The On-Line Voltage Management and Control Solution of Distribution Systems Based on the Pattern Recognition Method

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Abstract – This paper proposes an on-line voltage management and control solution for a distribution system which can improve the efficiency and accuracy of existing off-line work by collecting customer voltage on-line as well as the voltage compensation capability of the existing ULTC (Under Load Tap Changer) operation and control strategy by controlling the ULTC tap based on pattern clustering and recognition. The proposed solution consists of an ADVMD (Advanced Digital Voltage Management Device), a VMS (Voltage Management Solution) and an OLDUC (On-Line Digital ULTC Controller). An on-line voltage management emulator based on multi-thread programming and the shared memory method is developed to emulate on-line voltage management and digital ULTC control methodology based on the on-line collection of the customer's voltage. In addition, using this emulator, the effectiveness of the proposed pattern clustering and recognition based ULTC control strategy is proven for the worst voltage environments for three days.

Keywords: Digital ULTC Controller, Distribution System, Voltage Management

1. Introduction

Voltage management work is performed branch by branch once or twice a year according to it's guidelines. First, several voltage measuring sites among electricity customers are determined by the voltage management worker at each electricity branch. The voltage management devices are installed at the measured sites, and the voltage data recorded for several days. Next, the devices are removed from the measured sites, and it is then verified whether the measured voltage data was maintained within the prescribed extent or not. If the measured voltages violate the prescribed voltage extent, the sites are classed as inappropriate voltage sites. A new operation and control strategy for the substation transformer's ULTC (Under Load Tap Changer) is reviewed as a counter plan of voltage improvement for customer sites. The ULTC consists of 17 taps, has ± 10% voltage compensation capability based on 9 taps, and is operated as ether the line voltage drop compensation method or the programming method. The line voltage drop compensation method is based on the load center point determined by the setting value [1]. At this time, these setting values can be determined using measured voltage data. This method has an advantage in that the customer voltage can be measured and identified, and compensated directly by the ULTC. However, the workers in this off-line work experience some difficulty in getting to the sites because of severe traffic congestion and the long-distance feeders.

So far, to solve such problems several ULTC control strategies were studied based on the programming method seen in [2-6]. In Ref. [4], the ULTC tap changing time is determined based on control sensitivities obtained using the mean voltage errors and the time scheduled fuzzy rules made by dividing a day into five periods. However, it is difficult to classify appropriate periods because of the separately changed load characteristics and seasonal load variations. In Refs. [5-10], those ULTC and capacitor (or step voltage regulator) control strategies are discussed which minimize the main transformer's secondary voltage deviation and reactive power based on the primary bus voltage and forecasted feeder load. However, it is not easy to guarantee the effectiveness of the obtained hourly strategies from the forecasted load. In Ref. [11], the ULTC tap position is determined on-line by solving the integer optimal problem minimizing the total statistical error between the highest and lowest customer voltage for each feeder. Here, the customer voltages for each feeder are computed using a load flow method based on the measured feeder bus voltage and feeder current, and also the voltage drop from pole transformer to the last customer is not considered. It is time-consuming work and it is difficult to guarantee the accuracy of the estimated customer voltage. In particular, these papers do not propose efficient ULTC operation and control methodology based on voltage management work.

Accordingly, in this study, an advanced voltage management and control solution based on customer voltage data collected on-line and the digital ULTC controller operated on-line is proposed which can improve the efficiency and accuracy of the existing off-line voltage management work and the voltage compensation capability of the existing ULTC operation and control strategy. In the proposed method, the voltages of customers on feeders are

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collected on-line using a ubiquitous network and classified into several clusters utilizing the clustering method, and a load center point is designed for each cluster. The digital ULTC controller of the proposed solution searches for the most similar cluster to voltage pattern data measured periodically from the determined customer sites based on the pattern recognition method, and determines the corresponding load center point to the cluster as the new ULTC operating load center point. Here, the minimum distance classification method is adopted as the pattern recognition [14].

2. The Existing Voltage Control Method

Fig. 1 shows the existing off-line voltage management work. In Fig. 1, $V_{PTi,j}(t)$ represents the voltage data recorded from electricity customer j of the PTr i. Here, j is 1 or 2, the former means the first electricity customer of the transformer, the latter the last customer of the transformer. First, the optimal tap positions are determined for PTr 0 and PTr 2 from among the pole transformers pertaining to the selected substation transformer in order to minimize the deviation between the high limit voltage V_{max}(233V) and the low limit voltage V_{min}(207V), which is based on the tap position data of the pole transformers and the measured voltage data from their voltage measuring sites.

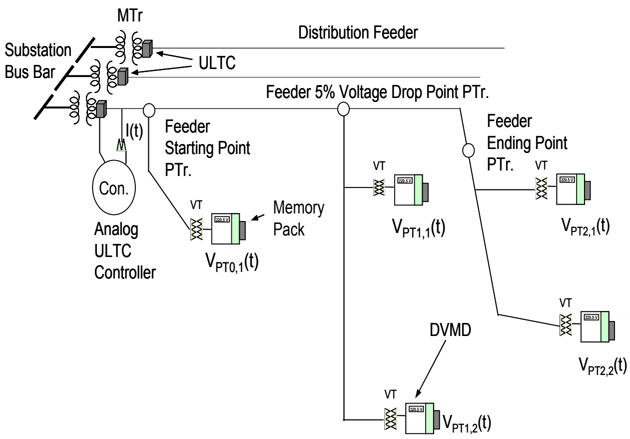

Fig. 1. The existing voltage management environments

The measured voltage data from each of the measuring sites is converted into optimal voltage data by changing the current tap position to the optimal tap position. Here, the PTr 0 is a high voltage site, as shown in Fig. 1, and PTr2 is a low voltage site. Next, the optimal tap of the substation transformer NLTC (No Load Tap Changer) is determined, and $V_{PT0,1}(i)$ and $V_{PT2,2}(i)$ are compensated by the optimal tap position. The optimal voltage compensation ratio of the ULTC minimizing Equation (1) is computed using these data.

$$Q(i)=\left\{V_{\max}-V_{PT0,1}(i)\frac{U_x(i)}{U_c(i)}\right\}^2+\left\{V_{PT0,1}(i)\frac{U_x(i)}{U_c(i)}-V_{\min}\frac{V_{PT0,1}(i)}{V_{PT2,2}(i)}\right\}^2 \quad (1)$$

In Equation (1), $U_c(i)$ is the 1+ULTC voltage compensation ratio of the *ith* voltage measuring time, $U_x(i)$ is 1+the optimal ULTC voltage compensation ratio of the *ith* voltage measuring time. Accordingly, the optimal voltage compensation ratio is obtained as shown in Equation (2) from $dQ(i)/dU_x = 0$.

$$U_x(i)=\frac{U_c(i)(V_{\max}+V_{\min}\bullet V_{PT0,1}(i)/V_{PT2,2}(i))}{2V_{PT0,1}(i)} \quad (2)$$

The substation transformer optimal supply voltage $V_{opt}(i)$ is computed by $V_{PT0,1}(i)\cdot U_x(i)/U_c(i)$ from Equation (2). At this time, the ULTC setting value is determined from the load center point, which makes the obtained voltage compensation result the same as $V_{opt}(i)$ according to the variation of the substation transformer load current I(i). Accordingly, the impedance Z corresponding to the load center point and the maintaining voltage V_o of the load center point can be obtained by minimizing Equation (3) using the least mean square method

$$Q=\sum_{i=1}^{n}\left[V_{opt}(i)-\left\{V_o+Z\bullet I(i)\right\}\right]^2 \quad (3)$$

That is, satisfaction of the values Z and V_o is obtained as shown in Equations (4) and (5). The ULTC setting value (U_r, U_x) is obtained from Z. The optimal tap decision procedure of the pole transformer and substation transformer is explained in Refs. [1,11]. This method determines the load center point using the voltage management program according to the existing voltage management manual.

$$Z=\frac{\sum_{i=1}^{n}V_{opt}(i)\sum_{i=1}^{n}I(i)-n\sum_{i=1}^{n}I(i)V_{opt}(i)}{\left(\sum_{i=1}^{n}I(i)\right)^2-n\sum_{i=1}^{n}\left(I(i)\right)^2} \quad (4)$$

$$V_o=\frac{\sum_{i=1}^{n}V_{opt}(i)\sum_{i=1}^{n}I(i)-Z\sum_{i=1}^{n}\left\{I(i)\right\}^2}{\sum_{i=1}^{n}I(i)} \quad (5)$$

Here, because the voltage management data is collected off-line by the worker and the ULTC is operated with a fixed load center point determined by the voltage management data, the efficiency of the work and the voltage compensation capability of the ULTC to the seasonal load variation can deteriorate.

3. The Proposed Voltage Control Method

The proposed on-line voltage management and control solution consists of an ADVMD (Advanced Digital Voltage Management Device), VMS (Voltage Management Solution) and an OLDUC (On-Line Digital ULTC Controller). The free information exchange capability among these components is designed under ubiquitous network environments. Fig. 2 shows the structure of the on-line voltage management solution.

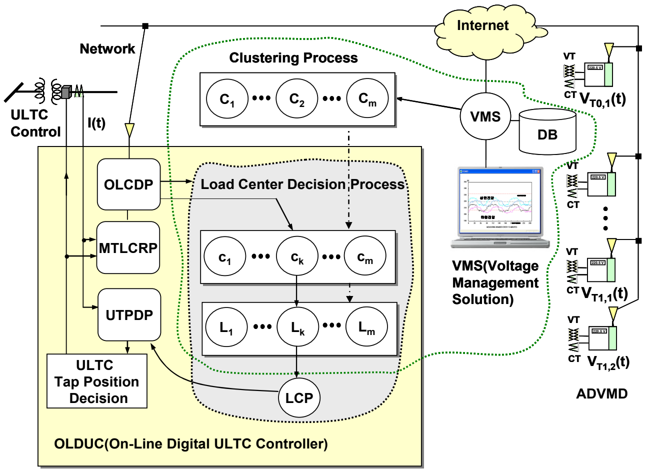

Fig. 2. The on-line voltage management solution

3.1 ADVMD Design

In the ADVMD, the voltage and current data as well as the watt-hour data recording function are designed based on the VT (Voltage Transformer) and the CT (Current Transformer) for reasons of economy and efficiency. The ADVMD averages the accumulated voltage data and saves it in the external memory every three-day period based on a selected period of either 10, 15, or 30 minutes, and transmits the data to the VMS according to its request.

3.2 VMS Design

The VMS collects the voltage history data from the ADVMD and the ULTC operation history data of the substation transformer from the OLDUC every season and month, or as otherwise required. At this time, the operation information of the substation transformer includes the substation transformer load current I(i), and the ULTC's operation history data $ULTC_{TAP}(i)$. Here, the operation information set of the substation transformer is represented as u_i= $\{I(i), ULTC_{TAP}(i)\}$. It collects the first electric customer voltage data $V_{PTk,1}(i)$ and the last electric customer voltage data $V_{PTk,2}(i)$ of the distribution transformers pertaining to each substation transformer. It determines the optimal tap which minimizes the deviation between high limit voltage and low limit voltage for each distribution transformer, and computes the compensated voltages $V_{PTk,1}(i)$, $V_{PTk,2}(i)$ by applying the tap position to the measured voltage data. It then determines the highest voltage transformer PTr 0 and the lowest voltage transformer PTr 2, and obtains $V_{PT0,1}(i)$, $V_{PT2,2}(i)$ for each substation transformer as shown in Fig. 3. The optimal tap position of the substation transformer is determined from the current tap position and the ULTC operation history data of the substation transformer, which minimizes the deviation between the high limit voltage and low limit voltage. The voltage $V_{PT0,1}(i)$ and $V_{PT2,2}(i)$ compensated are computed by the optimal tap position. The voltage patterns $p_i=\{V_{PT0,1}(i), V_{PT2,2}(i)\}$ are normalized, the CCPS (Cluster Center Point Set) is obtained by applying the clustering method to the normalized voltage patterns, the LCPS (Load Center Point Set) is constructed using the designed load center points for each cluster, and finally the results data are transmitted to the OLDUC.

3.2.1 Voltage Pattern Clustering

Voltage pattern clustering involves the gathering of similar voltage patterns from among the measured voltage patterns p_i for several days through the ADVMD. Here, the max-min. distance algorithm is adopted as the clustering method. At first, the normalized voltage pattern p_i is solved using Equation (6). In Equation (6), j is 0 or 2, k is 1 or 2.

$$p_i = \left(V_{PTj,k}(i) - 220\right)/13 \tag{6}$$

It selects the one pattern p_x arbitrarily among the voltage patterns and determines the pattern as the initial cluster center point c_1. It also selects the furthest pattern p_z from the pattern p_x as c_2, and then determines to which cluster the voltage patterns besides the selected p_x and p_z pertain among the two clusters c_1 and c_2 by computing the distance of Equation (7) for those using the minimum distance classifier. At this time, if the voltage pattern sets pertaining to c_1 and c_2 are defined as C_1 and C_2, the CS (cluster set) becomes $\{C_1, C_2\}$.

$$D_{ik} = \left[\omega_1(c_{1i}-p_{1k})^2+\omega_2(c_{2i}-p_{2k})^2+...+\omega_q(c_{qi}-p_{qk})^2\right]^{1/2} \tag{7}$$

In Equation (7), D_{ik} represents the Euclidean distance between the *ith* cluster center c_i and the *kth* voltage pattern p_k, c_{qi} and p_{qk} mean the *qth* elements of c_i and p_k, q is the element number, and w_i is the weight function. Here, q is 2. Then, c_i is solved, which is the *ith* cluster center point. At this time, the center point of the *ith* cluster can be represented as shown in Equation (8).

$$c_i = \frac{1}{N}\left[\sum_{j=1}^{N} p_{1j}\ ,\ \sum_{j=1}^{N} p_{2j}\ ,\ \ ...\ \ ,\ \sum_{j=1}^{N} p_{qj}\right] \tag{8}$$

Next, after searching the furthest pattern from the center point of the cluster among the voltage patterns pertaining to each cluster, the maximum distance from the cluster center point to the pattern is compared with the average distance between the cluster center points. At this time, the average distance between the *ith* and *kth* cluster center points is represented in Equation (9).

$$AD_{ik} = \frac{1}{2}\left[\left(c_{1i}-c_{1k}\right)^2+\left(c_{2i}-c_{2k}\right)^2+...+\left(c_{qi}-c_{qk}\right)^2\right]^{1/2} \tag{9}$$

If the maximum distance is greater than the average distance, this pattern becomes the new cluster center point c_3. At this time, CCPS is $\{c_1, c_2, c_3\}$. Then, one must go to Equation (8) and obtain the CS for the CCPS as $\{C_1, C_2, C_3\}$. Such a clustering process is repeated until any new cluster center point disappears. In this process, if all of the voltage patterns p_i are classified into m clusters, CS is $\{C_1,C_2,...,C_m\}$ and CCPS becomes $\{c_1, c_2 ,...,c_m\}$. In the threshold clustering algorithm, the clustering process greatly depends on the threshold value. On the other hand, the max-min. distance clustering method has the advantage that the cluster based on the average distance between the clusters can expand autonomously and rationally, as the max-min. distance clustering method uses the max-min. distance based on Euclidian distance.

3.2.2 Variable Load Center Point Design

For C_1, the first cluster of the CS, the substation transformer's optimal output voltage $V_{opt}(i)$ is obtained, which is computed from $V_{PT0,1}(i) \cdot U_x(i)/U_c(i)$ as explained in the decision method of the existing ULTC stetting values. Here, $U_x(i)$ is the optimal voltage compensation ratio minimizing the Equation (1). So, the load center point $L_1(V_{o1}, Z_1)$ is determined using Equations (4) and (5) which make the voltage compensation results according to the variation of the substation transformer's load current I(i) the same as the substation transformer's optimal output voltage. Next, the second load center $L_2(V_{o2}, Z_2)$ is decided by repeating this procedure to the second cluster C_2.

Then, by repeating this procedure up to C_m, the LCPS (Load Center Point Set) is finally obtained as $\{L_1,...,L_m\}$. Here, L_i is the *ith* load center point and is represented to the load center point information (Vo_i, Z_i). Fig. 3 shows the business processing procedure of the VMS.

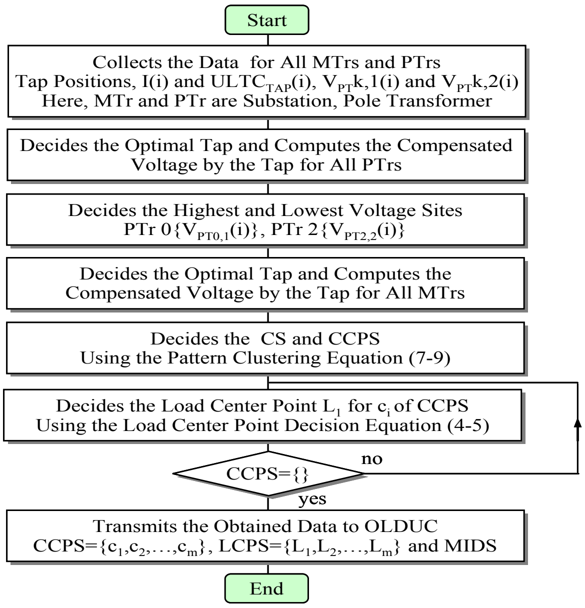

Fig. 3. The business processing procedure of the VMS

3.3 OLDUC Design

The OLDUC is designed basically as three processes which are the MTLCRP (Main Transformer Load Current Recording Process), OLCDP (On-Line Load Center Point Decision Process) and UTPDP (ULTC Tap Position Decision Process ULTC).

At first, the MTLCRP saves the operation information $u_i=\{I(i),ULTC_{TAP}(i)\}$ of the substation transformer to the external memory for the given term according to the selected and transmits the substation transformation operation information set $\{u_1,u_2,...,u_n\}$ to the VMS according to its request. The OLCDP receives the data such as CCPS$\{c_1,c_2,...,c_m\}$, LCPS $\{L_1,L_2,...,L_m\}$ and the MIDS (Multiple ID (IP) Set) of the voltage measuring sites online from the VMS, and saves those data to the predefined memory. It also obtains on-line the voltage pattern set $p_i=\{V_{PT0,1}(i), V_{PT2,2}(i)\}$ according to the selected searches for the most similar cluster to the obtained on-line real-time voltage pattern among the CCPS using the pattern recognition, finds the load center point (V_o, Z) corresponding to the searched cluster from the LCPS, and determines the found load center point as the new load center point for the ULTC.

At this time, the minimum distance classification method of Equation (10) is used as the pattern recognition, which has certain disadvantages from the viewpoint of linear/nonlinear interpolation capability when compared to the fuzzy logic or ANN; on the other hand, it is favorable from the perspective of the development of a practical solution because it can avoid the professional technology or time-cost required in the membership function design and tuning work and the knowledge required to learn how to work it [12-13].

In the minimum distance classification method, the degree of similarity is identified by the Euclidian distance D_k, whence the minimum distance cluster among the cluster sets becomes the most similar cluster.

$$D_k = \left[\omega_1(p_{1i}-c_{1k})^2+\omega_2(p_{2i}-c_{2k})^2+...+\omega_q(p_{qi}-c_{qk})^2\right]^{1/2} \quad (10)$$

In Equation (10), c_{jk} is the *jth* element of the *kth* cluster center pattern determined by the clustering method, and p_{ji} is the *jth* element of the on-line real-time input voltage pattern p_i. w_j is the weight function, and is introduced to improve the accuracy and reliability of the result.

On the other hand, the UTPDP monitors the substation transformer load current I(t) and the ULTC tap position information $ULTC_{TAP}(t)$ according to the selected period. It determines and controls in real-time the ULTC tap position based on the LCP determined by the OLCDP.

4. Simulation Results

An on-line voltage management and control emulator is developed in Visual C++ MFC. In the emulator, the on-line ULTC operation and control environments are emulated by implementing the information exchange function among the VMS, OLDUC and ADVMD based on the multi-thread programming and the shared memory method. Fig. 4 shows the developed on-line voltage management emulator.

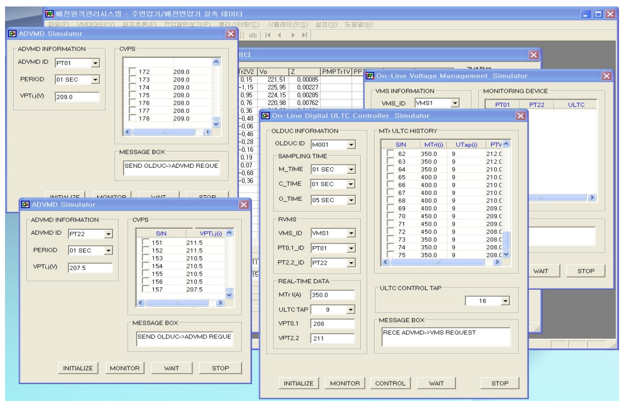

Fig. 4. The developed voltage management emulator

4.1 ADVMD Emulator

Two ADVMD processes are designed. The first ADVMD PT01 emulates the voltage history data $V_{PT0,1}(i)$ for the first electricity customer of the highest voltage pole transformer PTr 0 and the second ADVMD PT22 the voltage history data $V_{PT2,2}(i)$ for the last electricity customer of the lowest voltage pole transformer PTr 2.

4.2 VMS Emulator

The VMS first requests the ULTC operation history data set $\{u_1, u_2,..., u_{288}\}$ from the OLUDC "M001". Next, it obtains the customer voltage history data set $\{V_{PT0,1}(1), V_{PT0,1}(2),\ldots, V_{PT0,1}(288)\}$ from the ADVMD "PT01" and the customer voltage history data set $\{V_{PT2,2}(1), V_{PT2,2}(2), \ldots, V_{PT2,2}(288)\}$ from the ADVDM "PT22", and then composes the voltage management pattern set $\{p_1, p_2,..., p_{288}\}$ from the two history data sets. Here, p_i means $\{V_{PT0,1}(i), V_{PT2,2}(i)\}$.

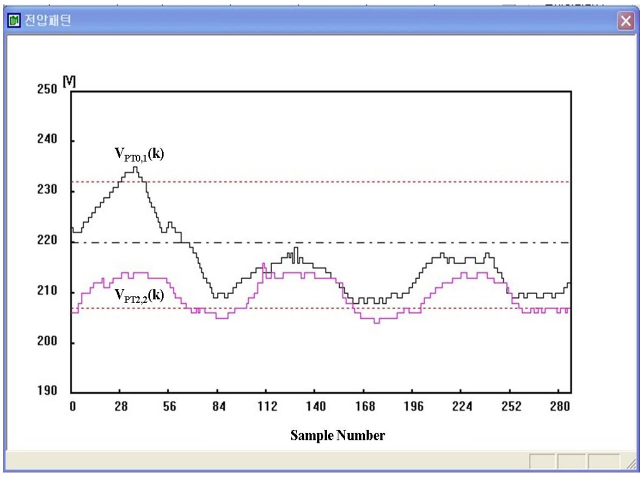

Fig. 5. The voltage management data pattern p_i

Fig. 5 shows the customer voltage history data p_i for three days collected from ADVMD PT01 and ADVMD PT22. Here, the ULTC operation tap position is supposed as the basic tap position 9 for all times in order to simulate the worst case. In addition, the VMS computes the compensated voltage management pattern set $\{p_1, p_2,..., p_{288}\}$ by the optimal taps of the pole transformer and the substation transformer.

Fig. 6 shows the compensated voltage management pattern p(i), which was arranged on the basis of 220V. However, Fig. 6 shows that the voltage VPT0,1(i) violates the high limit voltage and that the VPT2,2(i) violates the low limit voltage. Accordingly, the VMS performs the normalization procedure of Equation (6) for all pi, and obtains the CS and CCPS by applying the max-min. clustering method represented as Equations (7-9) to the normalized pi. It then obtains the LCPS (Load Center Point Set) by applying Equations (1-5) to each cluster. Table 1 shows the CCPS and LCPS obtained by the VMS's clustering procedure. The CCPS and LCPS consist of a total of 14 clusters. At this time, it must identify the clustering results to prove the accuracy and efficiency of the clustering.

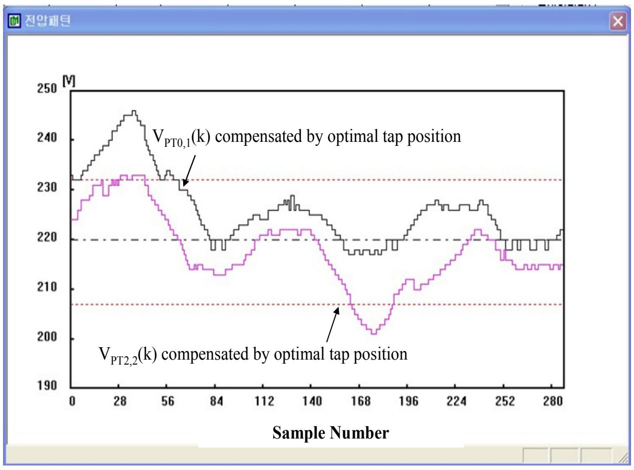

Fig. 6. The compensated voltage management pattern p_i

Table 1. VMS's clustering results

CS#	CCPS		LCPS	
	c_{i1}	c_{i2}	V_o	Z
1	0.50	0.15	221.51	0.00085
2	-0.10	-1.15	225.95	0.00227
3	1.82	0.95	224.15	0.00285
4	1.32	0.76	220.98	0.00762
5	1.01	0.36	219.68	0.01331
6	0.57	-0.48	227.18	-0.00146
7	0.84	-0.06	226.16	-0.00122
8	0.00	-0.46	223.86	-0.00243
9	0.24	-0.28	223.45	-0.00180
10	0.50	-0.16	221.58	-0.00474
11	0.62	0.19	220.40	0.00464
12	0.37	0.07	222.82	-0.00238
13	0.34	-0.68	227.89	-0.00565
14	0.75	-0.36	231.22	-0.01035

Accordingly, the VMS applies the pattern recognition method based on LCPS to all voltage management patterns $\{p_1, p_2,..., p_{288}\}$ and verifies the improvement effect of the voltage compensation capability of the ULTC.

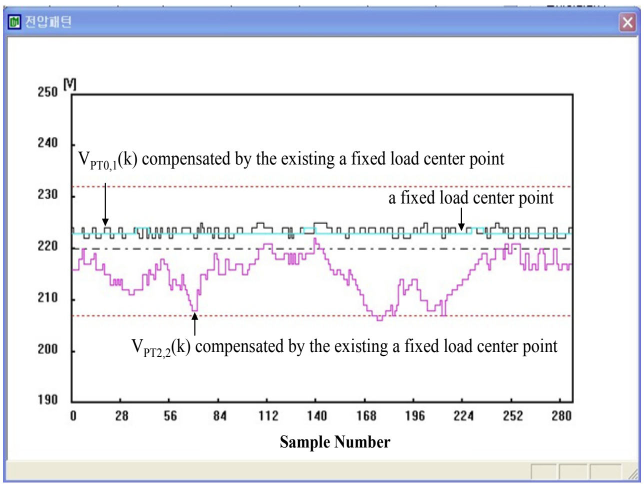

Fig. 7. The compensated result by the existing method

Fig. 7 shows the simulation results based on the existing ULTC operation and control strategy with the fixed load center point. The lowest voltage $V_{PT2,2}(i)$ violates severely the low limit voltage 213V in the ranges of 56 to 84 and 150 to 220. Accordingly, the existing fixed load center point based ULTC operation and control strategy cannot improve the worst voltage environments.

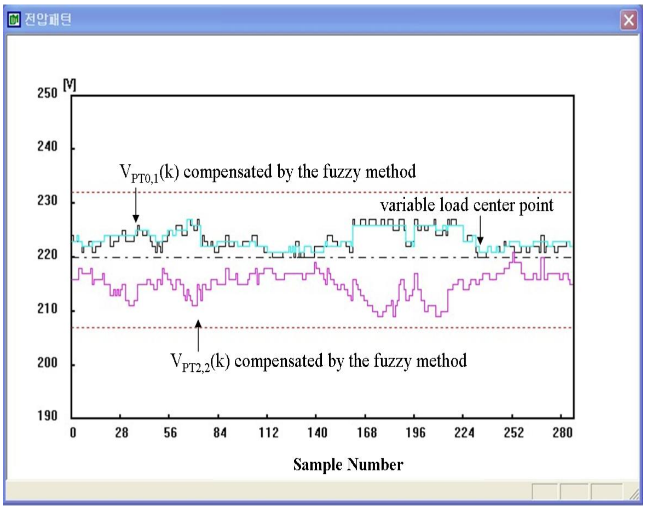

Fig. 8. The compensated result by the fuzzy method

Fig. 8 shows the compensated results obtained by the fuzzy based control method [15] and Fig. 9 the proposed pattern recognition based control method. The lowest voltage $V_{PT2,2}(i)$ is improved greatly in the range of 56 to 84 and 150 to 220. In Figs. 8 and 9, the fact that the proposed ULTC operation and control strategy can improve the voltage compensation capability of the ULTC is proved by making the ULTC's operation load center point move to the appropriate load center point of the designed multiple load center points according to the variation of the customer voltage pattern.

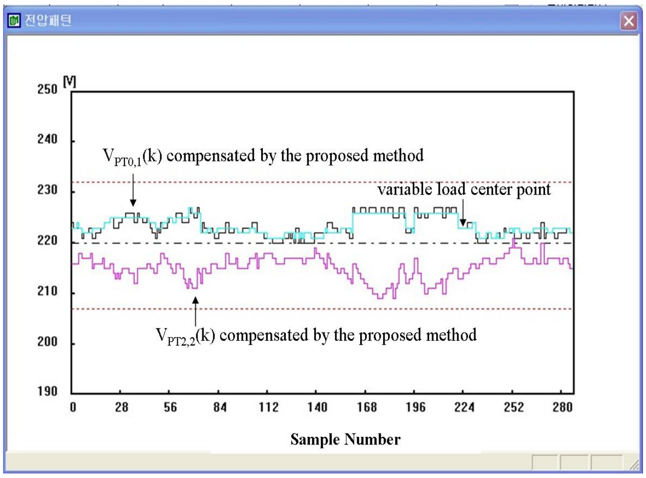

Fig. 9. The compensated result by the proposed method

Although the same results were obtained, the proposed pattern recognition based control method is favorable from the perspective of the development of a practical solution because it can avoid the professional technology or time-cost required in the design of the complicated membership function and tuning work. Finally, the voltage pattern clustering procedure and the load center point decision procedure for all clusters are finished and then, if the efficiency is proven as shown in Fig. 6, the VMS sends the result data shown in Table 1 to the OLDUC using the shared memory method.

4.3 OLDUC Emulator

The MTLCRP module retrieves the ULTC operation and control information set $\{u_1,u_2,...,u_{288}\}$ for three days at15 minute intervals from the external file furnished for the simulation, and then saves it to the internal memory. It updates the last ULTC operation and control information according to the selected period and sends the substation transformer operation information set $\{u_1,u_2,...,u_{288}\}$ to the VMS using the shared memory method according to its request. The DLCDP receives the MIDS information set {PT01, PT22} and the CCPS information $\{c_1,c_2,..,c_{14}\}$ and LCPS information $\{L_1,L_2,...,L_{14}\}$ shown in Table 1 from the VMS under the operating environments, and then saves that information to the internal memory. Here, the saved data was as accurate as the data shown in Table 1. Accordingly, the accuracy of the information exchange could be verified between emulators. Next, it sends the request for the last voltage data to the ADVMD processes PT01 and PT22 and obtains the voltage pattern $p_i=\{V_{PT0,1}(i), V_{PT2,2}(i)\}$, searches the most similar cluster to p_i among the CCPS shown in Table 1 using the minimum distance classification method and determines the load center point (V_o, Z) corresponding to the clusters searched among the LCPS.

On the other hand, the UTPDP module computes the voltage compensation value based on the last updated load center point which is determined by the OLCDP by monitoring periodically the I(i) and $ULTC_{TAP}(i)$, determines the appropriate ULTC tap position and controls the ULTC tap position. In the emulation environments, the OLDUC shows the accuracy by tracking accurately the ULTC's optimal tap position.

5. Conclusions

In this paper, an on-line voltage management and control solution was proposed which can improve the efficiency and accuracy of the off-line work and the extent of voltage compensation based on the existing ULTC operation and control methodology. In the proposed method, customer voltage history data is collected on-line and classified into several clusters using the max-min. distance clustering method, and the ULTC's load center point is moved into the optimal position among the designed clusters according to the variation of the customer voltage pattern based on the minimum distance classification method. The on-line voltage management and control emulator based on multi-thread programming and the shared memory method was developed to emulate the proposed on-line digital ULTC operation and control environments. In the simulation, the proposed strategy was proven to improve to a much greater extent the voltage compensation capability than the existing strategy for the worst voltage environments for three days.

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