INTERACTION AMONG MULTIPLE CONTROLS IN TAP CHANGE UNDER LOAD TRANSFORMERS

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Abstract -- **This paper investigates the dynamic behaviour of tap changing operations in Tap Change Under Load (TCUL) transformers. Interactions among multiple TCUL controls cause oscillatory behaviour in tap changing actions, which unnecessarily increases tap operations before they reach equilibrium. Sufficient conditions for stability are derived and features of the phenomena are examined through theoretical analysis as well as through numerical simulation.**

Keywords -- **Tap Change Under Load, TCUL, On Load Tap Changer, OLTC, Tap Changer Control, Transformer Control, Voltage Stability**

I. Introduction

In present transmission and distribution systems, a number of tap change under load (TCUL) transformers are equipped to adjust appropriate voltage profiles. Typically, these TCULs are controlled in a distributed way so that it is possible to individually maintain constant voltage levels on subtransmission and distribution-level buses. Requirements for TCUL controls are, however, not only to keep the voltage profile but also to suppress the frequency of operations to the lowest possible. These requirements basically contradict since frequent operations are usually needed to perform a higher quality of voltages. Under such circumstances, there is a trend towards new control designs for TCUL controllers [1,2].

The purpose of this paper is to analyze the control actions of multiple TCULs and to provide a guideline for the assessment and coordination of existing controllers toward better treatment of this problem. Since most existing controllers work independently in order to adjust to their individual targets, interactions among the control actions are a natural consequence. This is because a tap operation affects nearby bus voltages controlled by other controllers, causing further operations in tap changers. Since the interdependency between voltages and tap positions is a 'built-in' or inherent characteristic of transmission and distribution networks, such an interaction among multiple TCUL controls may not be a problem of specific control designs only.

Recently, problems concerning TCUL control actions have been the subject of numerous voltage stability studies. Of such studies, stability problems mainly concerned with TCUL dynamics are treated in [3-12]. Conditions for stability are examined using idealized continuous TCUL models in [3-6] or using a discrete model in [7]. Reverse control action of TCUL control is studied as a possible factor causing voltage collapse in [8-10]. These studies contribute to clarify the relationship between TCUL dynamics and voltage instability problems. However, general features of multiple TCUL controls, including the interaction between them, have not yet been treated in existing literature except in [11] as far as the authors know. In [11], some primitive cases of this problem have been studied.

In this paper, extending the results obtained in [11], we analyze the interaction among multiple TCUL control actions. A discrete TCUL model, which has been used in voltage stability studies [7,10] is used for analysis as well as in numerical simulations. Liapunov's stability theorem is applied to derive sufficient conditions for stability. It is shown that, when some of the conditions are violated, oscillatory behaviour in tap changing actions can occur. Features of the phenomena are examined through theoretical analysis as well as through numerical simulation.

II. Problem Statement

Previous voltage stability studies associated with tap actions have been mainly concerned with major problems such as existence of equilibria, their stabilities, region of attraction, global behaviour of voltages and so on [3-10,12]. In these studies, it has been assumed that "existence of equilibrium" is equivalent to that where its size is large enough to avoid the hunting of taps. We refer to this assumption as "assumption for equilibrium size," and the region of attraction under this assumption as "voltage stability region" hereafter in this paper. On the other hand, this paper exactly study the hunting, oscillatory behaviour of taps. One of the simplest examples of the oscillations is such a phenomenon as shown in Fig.1. The existence of such phenomena is totally governed by the size of the deadband of TCUL control, or the size of the equilibrium. In this paper, we study how the oscillatory actions occur and what size of equilibrium is necessary to guarantee the nonexistence of such oscillations when multiple TCUL controls are activated. Since the equilibrium of the system to be studied is not characterized by a point, we will sometimes use terminologies "equilibrium region" and "equilibrium size" to indicate the equilibrium and its size respectively hereafter.

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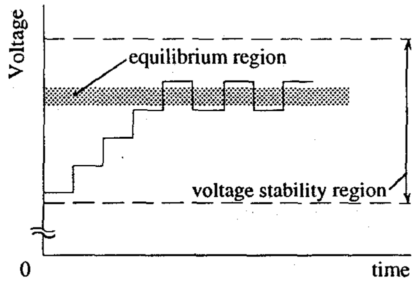

Fig. 1 Hunting Phenomenon

In the analysis in this paper, we assume the existence of an equilibrium. Then, a similar approach to reference [7] is adopted, where the Liapunov's stability theorem is applied. In the application of the theorem, our intention is to judge whether or not the voltages around the equilibrium region finally reach inside it, while a standard application of the theorem is carried out in [7] under "the assumption for equilibrium size." Then, two kinds of conditions will be obtained in this paper. One is a newly obtained condition, (8) in section 4, prescribing the size of the equilibrium guaranteeing the nonexistence of oscillatory behaviour. The other is condition (9) in section 4, which should correspond to a sufficient condition for stability of the equilibrium under "the assumption for equilibrium size." The latter condition could be almost equivalent to a set of conditions obtained in [7], though they do not exactly agree since the selected Liapunov functions, as well as the formulations, are different from each other. Condition (9) will not be discussed further in this paper since our concern is with the oscillation phenomena. Therefore, condition (8) will be discussed extensively in the last half of the paper.

We use linearlization in our analysis to derive conditions (8) and (9). Therefore, the analysis may be only valid for small deviations of voltages around the equilibrium. However, this treatment seems to be justified since the oscillation phenomena themselves occur in a small area around the equilibrium as shown in Fig. 1. (Global behaviour of voltage inside or outside the voltage stability region, which is outside the region of oscillatory phenomena, have been extensively studied in [4,5,6].)

III. The System Representation

The purpose of this study is to analyze interaction among TCUL controls as mentioned in the Introduction. A typical control in TCUL transformers is to change the tap ratio discretely to regulate the secondary voltage magnitude within a specified voltage width. There are different types of controllers adopting different criteria for changing tap positions, which characterize the types of time delays of the controls [14]. A voltage integration type controller is widely used in Japanese systems, where the time delay is determined based on the integral of the voltage deviation exceeding a threshold. In this paper, since we pay attention only to the process of interaction among TCUL controls, we assume that the time delay is treated as unit time. Such a treatment is also seen in [7,10]. That is, in this paper, TCUL transformers are represented by a set of discrete equations as follows.

$$n_k(t+1) = n_k(t) - d_k f_k(v_k - v_{Rk}) \tag{1}$$

$$f_k(u_k) = \begin{cases} 1 & (u_k > \varepsilon_k) \\ 0 & (-\varepsilon_k \le u_k \le \varepsilon_k) \\ -1 & (u_k < -\varepsilon_k) \end{cases} \quad k = 1, \cdots, N$$

where

$$u_k = v_k - v_{Rk}$$

where $n_k(t)$ is the tap position of k-th TCUL transformer at time t. v_k and v_{Rk} are the controlled voltage and its reference value, respectively. ε_k is the threshold, d_k is the step size of tap position, and N is the number of TCUL transformers. Equation (1) states that each tap position is changed by d_k at t+1 only when the voltage violates the specified voltage width $2\varepsilon_k$ at t.

Load modelling is probably an important issue in this type of analysis as well as in voltage stability analysis. Various types of load models have been proposed to represent different time scale behaviour of loads. The time scale for TCUL control actions is in general of the order of several tens of seconds to minutes. An elementary but widely used model for this time scale is of a nonlinear voltage dependent type. Therefore, in this paper, real and reactive loads are represented as

$$P_i = P_{0i} \cdot v_{Li}^{\alpha_i}, \quad Q_i = Q_{0i} \cdot v_{Li}^{\beta_i}, \quad i = 1 \cdots M \tag{2}$$

where v_{Li} represents the voltage magnitude of load bus i. Further, we assume the network equation as

$$y = g(x) \tag{3}$$

where y is a vector of real and reactive bus injections, and x is a vector of bus voltage magnitudes and angles, which contains TCUL transformer voltages, v_k, and load voltages, v_{Li}, as its elements. Equation (3) stands for the load flow equations, where we assume that the voltage magnitudes of generator buses are constant.

In the following, we analyze the system model represented by (1) - (3). First, we define the following vectors.

$$v = [v_1 \cdots v_N]^T, \quad n = [n_1 \cdots n_N]^T, \quad u = [u_1 \cdots u_N]^T$$

$$L = [P_{01}, Q_{01} \cdots P_{0M}, Q_{0M}]^T$$

Now, we linearize (2) and (3) around an operating point and eliminate dependent variables. Then, we obtain

$$\Delta v = A\Delta n + B\Delta L \tag{4}$$

where

$$A = [a_{ij}] = \left[\frac{\partial v}{\partial n}\right]_{\substack{n=n(t)\\L=L(t)}}, \quad B = \left[\frac{\partial v}{\partial L}\right]_{\substack{n=n(t)\\L=L(t)}}$$

By taking into account the relationships, $u(t+1) = u(t) + \Delta v$ and $n(t+1) = n(t) + \Delta n$, and using equations (1) and (4), we obtain the following expression for the total system.

$$u(t+1) = u(t) - ADf(u(t)) + B\Delta L \tag{5}$$

where

$$D = diag[d_1 \cdots d_N]$$

$$f(u(t)) = [f_1(u_1(t)) \cdots f_N(u_N(t))]^T$$

Note that the equilibrium, or the equilibrium region, of (5) is defined as a set of u such that $f(u)$=0. It should be noted that the above equation corresponds to a linearized version of the slow subsystem discussed in [12], where only the slow dynamics of tap changers are expressed together with the slow variation of load parameters, while fast dynamics of generators and existing controllers are neglected. It is also confirmed in [12] that the effect of the fast dynamics of generating units on the tap operations is normally negligible unless the fast dynamics are close to instability. It is noted that matrices A and B in (5) are time variant and are to be evaluated at each operating point n=$n(t)$ and L=$L(t)$. Therefore, A=$A(t)$ and B=$B(t)$. Such a treatment can mostly eliminate the linearization error in (5). However, due to the fact that A and B normally do not vary so much during a specific time duration, they may be treated as constants, which are to be evaluated at a point near the equilibrium, where $|u| \ll 1$. In the next section, the Liapunov's theorem will be applied to the difference equation (5), where no major problems arise regardless of the treatments of the coefficients.

IV. Conditions For Stability

In this section, extending the results obtained in [11], we study the conditions for occurrence of interaction among multiple TCUL controls. Liapunov's stability theorem [13] is applied to (5) to examine stability conditions. For this purpose, we first define a positive definite function in terms of $u(t)$ of (5) as follows.

$$V(t) = u(t)^T u(t) \quad > 0 \tag{6}$$

By the Liapunov's theorem, the sufficient condition for stability is written as

$$\Delta V = V(t+1) - V(t) \quad < 0 \tag{7}$$

The substitution of (5) and (6) into (7) yields a set of sufficient conditions for stability. This derivation has been done in reference [11], which is briefly described in the Appendix. Then, we obtain the following two conditions.

$$|c_k| < 2|u_k| \qquad k = 1, \cdots, N \tag{8}$$

$$c_k u_k > 0 \qquad k = 1, \cdots, N \tag{9}$$

where

$$c_k = \sum_{j=1}^{N} a_{kj} d_j f_j(u_j) \quad : k\text{-th element of } ADf(u)$$

As was mentioned in section 2, the first conditions (8) relate to the size of the equilibrium, and correspond to sufficient conditions for stability with respect to the oscillatory interaction of multiple TCUL controls. As will be studied later, when all the deadbands ε_k's in (1) are sufficiently large, these conditions always hold, guaranteeing "the assumption for equilibrium size" defined in section 2. On the other hand, the second conditions (9), which have not yet fully been analyzed, correspond to sufficient conditions for stability under "the assumption for equilibrium size." Therefore, the latter conditions are expected to be equivalent to the voltage stability conditions derived in the previous studies such as [7]. For example, (9) exactly agrees with the voltage stability condition in [9,10] for the special case of N=1. Although analysis of conditions (9) as well as comparison with those proposed by existing literatures will be needed, this is not within the scope of this paper. Therefore, we will not discuss conditions (9) hereafter.

From the definition of voltage deviation u_k in (1), it is understood that $|u_k| \le \varepsilon_k$ inside the deadband does not affect control action at all since $f_k(u_k) = 0$ for such u_k. Therefore, we must examine stability conditions (8) for $\varepsilon_k < |u_k|$. Therefore, since the lower bound of $|u_k|$ is ε_k and $|f_j(u_j)| \le 1$, sufficient conditions for (8) are written as follows.

$$\sum_{j}^{N} |a_{kj}| \cdot d_j < 2\varepsilon_k \qquad k = 1, \cdots, N \tag{10-1}$$

or

$$\begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1N} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{N1} & \tilde{a}_{N2} & \cdots & \tilde{a}_{NN} \end{bmatrix} \cdot \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix} < 2 \cdot \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_N \end{bmatrix} \tag{10-2}$$

where $\tilde{a}_{ij} = |a_{ij}|$. Conditions (10) consist of N sufficient conditions for stability with respect to the oscillatory interaction of multiple TCUL controls.

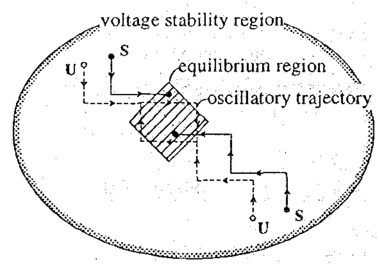

Fig. 2 Stable and Unstable Trajectories

When we pay attention to specific M controls among N controls and assume that the remaining N-M controls are blocked, sufficient conditions for stability among the M controls are written as follows:

$$\sum_{j \in S} \tilde{a}_{kj} \cdot d_j < 2\varepsilon_k \qquad k \in S \tag{11}$$

where S represents the set of M controls to be studied among N controls. Conditions (11) guarantee that sustained oscillations among the M controls themselves cannot occur unless the remaining N-M controls interfere. Therefore, we refer to conditions (11) as local stability conditions for a set of controllers, S, hereafter. Note that the violation of (11) implies the violation of (10).

Interpretations of these conditions may be given as follows. The left side of (10) represents the maximum possible change in the k-th controlled voltage when all the tap positions are changed by one step. The right side is the deadband around the reference voltage as defined in (1). Therefore, if conditions (10) hold, it is guaranteed that voltages starting from outside the deadbands can finally reach inside them. On the other hand, if one of the conditions in (10), say the k-th condition of (10), does not hold, the voltage controlled by the k-th TCUL may jump over the deadband, resulting in oscillatory behaviour of the k-th tap changer. In order to observe this, we consider an extreme case, as follows.

$$\tilde{a}_{kk} \cdot d_k > 2\varepsilon_k \tag{12}$$

This condition itself is possibly unrealistic in an actual system, but may be helpful in the study of conditions (10). A possible phenomenon under this condition is given in Fig. 1. Condition (12) is interpreted as the violation of the local stability condition for $S=\{k\}$, the k-th TCUL control. This condition implies that, for the k-th TCUL control, the change in secondary voltage by the unit tap operation is greater than its deadband. Therefore, the voltage may not be able to go into the deadband and will instead oscillate around it. Note that such oscillations do not always occur even under (12) since it is a possible situation that the voltage may happen to go into the deadband.

The derived conditions provide sufficient conditions only. However, this does not mean there is any weakness in our results. This is explained using Fig. 2 as follows. The derived conditions prescribe the size of the equilibrium region determined by deadbands. If this region is large enough compared with unit changes in discrete variables, all the trajectories starting from inside the voltage stability region can reach the equilibrium region. But if it is too small, some trajectories may not go into the region and will instead oscillate around it. In such cases, whether or not a trajectory can reach the equilibrium only depends on the location of the initial point of the trajectory. In this sense, it is understood that, when the conditions are violated, the percentage of trajectories that can reach the equilibrium depends on how large the equilibrium region is compared with the unit changes in discrete variables, that is, on the extent of the violation of (10). Therefore, even though the violation of (10) does not directly imply instability for all the solutions, the violation guarantees the existence of interaction for some solutions; it can be stated that the extent of the violation correlates to the statistical probability of the interaction.

V. Numerical Simulations

Patterns of interactions among multiple TCUL operations are examined here for several combinations of conditions (10). In order to see the interactions clearly, we use a simple but typical network as an example system as shown in Fig. 3, which represents a selected path from a transmission line to a distribution feeder in an actual radial network. This example system has three TCUL transformers, which regulate their secondary voltages. The purpose of this study is to clarify a qualitative mechanism in the oscillatory behaviour in tap changers. For this purpose, a detailed modelling such as for an integration type controller would make the problem unnecessarily complicated. Therefore, again, we use equation (1), an ideal expression for TCUL control, for this examination. That is, the numerical simulations here are based on equations (1) - (3).

Five cases are set for different reactances of the network as listed in Table 1. Cases 1 and 2 correspond to regular cases where typical parameters of actual transmission and distribution networks are assumed. In cases 3 - 5, we set parameters representing the original radial configuration of the network where several lines and transformers are connected to the same bus. Therefore, smaller reactance values for lines and transformers are set to represent the parallel connections of feeders in these cases. Case 5 is an artificial case where the deadbands ε_2 and ε_3 are reduced by about 45% to observe sustained oscillation among the tap changers. The load consumptions listed in Table 1 are typical values for the above network representations and are used as base values for these cases at $t=1$. In this numerical simulation, these base values are changed slightly at $t=2$ as load disturbances to observe the transient behaviour of TCUL controls after $t=3$. Patterns of the load disturbances vary from case to case, but have less than 10% of the base load values for each case. Loads are assumed to be constant admittance loads, that is, $\alpha_i = \beta_i = 2$ in (2) for all the loads. The sensitivity values, a_{kj}, vary depending on loading conditions as well as on tap positions, and are consequently different from case to case. Therefore, only the pre-disturbance values for the base load conditions are given in Table 2 for reference. Fig. 4 shows transient behaviour of voltages and tap ratios obtained by the numerical simulations. In this Figure, plots "○△□" indicate that their voltages are regulated within their thresholds, while "●▲■" represent the violations. In the following, the simulation results are examined for each case.

Cases 1 and 3

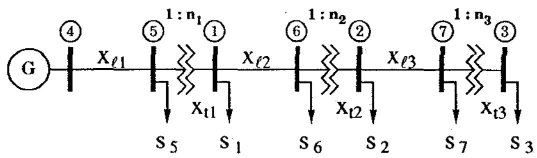

Fig. 3 An Example System

Since the example system includes three TCUL transformers, sufficient conditions for stability are given by (10) with $N=3$. In cases 1 and 3, these conditions hold except for the third condition relating to tap changer No. 3 as follows.

$$\tilde{a}_{31} \cdot d_1 + \tilde{a}_{32} \cdot d_2 + \tilde{a}_{33} \cdot d_3 > 2\varepsilon_3 \tag{13}$$

where the local stability condition for $S=\{3\}$ holds as follows.

$$\tilde{a}_{33} \cdot d_3 < 2\varepsilon_3 \tag{14}$$

Conditions (14) guarantees that n_3 itself is locally stable and the sustained oscillation of n_3 never occurs independently. However, condition (13) implies that oscillatory behaviour in n_3 may occur depending on initial conditions of voltages. When we observe Fig. 4 for case 1, surplus tap operations of n_3 are seen at $t=3$ and 4, caused by the tap operations of n_1 and n_2 at $t=2$ and 3, respectively. In case 3, we can see that more operations of n_3 are required before reaching the equilibrium. In these cases, only n_3 shows the oscillatory behaviour predicted by condition (13).

Cases 2 and 4

These cases represent oscillatory behaviour of two tap changers, where conditions (10) for $k=2$ and 3 are violated as follows.

$$\begin{cases} \tilde{a}_{21} \cdot d_1 + \tilde{a}_{22} \cdot d_2 + \tilde{a}_{23} \cdot d_3 > 2\varepsilon_2 \\ \tilde{a}_{31} \cdot d_1 + \tilde{a}_{32} \cdot d_2 + \tilde{a}_{33} \cdot d_3 > 2\varepsilon_3 \end{cases} \tag{15}$$

where the local stability conditions for $S=\{2\}$, $\{3\}$, $\{2,3\}$ are satisfied. Observation of Fig. 4 for these cases shows that the increased tap operations are carried out in n_2 and n_3 due to the interaction among tap changers, making the transient term longer.

Case 5

This case is to examine unstable oscillations as an extreme situation. In this case, the local stability conditions for $S=\{2,3\}$ are violated as follows.

$$\begin{cases} \tilde{a}_{22} \cdot d_2 + \tilde{a}_{23} \cdot d_3 > 2\varepsilon_2 \\ \tilde{a}_{32} \cdot d_2 + \tilde{a}_{33} \cdot d_3 > 2\varepsilon_3 \end{cases} \tag{16}$$

where the local stability conditions for $S=\{2\}$, $\{3\}$ are satisfied. From the

Table 2 Sensitivity Value $A = [\partial v / \partial n]$

Cases 1, 2	Cases 3 ~ 5
$A = \begin{bmatrix} 0.96233 & 0.00236 & 0.00004 \\ 1.02951 & 0.93918 & 0.00008 \\ 1.05102 & 0.95880 & 0.99122 \end{bmatrix}$	$A = \begin{bmatrix} 0.83380 & -0.03895 & -0.02878 \\ 0.88128 & 0.92765 & -0.03365 \\ 0.88543 & 0.93203 & 0.97769 \end{bmatrix}$

Table 1 Parameters Used for Numerical Simulations

	transfomer and line impedances (%)						load consumptions (p.u.)					
	x_{t1}	x_{t2}	x_{t3}	$x_{\ell 1}$	$x_{\ell 2}$	$x_{\ell 3}$	s_1	s_2	s_3	s_5	s_6	s_7
Cases 1, 2	j0.84	j1.00	j8.15	0.04+j0.69	0.07+j0.69	0.16+j0.97	3.00+j1.44	1.00+j0.48	0.10+j0.05	12.0+j5.76	3.00+j1.44	0.90+j0.43
Cases 3 ~ 5	j0.84	j0.20	j0.33	0.04+j0.69	0.01+j0.14	0.01+j0.03	2.20+j1.06	0.55+j0.26	2.50+j1.20	12.0+j5.76	2.20+j1.06	0.55+j0.26

$2\varepsilon_1 = 2\varepsilon_2 = 2\varepsilon_3 = 1.8$ (%) for Cases 1 ~ 4. $2\varepsilon_1 = 1.8$, $2\varepsilon_2 = 0.94$, $2\varepsilon_3 = 1.0$ (%) for Case 5. $d_1 = d_2 = d_3 = 1.0$ (%) for all Cases. (100 MVA base)

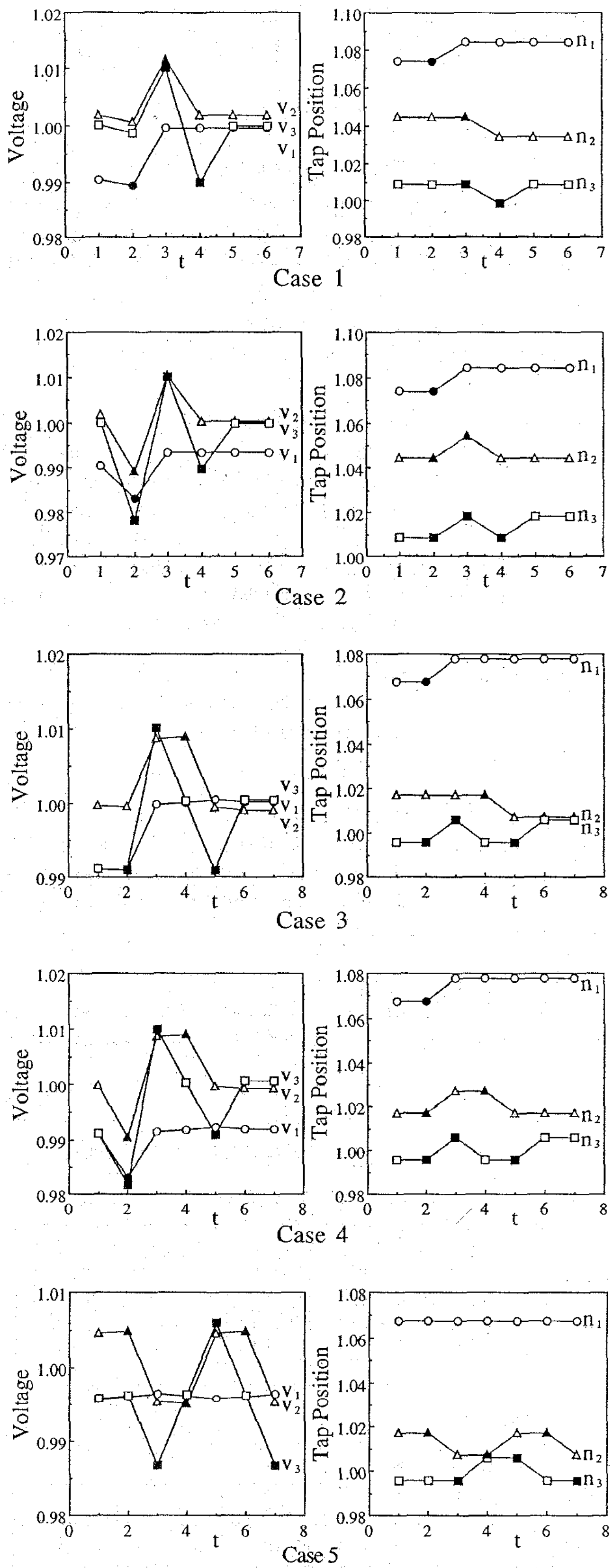

Fig. 4 Simulation Results (Simplified TCUL Model)

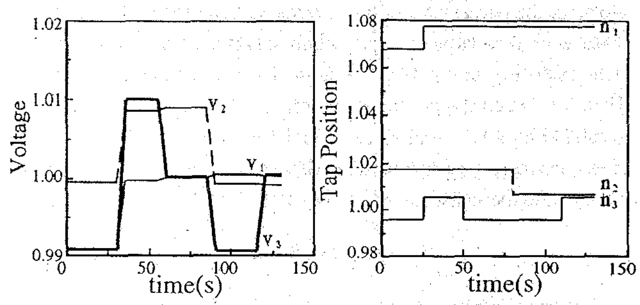

Fig. 5 Simulation Results for Case 3 (Detailed TCUL Model)

simulation results, sustained oscillations between n_2 and n_3 are observed, where v_2 and v_3 in turn exceed their thresholds and interfere with each other. Even though such situations are not likely to occur in real systems, this case may be helpful to interpret the stability conditions derived in this paper as well as to analyze more complicated phenomena in actual situations.

Fig. 5 shows the behaviour of voltages for case 3 obtained by using a detailed model of a voltage integration type controller, where the time delay is a function of the voltage deviation exceeding the deadband; typical parameters (an integration threshold of 20 %s and an additional time delay of 10 s) are used here. As is seen from the Figure, an oscillatory action similar to that obtained by the simplified model is observed. Similar results have also been obtained in the other cases.

As seen from these examples, we can understand that when some of the conditions (10) are violated the corresponding tap changers may behave in an oscillatory way, resulting in increased tap changing operations. Such situations have been examined in cases 1-4. Another point to be noted is that conditions (10) for stability of the total system include various combinations of local stability conditions for a set of TCUL controls. If such local stability conditions are violated, sustained oscillation may occur among the corresponding tap changers. This situation has been examined in case 5.

VI. Conclusions and Discussions

Tap changing operations of existing types of TCUL controls are investigated using a discrete model of tap changing dynamics. Interference among multiple TCUL controls can be a factor in unnecessarily increasing tap operations. The oscillation phenomena are caused by the insufficient size of the equilibrium, that is, unsuitably small values of the deadbands of TCUL controls, while an equilibrium of sufficient size to guarantee the non-existence of oscillations has been assumed so far in previous voltage stability studies. In this sense, newly obtained results in this paper and those in the previous works should compliment eachother.

Sufficient conditions for stability with respect to the interaction between multiple TCUL controls are derived based on Liapunov's stability theorem. The derived stability conditions can be divided into multiple sets of local stability conditions with respect to interactions between specific TCULs, expressed in terms of the step sizes of tap positions, deadbands of voltages, and sensitivity values of voltage to tap positions (dv/dn). The satisfaction of the derived conditions guarantees the nonexistence of interaction for all the initial voltages, while a violation implies the existence of interaction for some initial voltages.

Numerical examinations are carried out on a typical radial network with multiple TCUL controls, where a simplified model as well as a detailed model of the voltage integration type controller are used. The examinations show that unnecessarily increased tap operations and further sustained interaction occur, if coordinated design of deadbands and step sizes of tap positions is not carried out taking into account the sensitivity dv/dn. The cases studied may be very elementary when compared with real phenomena. Generally, for different models or types of TCUL controllers, different phenomena or even different sequences of tap operations may be observed. However, this does not affect the validity of the derived conditions since the essence of the oscillatory action is whether or not some tap operations cause violation of the voltage controlled by the other taps, and the derived conditions are exactly what are needed to predict it.

The conditions derived here may also give useful knowledge in the assessment of existing TCUL controls as well as in coordinating them. Possible performance criteria for these problems may be those to evaluate both "the quality of voltage" and "the life of the apparatus," such as the standard deviation of voltage violations and the total number of tap movements throughout a year, respectively. The minimum value of the deadband given by each of the obtained conditions seems optimal in the sense that the values smaller than this will make the number of tap operations unnecessarily large due to the oscillatory action, while larger values will increase the voltage deviations. It seems a possible strategy that the deadbands are first set based on the conditions derived here and then parameters concerning the time delays are adjusted to satisfy the requirement for the voltage quality. The fact that the optimal values of deadbands vary depending on loading conditions, as well as on the operation modes of TCULs (activated or blocked), also implies the possibility of more sophisticated coordinated schemes such as time variant setting of parameters, or adaptive type controllers. We feel this paper would seem to provide the starting point for tackling such future problems. We suggest that the present situation should be assessed first from the viewpoint of the conditions derived in this paper since, when tap operations look normal as is the case in usual situations, the problem seems to be overlooked, even if tap operations are unnecessarily increased.

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Appendix

Function $V(t)$ of (6) is written as

$$V(t)=\sum_{k=1}^{N} V_k(t) \quad ; \quad V_k(t)=u_k(t)^2 \tag{A-1}$$

where each term $V_k(t)$ directly represents voltage deviation at TCUL node k.

Substituting (5) and (6) with $\Delta L = 0$ into (7), we obtain

$$\Delta V=\sum_{k=1}^{N}\Delta V_k<0 \quad ; \quad \Delta V_k=-c_k(2u_k-c_k) \tag{A-2}$$

Sufficient conditions for $\Delta V<0$ are given as $\Delta V_k<0$ for $k=1,\cdots,N$. Note that each condition $\Delta V_k<0$ represents a necessary and sufficient condition for $V_k(t)$ to be a monotonically decreasing function with respect to t; The condition $\Delta V_k<0$ is equivalent to

$$\begin{aligned} &0<c_k<2u_k \quad (u_k>0)\\ &2u_k<c_k<0 \quad (u_k<0)\end{aligned} \tag{A-3}$$

Conditions (8) and (9) are equivalent to (A-3) for $k=1,\cdots,N$.

Note that the violation of k-th condition in (10) implies that there exist solutions $u(t)$ such that $u_k(\tau)<\varepsilon_k$ and $\Delta V_k>0$ at some τ. Therefore, the violation of (10) means the existence of such oscillatory solutions for some initial conditions.

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Discussion

Y. Liang and C.O. Nwankpa Drexel University, Philadelphia, PA 19104): The authors are to be congratulated for starting to tackle the interactions among multiple TCULs. This is an existing problem which is often overlooked in power industry. Traditionally, this problem can be solved or alleviated by widening deadband settings. Unfortunately, wider deadband will cause the system voltage to deviate more from the desired value. This conflicts with the purpose of installing TCUL transformers in power system. The appropriate goal is to set the deadband as small as possible while not causing voltage oscillation. With respect to the method developed in the paper, we have the following comments and questions.

1. The authors have developed sufficient conditions for stability based on Liyapunov's theorem. As this theorem is conservative, we would like to know how close is the deadband settings that satisfy this sufficient condition to the smallest possible values?

2. In this paper, the authors employed a static load model in deriving the dynamic system equations. The justification of doing this is that "the time scale for TCUL control actions is in general of the order of several tens of seconds to minutes." But, the time constant for a nonlinear dynamic load model in many cases are also around tens of seconds to minutes[D1][D2]. What measures should be taken for such cases in the system under investigation?

3. We have noticed in our experience that oscillations will more likely occur among cascaded TCULs than among the paralleled TCULs. Do the authors experience concur with this?

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N. Yorino, M. Danyoshi and M. Kitagawa: We would like to express sincere thanks to the discussers for their interest in the paper and for their valuable remarks and questions. We would like to offer the following comments in response.

In reply to the first question, we wish to mention that the derived conditions are sufficient conditions but are not conservative. As is investigated in the last part of section IV in the main text, the occurrence of the oscillatory actions depends not only on too small deadband setting but also on initial conditions of voltages. In this sense, conditions (10) give the critical values of the deadbands which guarantee the nonexistence of the oscillatory behaviour for all the initial voltages. In other words, smaller values than those cause oscillatory behaviour for some initial voltages. In fact, the numerical simulations of Fig. 4 in this paper show that only slight violations of conditions (10) allow the oscillations. It is noted that these oscillations do not always appear for the same setting of the deadbands when the initial voltages are changed due to the modification of the initial loading conditions.

Concerning the second question, we must admit that the treatment of loads in this paper is not fully satisfactory when we look at real loads. To take into account the load dynamics more exactly, it would require a more complicated expression than our formulation (5). However, since load dynamics are different from feeder to feeder and always vary with respect to time, it seems difficult to obtain enough data from the system to be used in such an exact formulation. Therefore, in this reply, we would like to only add some remarks about the usage of the derived conditions from the practical point of view. As is known, a secondary voltage of transformer after a tap movement changes with respect to time; typically, the initial variation or oscillation decays very fast of the order of seconds and then varies slowly. Although it is difficult to identify whether the slow variation of such a specific voltage comes from the load dynamics or static change in load consumptions, seemingly enough converged values of voltage can practically be obtained within the time scale of tap movement to compute the sensitivity of the voltage to the tap position, corresponding to a_{kj} in conditions (10). Since, as is investigated in this paper, the oscillatory phenomenon occurs only around the reference voltage, the sensitivity data gathered from daily normal operation in such a way seems to be highly reliable to be used in conditions (10). We think that the derived conditions are useful but require great care for the treatment of the sensitivities a_{kj} particularly for slow dynamic loads.

In reply to the final question, we have exactly the same experience. This is explained from a characteristic of sensitivity matrix $A=[a_{kj}]$ as follows. In our experience, the difference between the cascaded and paralleled connections appears in the off-diagonal terms of A mainly. To be specific, the off-diagonal terms for the cascaded case are in general larger than those for paralleled case, while no major differences appear in the diagonal terms between both cases. This results in large values of the left-hand side of conditions (10) for the former case and small values for the latter case. Therefore, it follows that, when a same setting of deadband is used for both cases, the conditions (10) tend to be violated for the cascaded case.

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