Abstract—Increased penetration of photovoltaic (PV) generation is expected in Japan in the near future; thus a new voltage control scheme is required in order to improve the operation of distribution networks. We propose a new voltage control scheme for distribution networks based on a multi-agent system, in which large voltage fluctuations caused by PV generations are effectively regulated by controlling the conventional types of tap-changing controllers. We achieved an optimal control performance by developing an optimal control law that is applicable to decentralized autonomous control. The autonomy is accomplished by using a multi-agent system instead of the centralized control scheme. The proposed method can be applied to general distribution network but effective approximations have been made to achieve high computation efficiency for popular radial networks. The effectiveness of the proposed scheme is demonstrated through numerical simulations with successful results.

Keywords—autonomous voltage control; distribution system; distributed generator; multi-agent; renewable energy; photovoltaic generation

I. INTRODUCTION

In recent years, a large penetration of renewable energy causes various problems relating to degradation of power system reliability. In particular, a huge photovoltaic (PV) generation penetration is expected in Japan, which will introduce considerable uncertainties and requires new approaches for reliable power system operation. PV generations are being mainly introduced in distribution feeders, in which the voltage regulation problems are critical. New control strategies are required for effective management of the voltage regulation equipment as well as control of DGs.

Previous studies are classified into several categories. The first approach is concerned with optimal scheduling problems taking into account a whole day load profile to realize loss minimization with limited switching operations [1]-[10]. The optimal schedule is useful when uncertainty in power flow is negligible even if DGs are installed. The second approach is “local control method” which performs real-time control based on local measurements, which include optimal parameter settings for OLTC [11], [12], dead band control for OLTC [13], coordination of OLTC and STATCOM [14], online and optimal OLTC control with considering multiple feeders [15], [16], and so on. Those methods focus on control of OLTC and/or SC (or STATCOM) in individual substations. These local control methods, including combined methods with optimal scheduling [17], [18], DG voltage control [19]-[21] and DG curtailment [22], are in general reliable due to their independency and simplicity of control system configuration, while the control performance tends to be limited from the point of view of coordination of multiple control devices.

Centralized control [23]-[27] is straightforward solution that maximizes the control performance. Real-time optimality is considered for whole distribution system using state estimation and optimal power flow. This approach, however, requires reliable communication link among sensors, voltage control devices and the distribution network control center. Moreover, their control schemes tend to become complicated, implying less reliable even though feasible. Such systems usually rely on the synchronized measurements for state estimation for voltage control function. This means that high performance is obtained, while a large investment as well as special attention is required for reliability against system faults.

On the other hand, distributed control method is another approach for compromising the control optimality, autonomy and reliability of control system [27]-[32]. The use of multi-agent makes possible the communication among local controls for improving control performance. In [27], a multi-agent based control scheme is proposed for dispatching DGs. Reference [28] proposes a coordinated voltage control for OLTC controls, in which remote terminal units (RTU) are treated as agents. A coordinated control between voltage regulator and DGs is proposed in [29], [30]. In such systems, control performances highly depend on their control design since the control optimality tends to be degenerated by the negotiation process among agents.

This paper proposes a new voltage control scheme for on-load tap-changing transformers for distribution systems by extending the authors previous studies [31][32]. The following characteristics (a)-(c) are new features of the proposed method different from the existing approaches.

(a) Optimal control problem is formulated to derive the optimality condition (index S) which is suited for multi-agent system. Thus, control optimality is guaranteed in a simple manner without using centralized control scheme. The word “optimal control” means the most effective tap control to minimize voltage violation, which will be defined later in equation (1). In the rest of this paper, the words are used in this context.
(b) Distributed autonomous system is constructed in which each controller reacts independently based on local measurements and the common memory called blackboard memory (BM). Advantageous feature of this control model is to guarantee autonomy of the individual controllers, using a very simple and reliable control configuration.

(c) The optimal operation of the system is provided in accordance with available data, even when the communication system is down.

The method overcomes the weakness of the centralized control schemes, while retaining the optimal performance. The effectiveness of the proposed method is confirmed through numerical simulations that include severe cases with photo-voltaic generations.

This paper focuses on a voltage control scheme for on-load tap-changing transformers. Other topics, like FACTS devices (SVC), demand response, PV inverter control and so on, are not included. These factors can be effectively included in the proposed framework but are left as our future works.

II. THE PROPOSED CONTROL SCHEME WITH MULTI-AGENTS

A. Multi-agent System

An agent is an autonomous entity that can perceive its environment, create an action according to its own decision-making, and affect to the environment by the action. Plural agents can consist of a multi-agent system, in which each agent acts autonomously in a coordinated manner to achieve a common goal. In this kind of system, the coordination between agents is one of the most essential factors and a communication function plays an important role.

In this paper, the blackboard model is adopted to achieve a seamless communication platform, in which each agent can exchange and share the information and knowledge.

B. Proposed Control System

In this paper, two kinds of agents are prepared to build an efficient system according to their roles: one upper agent (Management Agent) and many lower agents (Local Agent). Management Agent is helpful for auxiliary tasks such as system monitoring and so on but has no direct roles for real-time control, which is performed by Local Agents by their own based on the communication to BM. Each agent’s three main function parts, Interface, Knowledge Base and Sub-optimization operate as follows:

Interface: This part is in charge of perceiving the agent’s own information and other agent’s information through the blackboard. In addition, this part issues a control command derived by the sub-optimal calculation and writes the obtained data onto the blackboard to share the knowledge with other agents.

Knowledge Base: This part stores all information obtained through Interface and calculated data brought by Sub-optimization part.

Sub-optimization: This part plays an important role of sub-optimization computation, which is described later.

Fig. 1 shows a conceptual diagram of the proposed control system. BM provides the information-sharing platform and each agent can perceive the situation of other agents to issue the control signals with well-coordinated manner [31][32][35]. In addition, the useful information stored in the Knowledge Base can contribute great flexibility to the agent ability for ill-conditioned situations, such as the lack of other agents’ information and/or system change.

III. CONTROL METHOD

A. Optimal but Autonomous Control

The most distinguishing point of the proposed method is that all controllers individually act by their own decision, while the control optimality is guaranteed. This characteristic is provided by an optimal control measure “index S” that has been studied in [31][32], which will be improved to meet multi-agent system. The use of index S based on the optimal control law will avoid unnecessary negotiation process among agents and guarantees the optimal coordination of controls with respect to the amount of voltage violation as well as the number of tap changing operations in the target network.

B. Formulation of Optimal Control Method

Objective of the proposed control scheme is to minimize a positive definite function as follows:

\[
\min \int_0^\infty V(v) \, dt, \quad V : \mathbb{R}^M \rightarrow \mathbb{R}^1
\]

with a voltage violation function:

\[
V(v) = \frac{1}{2}(v - v_R)^T \cdot m \cdot (v - v_R)
\]

\[
= \frac{1}{2} \sum_{i=M}^M m_i \cdot (v_i - v_{Ri})^2 \geq 0
\]

Where \( v = [v_1, \ldots, v_M]^T \in \mathbb{R}^M \) represents voltage vector at M observation points; \( v_R \in \mathbb{R}^M \) are reference voltages; \( m = \text{diag}[m_1, \ldots, m_M] \) are weight coefficients; dead band \( d \) is assumed to define an equilibrium zone \( E \) around the reference voltages.

\[
V(v) = 0 \quad \text{for} \quad v \in E = \{ v | v_{R} - d < v < v_{R} + d \}
\]

In general, the voltages are governed by the power flow equations, which are represented by the following expression for simplicity.

\[
v = h(L, n) \cdot v_R^0 \rightarrow \mathbb{R}^M
\]

where,

\[
n = [n_1, \ldots, n_M]^T \in \mathbb{R}^M : \text{tap positions of transformers}
\]

\[
L = [L_1, \ldots, L_M]^T \in \mathbb{R}^M : \text{load parameters}
\]
It is assumed that the tap positions are discrete variables, which are controlled by the following form.

\[ n(t + 1) = n(t) + \Delta n(t) \]

\[ \Delta n(t) = r_k f_k(t) : \text{control at time } t \]

\[ f_k(t) = \begin{cases} +1 & \text{(unit increase)} \\ 0 & \text{(no operation)} \\ -1 & \text{(unit decrease)} \end{cases} \] (5a)

\[ k = 1, 2, \ldots, N \]

The above equations are represented by the vector form as:

\[ n(t + 1) = n(t) + \Delta n(t) \]

\[ \Delta n(t) = R \cdot f(t), \quad R = \text{diag}[r_1 \cdots r_N], \] (5b)

\[ f(t) = [f_1(t) \cdots f_N(t)]^T \]

When tap position is controlled based on (5), the change in the objective function \( \Delta V(t) \) is given by the following equations.

\[ V(v(t + 1)) = V(v(t)) + V(n(t)) \] (6)

\[ \Delta V(t) = \frac{\partial V}{\partial v} \left[ \frac{dv}{dn} \right] \Delta n(t) \]

\[ = S(t) \cdot f(t) = \sum_{k=1}^{N} S_k(t) f_k(t) \] (7)

where

\[ S(t) = \left[ \frac{\partial V}{\partial v} \right] \left[ \frac{dv}{dn} \right] \cdot R = [S_1(t) \cdots S_N(t)] \] (8)

In the above equations, \( \left[ \frac{dv}{dn} \right] \) is the matrix of voltage/tap sensitivity determined from the power flow equation (4). An observation of the above equation shows that the most effective control for decreasing \( V \) can be identified by the values of \( S_k(t) \), which is referred to as index \( S \) hereafter.

C. Optimal Control Law

Assuming a control method that only a single tap is selectively controlled by unit step in each control cycle at time point \( t \), the best possible strategy for (1) is clearly to perform the control for minimizing \( V \) at each time \( t \) based on the following approximation.

\[ \min_n \int_0^1 V(v) dt = \sum_{i=1}^{n} \min_{n(i)} V(v(t(i))) \] (9)

Theoretical derivation of (7) implies that the minimization is achieved by a simple control law, that is, to select the tap having the maximum absolute value among index \( S \) and change it up or down to satisfy the following condition.

\[ \min_{n(i)} V(v(t + 1)) = V(v(t)) + \min_{f_k(t)} \{ S(t) \cdot f(t) \} \] (10)

That is, the optimal control law is given by

\[ f_k(t) = \begin{cases} 1 & \text{if } |S_k(t)| = \max_i |S_i(t)| \text{ and } S_k(t) < 0 \\ -1 & \text{if } |S_k(t)| = \max_i |S_i(t)| \text{ and } S_k(t) > 0 \\ 0 & \text{if } |S_k(t)| < \max_i |S_i(t)| \end{cases} \] (11)

Note that the optimal control law requires the comparison among index \( S \) to find their maximum.

D. Sub-optimal Control Law

Introducing system wide threshold value can avoid the comparison of index \( S \). The tap change is determined by the following rule:

\[ f_k(t) = \begin{cases} 1 & \text{if } S_k(t) < -\alpha & \text{[up] for all } k \\ -1 & \text{if } S_k(t) > \alpha & \text{[down] for all } k \\ 0 & \text{if } |S_k(t)| < \alpha & \text{no operation} \end{cases} \] (12)

where, \( \alpha \) is a threshold value for all the taps throughout the target system. Based on this control law, each controller \( k \) can judge its control only by its own index, while the control performance may be neglected. In the proposed method, the optimal control law will be used primary and the suboptimal control law is also used for “timer” control logic as well as for back up control.

E. Computation of Index \( S \)

The optimal control law can also be useful in constructing a centralized optimal control system, where index \( S \) may be computed based on the state estimation in optimal manner. However, the authors are more interested in less complicated and more reliable autonomous decentralized system as mentioned in the Introduction. In this case, a key subject is a computation of Index \( S \), which is given as:

\[ S_k(t) = r_k \sum_{i=1}^{n_k} d_{vi} \frac{dv}{d_{ni}} = r_k \sum_{i=1}^{n_k} \left( m_i v_i - v_k \right) \frac{dv}{d_{ni}} \] (13)

The necessary data are the voltage deviation vector \( v(t) - v_k \) and the voltage/tap sensitivity matrix \( \left[ \frac{dv}{dn} \right] \). As is often discussed, the voltage/tap sensitivity plays an important role in voltage stability though this is not the case in distribution systems. In fact, various analyses have shown that the change in \( \left[ \frac{dv}{dn} \right] \) in distribution system is negligible. Furthermore, radial configuration is used for the distribution system in Japan, where the following characteristics are confirmed in the sensitivity matrix.

\[ \frac{\partial v}{\partial n_i} = \frac{\partial v}{\partial n_k} \quad \forall i \in U_k \]

\[ \frac{\partial v}{\partial n_k} = \frac{\partial v}{\partial n_k} \quad \forall i \in L_k \] (14)

\[ \frac{\partial v}{\partial n_k} = 0 \quad \forall i \in N_k \cup M_k \]

where

\( p_k \): node number of primary side of the target tap \( k \),

\( q_k \): node number of secondary side of the target tap \( k \),

\( L_k \): the set of node numbers in lower area than \( q_k \),

\( U_k \): the set of node numbers in lower area than \( q_k \) except \( p_k \) and \( L_k \),

\( N_k \): the set of node numbers in upper area than \( p_k \),

\( M_k \): the set of node numbers not belonging to \( U_k, L_k, N_k \).

Furthermore, all transformers are assumed “ideal” such that no core loss, no leakage flux and no copper loss of all windings.
exist. The assumption implies the following approximation in the evaluation of (13):
\[
\frac{\partial v_i}{\partial c_i} = 0, \quad \frac{\partial v_i}{\partial m_i} = 1
\] (15)

The above approximation considerably simplifies the computation of index \( S \) since the voltage/tap sensitivity matrix is simply determined by the network connection status. Most advantageous feature of this method is that no major degradation in the control performance is observed, while the required information and calculation burden is greatly reduced. Therefore, this method is more reliable due to its simplicity and is quite suited for the autonomous distributed control that relies on no centralized computations. It is however noted that the centralized computations are independently performed in Management Agent in Fig. 1 although there are no mandatory roles for carrying out the real-time control. The centralized computations are auxiliary function to improve the reliability and performance of voltage control in the proposed scheme.

IV. CONTROL OF DISTRIBUTION FEEDER VOLTAGES

A. Multiple Voltage Observations

In these days, voltages in a distribution feeder tend to vary more rapidly due to the increased installation of PV generators. Voltage variations are becoming larger depending on weather conditions, requiring a sophisticated control scheme that regulates all the fluctuating distributed voltages within the allowable band. We rather use SVR and OLTC, tap-changing transformers, than to use expensive FACTS devices such as SVC. Although series connected SVRs such as in Fig. 2 are known to be difficult to control, the proposed control method shows very high performance in such a series configuration without using SVC, providing a solution for the emerging voltage problem.

The purpose of voltage control of distribution feeder is that fluctuating set of voltages are all controlled within the upper and lower limits. Assuming that multiple SVRs are used, their individual control areas are defined as shown in Fig. 2. In each control area \((k)\), multiple voltages are measured and they are mainly under the control of tap \( k \) within their allowable upper and lower voltages as follows.

\[ v_{L,k} \leq v_i \leq v_{H,k}, \quad i \in \text{area}(k) \] (16)

The situation is described in Fig. 3. It is noted that voltages in control area \( k \) are not only controlled by tap \( k \) but also controlled by the other taps. The voltages in the same area act similarly since their voltage sensitivities to the controllers are almost the same, implying that they cannot be controlled independently. In order to keep the condition of (16), the following center voltage is monitored by controller \( k \) in each control area \((k)\).

\[ V_{c,k} = \frac{\max_{i \in \text{area}(k)} (v_i) + \min_{i \in \text{area}(k)} (v_i)}{2} \] (17)

\[ V_{c,k} = \frac{v_{H,k} + v_{L,k}}{2} \] (18)

Note that \( V_{c,k} = V_{CR,k} \) implies the ideal situation that the center voltage is controlled at the mid point of allowable bandwidth, where (16) can hold by appropriate control if the following voltage margin is positive.

\[ u_{M,k} = \frac{v_{H,k} - v_{L,k}}{2} - \frac{\max_{i \in \text{area}(k)} (v_i) - \min_{i \in \text{area}(k)} (v_i)}{2} > 0 \] (19)

It is also a possible situation where \( u_{M,k} \) becomes negative in stressed conditions due to the increase in the second term. In this case, where no controls exist to satisfy (16), the ideal situation can still be \( V_{c,k} = V_{CR,k} \) where voltage violations for the upper and lower directions equally appear. Then, the following control target is used.

\[ V_{CR,k} = \max (\varepsilon, u_{M,k}) \leq V_{c,k} \leq V_{CR,k} + \max (\varepsilon, u_{M,k}) \] (20)

with \( \varepsilon \) : small positive value.

The above mentioned control strategy may be successfully realized by setting the following objective to be applied to the method proposed in section III:

\[ V(v_c) = u(v_c)^T \cdot m \cdot u(v_c) = \frac{1}{2} \sum_{i=1}^{N} m_i \cdot u_i(v_c)^2 \] (21)

\[ u_i(v_c) = \text{sign}(v_{CR,i} - v_{CR,i}) (|v_{c,i} - v_{CR,i}| - \max (\varepsilon, u_{M,i})) \]

with \( V(v_c) = 0 \) when (20) holds for all \( k \).

Index \( S \) is computed from the above objective function.

B. Processing of control method

Voltage control algorithm is developed by paying attention to the following two issues.

(i) Prevention for unnecessary tap operation in short term: such as tap oscillation or mutual interference among plural controls.

(ii) Assurance of BM data under asynchronous update.

\[ \text{Fig. 2. Example of control areas of individual voltage regulators} \]

\[ \text{Fig. 3. Image of voltage control in control area} \ k.s \]
These problems are successfully managed by introducing operation timers, operation time limiters and credibility flags into the proposed control method. Fig. 4 shows a flowchart of control method for each voltage control equipment and common BM.

C. Credibility Flag

The credibility flag is introduced to verify accuracy of information such as voltage measurement data and tap position of voltage control equipment on BM. If credibility flag is “1”, it is indicated that information is new and is updated after the most recent tap operation. If credibility flag is “0”, it is indicated that information is old or not be accurate. Each agent changes credibility flag to “1” whenever it writes any information to BM. Whenever any tap operation is carried out or feeder configuration is changed, all credibility flags are reset to “0”. Therefore, an agent can judge credibility of information on BM. The data with “credibility flag = 0” may also be carefully treated in each agent such as (a) not use for calculation, (b) use calculation with small weight coefficient.

Advantageous feature of the proposed method lies in that the control actions are optimal when all agents work normally and they become suboptimal when some agents cannot work by system fault, where the objective is still minimized by neglecting the faulted area. In the worst case, where no data is available from the other agents, voltage control is still active to minimize the voltage violation inside the own control area. Thus, each agent is fully independent and is robust against faulted conditions.

V. NUMERICAL SIMULATIONS

A. Simulation Conditions

The proposed method is demonstrated compared with the conventional local control method. Fig. 5 shows the 6.6 kV test system that has 8 nodes and 3 voltage regulators with taps, OLTC and SVRs. A large photovoltaic generation system (PV) is connected to end of feeder on node 8. Loads are settled to node 4 to 8 which cause about 150 V voltage drop to the feeder. Total of active and reactive power of the load and PV output change pattern are shown in Fig. 6. Actual measurement data of solar insolation was used as the PV output pattern. The maximum power of PV output is 1500 kW. The setting of parameters of each voltage regulators such as OLTC, SVR1 and SVR2 are shown in TABLE 1, where the best settings are used for the individual methods. For the conventional local control method, we assume actual SVR controller where only local measurement data is used for voltage control. For the proposed method, the normal system condition is assumed where the credibility flags are all 1 without faults in the simulations. Upper and lower limits of allowable voltage in the feeder are assumed as 1.02 pu and 0.96 pu, respectively. These limits are determined based on the practical setting in Japan. The following 6 cases are considered in the simulation.

Case 1: conventional local control w/o PV (Fig. 7)
Case 2: proposed method w/o PV (Fig. 8)
Case 1pv: conventional local control with PV (Fig. 9)
Case 2pv: proposed method with PV (Fig. 10)
Case 3pv: proposed method w/o PV (SVR2 agent failure)
Case 3pv: proposed method with PV (SVR2 agent failure)

Two types of performance indices are used for evaluating the simulation results as follows.

Index 1: Average voltage deviations from the center value: Average value of voltage deviations for each node from the voltage center value (0.99 pu)

Index 2: Total voltage violations: Total amount of voltage violations exceeding the upper and lower limits

Fig. 5. Test system with 8 nodes and 3 taps.

Fig. 6. A test load and output of photovoltaic pattern.
B. Simulation Results

The simulation results are shown in Table II. Evaluation index of 1, 2 and the number of tap changes are indicated in the table. The waveforms for 24 hour of node voltages and tap positions of the voltage regulators are shown in Fig. 7 to 10 respectively.

In Case 1, tap oscillations are observed around 13:00, where unsuitable tap operations are caused by the interference between SVR1 and SVR2. This also affects the OLTC action that operates just after SVR1. Such a phenomenon often occurs and is analyzed in [33]. The index 2 in Table II also shows that voltage violation occurred in spite of the increased number of tap operations.

In Case 2, tap oscillations are not shown in the simulation results. It is observed that the tap change is minimum due to control optimality. In the case, each evaluation indices are smaller than case 1 and voltage violation is avoided.

In Case 1pv, the number of tap change and evaluation indices are increased compared with Case 1 because of PV output fluctuation. In Case 2pv, the number of tap changes and evaluation indices are kept at the same level as Case 2. Tap oscillations never appear as expected by the theory. No voltage violations are observed in spite of large fluctuations of PV generation. These simulation results have shown that the proposed method work effectively.

For Case 3 and Case 3pv (agent failure cases), small numbers appear in total voltage violations (Index 2) comparing with Case 2 and Case 2pv, in which there are no violations. However, comparing with Case 1 and Case 1pv of local control cases, both of the number of tap changes and the amount of voltage violation are still smaller. This is a piece of evidence that the proposed method is better than the conventional method even if a failure occurs.

If a fault occurs on the blackboard, no agents can get necessary information but each SVR can still work as a local controller with the conventional manner.

VI. CONCLUSIONS

A new voltage control scheme is proposed for distribution as well as transmission systems. In order to cope with increased penetration of renewable energy generations, an optimal control problem is formulated to be implemented in multi-agent control system, in which both the autonomy and optimality are realized. The use of “blackboard” memory data combined with the new control configuration can eliminate unnecessary negotiation process among agents and minimize data communications.

The new feature of proposed method assures that the conventional devices such as OLTC and SVRs are fully utilized in the existing system. It is required a small improvement in the existing controllers to communicate with the common blackboard memory. A monitoring system may be constructed additionally when necessary. This is an additional investment but the proposed system can be gradually introduced or extended according to situations, and the performance can be improved by replacing the conventional controller for automatic tap changers with the proposed agent system.

System reliability is achieved more easily due to the simple control configuration and the autonomy in the individual controllers compared with the centralized control system. Each controller is an agent that works independently even when some or rest of the agents fail to operate because of faulty conditions. In the worst case, the individual agent becomes the existing local controller that works based on its local measurement.

Numerical simulations show that the increase in photovoltaic generations increase the risk of failure of the existing voltage control scheme; the voltage violations cannot be compensated by increasing the tap changing operations. In such cases, the proposed control scheme operates successfully, realizing optimal tap control arrangements by adding the new function in the existing controllers.

REFERENCES


