A CONTROL PROBLEM FOR DECENTRALIZED AUTONOMOUS VOLTAGE CONTROLLERS

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Abstract – This paper studies an optimal control problem for decentralized autonomous voltage controllers for a future distribution system. An optimal control problem is formulated with an objective of minimizing the total voltage errors of the system. The control problem is extended into a decentralized autonomous control scheme, where operation data are assumed to transfer among controllers. The proposed control method guarantees that the control performance is nearly optimized, avoiding harmful interference among distributed controls and reverse control actions. The effectiveness of the proposed method has been confirmed through numerical simulations using a 53-bus test system having 39 TCUL transformers.

Keywords: tap change under load transformer (TCUL), Step Voltage Regulator (SVR), Static Var Compensator (SVC), distributed autonomous control, voltage control, electric power systems

1 INTRODUCTION

Conventionally, voltage controls in subtransmission and distribution systems have been performed based on the distributed control scheme, where tap changing devices such as TCUL, SVR as well as static capacitors are widely used. However, the circumstance has been changing considerably due to increased number of distributed generators as well as new control devices such as FACTS. This makes it difficult to coordinate the controls. Various studies have been carried out so far such as in [1-9]. A straightforward approach to the coordination problem is to introduce a centralized control scheme in a specific control area. In this case, the control performance can be optimized among the existing controllers, but the maintainability, flexibility for future extension as well as the fault tolerance will be degraded.

Another trend is to develop a decentralized control scheme to coordinate the distributed controllers. In this case, although it is free from the disadvantageous issues of the centralized control scheme, a coordination problem is critical among various and numerous controllers. The problem includes:

- coordination between slow control devices (tap changing devices) and new types of fast controllers such as SVC
- optimization of control performance as a total system

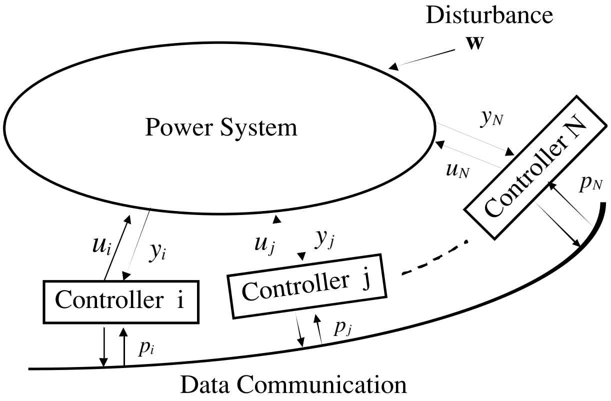


Figure 1: Distributed Voltage Controllers

Concerning the first problem, a new type of SVC has been developed, where a special design of steady state characteristic (droop) is applied to the controller, making possible the coordinated operation with the conventional SVR [8]. The second problem includes detrimental characteristics of the existing tap changing devices [10-16]. It has been clarified that the existing types of TCUL can cause unnecessary tap operations due to the interaction among controls. Furthermore, they can accelerate the voltage collapse in heavy load conditions.

This paper studies a decentralized autonomous voltage control problem, taking into account the existing problems as well as a circumstance in a future power system. It is assumed that various types of numerous voltage controllers are distributed in a system and that data communication lines are available connecting controllers as shown in figure 1, where frequency of the data transfer is assumed to be of the order of minutes. To develop a new scheme in the circumstance, we first formulate an optimal control problem to maximize the control performance from a point of view of the total system. In the control problem, tap changing transformers such as TCUL and SVR are major target controllers to be controlled. Static capacitors are not treated in the problem but will be discussed in this paper. Fast devices such as SVC are assumed to have a proper design for the steady state characteristics. Since the steady state characteristics of fast devices may affect considerably the performance of the total system, they are included in the formulation of the proposed optimal control problem. Then, two approaches will be presented. One is a centralized control scheme where the control performance is optimized. The other is decentralized autonomous control scheme, which is a main topic of this paper. It will be shown that the performance of the latter scheme is high enough compared with the centralized scheme.

2 DEFINITION OF OPTIMAL VOLTAGE CONTROL PROBLEM

In the circumstance of figure 1, the frequency of data communications among controllers is assumed to be of the order of minutes as mention in the Introduction. Therefore, to formulate a problem, fast dynamics of the order of seconds will be neglected and their steady state characteristics will be taken into account. This treatment is based on the time scale separation technique to coordinate the controls of the order of minutes [16,17]. In this time scale, we assume the following system model.

$$v(t+1) = g(v(t), u(t), w(t)) \tag{1}$$

where, v is voltage vector whose elements are individually controlled by voltage regulators; w is a disturbance vector representing load consumptions; u is a control vector by the voltage regulators. In this model, system (1) is assumed to contain the following type of local controllers.

$$u_k(t) = h_k(v_k(t), p_k(t)) \tag{2}$$

where $v_k(t)$ is an element of $v(t)$ representing the local voltage, and $p_k(t)$ is a vector given by data communication. Note that all the fast dynamics are neglected in (1) and (2) based on the time scale separation theory. More exact forms for voltage control devices will be given in the latter sections.

By linearizing (1), we obtain:

$$\Delta v(t+1) = A(t)\cdot\Delta v(t) + B(t)\cdot\Delta u(t) + C(t)\cdot\Delta w(t) \tag{3}$$

where

$$\Delta v(t) = v(t) - v_{ref}$$
$$\Delta u(t) = u(t+1) - u(t)$$
$$\Delta w(t) = w(t+1) - w(t)$$

Note that v_{ref} is a vector of reference values of controlled voltages so that $\Delta v(t)$ directly represents the voltage error vector. In general, matrices A, B and C vary with time depending on the linearization point (v_{ref}, $u(t)$, $w(t)$).

Then, an optimal control problem is defined as follows:

$$\min_{\Delta u(t), t=0,1,\cdots} \sum_{t=0}^{\infty} V(\Delta v(t)) \tag{4}$$

where

$$V(\Delta v(t)) = \sum_{k=1}^{N} m_k\{\Delta v_k(t)\}^2 = \Delta v(t)^T \cdot M \cdot \Delta v(t) \geq 0 \tag{5}$$
$$M = diag[m_1, m_2, \cdots, m_N]$$

where M is a diagonal weight matrix, representing the weights for bus voltages. The above objective function represents the total voltage errors of the system studied. An important issue is that function (5) is a monotonically increasing positive definite function of $|\Delta v|$, and therefore, the stability of the system is guaranteed by the Liapunov theorem if

$$\Delta V(t) = V(t+1) - V(t) < 0 \tag{6}$$

Thus, condition (6) is adopted as a necessary condition for control. Now, an equivalent expression of the objective function of (4) with finite time T is written in terms of $\Delta V(t)$ of (6) as follows.

$$\sum_{t=0}^{T} V(t) = \sum_{t=0}^{T-1} (T-t)\cdot\Delta V(t) + (T+1)\cdot V(0) \tag{7}$$

For this control problem, since control $u(t)$ will be determined sequentially at each time t, a best possible strategy may be to minimize each term of (7) sequentially. That is, the following control strategy is adopted as an optimal control law in this paper.

$$\min_{\Delta u(t)} \Delta V(t) < 0 \tag{8}$$

The condition implies that control at each time is determined so that the total voltage error is maximally reduced, and that unless satisfying condition (6) no controls are carried out. This control law guarantees that the reverse control actions as well as oscillatory actions are avoided since these phenomena are accompanied with the violation of (6) [12,15].

3 VOLTAGE CONTROLLERS

3.1 Tap Changing Transformers

Tap changing transformers include TCUL, SVR, etc. They are modeled as follows.

$$\left.\begin{aligned} & n_k(t+1) = n_k(t) + r_k \Delta u_k(t) \\ & \Delta u_k(t) = \begin{cases} 1 \\ 0 \\ -1 \end{cases} \\ & \underline{n}_k \leq n_k(t) \leq \overline{n}_k \end{aligned}\right\} \tag{9}$$

where

$n_k(t)$: tap position of device k at time point t

r_k : unit size of tap change

The purpose of this paper is to determine an optimal control for $\Delta u_k(t)$ in (9) to design the controller of (2).

3.2 Fast Control Devices

Recent trend for fast devices such as SVC is that a special control design is adopted so as to respond to the fast voltage deviations only in order to perform the coordination with the existing tap changing devices [8]. Such a fast device can be treated as the static device having steady state voltage dependent characteristic in (2), which is similar to voltage dependent load. In this situation, the tap changing devices are responsible for absorbing the slow voltage deviations, and therefore, the coordination among the tap changing controllers is an essential problem. This is exactly the purpose of the paper. It should be noted that an optimal design of the steady state characteristics for the fast control devices is another important subject for this study, but it will not be discussed hereafter.

3.3 Static Capacitors

Although static capacitors are important voltage control devices, frequency of control action is much less than those of tap changing transformers. This is at least the case in Japan. This implies that an examination in further slower time scale is necessary to construct an optimal control design for the total system, where the result of this paper can be fully applied since the time scale separation theory allows independent design for different time scales. Although this is not a scope of this paper, it is expected that a quite similar approach to this paper is possible. At present, we suppose that the conventional scheme is useful for the static capacitors.

4 OPTIMAL CONTROL CRITERION

4.1 Optimal Centralized Control Method

A simple control index as well as a control method will be presented based on the control law given in section 2. For this purpose, we will add the following assumption in (3).

$$A(t) = I \tag{10}$$

This assumption implies that slow network dynamics are negligible. This assumption may not always hold as investigated in various studies concerning load dynamics such as [18]. However, it is also a fact that no apparent slow dynamics have been detected in Japanese systems in previous measurement data. Therefore, the above treatment may be valid for such systems.

With the above assumption (10), we substitute the system model (3) into (5), with taking into account device model (9). Then, we obtain the following equation. (See Appendix.)

$$\Delta V(t) = V(t+1) - V(t) \cong -\sum_i 2 \cdot s_i(\Delta v) \cdot \Delta u_i \tag{11}$$

where $s_i(\Delta v)$ is a element of

$$s(u(t)) = u(t)^T \cdot M \cdot B(t) \tag{12}$$

Equation (11) implies that the most effective device to reduce $\Delta V(t)$ is found from the values of $s_i(\Delta v)$. That is, an optimal control criterion may be written as:

Device k with the maximum absolute value such that

$$\left|s_k(\Delta v)\right| = \max_i \left|s_i(\Delta v)\right| > \alpha \tag{13}$$

will be activated to satisfy (6).

This criterion only specifies a single device to act at each moment. After the device takes the action, no devices should not be activated until the values of s_k are updated due to the action. Note that criterion (13) requires a centralized control scheme to compare the values of s_k to perform the control.

4.2 Distributed Autonomous Control Method

To construct a distributed control scheme, a slightly less restrictive criterion is defined. A suboptimal criterion may be written as:

All the devices satisfying

$$\left|s_k(\Delta v)\right| > \alpha \tag{14}$$

will be activated to satisfy (6).

In this case, although the control performance may slightly be deteriorated, the individual control actions are possible based on their own decisions by the individual controllers. In order to evaluate the left term of (14), voltage deviation vector Δv is necessary. We assume that the data of Δv are obtained based on data transfer through the communication line connected among the controllers. It is noted that only a part of the elements of Δv is required for a specific device to estimate $s_k(\Delta v)$ in our previous examinations. Therefore, data communications may be limited in a local area in actual situations. Although further examinations are required to develop a suitable scheme for data communications, this is not a scope of this paper. In the following numerical examinations, we assume that all the elements of Δv are available in every device. Then, the control performances will be studied to examine the above control criteria.

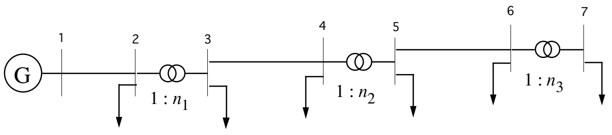


Figure 2: 7bus 3 Tap system

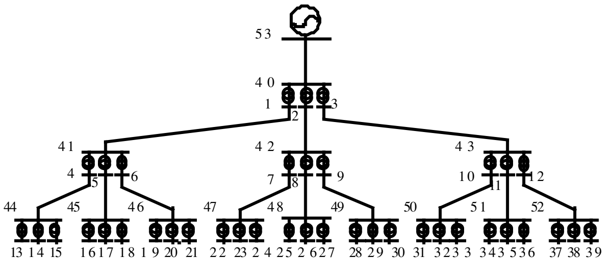


Figure 3: 53 bus 39 Tap system

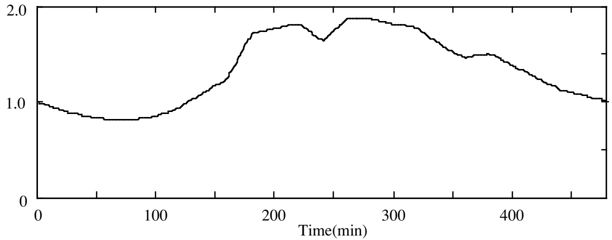


Figure 4: Load pattern

5 NUMERICAL SIMULATIONS

Numerical Examinations have been carried out using example systems shown in figures 2 and 3, where load pattern is assumed as shown in figure 4 for all the loads. Then, we will pay attention to the tap control actions in this examination.

Figure 5 shows the simulation algorithms for the optimal control scheme and the distributed autonomous control scheme proposed in the previous section. In theses simulations, we use typical parameters for the existing TCUL transformers. The duration of unit time is assumed to be one minute. The algorithm adopted for the optimal control is such that in each time a most effective tap is repeatedly changed until the condition is satisfied, which is based on the optimal control criterion of (13). On the other hand, the criterion of (14) is used as the distributed control algorithm, which allows that individual controllers change their tap positions on their own decisions. For both the algorithms, we add a restrictive condition that for each device only the unit change in tap position is permitted during the unit time. It is noted in figure 5 that $\Delta v \in E$ implies that no voltages are violated.

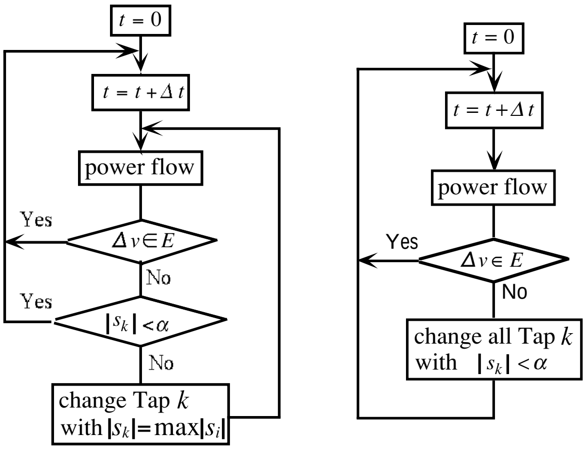
For the comparison of control schemes, we have carried out simulations for a typical tap controller referred to as the 90 relay, which is widely used in Japan. The existing 90 relay works such that the tap position is changed by unity when the integration of voltage deviation with respect to time hits a threshold.

The threshold of the 90 relay is usually an adjustable parameter to optimize the control performance. For a larger value of the threshold, the mean voltage deviation with respect to time will increase but the number of tap control actions will decrease, and vice versa. In the proposed control schemes, such an adjustable parameter is the control threshold α in (13) and (14).

The performance of a control scheme will be evaluated through the mean voltage error and the number of tap actions for a specific time duration. Therefore, numerical simulations have repeatedly been carried out to obtain statistical data for the above two indices for different setting of the thresholds.

The results are shown in figures 6 and 7, where the square plots have been obtained by the optimal control scheme, the triangle plots by the distributed autonomous control scheme, and the circle plots by the conventional control scheme by the 90 relays. Each plot shows the total number of tap action and the mean voltage error obtained by the simulation for 480 minutes under the load disturbance of figure 4. The loci of the plots indicates the performance of each control scheme for different settings for the threshold.

It may be observed from figures 6 and 7 that the distributed autonomous control scheme shows almost equivalent performance to that of the optimal control scheme, which has much higher performance compared with the conventional scheme. This follows from the fact that the loci for the proposed control scheme is located closer to the origin compared with that of conventional scheme, implying that a smaller voltage error and/or less tap actions for all possible settings of the threshold.



Optimal scheme Proposed scheme

Figure 5: Algorithms for simulations

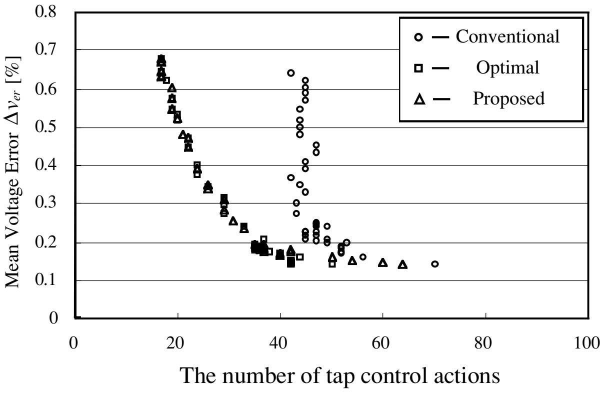


Figure 6: Control performances in 7 bus system

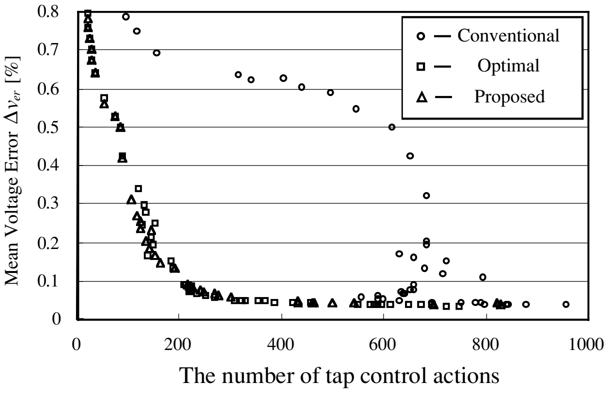


Figure 7: Control performances in 53 bus system

6 CONCLUSION

A new control scheme is proposed for distributed voltage control devices assuming a circumstance of a future power system, where data communications will be carried out among distributed controllers. Tap changing transformers such as TCIL and SVR are the target devices to be controlled. A suggested scheme is an autonomous control scheme where the individual controllers work autonomously based on their own decision in order to optimize the control performance from the point of view of the total system. An optimal control problem is formulated to minimize the voltage errors of the total system. A control criterion is derived for tap changing devices, where fast control devices are implicitly treated based on their steady state characteristics.

The proposed control scheme has been tested numerically for two example systems, where the conventional scheme and optimal control scheme are used as benchmarks for comparison. The mean voltage error and the total number of tap actions is used as indices for the comparison. The numerical simulations have shown that the distributed autonomous control scheme has much higher performance compared with the conventional scheme. The performance was almost equivalent to that of the optimal control scheme.

Our goal is a fully autonomous system, where no control or computation at a local control center is necessary. To realize the system, a key issue is that each controller is able to compute the control index, the left-hand side of (14), which requires the voltages in a restricted area, which are assumed to obtain through data communications. Since we suppose that the same type of hardware is used for all the controllers, the proposed scheme is highly economic. The roll of a local control center in this situation is, for example, to adjust on line the control threshold, the right-hand side of (14), through data transfer so as to meet the scheduled limits on the number of the tap actions during some period. We have confirmed that different settings of the threshold for different devices can also work, where the individual control performance are adjustable for the balance between the voltage violation and the number of tap actions.

Although fundamental ability of the proposed control scheme has been clarified in this paper, several subjects are left to be studied. They are concerned with an optimal method of data communications and an optimal design of steady state characteristics for fast control devices such as SVC, etc. An optimal control design for static capacitors, which requires a similar investigation in the slower time scales as discussed in the main text, is also an important subject in the future.

7 APPENDIX

Equation (9) may be written in vector form as:

$$n(t+1) = n(t) + R \cdot \Delta u(t) \qquad \text{(A-1)}$$

Under the assumption of (10), the controlled voltages, v, are determined uniquely from the network equation as functions of n and w. That is,

$$v(t) = f(n(t), w(t)) \qquad \text{(A-2)}$$

From the above two equations, we obtain

$$v(t+1) = v(t) + \left[\frac{\partial f}{\partial n}\right] \cdot R \cdot \Delta u(t) + \left[\frac{\partial f}{\partial w}\right] \cdot \Delta w(t) \qquad \text{(A-3)}$$

Subtracting v_{ref} from the both sides, we have

$$\Delta v(t+1) = \Delta v(t) + B(t) \cdot \Delta u(t) + C(t) \cdot \Delta w(t) \qquad \text{(A-4)}$$

where the coefficient matrices of the second and third terms in (A-3) are denoted as $B(t)$ and $C(t)$, respectively. This equation corresponds to (3) in the main text.

Next, (A-4) is substituted into (5), where we set

$$\Delta w(t) = 0 \qquad \text{(A-5)}$$

This treatment implies that the disturbance is not predicted in the control scheme, which is the common assumption to the linear optimal regulator in the modern control theory. It is noted that the disturbance prediction (load forecast) may be included in the future. Thus, we obtain

$$\begin{aligned} \Delta V(t) &= V(\Delta v(t+1)) - V(\Delta v(t)) \\ &= V(\Delta v(t) + B(t) \cdot \Delta u(t)) - V(\Delta v(t)) \qquad \text{(A-6)} \\ &= -2 \cdot s(\Delta v(t)) \cdot \Delta u(t) + \Delta u(t)^T \cdot D \cdot \Delta u(t) \end{aligned}$$

where

$$s(u(t)) = u(t)^T \cdot M \cdot B(t), \qquad D = B(t)^T \cdot M \cdot B(t)$$

Equation (A-6) corresponds to the expansion of $\Delta V(t)$ with respect to $\Delta u(t)$, where the higher terms do not exist since $V(t)$ is a quadratic function. Therefore, the first linear term dominates, which is also numerically confirmed. Therefore, neglecting the second term, equation (11) is obtained in the main text.

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