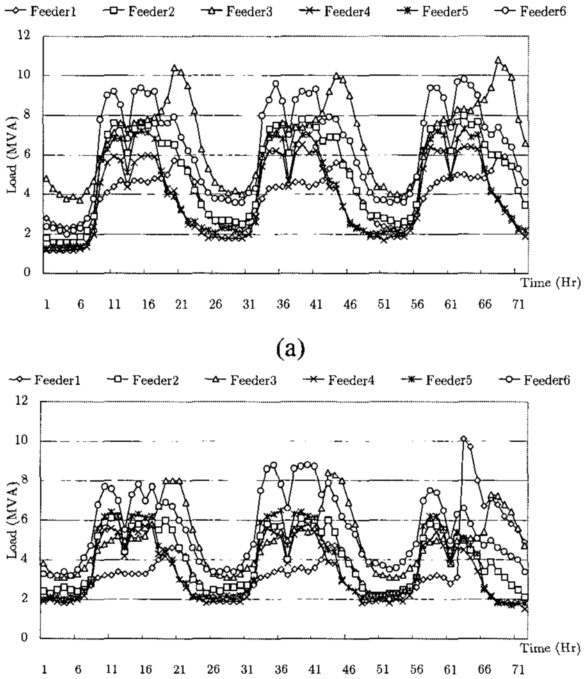


Fig. 5 Test system model

Table 1 Specifications of the test system model

System Base	MVA	100
Substation Main Transformer	Impedance (self base)	0.0042+j0.15 (*p.u.*)
	Rated Capacity	45/60 (MVA)
Distribution Feeder	Impedance	0.0347+j0.0746 (*p.u./km*)
	Number of Feeders	6
	Number of nodes per feeder	10
	Node Interval	1 (*km*)
Shunt Capacitor	Rated Capacity	20 (Mvar)



(a)

(b)

Fig. 6 Load demands of the test system: (a) July, (b) September

Table 2 LTC transformer and control parameters of the existing and proposed method

	Existing Method	Proposed Method
Compensating Impedance (*p.u.*)	$0.124+j0.064$	Eq. 9, 10 and 11
Coefficient of SC	$\alpha_1 : 0.7$ $\alpha_2 : 0.5$	$\alpha_1' : 0.6$, $\alpha_2' : 0.5$
Time delay of SC (min)	20	Eq. 13
Time delay of LTC (min)	2	5
Total Taps (*step*)	17	17
Initial Tap Position	0	0
Dead Band (*p.u.*)	0.0125	Eq. 9, 10 and 11
Tap Interval (*p.u.*)	0.0125	0.0125
Predefined Upper and Lower Tap	None	6, -1

4.2 Simulation Results

The performance index of voltage regulation at the distribution system can be defined by Eq. (14) as the sum of the squared differences between nominal voltage and maximum and minimum customer's voltages at each feeder. In the distribution voltage regulation, all of the customer's voltages should be distributed within the permissible voltage limits. Thus, the penalty factor (p) is applied when the maximum or minimum customer's voltage is deviated from the permissible voltage limits.

$$VR=\sum_{t=1}^{T}\sum_{n=1}^{N}\left\{(V_{n,max}(t)-V_{nom}(t))^2+(V_{nom}(t)-V_{n,min}(t))^2\right\}^{p} \tag{14}$$

Where

$$p=\begin{cases}2 & if\ V_{n,\max}>V_{\max}\ or\ V_{n,\min}<V_{\min}\\ 1 & otherwise\end{cases}$$

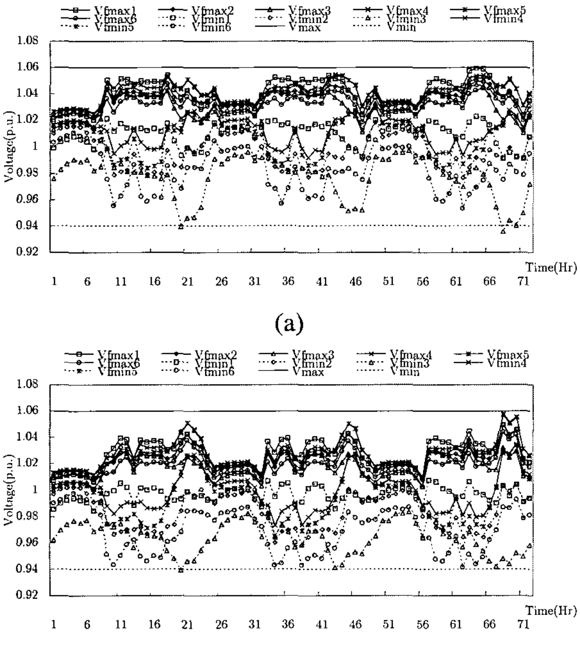
The customer's voltage profiles of the existing method and the proposed method are illustrated in Fig. 7 and Fig. 8 In Fig. 7 and Fig. 8, the maximum and the minimum customer's voltage profiles of the feeders are illustrated. Also, the tap and cap operation status of the existing method and the proposed method for case study are illustrated in Figs. 9 and 10. The normalized VR values for the case study are illustrated in Fig. 11. Table 3 shows the total tap changing number of the LTC transformer for the case study.

From the simulation study, the effectiveness of the proposed method is verified by the related simulation works. It is summarized as follows:

1. It is verified that the voltage regulation performance of the proposed method is more accurate and flexible than that of the existing method, especially, at the distribution system with unbalanced load diversity on different feeders.

2. It can be seen that the proposed cooperation schemes, cooperation of the LTC and SC, contribute to reducing the LTC tap changing operation and improving customer voltage quality.

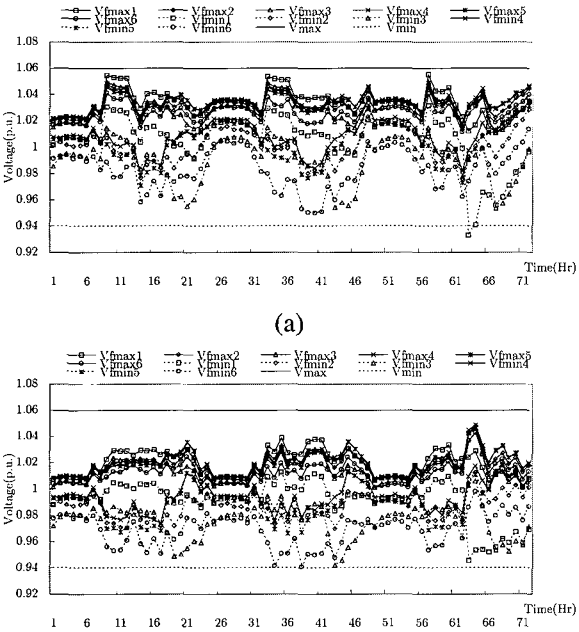
Hence, the proposed cooperation method is efficient for real distribution systems, which have unbalanced load diversity on different feeders.



(a)

(b)

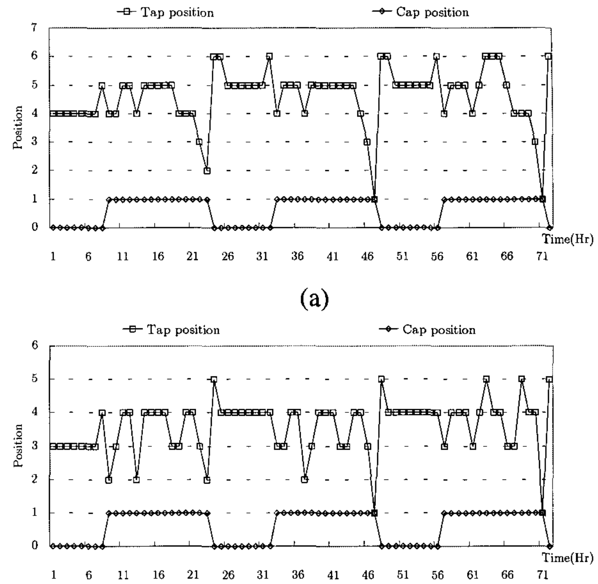
Fig. 7 Voltage profiles of the sample system (July): (a) existing method, (b) proposed method



(a)

(b)

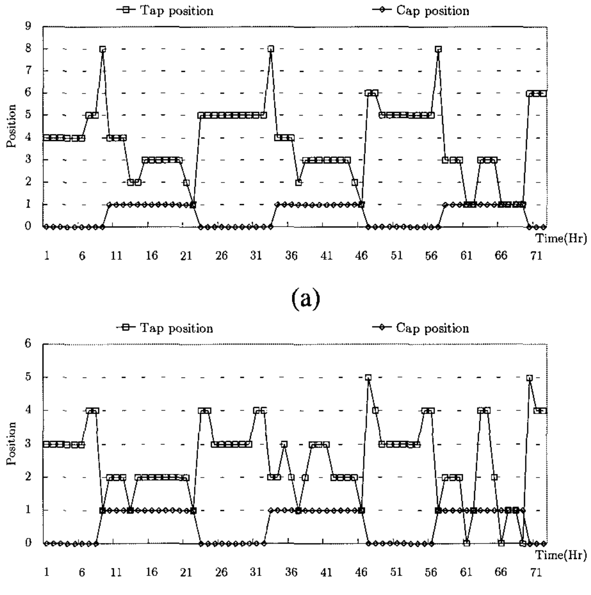
Fig. 8 Voltage profiles of the sample system (Sep.): (a) existing method, (b) proposed method



(a)

(b)

Fig. 9 LTC tap and SC operation status (July): (a) existing method, (b) proposed method



(a)

(b)

Fig. 10 LTC tap and SC operation status (Sep.): (a) existing method, (b) proposed method

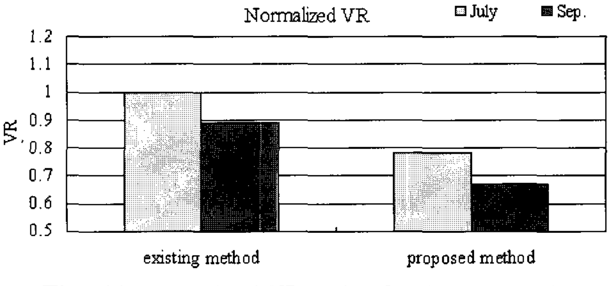


Fig. 11 Normalized VR Value for the case study

Table 3. Total tap changing numbers for the case study

	Existing Method	Proposed Method
July	48	53
Sep.	59	55

5. Conclusion

In this paper, a new cooperation scheme of the main transformer with the LTC and SC is proposed for distribution volt/var control. The proposed control schemes of the LTC transformer improve the voltage regulation over the multiple feeders at the distribution substation while those of the SC enhance the power factor at the substation and reduce the tap changing operation of the LTC transformer. The main features of the proposed schemes are the volt/var regulation for the multiple feeders with the unbalanced load diversity, which is common in real distribution network. The simulation results indicate that the proposed cooperation schemes are very efficient for distribution substations with the LTC and SC to regulate the distribution volt/var. It is expected that the proposed control schemes are easily adopted in the existing substation volt/var controller.

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