The Dead Band Control of LTC Transformer at Distribution Substation

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***Abstract*—In this paper, dead band control algorithms using a performance index of the *load tap changing* (LTC) tap position are proposed to reduce the tap changing operation times. The performance index is defined as the customer voltage quality with the tap position of LTC transformer. In addition, dead band control algorithms using the load diversity values of the feeders are proposed. The mathematical formulations of the proposed dead band control algorithms are introduced. A sample case study is shown to verify the effectiveness of the proposed dead band control algorithms.**

***Index Terms*—Dead band control, distribution substation, line drop compensation (LDC), load diversity, load tap changing (LTC) transformer, voltage control.**

NOMENCLATURE

$T(t)$	Tap position of LTC.
$c(t)$	Counter element of LTC.
$f(t)$	Tap changing element of LTC.
$e(t)$	Measuring element of LTC.
a_k	Tap interval of LTC.
$\nabla V(t)$	Voltage error of LTC.
db	Dead band.
dt	Time delay.
k	Number of LTC taps.
$V_{ser}(t)$	Sending end reference voltage.
V_{ce}	Reference voltage of LDC.
Z_{eq}	Compensating impedance of LDC.
$I(t)$	Load current at a substation bus.
$V_{se}(t)$	Sending end voltage.
$V_k(t)$	Secondary voltage of the LTC transformer when the tap is located on the kth tap position.
$Z_k(t)$	Impedance of the LTC transformer when the tap is located on the kth tap position.
$V_{n,\max}$	Maximum customer's voltages of the feeders.
$V_{n,\min}$	Minimum customer's voltages of the feeders.
$V_{\max}$	Maximum permissible voltage limit.
$V_{\min}$	Minimum permissible voltage limit.
N	Number of feeders.
$T^*(t)$	Optimal tap position of LTC at time t.
$T(t-1)$	Actual tap position of LTC at time $t-1$.
β	Inverse time delay coefficient.
ε	PIR tolerance.
p	Penalty factor.
$I_n(t)$	Load current of the feeders at time t.
I_α, I_β	Load diversity coefficient.

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I. INTRODUCTION

THE voltage control is a very important function of the distribution substation to maintain a suitable voltage level at the customer terminals. The *load tap changing* (LTC) transformer is the main control device of the secondary bus voltage of the distribution substation. The objectives of distribution voltage control equipment are to reduce the operation frequency of tap changers and to improve the voltage profiles over the feeders by decreasing the error between the *sending end voltage* (SEV) and the *sending end reference voltage* (SERV).

However, these objectives require a trade-off. It is difficult to fulfill both of them at the same time. Moreover, there is no judgment function in conventional voltage control equipment having voltage control limitations. To cope with this problem, some researchers have used *artificial intelligence* (AI) techniques to control LTC. In [1], the authors discussed the tap changing time in a substation by obtaining control sensitivities using mean voltage errors and time scheduled fuzzy rules. They made fuzzy rules by dividing a day into five periods. However, as each substation had different load characteristics, the load pattern showed seasonal variations. Thus, it was difficult to classify appropriate periods. In [2], Kojima *et al.* proposed a control method of simultaneously using LTC transformer taps and a *shunt capacitor* (SC) bank using *artificial neural networks* (ANNs). This method needs large amounts of data for the training of the ANN. It is difficult to obtain enough input data for optimal output. In [3], Abdul-Rahman *et al.* proposed a control method for voltage and reactive power in a large system using a central fuzzy expert system. However, this method is difficult to implement in real power systems, since there is a limitation in the exact control of the local voltage in a large system. Also, the combined artificial neural network-fuzzy *dynamic programming* (DP) [4] and DP [5], [6] have been proposed to achieve voltage and reactive power control for a distribution network. In [7], Wang *et al.* proposed a time-interval based approach using genetic algorithms for distribution voltage and reactive power control. In [8], Baran *et*

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al. proposed heuristic supervisory control methods to achieve voltage and reactive power control for a distribution network.

In practice, the load diversity of substation feeders is not balanced since the compositions of customers at each of the feeders are different. The load varies during the day because people get up, go to work, and return in the evening using different amounts of electricity to support their various activities. Similarly, residential, industrial, and commercial power use varies during a day. There are also weekly and seasonal variations in electricity usage. To cope with this challenge, Choi *et al.* proposed online voltage control methods for a distribution substation with different diversity on feeders [9], [10]. However, this method has frequent tap changing operation times as compared to the conventional *line drop compensation* (LDC) method. In this paper, advanced dead band control algorithms using a performance index of the LTC tap position and the load diversity of the feeders are proposed to reduce the frequency of operation of LTC.

II. Conventional Control Methods of an LTC Transformer

A. A Typical LTC Transformer Control Method

In general, voltage regulation practices in a distribution system are based on radial power flow from the distribution bus side to the loads side. The LTC transformer is the main control devices for distribution voltage regulation. In general, the tap position of the LTC transformer is changed by the tap interval (a_k) when the voltage error deviates from the specified dead band (db) during a specified time delay (dt). The dead band and time delay element are adopted to reduce the effects of transient voltage variations and to avoid unnecessary tap changing operations. Thus, the tap changing operation depends on the dead band and the time delay. The simplified discrete mathematical models of an LTC transformer are given by [9]–[11]

$$e\left(\nabla V(t), db\right) = \left| \begin{array}{ll} 1, & \text{if } \nabla V(t) > db \\ -1, & \text{if } \nabla V(t) < -db \\ 0, & \text{otherwise} \end{array} \right. \tag{1}$$

$$c\left(e(t), c(t-1)\right) = \left| \begin{array}{ll} c(t-1)+1 & \text{if } e(t)=1 \text{ and } c(t-1) \geq 0 \\ c(t-1)-1 & \text{if } e(t)=-1 \text{ and } c(t-1) \leq 0 \\ 0, & \text{otherwise} \end{array} \right. \tag{2}$$

$$f\left(e(t), c(t)\right) = \left| \begin{array}{ll} 1, & \text{if } e(t)=1 \text{ and } c(t) > dt \\ -1, & \text{if } e(t)=-1 \text{ and } c(t) < -dt \\ 0, & \text{otherwise} \end{array} \right. \tag{3}$$

$$T(t) = T(t-1) + a_k f\left(e(t), c(t)\right). \tag{4}$$

The LDC method is a widely used method for control algorithms for an LTC transformer to regulate voltage at a distribution substation. In the LDC method, the SEV and SERV are given by

$$V_{ser}(t) = V_{ce} + Z_{eq} I(t) \tag{5}$$

$$V_{se}(t) = V_k(t) - Z_k(t) I(t). \tag{6}$$

In the LDC method, the voltage of the substation secondary bus is controlled by the load current at the substation bus and the bus voltage. The LTC and voltage regulator are used to keep the SEV at the SERV. Hence the SEV is controlled within the SERV plus the negative or positive dead band. It is well known that the relationship between the SERV and the SEV has a hysteric behavior due to the dead band of the LTC control mechanism [9]–[11]. Thus, the large value of the dead band of the LDC method results in poor voltage regulation performance. In contrast, the small value of the dead band of the LDC method results in frequent tap changing operation times and unstable tap changing operation.

In practice, the distribution substation bus has multiple feeders with different load diversity. Therefore, it can be seen that determination of LDC coefficients, i.e., V_{ce} and Z_{eq}, for the distribution substation with multiple feeders is not accurate because of the dissimilar load diversity and/or *voltage drop* (VD) characteristics on the feeders.

III. Proposed LTC Control Method

The proposed method reduces the tap changing operation of the LTC transformer as compared to the *multiple line drop compensation* (MLDC) method [9], [10] by adopting a dead band control. The dead band control algorithms using a voltage regulation performance index with the LTC tap position and load diversity of the feeders are introduced.

A. MLDC Control Method

In practice, the modern distribution substation has a *current transformer* (CT) and a *potential transformer* (PT) on multiple feeders. Generally, the *root mean square* (RMS) values of the load current of the distribution feeders are monitored and recorded in real time for a *supervisory control and data acquisition* (SCADA) system.

The MLDC method was designed to consider different load diversity on multiple feeders and the interconnection of *distributed generation* (DG) units in order to regulate customers' voltage requirement within permissible limits [9], [10]. In the MLDC method, at time t, the optimal tap position and error of an LTC transformer are determined by solving an integer optimization problem. The objective function is defined as how close the customer's voltages of the distribution feeders are to the nominal voltage. The objective function becomes

$$\begin{aligned} &\text{Minimize} \\ &\quad J = \sum_{n=1}^{N} \left[(V_{n,\max} - V_{nom})^2 + (V_{nom} - V_{n,\min})^2 \right] \\ &\text{Subject to} \\ &V_{n,\min} \geq V_{\min} \\ &V_{n,\max} \leq V_{\max}. \end{aligned} \tag{7}$$

The SEV and optimal tap position are determined by minimizing the objective function. In (7), the *linear problems* (LP) is applied by ignoring the integer restriction and then either rounding off or truncating the fractional values of the LP optimal solution to get a feasible integer solution. However, the procedure can become computationally expensive for large problems. Furthermore, even after examining all combinations, we cannot guarantee that one of them is an optimal integer solution to the problems.

Fortunately, all candidates of the optimal integer solution of the problems in (7) are identical to the number of LTC taps (k) which does not contribute to the computational burden of the problems. In this paper, the problems in (7) are solved by quasi-NR method, which finds an optimal SEV, and then find the two LTC tap positions that are fit to an optimal SEV. Finally, one of these candidate tap positions can be selected as an optimal tap position. When the optimal tap position in accordance with the optimal SEV is determined, then (1) is adjusted as follows:

$$e\left(T^{*}(t), T(t-1)\right)=\left|\begin{array}{ll}1, & \text{if } T^{*}(t)>T(t-1) \\ -1, & \text{if } T^{*}(t)<T(t-1) \\ 0, & \text{otherwise.}\end{array}\right. \tag{8}$$

In the MLDC method, the simplified inverse time delay of the LTC transformer can be easily implemented by

$$dt(t)=\left|\begin{array}{ll}\frac{dt}{\beta(T^{*}(t)-T(t-1))}, & \text{if } T^{*}(t) \neq T(t-1) \\ dt, & \text{otherwise.}\end{array}\right. \tag{9}$$

Note that the major goals of the MLDC method are to find and locate an LTC tap position in an online manner. This requires more computational effort than the conventional LDC method. But, the major goals of the conventional LDC method are to find LDC coefficients over particular study periods. This requires frequent and periodic changes of the LDC coefficients to maintain the voltage regulation performance because the load diversity of distribution feeders has both time and seasonal variations.

B. Proposed Dead Band Control Algorithms

The conventional LDC method has only two inputs of bank current and bus voltage. Thus, it cannot consider the different load diversity on multiple feeders. Furthermore, the load diversity on multiple feeders has time and seasonal variations. Therefore, it can be seen that LDC coefficients are frequently adjusted to proper regulation of the distribution voltage profiles. However, the MLDC method has multiple inputs for current of the multiple feeders and bus voltage to optimize the tap position of LTC transformer for distribution voltage regulation.

In the conventional LDC method, the dead band is adopted to reduce the effects of transient load fluctuations or voltage variations. It is known that the disadvantage of the MLDC method has more frequent tap changing operation as compared to the LDC method [9], [10]. The dead band control algorithm is adopted to reduce the tap changing operation times of the MLDC method. In the proposed dead band control algorithm, *performance index ratio* (PIR) is adopted to the reduce tap changing operation times of the LTC transformer. The performance index is the objective function values in (7). The PIR is defined as the ratio of the objective function values between the optimal tap position and the actual tap position, as follows:

$$\text{PIR}=1-\frac{J\left(T^{*}(t)\right)}{J\left(T(t-1)\right)}. \tag{10}$$

In the MLDC method, the tap position should be changed with the variation of loads on multiple feeders. If the errors of the PIR between the optimal tap position and the existing tap position are small enough, then tap changing operation should be delayed or sustained. Thus, the tap changing operation should be delayed or sustained with small changes of the load diversity on multiple feeders. This can be implemented by a PIR that is smaller than the specified error tolerance. Thus, error of (8) is readjusted as follows:

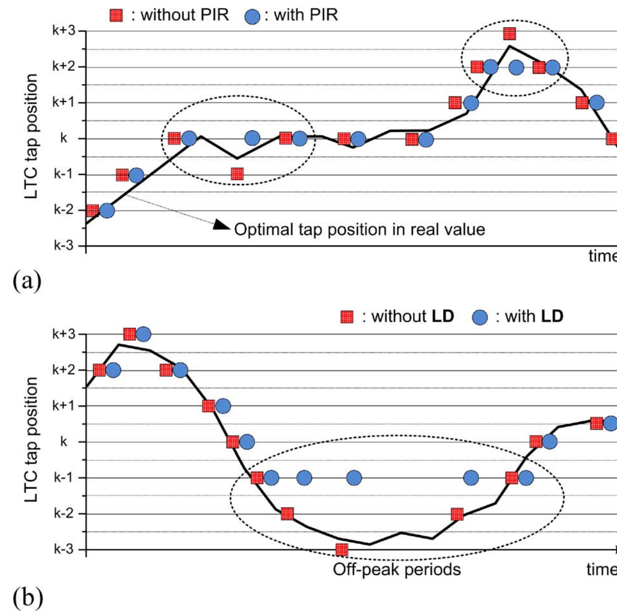


Fig. 1. Illustrations of the tap changing operations with/without the proposed dead band control method. (a) Dead band control with/without the PIR. (b) Dead band control with/without the LD.

$$e\left(T^{*}(t), T(t-1)\right)=\left|\begin{array}{ll}1, & \text{if } T^{*}(t)>T(t-1) \text{ and } PIR>\varepsilon \\ -1, & \text{if } T^{*}(t)<T(t-1) \text{ and } PIR>\varepsilon \\ 0, & \text{otherwise.}\end{array}\right. \tag{11}$$

From (11), the LTC tap changing operation can be delayed with a small improvement of voltage regulation performance between the optimal tap position and the actual tap position. Therefore, an unnecessary or inefficient tap changing operation could be reduced by adopting the PIR during the small variations of loads on the multiple feeders as shown in Fig. 1(a).

In general, the tap position of the conventional LDC method moves toward upper limits of the LTC taps with the increasing of the total load current, and vice versa. Whereas, the tap position of the MLDC method moves toward the upper limits of LTC taps with increasing of maximum load current of feeder or total load current, and vice versa.

Hence, the typical cyclic changes of the load current of the feeders result in a cyclic tap changing operation from its higher tap position to its lower tap position. This increases the number of tap changing operations of the LTC transformer. A typical VD for off-peak periods is smaller than that of peak periods. Thus, during off-peak periods, the number of tap positions which satisfying customers' requirements for voltages within permissible limits is larger as compared to the number of tap positions with the peak periods.

In the proposed dead band control method, if customers' voltages fit within permissible limits with the current tap position during the off-peak periods, the LTC tap changing operation could be delayed to reduce the tap changing operation times of the LTC transformer. In the dead band control algorithms

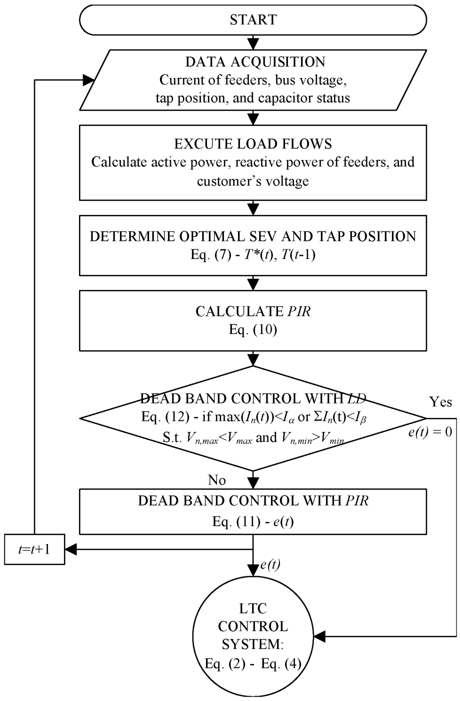


Fig. 2. Flowchart of the proposed dead band control algorithms.

using the *load diversity* (LD) of feeders, the tap changing operation should be delayed when the total load current or maximum load current of distribution feeders is smaller than the specified values (LD coefficients). Thus, (11) becomes

$$e\left(T^{*}(t), T(t-1), I_n(t)\right) = \left| \begin{array}{ll} 0, & \text{if } \max\left(I_n(t)\right) < I_\alpha \text{ or } \sum I_n(t) < I_\beta \\ & \text{s.t } V_{n,\max} \le V_{\max} \text{ and } V_{n,\min} \ge V_{\min} \\ \text{Eq. (11)}, & \text{otherwise.} \end{array} \right. \quad (12)$$

From (12), the tap position ranges with dead band control with LD during the off-peak periods are limited to small regions as compared to that of the MLDC or the LDC method. This results in reduction of tap changing operations times of the LTC transformer as shown in Fig. 1(b).

The Fig. 2 shows a flowchart of the proposed dead band control algorithms.

IV. Case Study

A. Sample System

The load diversity of distribution feeders is not practically balanced since living styles of customers are not the same. In this paper, the sample loads curves of the sample system are taken from the actual load data of the A. substation in Korea for July, June, and September. The sample load curves at July, June, and September are shown in Fig. 3, respectively. From the load profiles of the feeders of the sample load curves, it can be seen that feeders 1 and 3 are residential customers and the other feeders are commercial customers. Thus, the peak demands of the different feeders occur at different times. A sample distribution system is shown in Fig. 4. The specifications of the sample distribution system are shown in Table I.

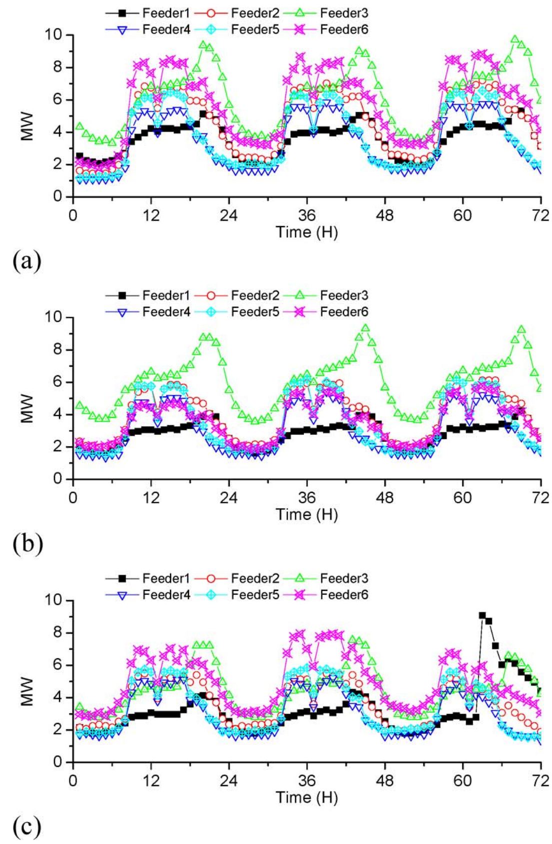


Fig. 3. Sample load curves. (a) June. (b) July. (c) September.

B. Customer Voltage Quality (CVQ) Index

It is necessary to define a criterion index for voltage regulation performance to evaluate each voltage control method. It can be defined as the sum of the squared differences between nominal voltage and the maximum and minimum customers' voltages at the feeders. In distribution voltage regulation, all of the customers' voltages must be distributed within the permissible voltage limits. Thus, the penalty factor (p) is applied when maximum or minimum customers' voltages are deviate from permissible voltage limits, as follows:

$$CVQ = \sum_{n=1}^{N} \left\{ (V_{n,\max} - V_{nom})^2 + (V_{nom} - V_{n,\min})^2 \right\}^p \quad (13)$$

where

$$p = \left| \begin{array}{ll} 2, & \text{if } V_{n,\max} > V_{\max} \text{ or } V_{n,\min} < V_{\min} \\ 1, & \text{otherwise.} \end{array} \right.$$

C. Simulation Results

The voltage control simulation studies for the sample distribution system are performed by the conventional LDC method, MLDC method, and proposed dead band control method, respectively. The reference voltage and compensating impedance of the conventional LDC method were obtained from the statistical approach method. The parameters of the conventional

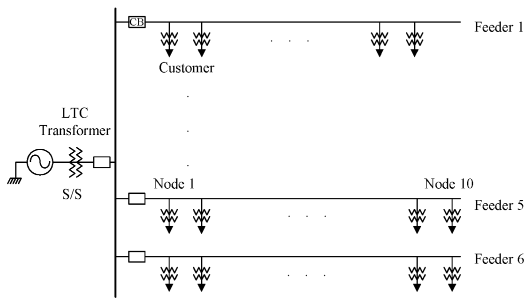


Fig. 4. Sample distribution system.

TABLE I
PARAMETERS OF THE SAMPLE DISTRIBUTION SYSTEM

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 feeder	6
	Number of node	10
	Node interval	1 [km]
Customer Side	Peak load per node	0.01 [p.u.] (lagging PF 0.9)
	Voltage drop at the peak load	LV distribution line : 5 [%]
		Pole transformer : 3 [%]

TABLE II
PARAMETERS OF THE CONVENTIONAL METHOD AND PROPOSED METHOD FOR THE CASE STUDY

	LDC method	MLDC method	Proposed method
Total taps	17 [step]	17 [step]	17 [step]
Initial tap position	0	0	0
Tap interval	0.0125 [p.u.]	0.0125 [p.u.]	0.0125 [p.u.]
Time delay (dt)	240 [s]	240 [s]/ Eq. (9)	240 [s]/ Eq. (9)
Dead band	0.0125 [p.u.]	None	Eq. (11)-(12)
Control error	$e(t)$: Eq. (1)	$e(t)$: Eq. (8)	$e(t)$: Eq. (11)-(12)
PIR tolerance (ε)	-	-	5 %
LD coefficients	-	-	I_α: 5 [MVA] I_β : 21 [MVA]

method and proposed method for the case study are shown in Table II.

The simulation results of the conventional LDC method, the MLDC method, and the proposed dead band control method are illustrated in Figs. 5–8. Table III shows the number of LTC tap changing operations and CVQ values for each voltage control method.

From the simulation results shown in Fig. 5, the customers' voltages are deviated from permissible voltage limits at the peak demand periods. It is obvious that the conventional LDC method cannot maintain a customer's voltage within the permissible limits with severe unbalanced load diversity on multiple feeders, i.e., one feeder has peak demands and the other feeders have mid or off-peak demands.

From the simulation results shown in Fig. 6, customers' voltages are maintained within the permissible voltage limits except for peak demands periods in July. In the case of July, at 45-h, there is no feasible solution for the LTC tap position that satisfies customers' voltages within the permissible voltage limits. But, the deviation errors from permissible voltage limits are very small as shown in Fig. 6. It is obvious that the voltage regulation

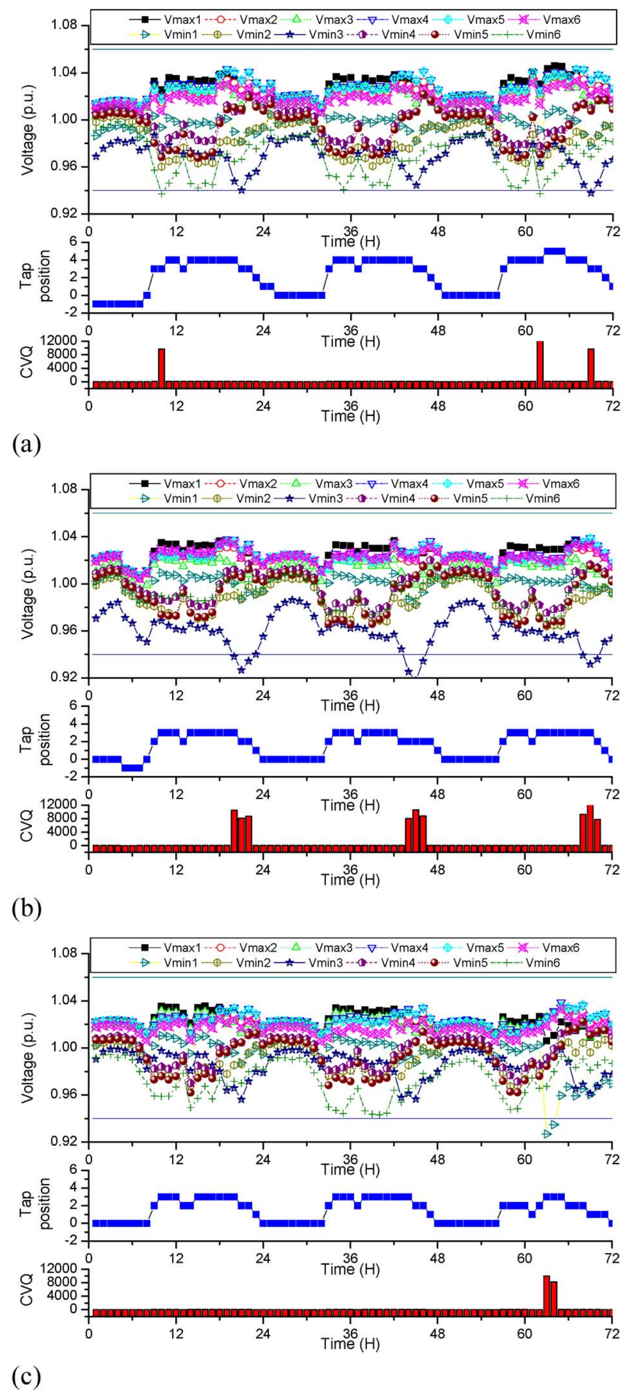
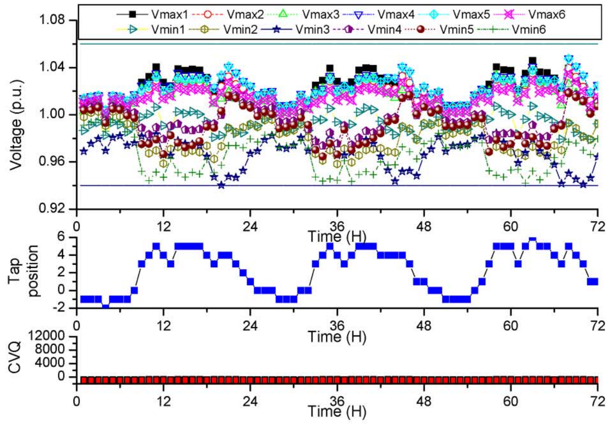


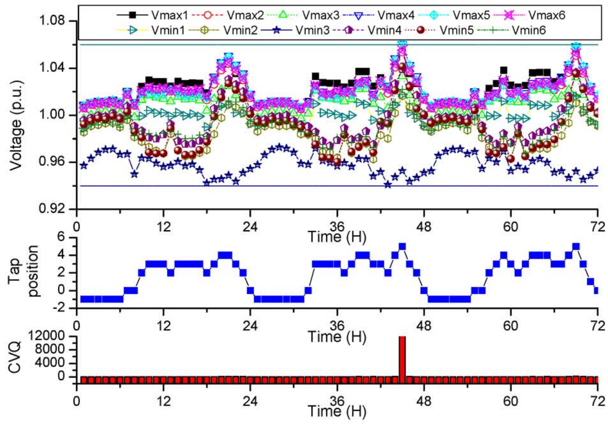
Fig. 5. Customer's voltage profiles, LTC tap position, and CVQ by the LDC method. (a) June. (b) July. (c) September.

performance of the MLDC method is more accurate at the distribution substation with the severe unbalanced load diversity on the multiple feeders. However, the tap changing operation times of the MLDC method are larger than that of the LDC method.

From the simulation results shown in Fig. 7, the dead band control algorithms with the PIR, the tap position is sustained or the tap changing operation is delayed when there is a small variation of load diversity on the feeders as compared to MLDC method, i.e., the tap position of the 19 $\sim$ 22-h period in June, the tap position of the 34 $\sim$ 43-h period in July and the tap position of the 58 $\sim$ 60-h period in September. These contribute



(a)



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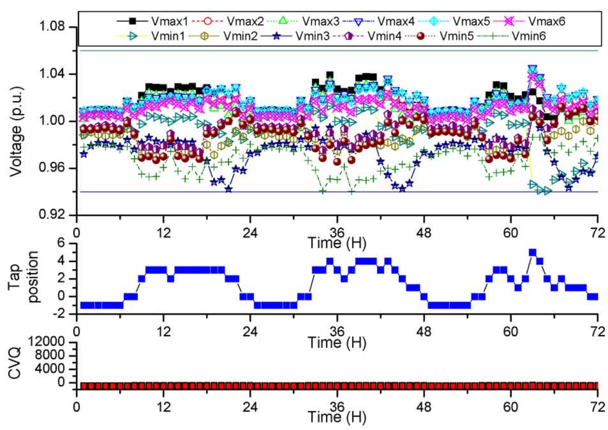
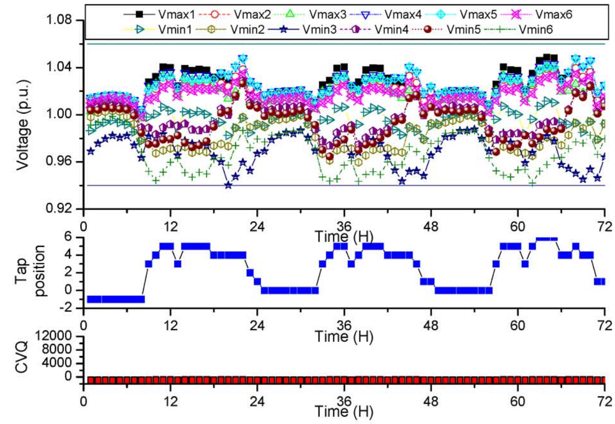
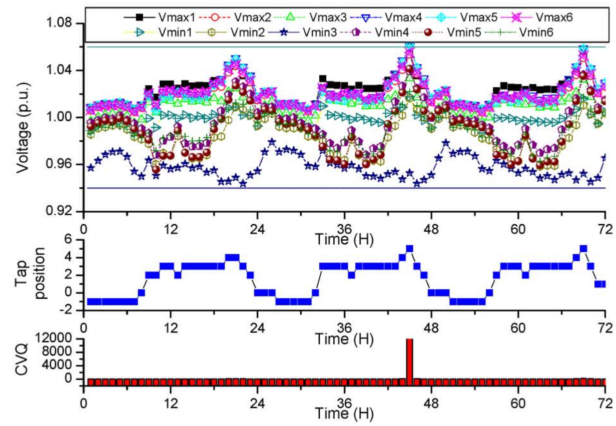


(c)

Fig. 6. Customer's voltage profiles, LTC tap position, and CVQ by the MLDC method. (a) June. (b) July. (c) September.



(a)



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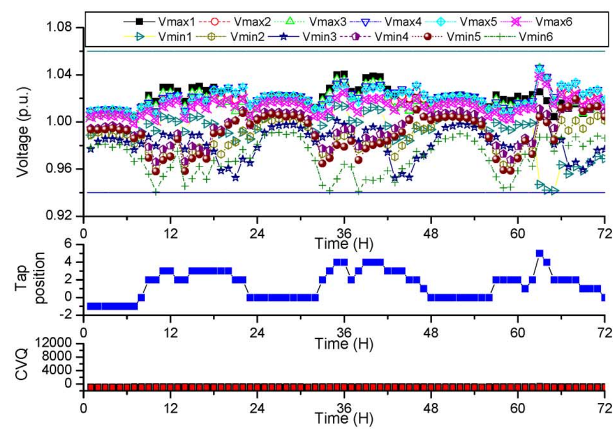


(c)

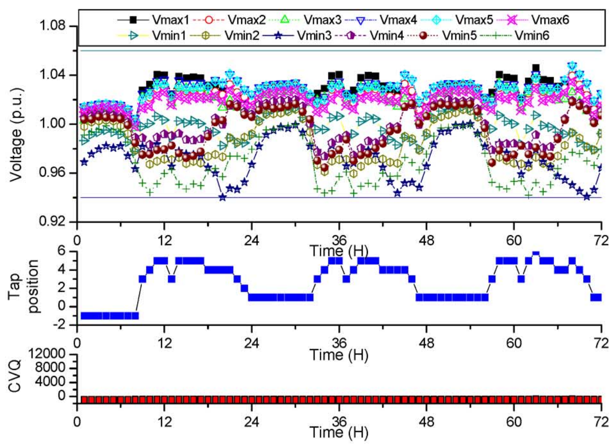
Fig. 7. Customer's voltage profiles, LTC tap position, and CVQ with the proposed method with dead band control using a PIR. (a) June. (b) July. (c) September.

to the reduction of the tap changing operation times of the LTC transformer.

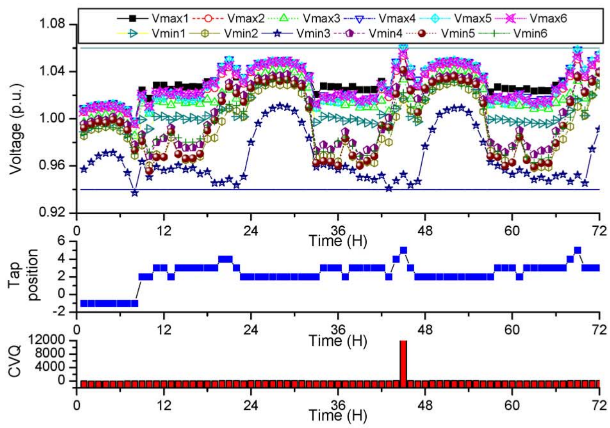
From the simulation results shown in Fig. 8, the dead band control algorithms with the LD, the tap changing operation is delayed and it lies on higher position of LTC taps when in the off-peak periods as compared to the MLDC method and the MLDC method with a PIR, i.e., the tap position of the 24 $\sim$ 33-h period and the 47 $\sim$ 57-h period in July and the tap position of the 22 $\sim$ 33-h period and the 48 $\sim$ 56-h period in September. These contribute to the reduction of the tap changing operation times of the LTC transformer.

From the results of the simulation case study, the effectiveness of the proposed dead band control method 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 conventional LDC method, especially at distribution substation with severely different load diversity on the feeders.
2) It can be seen that the proposed LTC control algorithm with dead band control using the PIR, contributes to reducing



(a)



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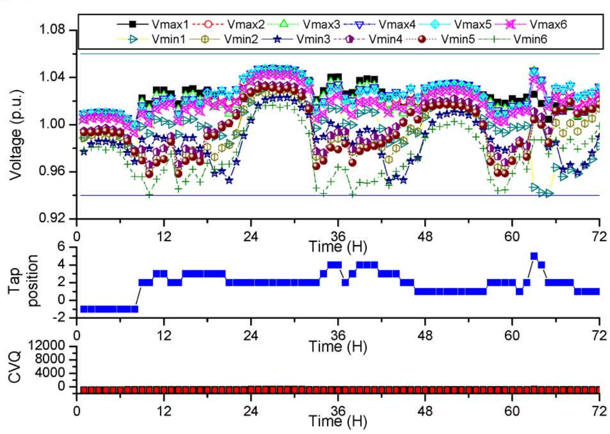

(c)

Fig. 8. Customer's voltage profiles, LTC tap position, and CVQ with the proposed method with dead band control using PIR and LD. (a) June. (b) July. (c) September.

the number of LTC tap changing operations as compared to the MLDC method and giving a superior voltage regulation performance as compared to the LDC method.

3) It can be seen that the number of tap changing operations is dramatically reduced by introducing dead band control algorithms using the PIR and LD as compared to the MLDC method and giving a reasonable voltage regulation performance as compared to the LDC method.

TABLE III
SUM OF CVQ INDEX AND THE NUMBER OF LTC TAP CHANGING OPERATION TIMES FOR EACH VOLTAGE CONTROL METHOD (NOMINAL VOLTAGE: 100)

		June	July	Sep.
LDC method	Tap operations	30	26	24
	Σ CVQ	37434	88712	21953
MLDC method	Tap operations	56	49	43
	Σ CVQ	4903	61394	3677
Proposed method with dead band control using *PIR*	Tap operations	46	38	33
	Σ CVQ	5043	61537	3754
Proposed method with dead band control using *PIR* and *LD*	Tap operations	42	26	26
	Σ CVQ	5418	64178	5320

V. CONCLUSION

In this paper, dead band control algorithms of LTC transformer at a distribution substation are proposed to reduce tap changing operation times. The PIR and LD are introduced in the proposed dead band control algorithms. The proposed dead band control algorithms provide a trade-off solution for tap changing operation times and voltage regulation performance for an LTC transformer. From the simulation results, the proposed dead band control algorithms of the LTC transformer improve voltage profiles over the distribution feeders as compared to the LDC method and giving reasonable LTC tap changing operation times as compared to the MLDC method.

The MLDC method has flexible structures as compared to the conventional LDC method because it has multiple inputs of load current of feeders, bus voltage, and output of DG units. The proposed dead band control method is modification of the MLDC method to reducing the number of tap changing operations. It is expected that the proposed dead band control method is applicable to the automated distribution system with severely different load diversity on feeders and/or with DG units.

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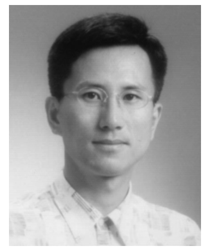

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