\INDIVIDUAL CONTROL METHOD FOR HYBRID VOLTAGE REGULATOR

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ABSTRACT

In recent years, photovoltaic power generation systems (PVs) have been installed in distribution systems after Feed-in tariff (FIT) operation. Voltage unbalance due to the difference in interconnection rates of PVs at each phase reduces power quality. To reduce the voltage unbalance, the hybrid voltage regulator (HVR), which can control each phase voltage, was developed. In this paper, the authors propose an HVR individual control method to control the unbalance factor and phase voltage within a specified range. Numerical simulations were performed to validate the proposed method. The results showed that the proposed HVR method reduced the unbalance factor from 3.0% to 1.6% while maintaining the specified phase voltage range.

INTRODUCTION

In recent years, photovoltaic power generation systems (PVs) have been installed in distribution systems after Feed-in tariff (FIT) operations. PVs for domestic use are connected to a single phase in a low-voltage system, and the PV capacity is different at each node. Moreover, large capacity loads, such as batteries, heat-pump water heaters, and so on, have been installed in low-voltage systems. Load unbalance and PV capacity at each node causes an excessive voltage unbalance [1][2] of each node and increases the difference between each phase-to-phase voltage in a three-phase distribution system.

Generally, to control node voltages within a specified range, on-load tap changers (OLTCs) and step voltage regulators (SVRs) have been installed. To improve the unbalance factor of a distribution system, the number of PVs and the load are adjusted by replacing a low-capacity phase with a high-capacity phase. However, these technologies have difficulty controlling the unbalanced node voltage and rapid fluctuation of unbalance factors based on PVs and loads because they can control only three-phase voltage control.

To address the unbalanced node voltage and rapid fluctuation of unbalance factors, a hybrid voltage

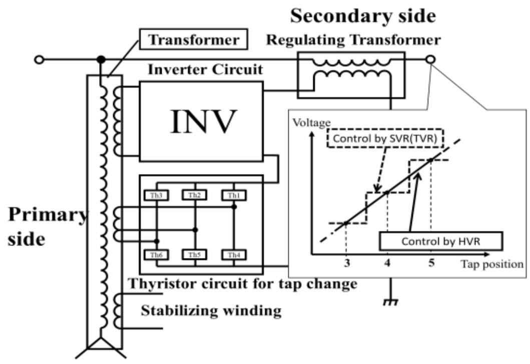


Fig. 1 HVR construction.

regulator (HVR) was developed. HVR can control each phase voltage individually, quickly, and continuously on account of the integration of a thyristor circuit and inverter circuit. The thyristor circuit rapidly changes the transformer ratio of the regulating transformer according to thyristor-based high-speed control. The inverter circuit compensates the difference between each secondary voltage from the thyristor circuit. HVR has unique features; however, a useful control method for HVR does not yet exist.

In this paper, the authors propose an individual control method for HVR to improve the unbalanced voltage and control phase-to-phase voltages within a specified range. The proposed method consists of an autonomous method based on the line drop compensator (LDC) and a centralized method using an switch with sensors (IT-switch. The autonomous method estimates the reference voltages and unbalance factor calculated from the secondary voltage and HVR passing current. This approach contrasts with the centralized method, which obtains each node voltage and unbalance factor from the IT-switches in distribution systems.

The proposed method defines the optimization problem to determine each phase voltage in the HVR secondary side from the reference voltages of the respective autonomous and centralized control methods. To maximize the effectiveness of the continuous, rapid control base on the inverter circuit, the proposed method solves the optimization problem by a complete search under two constraints of the three-phase node voltage and unbalance factor. To verify the effectiveness of the proposed method for HVR, the authors performed numerical simulations using a distribution system model with PVs.

HYBRID VOLTAGE REGULATOR

HVR consists of a thyristor circuit and inverter circuit, as shown in Fig. 1. HVR offers high-speed continuous voltage control in each phase voltage. To achieve high-speed control, thyristors are adapted for switching the transformer ratio. The inverter circuit compensates discrete fluctuations when the thyristor circuit changes the transformer ratio to achieve continuous control. These circuits are placed in each phase and individually operate. The thyristor circuit switches a thyristor switching pattern in accordance with the transformer ratio (1 tap = 0.0113 pu). The inverter circuit is installed at the secondary side of the thyristor circuit. The inverter available control range is –5.68e-3 pu (–0.5 tap) to +5.68e-3 (+0.5 tap) against the transformer ratio.

THREE-PHASE LINE DROP COMPENSATOR

The three-phase LDC is applied to many OLTCs and SVRs to manage all node voltages from them. LDC calculates each phase line drop based on the secondary voltages of each phase and the passing current from these technologies, as shown in (1).

$$\begin{bmatrix} \dot{V_{ra}}(t) \\ \dot{V_{rb}}(t) \\ \dot{V_{rc}}(t) \end{bmatrix} = \begin{bmatrix} \dot{V_a}(t) \\ \dot{V_b}(t) \\ \dot{V_c}(t) \end{bmatrix} - \begin{bmatrix} \dot{Z_{aa}} & \dot{Z_{ab}} & \dot{Z_{ac}} \\ \dot{Z_{ba}} & \dot{Z_{bb}} & \dot{Z_{bc}} \\ \dot{Z_{ca}} & \dot{Z_{cb}} & \dot{Z_{cc}} \end{bmatrix} \begin{bmatrix} \dot{I_a}(t) \\ \dot{I_b}(t) \\ \dot{I_c}(t) \end{bmatrix} \quad (1)$$

where V_{ra}, V_{rb}, and V_{rc} are the phase voltages at the reference point, and V_a, V_b, and V_c are the secondary phase voltages. In addition, the diagonal components of impedance matrix Z are the line impedances at each phase, and the non-diagonal components of Z are the mutual inductances between each phase.

The positive- and negative-phase voltages are respectively given by (2) and (3) from the three-phase voltages at the reference point. The unbalance factor at the reference point is calculated from the positive and negative voltages.

$$\dot{V_1}(t) = \dot{V_{ra}}(t) + v^2\dot{V}_{rb}(t) + v\dot{V_{rc}}(t) \quad (2)$$

$$\dot{V_2}(t) = \dot{V_{ra}}(t) + v\dot{V}_{rb}(t) + v^2\dot{V_{rc}}(t) \quad (3)$$

$$v = -\frac{1}{2} + \mathrm{j}\frac{\sqrt{3}}{2} \quad (4)$$

$$UF(t) = \frac{|\dot{V}_2(t)|}{|\dot{V}_1(t)|} \times 100 \quad (5)$$

where V_1 and V_2 are the respective positive- and negative-phase voltages at the reference point, v is the vector operator, and UF is the unbalance factor at the reference point. The reference voltages in accordance with (6) are performed.

$$\mathbf{V_{ref}}(t) = \begin{bmatrix} |\dot{V_{ra}}(t) - \dot{V_{rb}}(t)| \\ |\dot{V_{rb}}(t) - \dot{V_{rc}}(t)| \\ |\dot{V_{rc}}(t) - \dot{V_{ra}}(t)| \end{bmatrix} \quad (6)$$

where $\mathbf{V_{ref}}$ is the reference voltage containing each line voltage.

To determine the transformer tap position, the “90Relay” autonomous method compares the reference voltage with a target voltage given by (7) and (8). $D(t)$ is compared with a specified value of the deviation from the target voltage, and the autonomous method determines the tap position shown in (9).

$$\Delta V(t) = V_{ref}(t) - \mathrm{V_{Tar}} \quad (7)$$

$$D(t) = \int \mathrm{sgn}(\Delta V(t)) \cdot |\Delta V(t) - \varepsilon| dt \quad (8)$$

$$Tap(t) = \begin{cases} Tap(t-1) + 1 & (D(t) > D_s) \\ Tap(t-1) & (-D_s \le D(t) \le D_s) \\ Tap(t-1) - 1 & (D(t) < -D_s) \end{cases} \quad (9)$$

where V_{Tar} is the user-defined target voltage, ΔV is the difference between the reference voltage and target voltage, D is the sum of ΔV(t), ε is the dead band width, Tap is the tap position, and D_s denotes the specified value of the deviation from the target voltage.

INDIVIDUAL CONTROL METHOD

The individual control method consists of respective autonomous and centralized control methods. The autonomous method regulates the reference voltages estimated by the LDC method; the centralized control method obtains and controls all node voltages from the IT-switches.

Autonomous control method

The autonomous control method is adapted to determine HVR each phase output. A flow chart of the proposed method is shown in Fig. 2. The proposed method is defined as an optimization problem that minimizes the object function under the respective voltage and voltage unbalance constraints. To solve this problem, each HVR phase output is discretized with a fixed-range scale. The range is determined as continuous phase voltages. The discrete values are gives by (10).

$$\mathbf{H} = [H_1^k \quad H_2^k \quad H_3^k] \quad (10)$$

where $\mathbf{H}$ is the HVR output vector, and H_i^k are each phase output at k^{th}.

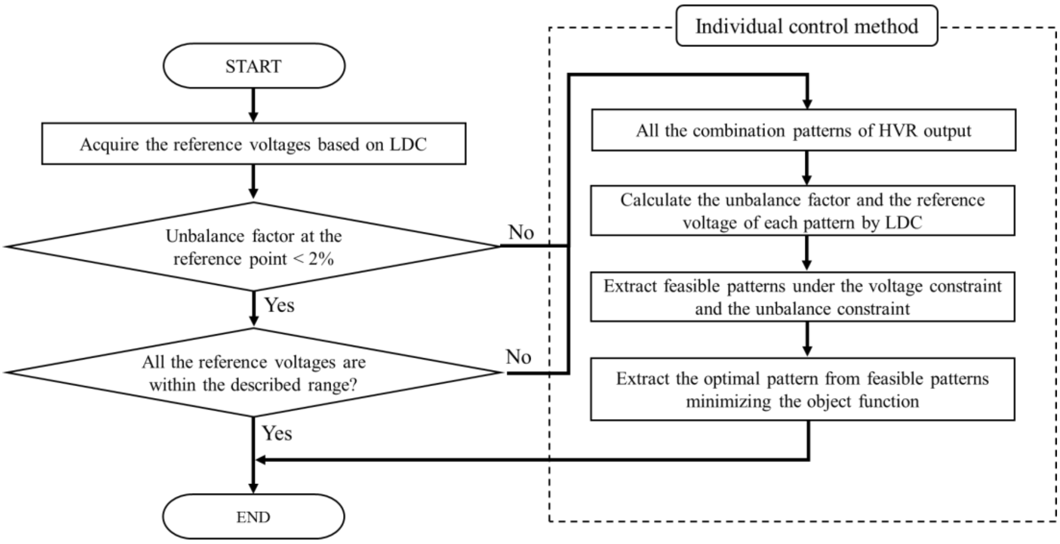


Fig. 2 Flow chart of the individual control method.

The reference voltage and unbalance factor acquired by the LDC method are modified by HVR output **H** given by (11).

$$\begin{bmatrix} \dot{V}^k_{r_{(1)}}(t,\mathbf{H}) \\ \dot{V}^k_{r_{(2)}}(t,\mathbf{H}) \\ \dot{V}^k_{r_{(3)}}(t,\mathbf{H}) \end{bmatrix} = \begin{bmatrix} H^k_1 \\ H^k_2 e^{-j(\frac{2}{3}\pi)} \\ H^k_3 e^{j(\frac{2}{3}\pi)} \end{bmatrix} + \begin{bmatrix} \dot{V}_{r1}(t) \\ \dot{V}_{r2}(t) \\ \dot{V}_{r3}(t) \end{bmatrix} \tag{11}$$

where $\dot{V}^k_{r_{(i)}}$ is the modified reference voltages at kth. The reference voltages and unbalance factors against all HVR output combination patterns are acquired by the LDC method. The optimal combination pattern is determined by:

$$\min \quad \sum_{i=1}^{3} |H_i(t) - H_i(t-1)| \tag{12}$$

which is subject to

$$\mathrm{V_L} \leq {}^{\forall}V_{ref}(t,\mathbf{H}) \leq \mathrm{V_H} \tag{13}$$

$$UF(t,\mathbf{H}) \leq \mathrm{UF_{def}} \tag{14}$$

where $\mathrm{V_L}$ and $\mathrm{V_H}$ are the respective lower and higher limits of the described range, and $\mathrm{UF_{def}}$ is the described limit for the unbalance factor.

The optimization problem given by (12) aims to minimize the sum of the HVR output change. The object function is modeled to preferentially use the output from the inverter circuit, which secures continuous control. The voltage and voltage unbalance constraints shown in (13) and (14) ensure the distribution-system power quality. To solve the optimization problem, exhaustive searching is applied.

Centralized control method

To determine the output patterns, the centralized control method obtains the active and reactive data in each node. The node voltage and unbalance factor, with consideration of each HVR output, are obtained by the flow calculation [3]-[5]. This method replaces the reference voltage for the calculated voltage and unbalance factors to solve the above optimization problem. Therefore, the optimal HVR output pattern is obtained by the centralized control method.

NUMERICAL SIMULATION

To verify the effectiveness of the proposed method, numerical simulations were performed. HVR with the proposed method (autonomous and centralized methods) were compared with the thyristor voltage regulator (TVR) operation.

Numerical simulation condition

The distribution system model for the numerical simulations consisted of ten nodes with PVs and loads. The voltage profile in Fig. 3(a) was applied to the OLTC primary voltage with consideration of the rapid fluctuation in the power transmission side. The load capacity based on the current ratio measured in the distribution system was assigned to each node. The load profile is shown in Fig. 3(b). The amount of PV installation was 100% against the sum of all load capacities. The PV distribution pattern was uniform. The PV profile shown in Fig. 3(c) was a cloudy day, when it was difficult to regulate node voltages.

Table 1. Numerical simulation conditions

Parameter			Values
OLTC	Tap ratio [pu]		0.0114
	Total number of taps		17
	Base tap position		9
	Dead band [pu]		0.015
	Target voltage		0.992
HVR (TVR)	Range of voltage regulation [pu]		–0.04 ~ +0.04
	Dead band [pu]	HVR	-
		TVR	0.008
	Target voltage		0.992
	Operation		Centralized or autonomous
Voltage range		Upper [pu]	1.02
		Lower [pu]	0.971
Amount of PV [%]			100
Described unbalance factor [%]			2.0
Distribution pattern of PV			uniform
Sampling time [s]			10

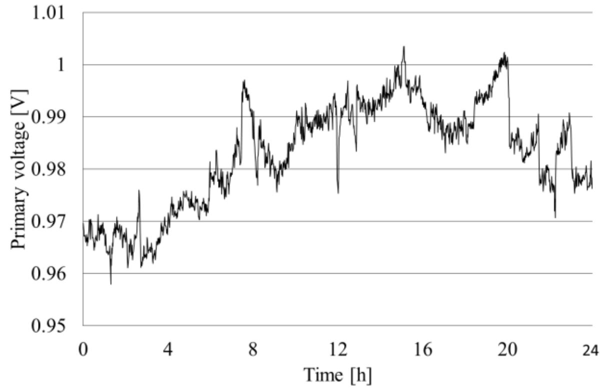
PV output was normalized by the average PV capacity for domestic use. Assuming the high unbalance factor of 3.0%, the PVs were installed to only one phase (A-B phase). Table 1 shows the criteria of OLTC and HVR. OLTC, TVR, and HVR operations were based on the LDC method. To compare the optimal operation of HVR with the proposed method, the centralized control method and autonomous method were adapted in HVR.

RESULTS AND DISCUSSION

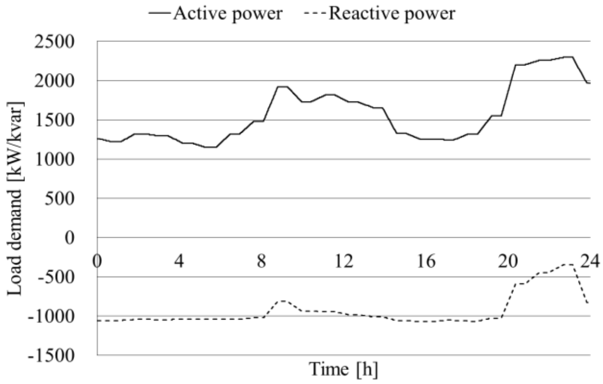
Fig. 4 shows the node voltages and the unbalance factor at the end of the distribution model. Fig. 4(a) shows that the A-B phase monitored by TVR was controlled within the described range, whereas the other phase voltage deviates from the described range.

TVR had difficulty controlling the unbalance voltages and the unbalance factor within the described range because of the three-phase collective control. HVR could individually control the three-phase voltages based on the proposed method. HVR improved the deviation of the node voltages and the unbalance factor from the described range shown as Figs. 4 (c)-(f). HVR with the centralized control reduced the maximum unbalance factor from 3.0% during TVR control to 1.6% while maintaining three-phase voltages within the described range. These results reveal that HVR is effective at improving the voltage unbalance and controlling the rapid fluctuation based on PVs.

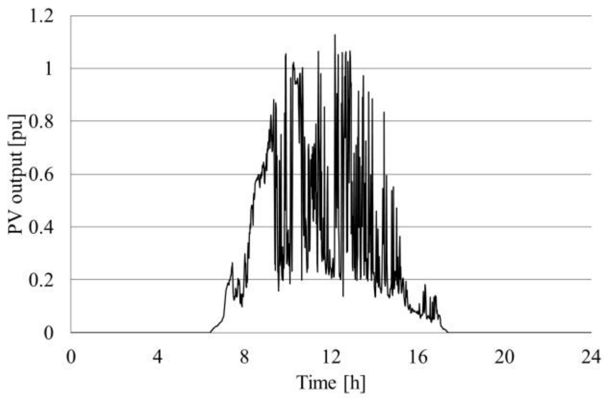
The autonomous method for HVR could reduce the unbalance factor from 3.0% to 1.93%; however, the A-B voltage transgressed the upper limit. The autonomous control method determined the HVR output in accordance with only the reference voltage as a



(a) Primary voltage profile



(b) Load profile



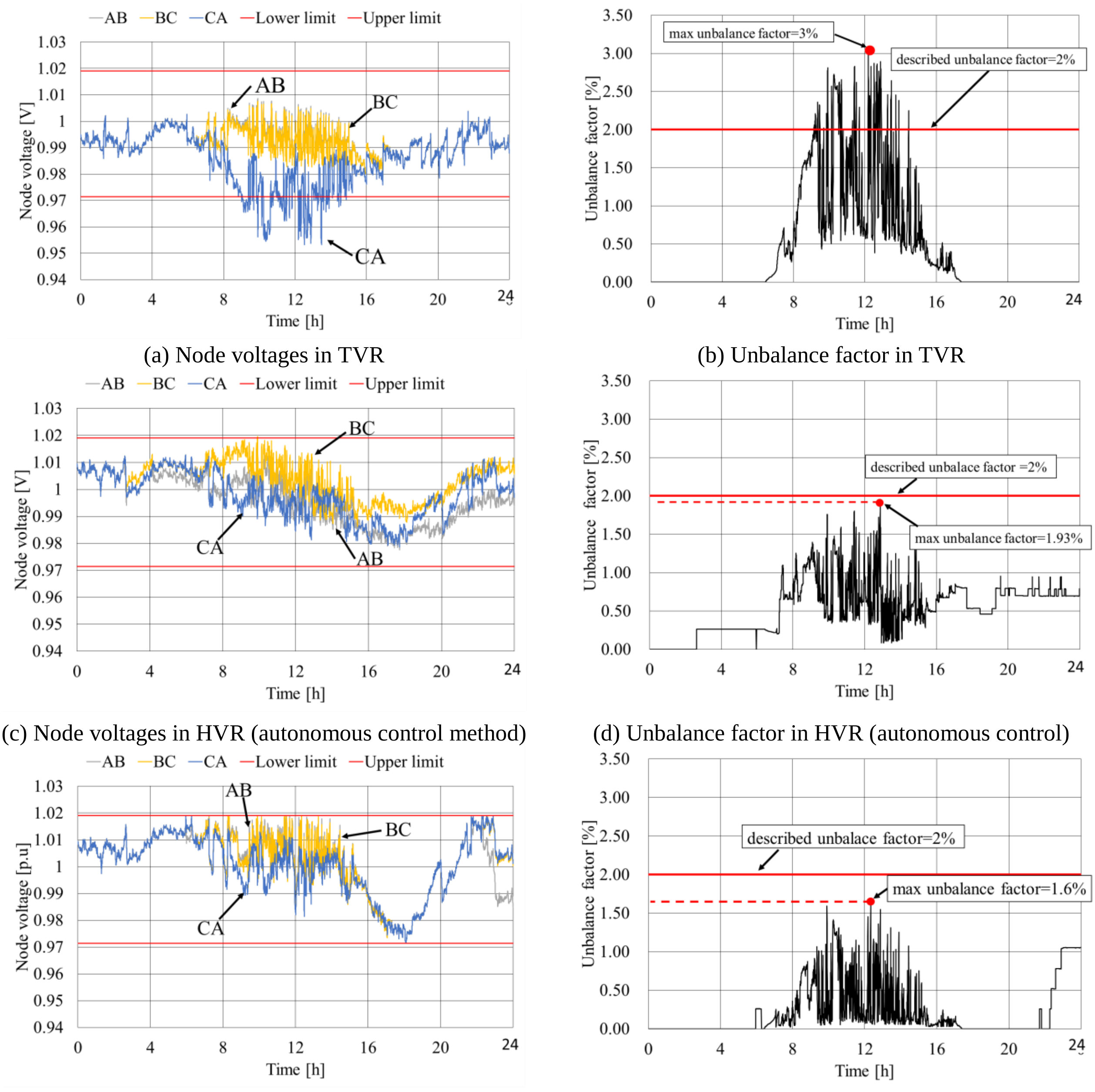
(c) PV profile

Fig. 3 Each profile assigned to nodes.

representative voltage of all node voltages. The performance of the autonomous method heavily depended on the accuracy of LDC method.

CONCLUSIONS

This paper presented an HVR individual control method that provides high-speed continuous voltage control. To determine HVR output utilizing the HVR characteristic, the optimization problem was formulated. To verify the effectiveness of the proposed method, numerical simulations were performed using a distribution system with a voltage unbalance. It was revealed that HVR



(a) Node voltages in TVR (b) Unbalance factor in TVR

(c) Node voltages in HVR (autonomous control method) (d) Unbalance factor in HVR (autonomous control)

(e) Node voltages in HVR (centralized control) (f) Unbalance factor in HVR (centralized control)

Fig. 4 Node voltage and unbalance factor at the feeder end.

installed with the proposed method was effective for the unbalance factor correction and three-phase voltages compared with three-phase collective control by TVR.

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