Zonal Operation Scheme of Distributed Generations for Voltage Regulation in Distribution Networks

Y. S. Oh, G. J. Cho, M. S. Kim, J. S. Kim, S. B. Ali Bukhari, R. Haider, M. S. Zaman, C. H. Kim

***Abstract*—Due to high penetration level of Distributed Generations (DGs) on weak distribution networks, voltage rise problem can often occur due to reverse power flow which is not expected in conventional distribution networks. In order to overcome the voltage problem, DGs can be actively participated as a part of voltage regulating system because those can possibly change both active and reactive output by using power electronic devices, thereby locally control voltage profile in the network. This paper presents a zonal operation scheme of DGs with explicit rules for zone division and output control of DGs in order to achieve successful voltage regulation in a distribution network based on measurements using SCADA system. Optimal partitioning method based on impedance data of the distribution network with high penetration of PVs is utilized to divide the whole network into several voltage regulation zones. The DGs in each zone are responsible for voltage violations only in corresponding zone. Computer simulations using MATLAB have been conducted and the results show that the scheme is effective for voltage regulation in distribution networks with DGs.**

***Keywords*: Distributed Generation (DG), distribution network, MATLAB, voltage violation and regulation, zonal operation.**

I. INTRODUCTION

As penetration level of Distributed Generations (DGs) on weak distribution networks gets higher, voltage rise problem can often occur due to reverse power flow which is not expected in conventional distribution networks[1-2]. Because of the intermittent characteristic of DGs such as PhotoVoltaic (PV) and Wind Turbine (WT) where generation is easily affected by weather conditions, it is hard to expect that conventional voltage regulation devices such as On-Load Tap Changing transformers (OLTCs), Step Voltage Regulators (SVRs) and capacitor banks effectively operate (i.e. excessive operation of regulating devices in a system). In order to overcome this problem, DGs can be participated as a part of voltage regulating system because those can possibly change both active and reactive output by using power electronic devices, thereby control voltage profile in the network[3-4].

Recently, many researchers have developed schemes for voltage regulation in distribution networks with DGs by using optimization of several objective functions in terms of operation cost and/or losses[5-7]. Although it provides fully coordinated solutions if it is well-coordinated and may adapt to presence of DGs, it requires very high cost of field equipment such as substation processors and field measurements. Furthermore, a full-blown power flow model has to be equipped and it hasn't been proved in field tests. On the other hands, in case of Supervisory Control and Data Acquisition (SCADA) based schemes using feeder level and system level measurements, cost is moderate if distribution SCADA exists. Also, coordination controls between voltage regulation devices are possible to be used. Therefore, a SCADA based DG control scheme is proposed in this paper.

This paper presents a zonal operation scheme of DGs for voltage regulation in distribution networks based on measurements using SCADA system. It provides explicit rules for zone division by using optimal partitioning method as well as an advanced zonal operation with reasonable and feasible scheme. Partitioning method based on impedance data of distribution network is utilized to divide whole network into several voltage regulation zones and DGs in each zone are responsible for voltage violations only in corresponding zone. Therefore, DGs in zones where voltage violations happen operate first by changing their output. The scheme presented has been demonstrated in Korean distribution network run by Korea Electric Power Corporation (KEPCO) based on actual data. Computer simulations using MATLAB has been conducted and the results show that the scheme is effective for voltage regulation in distribution networks with DGs.

II. VOLTAGE REGULATION IN DISTRIBUTION NETWORKS

A. Conventional Distribution Networks

Distribution networks generally utilize OLTCs and SVRs with multiple taps automatically adjusted by Line Drop Compensator (LDC) scheme, in order to regulate voltages[8-9]. The LDC scheme in Fig. 1 estimates the line voltage drop based on line current and impedance of the line, and performs voltage corrections to keep the voltage at regulated point, V_{RP} constant within the allowable range as shown in (1).

$$\begin{aligned} & V_{LB} \le V_{RP} \le V_{UB} \\ & V_{LB} = V_{SET} - 0.5V_{DB}, \quad V_{UB} = V_{SET} + 0.5V_{DB} \end{aligned} \tag{1}$$

Where, V_{LB} and V_{UB} are the lower boundary and upper boundary limits, respectively. The set voltage, V_{SET} and deadband voltage, V_{DB} are the controller parameters for LDC scheme.

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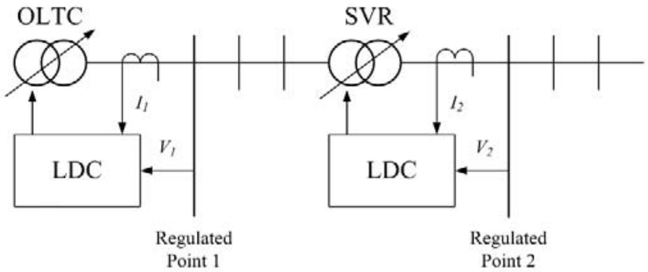

Fig. 1. A topology of distribution network with multiple voltage regulating devices

B. Distribution Networks with DGs

Due to the intermittent characteristic of DGs where generation is easily affected by weather conditions, we can't expect no longer that OLTCs and SVRs with LDC scheme effectively operate because output of DGs is not considered when setting LDC parameters. Therefore, the changes in both active and reactive power flows will affect the performance of voltage regulating devices, so that the LDC error may result in additional tap operations of the devices which lead to reduction in life span.

Given the problems of conventional voltage regulating devices, it is necessary to use output control function of inverters used for interconnecting DGs to distribution networks. IEEE Std. 1547.2-2008 suggests that DGs can't actively take part in the voltage regulation of the distribution network unless distribution system operators require them to change their outputs for the voltage regulation of a distribution network[10]. The recommendation, however, was made under circumstance where penetration level of DGs is expected insignificant enough not to cause voltage problems. Some countries such as Japan and Germany recently have been suggesting that DGs can be participated as a part of voltage regulating system by changing their both active and reactive output using power electronic devices[11-12]. As a result of the suggestion, smart inverters which can change their outputs have been developed. As shown in Fig. 2, the inverter can locally regulate voltages by increasing reactive power output and decreasing active power output in case of voltage rise problems when voltage violation occurs in a distribution network.

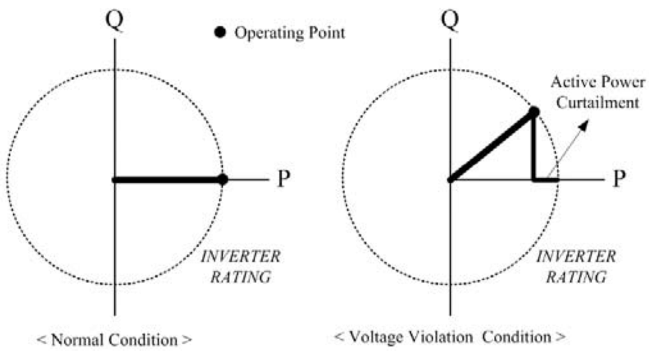

Fig. 2. Principle of active and reactive power control of smart inverter

III. ZONAL OPERATION SCHEME OF DISTRIBUTED GENERATION

A. Voltage Sensitivity Analysis

In order to solve the voltage problems due to high penetration of DGs, output of DGs can be controlled. In addition, it is very important to determine which DG should be participated to achieve successful voltage regulation with minimal changes in DG's outputs. In this paper, we decide best candidates for voltage regulation in a distribution network based on result of voltage sensitivity analysis.

Voltage sensitivity can be used to develop a voltage regulation scheme by analyzing voltage variation of nodes in a system due to changes in active and reactive power flows. As can be seen in (2), voltage sensitivity, Λ expressed by Jacobian matrix is an index that can expect voltage variations when active or/and reactive power is changed. As this paper focuses on only voltage variation, only Λ_{VP} and Λ_{VQ} are considered in (2). The Λ_{VP} and Λ_{VQ} can be expressed by (3) and (4), respectively, but those contain too much variables to obtain and calculate. To avoid complexity of parameters and calculations, we use the constant current model in [13] to simplify voltage sensitivity as shown in (5).

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Lambda_{\theta P} & \Lambda_{\theta Q} \\ \Lambda_{VP} & \Lambda_{VQ} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{2}$$

$$\frac{\partial Q_i}{\partial V_j} = V_i (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \tag{3}$$

$$\frac{\partial P_i}{\partial V_j} = V_i (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \tag{4}$$

$$S_{P_{ij}} = \frac{\partial V_i}{\partial I_{Pj}} = -R_{ij} \quad and \quad S_{Q_{ij}} = \frac{\partial V_i}{\partial I_{Qj}} = -X_{ij} \tag{5}$$

Where, G and B are conductance and susceptance, respectively, and S is voltage sensitivity. As shown in (5), voltage sensitivity with respect to active and reactive power strongly depends upon resistance and reactance, respectively. Therefore, it can be concluded that voltage sensitivity in a distribution network with DGs can be expressed as an impedance between a violation node and the other nodes with changes in active or reactive power. The smaller the impedance is, the larger the effect on the violation node is.

B. Optimal Partitioning Method based Zone Division

Optimal partitioning method divides a series of data into a few segments based on their homogeneity, e.g., minimum standard deviation, and keeps the order of the original data[14]. In a same segment, similar characteristic can be expected.

In this paper, all nodes in a distribution network are divided into several zones and DGs in a same zone simultaneously participate in voltage regulation for a violation node in the zone as shown in Fig. 3. It guarantees same performance with lower changes in output of DG and avoids unnecessary output

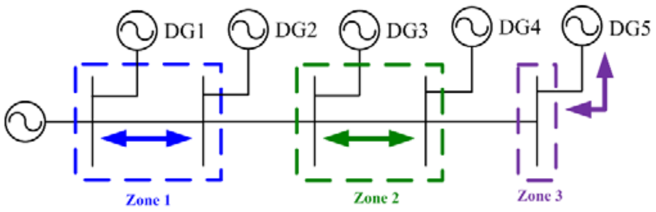

Fig. 3. Principle of zonal operation of DGs

control of DGs which are expected to have relatively small effect on the violation node.

The procedures for division of zones are as follows;

1) Obtaining impedance between substation and i_{th} node, x_i, and calculating distance matrix D between nodes in (6). All nodes in a network are considered and impedance between nodes should be classified with respect to resistance and reactance. $M(x_i, x_j)$ is the average value of x_i and x_j.

$$D(i,j) = (x_i - M(x_i, x_j))^2 + (M(x_i, x_j) + x_j)^2 \quad (6)$$

2) Finding optimal partitioning set of zones which guarantees smallest deviation with respect to impedance between nodes. The details for calculating and finding the case are presented in [14].

C. Proposed Voltage Regulation Scheme

The voltage regulation scheme proposed in this paper exploits the result of optimal partitioning method. DGs in the zone with voltage violation nodes control their outputs first, and the others participate in the regulation only when DGs in the zone are uncontrollable and there is no margin for outputs. As shown in Fig. 4, each zone is controlled by the corresponding zone controller. The main controller performs division of zones using obtained impedance data from Feeder Remote Terminal Unit (FRTU) and checks voltage violation nodes.

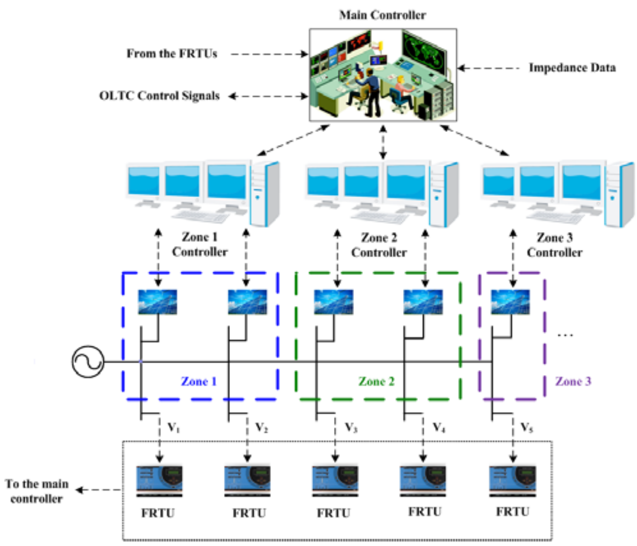

Fig. 4. Concept and components of the proposed scheme

Fig. 5 shows the DG control algorithm of zone controller. If there is a violation node in the zone, the corresponding zone controller is notified by the main controller and performs output control. Reactive power should be controlled first because active power curtailment is directly connected to profit of utility owner. Outputs are determined as new output set points, Q_{new} and P_{new}, in order to lower voltages within allowable range in case of voltage rise problems. The amount of changes in outputs is varied according to the voltage sensitivity (S_T) and lower sensitivity index means more effect on the voltage. Hence, the lower sensitivity is, the more the change in outputs. If there no longer is margin of output to be used, an alarm signal is issued to the distribution network operator.

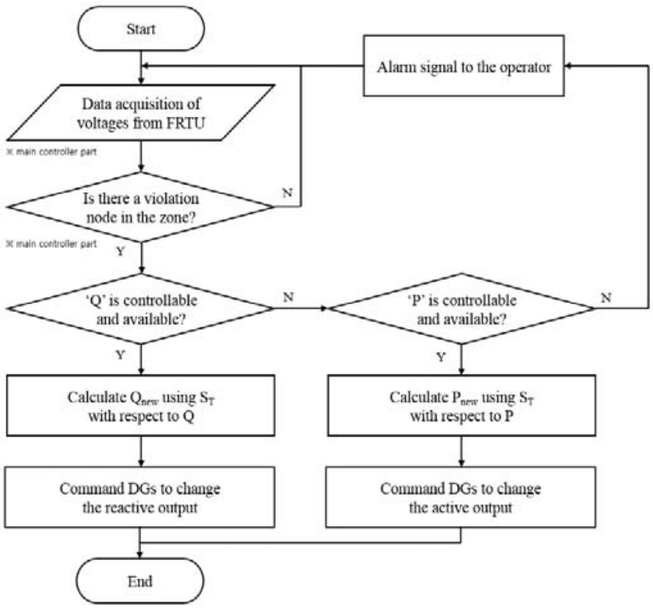

Fig. 5. DG control algorithm of zone controller

IV. Simulation

A. Simulation System and Conditions

A test distribution system run by KEPCO in Fig. 6 is considered to verify performance of the proposed scheme, and PVs are assumed to be connected to all nodes. The line impedance data is presented in Table I. Due to the short line length in '111' section in Fig. 6, the '110' and '111' sections are considered one section, so that there are 11 nodes in the system. The results of zone division based on optimal partitioning method with respect to are indicated in Table II. DGs participate in voltage regulation based on the results in Table II. In this paper, daily load curve and irradiation data in summer season are utilized as shown in Fig. 7 and Table III.

To cause voltage rise problems in the test system, large amount of PVs are connected to node 10 and 11 located at the end of the network as indicated in Table IV. It is assumed that all inverters can change outputs and margin of changes in power is set as 500[kVAR] and 500[kW]. Therefore, there is no output change if the amount of changes in outputs reaches margin of output.

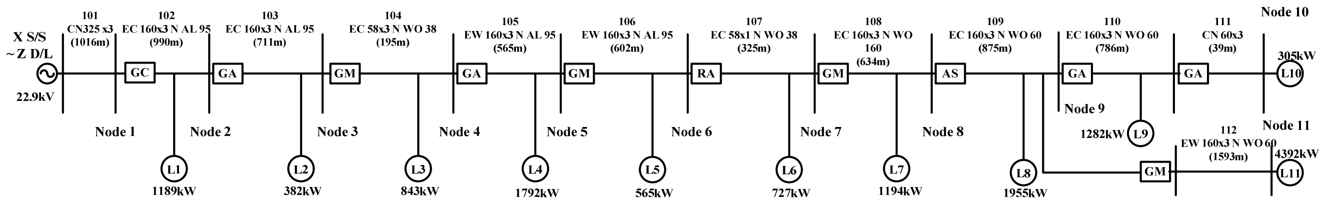

Fig. 6. Test distribution system model

TABLE I
LINE IMPEDANCE DATA OF TEST DISTRIBUTION SYSTEM

Section/Node	R/km[Ω]	R/km[Ω]	Length[km]
101/1	0.0869	0.00025	1.016
102/2	0.1823	0.00103	0.990
103/3	0.1823	0.00103	0.711
104/4	0.4842	0.00115	0.195
105/5	0.1823	0.00103	0.565
106/6	0.1823	0.00103	0.602
107/7	0.4842	0.00115	0.325
108/8	0.1823	0.00103	0.634
109/9	0.1823	0.00103	0.875
(110,111)/10	0.1823	0.00103	0.786+0.039
112/11	0.1823	0.00103	1.593

TABLE II
RESULTS OF ZONE DIVISION

With respect to active power				
Zone #	Zone 1	Zone 2	Zone 3	Zone 4
Node #	1,2	3,4,5,6	7,8,9	10,11
With respect to reactive power				
Zone #	Zone 1	Zone 2	Zone 3	Zone 4
Node #	1,2	3,4,5,6,7	8,9,10	11

TABLE III
AVERAGE IRRADIATION DATA ON JULY IN SEOUL

Time[h]	5 ~ 6	6 ~ 7	7 ~ 8	8 ~ 9	9 ~ 10
Irradiation [kWh/m^2]	0.03	0.08	0.13	0.18	0.21
Time[h]	10 ~ 11	11 ~ 12	12 ~ 13	13 ~ 14	14 ~ 15
Irradiation [kWh/m^2]	0.24	0.25	0.25	0.24	0.21
Time[h]	15 ~ 16	16 ~ 17	17 ~ 18	18 ~ 19	19 ~ 20
Irradiation [kWh/m^2]	0.18	0.13	0.08	0.03	0.00

TABLE IV
AMOUNT OF PV CAPACITY [MW]

Node #	1	2	3	4	5	6
Capacity	0.5	0.5	0.5	0.5	0.5	0.5
Node #	7	8	9	10	11	-
Capacity	0.5	0.5	0.5	6.5	6.5	-

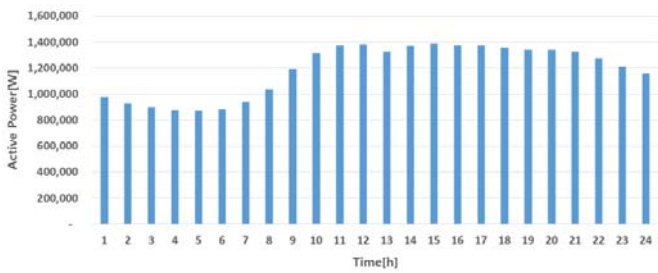

Fig. 7. Daily load curve in summer season – L1

The time of 0.1s represents one hour in simulations to consider daily data of load and irradiation (e.g. interval between 1.2s and 1.3s means the time between 12h and 13h), and only one DG in a zone participate in voltage regulation to compare performance of regulation according to the zone. Participating DGs are as follows.

- Zone 1 : DG connected to node 1
- Zone 2 : DG connected to node 4
- Zone 3 : DG connected to node 10 (violation node)
- Zone 4 : DG connected to node 11

B. Simulation Results and Discussions

Fig. 8 shows the voltage profiles in the test network during daytime. Due to the higher PV output, there are multiple voltage violation nodes in the network which should be regulated to avoid deterioration of power quality. As can be seen in Fig. 9 and Fig. 10, DGs participate in voltage regulation by controlling their outputs when the voltage above upper limit occurs. The DG starts changing the reactive power at 1.14s to lower voltages. In Fig. 9, the operation of zone 1 and 2 which are relatively far from the violation node fail to

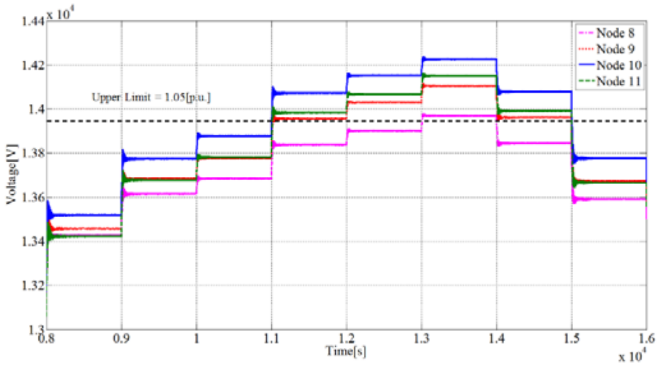

Fig. 8. Daytime voltage profiles in the test network

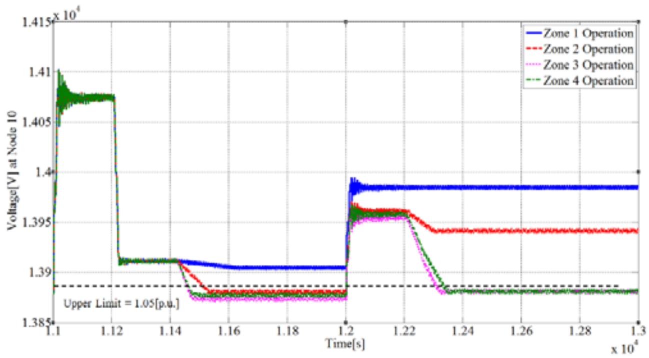

Fig. 9. Voltage profile of the node 10 according to the participating zone

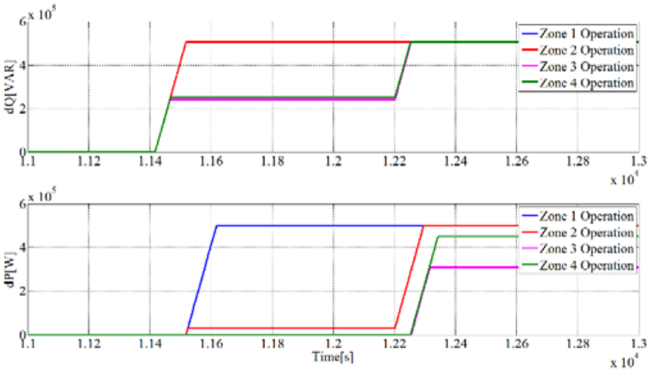

Fig. 10. Amount of output control according to the participating zone

decrease the voltage within allowable range whereas the operation of zone 3 and 4 achieve successful regulation. However, in spite of successful operation of zone 4, the zone 3 operation has the lower amount of output changes used for voltage regulation compared to the zone 4 operation which means better performance of zone 3.

V. Conclusions

This paper presents an advanced zonal operation scheme of DGs, which is feasible with the help of SCADA-based technology, in order to regulate voltages in a distribution network with high penetration of PVs by controlling outputs of those based on zonal operation. Optimal partitioning method, which provides explicit and reasonable rules for data clustering, is utilized to divide a network into several zones based on the impedance data directly related to the result of voltage sensitivity analysis. Computer simulations using MATLAB are conducted to verify the performance of the presented scheme. Daily load curve and irradiation data of PV are considered and simulation results show that the presented scheme can effectively regulate the voltage of distribution network with the low amount of changes in active and reactive power.

VI. References

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