European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality
(ICREPQ'10)
Granada (Spain), 23th to 25th March, 2010

Voltage Control for a Loop Distribution System with Renewable Energy Sources

Y. Hanai[1], Y. Hayashi[2] and J. Matsuki[1]

[1] Graduate School of Electrical and Electronics Engineering, University of Fukui
3-9-1, Bunkyo, Fukui, 910-8507 (Japan)
Phone/Fax number: +81-776-27-8930, e-mail: hanai@u-fukui.ac.jp, matsuki@fuee.u-fukui.ac.jp

[2] Department of Electrical Engineering and Bioscience, Waseda University
3-4-1 Ohkubo, Shinjuku-ku, Tokyo, 169-8555 (Japan)
Phone/Fax number: +81-3-5286-8122, e-mail: hayashi@waseda.jp

Abstract. This paper describes and verifies a voltage control for a loop distribution system. The proposed method adopts SCADA system based on voltage data from IT switches, which are sectionalizing switches with sensor installed at 6.6kV distribution line. The proposed voltage control combines centralized control of a LRT and autonomous control of decentrally-allocated RESs. The tap change control of LRT takes the major role of the proposed voltage control. It is the extended type of LDC method which is generally adopted, and minimizes voltage deviations based on voltage data from each IT switch. The output power control of RES additionally and autonomously supports the voltage control when the voltage violation from the upper limit is unavoidable. The reactive power control in the vacant capacity of RES's inverter mainly works, and the active power control works when not enough. In order to check the validity of the method, the experimental simulations using an analog distribution system simulator are carried out. This study is supported by a specially-promoted research grant of Power Academy in 2009 from the Federation of Electric Power Companies of Japan.

Key words

loop distribution system, voltage control, renewable energy resources, LRT, SCADA

1. Introduction

Renewable Energy Sources (RES) such as PV system and wind power generation system has been significantly increasing. Since integration of RES into a radial distribution system heightens uncertainty of power flow, it causes some operational and control problems to the distribution system. In particular, the voltage control problem is the foremost concern and the dominant constraint of the connection of RES to the distribution system. A configuration change from a radial network to a loop network is one of the most effective solutions. Although the configuration change makes acceptable capacity of RES significantly increased, an active voltage control would be needed, in addition to the configuration change, to compensate the unstable and rapid output variation of RES. However, the majority of reports about a loop distribution system are power flow control and sectionalizing switch operation including reconfiguration, and the study of the voltage control for a loop distribution system has not been carried out enough [1]-[7].

In this study, the authors propose and verify a voltage control for a loop distribution network. The proposed voltage control utilizes centralized control of a LRT and autonomous control of decentrally-allocated RESs. The tap change control of LRT takes the major role of the proposed voltage control. The method adopts SCADA system based on voltage data from IT switches, which are sectionalizing switches with sensor installed at 6.6kV distribution line. It is the extended type of LDC method which is generally adopted in Japan, and minimizes voltage deviations based on voltage data from each IT switch. The output power control of RES additionally and autonomously supports the voltage control when the voltage violation from the upper limit is unavoidable. The reactive power control in the vacant capacity of RES's inverter mainly works, and the active power control works when not enough. In order to check the validity of the method, the experimental simulations using an analog type distribution system simulator are carried out.

2. Proposed Voltage Control

At present, 6.6kV distribution line voltage is mainly managed by the tap change control of LRT at a distribution substation. The LRT adjusts several distribution feeders all together. When a large number of RESs are unequally distributed and connected among the distribution feeders, it is difficult for LRT to maintain all the voltages within the allowable range. To this problem, a configuration change to a loop network is the most effective solutions because the distribution of voltage and current are levelled between the looped feeders (Figure 1). On the other hand, in loop distribution system with long-distance distribution lines such as rural area, an active voltage control using measured voltage data would be needed to compensate the unstable and rapid output

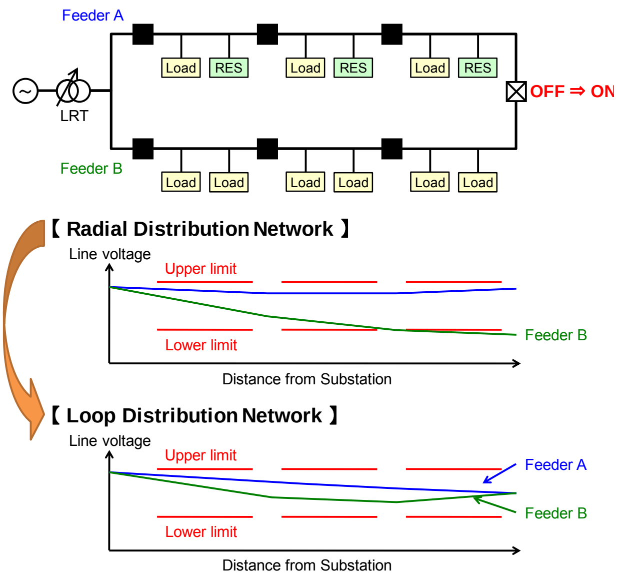


Fig.1. Voltage improvement by constructing loop network.

variation of RES. In recent years, for realizing more accurate distribution planning, load estimation and voltage management, IT switches which are sectionalizing switches with sensor are installed at several points in a distribution system [15]. The system information such as node voltage, active/reactive power flow, and line current are obtained by IT switches. Therefore, the tap change control of LRT using measured voltage data from IT switches is practicable and effective voltage control method.

However, it might be difficult for the control of LRT to solve voltage violations when a reconfiguration change to radial network according to fault clearance or planned outage is caused. If voltage drop or voltage rise is larger than the width of the allowable voltage range, LRT which cannot regulate the width of voltage drop or voltage rise would fail to maintain all the voltages within the allowable voltage. In order to this voltage problem, the output control of RES can be the effective solutions. Inverter type RES has voltage control capability for the voltage violation since its inverter can arbitrarily make the active/ reactive control. It would greatly contribute to emergency voltage control in future distribution system with a number of RESs although the voltage control capability of each RES is not large. However, the continual use of RES's control is undesirable because of the possibilities of output restriction of RES, decrease of power factor and increase of real/reactive power losses.

The proposed voltage control combines centralized control of a LRT and autonomous control of decentrally-allocated RESs as shown in Figure 2. It is assumed that fault section is instantaneously isolated by operating of high-speed circuit breakers via optical communication network, that is, IT switches except for the fault section maintain the state. Also, RESs outside the fault section can avoid a disconnection from distribution network by Fault Ride Through. The tap change control of LRT takes the major role of the proposed voltage control. It minimizes voltage deviations based on voltage data from each IT switch. The output power control of RES additionally and autonomously supports the voltage control when the voltage deviation from voltage limits is unavoidable. The reactive power control in the vacant capacity of RES's inverter mainly works, and the active power control works when not enough.

A. *Tap Change Control of LRT*

Conventional automatic voltage control method is a Line Drop Compensation (LDC) method which controls a load central voltage based on voltage and current at distribution substation into control deadband. Installation of IT switches would eliminate the calculation of load central voltage and make more flexible and active voltage control possible. The proposed tap change control of LRT is the extended LDC method and minimizes voltage deviations on basis of voltage data from each IT switch installed at several distribution lines. Thus, the method assumes that the voltage data can be continuously acquired from IT switches. The tap change control of LRT is described below.

At measurement point n (=1~N), the voltage deviation $\Delta V(n)$ from reference voltage $V_{ref}(n)$ is calculated by

$$\Delta V(n) = V(n) - V_{ref}(n) + E(n). \quad (1)$$

In (1), the reference voltage $V_{ref}(n)$ is given as central value of the allowable voltage range at measurement point n, i.e.,

$$V_{ref}(n) = \frac{V_{\min}(n) + V_{\max}(n)}{2}. \quad (2)$$

Also, when the measured voltage $V(n)$ deviates from the allowable voltage range, penalty $E(n)$ is added to $\Delta V(n)$. The penalty coefficient either α_U or α_L is given to $E(n)$ by

$$E(n) = \begin{cases} \alpha_U & (\ V(n) > V_{\max}(n)\ ) \\ 0 & (\ V_{\min}(n) \le V(n) \le V_{\max}(n)\ ) \\ \alpha_L & (\ V(n) < V_{\min}(n)\ ) \end{cases}. \quad (3)$$

An average value between the maximum and minimum voltage deviation $\Delta V(n)$ is defined as the voltage deviation index F, i.e.,

$$F = \frac{\max_{n \in N}\{\ \Delta V(n)\ \} + \min_{n \in N}\{\ \Delta V(n)\ \}}{2}. \quad (4)$$

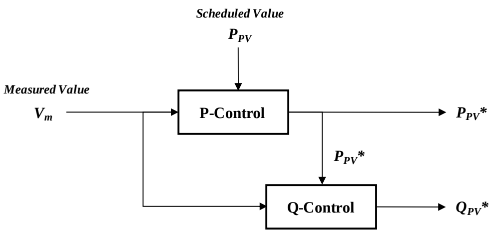
The tap change index D is derived by time integration of the voltage deviation index F from the dead-band ε, i.e.,

$$D = \int sign(F) \cdot (\ F - \varepsilon\ ) \cdot dt. \quad (5)$$

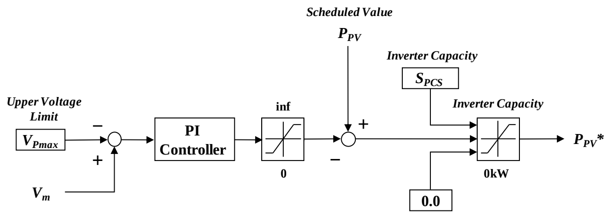
When the magnitude of D is in excess of threshold D_{ref}, the tap change instrument ΔTap to LRT is given as

$$\Delta Tap = \begin{cases} +1 & (\ D < -D_{ref}\ ) \\ 0 & (\ |D| \le D_{ref}\ ) \\ -1 & (\ D > D_{ref}\ ) \end{cases} \quad (6)$$

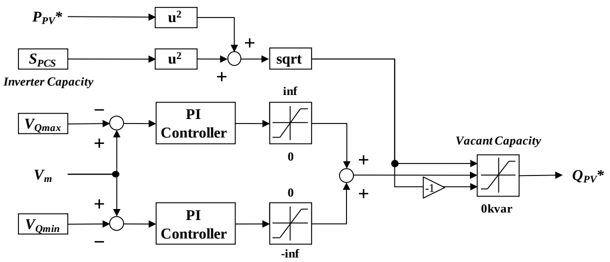
where ΔTap = +1 and -1 mean to change the tap position of LRT into one upper position and one lower position, respectively.



(a) Whole block diagram



(b) P-Control block diagram



(c) Q-Control block diagram

Fig. 2. Control block diagram of output power control of RES.

B. Output Control of RES

Recently some voltage/reactive power control methods are proposed [8]-[14]. Reference [13] proposed a voltage mitigation method using grid-connected inverter for PV system. It shows that the reactive power control in the vacant capacity of inverter works to compensate voltage rise caused by reverse power flow from PV systems without real power restriction. Also, an effectiveness of the reactive power control with unlimited power factor was shown in [14].

Based on these observations, we adopt the reactive power control in the vacant capacity of inverter with unlimited power factor. The reactive power control mainly works, and then the active power control works when it is not enough. However, the regular-use of RES's control is undesirable because of the possibilities of output restriction of RES, decrease of power factor and increase of real/reactive power losses. Thus, the output power control of RES supports distribution line voltage when the voltage violation because of excessive voltage rise and/or voltage drop is not solvable by the tap change control of LRT. Figure 2 shows the block diagram of the output power control of RES. As shown in Figure 2, the active/reactive power control (P-Control and Q-Control) of RES are modeled as PI controller to compensate voltage deviation from reference voltage value. The reference voltage value of P-Control is V_{Pmax}, and the upper and lower reference voltage values of Q-Control are V_{Qmax} and V_{Qmin}, respectively. Threshold V_{Pmax} of P-Control must be set smaller than threshold V_{Qmax} of Q-Control so as to avoid active power suppression. The

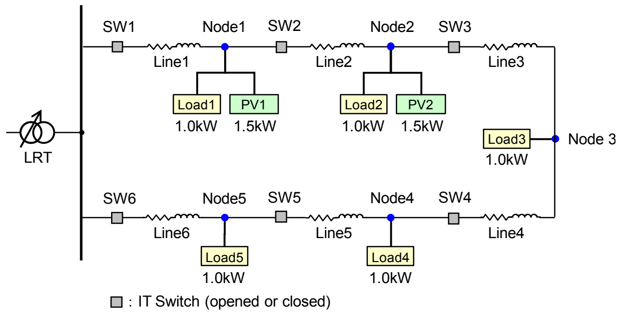
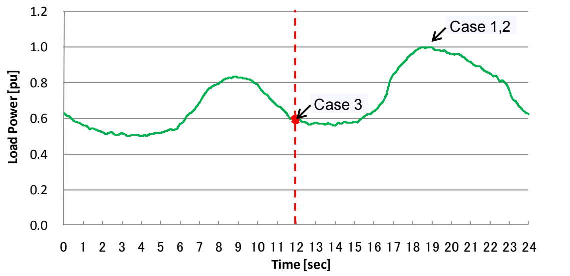
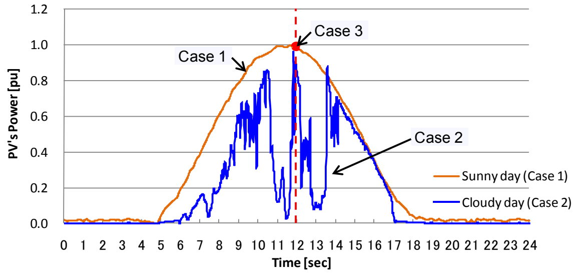


Fig. 3. Configuration of a test loop distribution system.



(a) Daily power curve of fluctuating loads (Load1~Load6).



(b) Daily power curve of PV systems (PV1~PV2).

Fig. 4. Daily power curve of fluctuating loads and PV systems (each peak value is set to 1.0 pu)

output power control of RES can work even at time of fault and configuration change; that is, it is assumed that RESs except fault section are not disconnected by FRT (Fault Ride Through) function or a low voltage ride through function.

3. Experimental Verification

In order to check the validity of the proposed voltage control, experimental simulations using an analog type distribution system simulator are carried out. The analog type distribution simulator is a three-phase three-wire non-grounded 200V system installed in University of Fukui in Japan; this simulator is scaled-down practical 6.6kV distribution system [16]. Through three case studies (Case 1 ~ Case 3), the voltage control capability are evaluated.

A. Simulation Conditions

The test loop distribution system is shown in Figure 3. This model consists of looped-feeders including a LRT, six distribution lines (Line1 ~ Line6), six IT switches

TABLE I
CONDITIONS FOR THE CASE STUDY

	Network configuration	Profile of PV system
Case 1	Loop	Sunny day profile
Case 2	Loop	Cloudy day profile
Case 3	Loop to Radial	Peak value (constant)

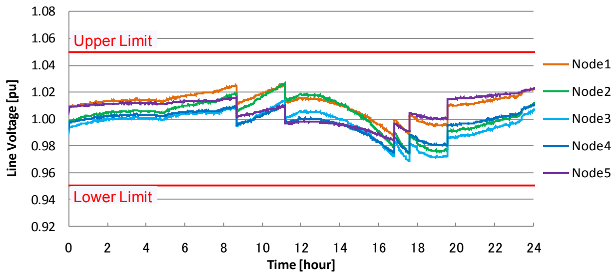
TABLE II
OTHER EXPERIMENTAL CONDITIONS

Experimental simulation time	2880 [sec]
Reference voltage of test system	200 [V]
Reference capacity of test system	40 [kVA]
Primary voltage of LRT	V_S = 1.0 [pu]
Impedance of distribution line	Z = 4.0 + j4.9 [%/km]
Upper voltage limit at each node	V_{MAX} = 1.05 [pu]
Lower voltage limit at each node	V_{MIN} = 0.95 [pu]
Number of LRT tap position	9 (No.1~No.9)
LRT tap voltage	V_{Tap} = 0.015 [pu]
Control deadband width	ε = 0.01 [pu]
Threshold of LRT tap change	D_{REF} = 50 [%・sec]
Penalty for voltage violation	α_U = 10.0, α_L = -10.0
Threshold for P-control of RES	V_{Pmax} = 1.05 [pu]
Threshold for Q-control of RES	V_{Qmax}= 1.045 [pu]
	V_{Qmin}= 0.95 [pu]

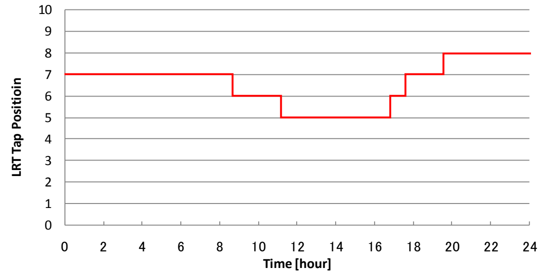
(SW1 ~ SW6), five fluctuating loads (Load1 ~ Load5) and two PV systems (PV1 ~ PV2). Power consumption of a fluctuating load is represented by three RLC loads and a three-phase inverter. Also, output power of a PV system is represented by a three-phase inverter. Suppose that two PV systems are connected only to the upper feeder, the daily power curves of fluctuating loads and PV systems are shown in Figure 4. As shown in Figure 3, total connection capacity of PV systems and loads are 3.0 kW and 5.0 kW, respectively; the ratio of PV systems to loads is 60%. At 12:00 at which PV systems have the maximum output, total power of PV systems amounts to 100% of total power of loads. The typical load profile of residential energy consumption is applied to all the loads (Load1 ~ Load6). The power factor of the loads and PV systems is set as 1.0.

Table I lists the evaluated cases. In Cases 1 and 2, a loop distribution system is reconstructed, and whether all the voltages are maintained under normal state operation of loop distribution system with PV systems is checked. PV systems have the output power profiles of a sunny day and a cloudy day in Case 1 and Case 2, respectively. In Case 3, the voltage control capability is evaluated in the case where configuration is changed from looped network into radial network; in order to evaluate it under the severest condition, switch SW3 is opened at 12:00.

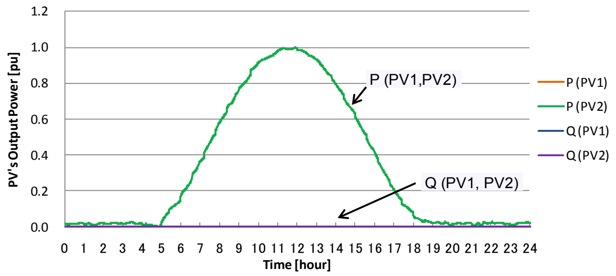
Table II shows the other experimental conditions. Simulation time is 2880 seconds, that is, daily change of the test loop distribution system is shortened as a



(a) Node voltage profile



(b) LRT's tap profile



(c) PVs' output power profile (self-capacity ratio)

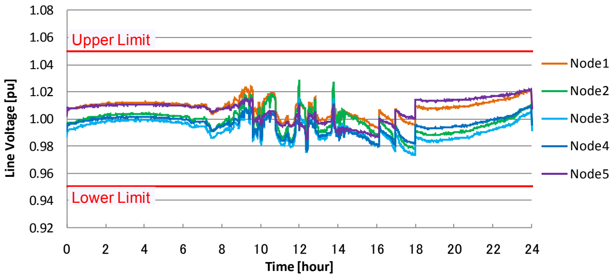
Fig.5. Experimental results in Case 1.

variation of 48 minutes. Note that time axes of graphs about experimental results in Case 1-2 are represented as the value by which 2880 seconds is converted into 24 hours. The line length between each node is assumed to be 1.5 km; the impedance of distribution line between each node is 6.00 + j7.35%. The allowable voltage range is from 0.95pu to 1.05pu at all the nodes. Thus, the reference voltage V_{ref} is 1.00pu all. For simplicity, it is assumed that sending voltage, line impedance, and load current balance on three-phase circuit.

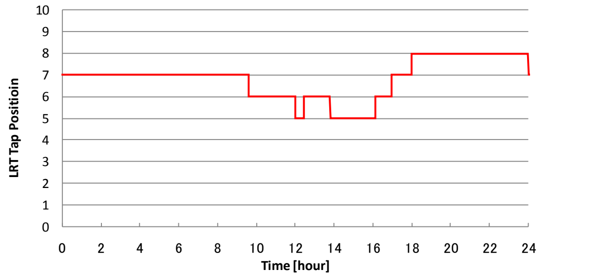
B. Experimental Results in Case 1

Figure 6 shows node voltages, the tap position of a LRT and active/reactive power of PV systems in Case 1. The node voltages rapidly rise by reverse power flow from PV systems during 5:00 ~ 12:00. The tap position of LRT is lowered to compensate the voltage rise. On the other hand, the node voltages rapidly drop by load power increase and output power decrease of PV systems during 12:00 ~ 19:00. The tap position of LRT is lifted to compensate the voltage drop. The output power control of PV system does not work since LRT can compensate the variation of loads and PV systems enough.

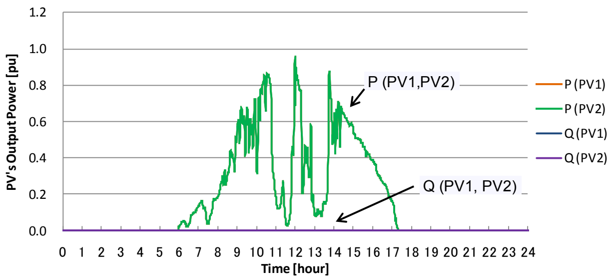
As shown in Figure 6, despite the condition that total power of PV systems amounts to 100% of total power of loads at 12:00, all the node voltages are maintained by



(a) Node voltage profile

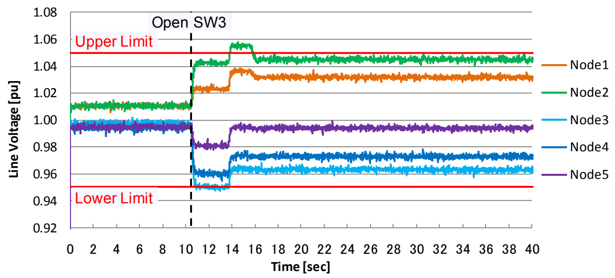


(b) LRT's tap profile

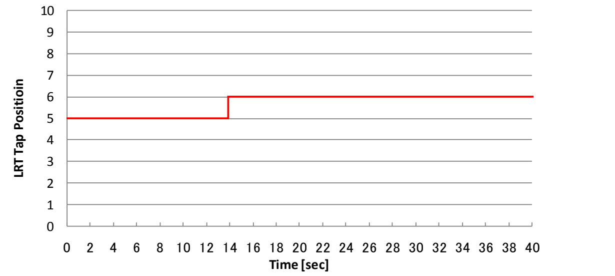


(c) PVs' output power profile (self-capacity ratio)

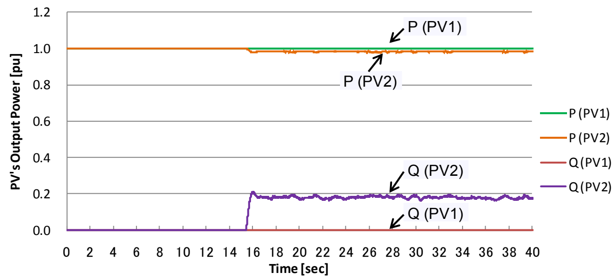
Fig.6. Experimental results in Case 2.



(a) Node voltage profile



(b) LRT's tap profile



(c) PVs' output power profile (self-capacity ratio)

Fig.7. Experimental results in Case 3.

only tap change control of LRT without any active power suppression of PV systems. It indicates that a configuration change to looped network is effective to reduce voltage rise caused by PV systems and to mazimize the acceptable capacity of PV systems.

C. Experimental Results in Case 2

In Case 2, all the node voltages are maintained without an active power suppression of PV systems as with Case 1. Figure 6 shows node voltages, the tap position of a LRT and active/reactive power of PV systems in Case 2. The node voltages are rapidly fluctuated by unstable reverse power flow from PV systems in day time period. Although the tap position of LRT is frequently changed to compensate the voltage variation, all the node voltages are maintained within the allowable range. Also, in order to compensate the voltage swell at 12:00, the reactive power control of PV2 adequately works. Therefore, distribution voltage is maintained by LRT as well as possible without excess reactive support of RES.

D. Experimental Results in Case 3

In Case 3, system configuration is changed from looped network into radial network by opening switch SW3. Figure 7 shows node voltages, the tap position of a LRT and active/reactive power of PV systems. When simulation time is around 10 seconds, switch SW3 is opened and a system configuration is changed to a radial system. Immediately after switch SW3 was opened, the line voltage at Node3 deviates from the lower voltage limit. The tap position of LRT is changed to solve the lower voltage violation at around 14 seconds. Although the tap change control causes upper voltage violations at Node2, the active/reactive power control of PV2 immediately works to solve the upper voltage violation; PV2 suppresses the active power and increases (absorbs) the reactive power, since there is no vacant capacity for reactive power output at 12:00.

As the consequence, all the node voltages are maintained within the allowable range in about 6 seconds. In order to shorten the duration time of voltage violation, an adjustment of threshold D_{REF}, which is a reference value for tap change of LRT, is needed. The lowered threshold value D_{REF} would yield shorter voltage violation duration; however, since it may cause interferences between LRT and RES, a response speed of LRT has to be slower than that of RES. The optimal threshold value should be determined with consideration for the daily tap change count of LRT and the duration of acceptable voltage violation.

4. Conclusion

In this paper, a voltage control for a closed-loop distribution system with RESs was proposed and verified. The proposed voltage control adopts SCADA system based on voltage data from IT switches, which are sectionalizing switches with sensor installed at 6.6kV distribution line. Also, the proposed voltage control combines centralized control of a LRT and autonomous control of decentrally-allocated RESs. The tap change control of LRT takes the major role of the proposed voltage control. It is the extended type of LDC method which is generally adopted, and minimizes voltage deviations based on voltage data from each IT switch. The output power control of RES additionally and autonomously supports the voltage control when the voltage violation from the upper limit is unavoidable. The reactive power control in the vacant capacity of RES's inverter mainly works, and the active power control works when the reactive power control is not enough.

In order to check the validity of the proposed voltage control, the experimental simulations using an analog type distribution system simulator were carried out. Through the three case studies, it was shown that all the voltages are maintained not only in the normal state, but also in the case where configuration is changed from looped network into radial network.

Acknowledgement

This study is supported by Specially Promoted Research Grant in 2009 from Power Academy which is powered by the Federation of Electric Power Companies of Japan.

References

[1] Yasuhiro Hayashi: "Trend and Future View of Voltage Control for Distribution Systems with Distributed Generators", IEEJ Trans. PE, Vol. 129, No. 4, pp.491-494 (2009). (in Japanese)

[2] Ljubomir A. Kojovic, Timothy R. Day: "Advanced Distribution System Automation", Proceeding of IEEE PES Transmission & Distribution Conference 2003 (2003-9).

[3] Russell P. Fanning P.E: "Premium Operating Districts Provide Superior Reliability for Industrial Customers using the DV 2010 Primary Voltage Network", Proceeding of Distribu TECH 2004 (2004-1).

[4] Nobuyuki Inayoshi, Mahmoud A. Sayed, Takaharu Takeshita, Norihisa Izuhara and Fukashi Ueda: "Construction Method of Loop Distribution System for Line Loss Minimization", IEEJ Trans. PE, Vol. 128, No. 6, pp.893-894 (2008). (in Japanese)

[5] Keiichi Shimizu and Takamu Genji: "Comparative Evaluation of Reliability by Monte Carlo Method among different Loop Distribution Systems", IEEJ Trans. PE, Vol. 128, No. 5, pp.751-760 (2008). (in Japanese)

[6] Rejeki Simanjorang, Yushi Miura and Toshifumi Ise: "A Series Type BTB Converter for Controlling Voltage Profile in Loop Distribution System with Distributed Generations", IEEJ Trans. PE, Vol. 128, No. 5, pp.769-778 (2008).

[7] Rejeki Simanjorang, Yushi Miura, Toshifumi Ise, Shigeyuki Sugimoto and Hideki Fujita: "A Method for Effective Utilization of Power Distribution Apparatus in Industrial Park by Looping Distribution Lines", IEEJ Trans. PE, Vol.127, No.11, pp.1127- pp.1136 (2007).

[8] Mesut E. Baran, and Ismail M. El-Markabi, "A Multiagent-Based Dispatching Scheme for Distributed Generators for Voltage Support on Distribution Feeders", IEEE Trans. Power Systems, Vol. 22, No. 1, pp.52-59, Feb. 2007.

[9] Panagis N. Vovos, Aristides E. Kiprakis, A. Robin Wallace, and Gareth P. Harrison, "Centralized and Distributed Voltage Control: Impact on Distributed Generation Penetration", IEEE Trans. Power Systems, Vol.22, No.1, pp.476-483, Feb. 2007.

[10] Ferry A. Viawan, and Daniel Karlsson, "Combined Local and Remote Voltage and Reactive Power Control in the Presence of Induction Machine Distributed Generation", IEEE Trans. Power Systems, Vol. 22, No. 4, pp.1002-1012, Nov. 2007.

[11] Ferry A. Viawan, and Daniel Karlsson, "Voltage and Reactive Power Control in Systems with Synchronous Machine-Based Distributed Generation", IEEE Trans. Power Delivery, Vol. 23, No. 2, pp.1079-1087, Apr. 2008

[12] Pedro M. S. Carvalho, Pedro F. Correia, and Luís A. F. M. Ferreira, "Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks", IEEE Trans. Power Systems, Vol.23, No.2, pp.766-772, May 2008.

[13] A. Izume, M. Hojo, T. Ohnishi, S. Taki, K. Oishi, and N. Fujiwara, "A Study of Reactive Power Compensation Method by Utility Interactive Inverter of Photovoltaic Generation System for Suppression of Voltage Rise", in Proc. the 17th Annual Conference of Power & Energy Society, IEE of Japan, No.355, pp.35-13, 35-14, Sept. 2006 (in Japanese)

[14] R. Nakanishi, K. Takahashi, and K. Tanaka, "A Study of Improve Reduction of PV Power Generation Connected to Distribution System", in Proc. 2009 Annual Meeting Record IEE Japan, No.6-080, pp.144-145, Mar. 2009 (in Japanese)

[15] T.Kasajima, R.Endo, Y.Wada, Y.Kudo, and H.Kanawa "The Development of the Advanced Distribution Automation System with Optical Fiber Network of Tokyo Electric Power Co., Inc.", IEEE Power Engineering Society General Meeting, (2004-6)

[16] Y. Hayashi, S. Kawasaki, J. Matsuki, S. Sakai, S. Wakao, J. Baba, M. Hojo, A. Yokoyama, N. Kobayashi, Y. Fuwa, K. Mori: "Development of Distribution Network Equipment to Support the Solution of Problem of Connecting Distributed Generators" 2008 National Conventional Record, IEE Japan, No.6-258, pp453-436 (2008-3) (in Japanese)