VOLT/VAR OPTIMIZATION OF THE KOREAN SMART DISTRIBUTION MANAGEMENT SYSTEM

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ABSTRACT

This paper introduces a prototype volt/var optimization (VVO) method for the Korean smart distribution management system (K-SDMS) considering control of distributed generations (DGs) and a looped distribution topology. The main function of the VVO is to determine the references of volt/var control devices, including DGs to eliminate violations, to minimize the switching operation of the on-load tap changer (OLTC), the step voltage regulator (SVR), and capacitors, and to minimize the active power loss of the distribution network. The effectiveness of the VVO is presented with case studies using the K-SDMS simulator.

INTRODUCTION

In 2009, the Korea Electric Power Corporation (KEPCO) undertook a project to develop a Korean smart distribution management system (K-SDMS). In the K-SDMS, interconnections between many distributed generations (DGs) and a looped distribution topology are considered to achieve more reliable and economical operation. For this type of distribution network, conventional volt/var control methods proposed based on the assumption of a unidirectional power flow with a radial topology cannot be applied due to an inverse power flow and looped topology. Therefore, a new volt/var control method considering a bidirectional power flow and a looped topology, known as volt/var optimization (VVO) in the K-SDMS, is being developed.

VOLT/VAR OPTIMIZAION OF THE K-SDMS

The volt/var control devices considered in the VVO are on-load tap changers (OLTCs), step voltage regulators (SVRs), static var compensators (SVCs), capacitors, and DGs. For DGs, only the reactive power output is considered as a controlling variable for the VVO. The operation constraints of the distribution network considered in the VVO are the node voltages and line flows of the distribution network and the power factors of the injected power through each main transformer (MTR) in the distribution network.

The objectives of the prototype VVO for the K-SDMS are classified according to their priority levels. These include eliminating violations; minimizing the switching operation of the OLTCs, SVRs, and capacitors; and minimizing the active power loss of the distribution. Because a switching operation decreases the device lifetime and can suspend the power supply for device management reasons, increasing the financial burden related to the operation of the system, minimization of the switching operation should come prior to the minimization of the active power loss [1]. Thus, only the DGs and SVCs are used to minimize the active power loss in the VVO.

Additionally, the VVO provides the following information.

1) If a violation occurs, the VVO determines the emergency level and corresponding operating ranges of the node voltages, line flows, and power factors. The emergency level is an integer representing the severity of the violation which occurred. If the violation can be eliminated by controlling the volt/var control devices, the emergency level is zero and the corresponding operating ranges are equal to the normal operating ranges. Otherwise, the emergency level is a positive integer and the operating ranges are enlarged proportional to the emergency level. From the emergency level, the system operator can decide whether to ignore the violation or eliminate the violation using other methods, such as an active power curtailment of DGs or a network reconfiguration.

2) The VVO calculates the states of the distribution network, including the node voltages and the line flows, when the calculated references are applied. This function helps the system operator decide whether or not to apply the calculated references to the actual system.

Considering the looped distribution topology, the VVO calculates the references for volt/var control devices using three optimal power flows (OPFs), emergency level minimization (ELM), switching operation minimization (SOM), and active power loss minimization (APLM). A flow chart of the VVO is shown in Figure 1. If a violation occurs, the ELM, the SOM, and the APLM are sequentially executed. Alternatively, only the APLM is executed.

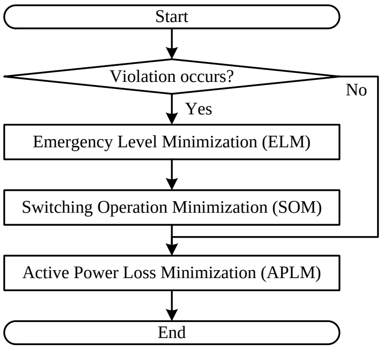

Figure 1. Flow chart of the VVO

Emergency level minimization

ELM is utilized to determine the minimum emergency level and corresponding references of the volt/var control devices. This problem is formulated as an OPF problem:

$$\underset{[L_{EM},u,v]}{\text{Minimize}} \quad L_{EM} \tag{1}$$

subject to

$$g(x,u,v)=0 \tag{2}$$

$$0 \le L_{EM} \tag{3}$$

$$u_{min} \le u \le u_{max} \tag{4}$$

$$v_{min} \le v \le v_{max} \tag{5}$$

$$V_{min,i}(L_{EM}) \le V_i(x,u,v) \le V_{max,i}(L_{EM}) \quad \text{for all node } i \tag{6}$$

$$-F_{max,j}(L_{EM}) \le F_j(x,u,v) \le F_{max,j}(L_{EM}) \quad \text{for all line } j \tag{7}$$

$$QP_{min,k}(L_{EM}) \le \frac{Q_k(x,u,v)}{P_k(x,u,v)} \le QP_{max,k}(L_{EM}) \quad \text{for all MTR } k\,. \tag{8}$$

Here, x is the vector of the state variables, which consist of the voltage magnitudes and angles at the nodes; L_{EM} is the emergency level, which is an integer; u is the vector of the references for OLTCs, SVRs, and capacitors; u_{min} and u_{max} are the minimum and maximum bounds of u; v is the vector of the references for SVCs and DGs; v_{min} and v_{max} are the minimum and maximum bounds of v; $V_i(x,u,v)$ is the magnitude of the voltage at node i; $V_{min,i}(L_{EM})$ and $V_{max,i}(L_{EM})$ are the minimum and maximum operating limits of $V_i(x,u,v)$, which are a function of L_{EM}; $F_j(x,u,v)$ and $F_{max,j}(L_{EM})$ are the power flow of line j and its maximum operating limit; $Q_k(x,u,v)$ and $P_k(x,u,v)$ are the reactive power and active power injected into the distribution system through the MTR k; and $QP_{min,k}(L_{EM})$ and $QP_{max,k}(L_{EM})$ are boundaries related to the power factor operating range.

In (6), the operating boundaries of the voltage magnitude at the node i are determined according to the emergency level:

$$V_{min,i}(L_{EM}) = V_{min0,i}(1-0.5L_{EM}\Delta V_{EL}) \tag{9}$$

$$V_{max,i}(L_{EM}) = V_{max0,i}(1+0.5L_{EM}\Delta V_{EL}) \tag{10}$$

Here, $V_{min0,i}$ and $V_{max0,i}$ are the minimum and maximum operating limits of the voltage magnitude at node i in the normal condition, respectively. Additionally, ΔV_{EL} is the increasing rate of the voltage operating range with respect to the increase in the emergency level.

The maximum power flow of line j in (7), $F_{max,j}(L_{EM})$, is c alculated as

$$F_{max,j}(L_{EM}) = F_{max0,j}(1+L_{EM}\Delta F_{EL}) \tag{11}$$

where $F_{max0,j}$ is the maximum allowable power flow of the line j and ΔF_{EL} is the increasing rate of the maximum allowable power flow with respect to the increase in the emergency level.

Boundaries of (8), $QP_{min,k}$ and $QP_{max,k}$, are determined by the emergency level and the normal operating limits of the MTR k, as

$$QP_{min,k}(L_{EM}) = -tan(cos^{-1}(PF_{lead,min0,k}(1+0.5L_{EM}\Delta PF_{EL}))) \tag{12}$$

$$QP_{max,k}(L_{EM}) = tan(cos^{-1}(PF_{lag,min0,k}(1+0.5L_{EM}\Delta PF_{EL}))) \tag{13}$$

where $PF_{lead,min0,k}$ and $PF_{lag,min0,k}$ are the minimum acceptable leading power factor and lagging power factor of the MTR k in the normal condition, respectively. In addition, ΔPF_{EL} is an increasing rate of the acceptable power factor range with respect to increase in the emergency level.

Switching operation minimization

SOM is used to minimize the switching operations of OLTCs, SVRs, and capacitors, while maintaining the voltages and line flows of the distribution network and the power factors of MTRs within their operating ranges as determined by the emergency level. This problem is formulated as an OPF problem of which the constraints are (2) and (4)-(8). The object function is:

$$\underset{[u,v]}{\text{Minimize}} \sum_{l\in\{OLTCs,SVRs\}} w_l\,|T_{0,l}-T_l(u)| + \sum_{m\in\{capacitors\}} w_m\,|S_{0,m}-S_m(u)| \tag{14}$$

where w_l and w_m are weight factors; $T_{0,l}$ and $T_l(u)$ are the tap position before the execution of the VVO and the tap position corresponding to u of the device l; and $S_{0,m}$ and $S_m(u)$ are the state index before the execution of the VVO and the state index corresponding to u of the capacitor m, respectively. The state index of a capacitor is zero if the capacitor is connected to the distribution system;

otherwise, state index is 1. In the constraints, L_{EM} determined during the emergency level minimization step is used to calculate each bound.

Active power loss minimization

In the APLM, the references for the SVCs and DGs are calculated to minimize the active power loss of the distribution system while satisfying the operating constraints. The APM is an OPF problem of which the object function is

$$\underset{[v]}{\text{Minimize}} \quad P_{loss}(v) \tag{15}$$

and the constraints are (2) and (5)-(8). In the constraints, L_{EM} as determined by the ELM and u as calculated by the SOM are used. If a violation does not occur and thus L_{EM} and u are not determined, L_{EM} and u are set to zero and the initial references before the execution of the VVO, respectively.

Solution method for OPFs

In order to solve OPFs, the sequential mixed integer liner programming method is utilized [2].

CASE STUDY

The case study was performed using the K-SDMS simulator shown in Figure 2. The test system used in the case study is based on the real distribution network connected to MTR#1 of the Sungsan substation on Jeju Island in Korea, as shown in Figure 3. In order to demonstrate the effects of DGs on the VVO, we added three DGs of which the maximum active power output is 3 MW and the power factor control range is from leading 0.9 to lagging 0.9.

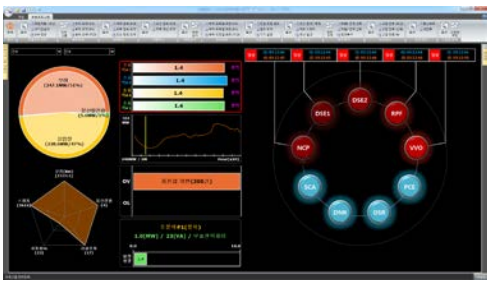

Figure 2. K-SDMS simulator

In the case study, it was assumed that the OLTC and SVR directly control their tap position. Therefore, the VVO calculates the tap position references for the OLTC and SVR and the power factor reference of the DGs. As the operating constraint, only the voltage constraint, of which the normal operating range of the voltages is from 0.96 p.u to 1.04 p.u., was considered.

In this paper, the results of two case studies that best illustrate the performance and effectiveness of the VVO are presented. In both of the case studies, the initial active and reactive power outputs of DGs were 2.7 MW and zero; i.e., the power factor of each DG was maintained at 1. Only the difference between the case studies was the total load:

Case 1) 7.92 MW and 3.19 MVAr
Case 2) 1.32 MW and 0.53 MVAr.

Case 1

The major states of the distribution network calculated by the real-time power flow (RPF) and the VVO are summarized in Table 1. The RPF is one of the K-SDMS applications and is executed directly before the execution of the VVO. In Table 1, V_{min}, V_{max}, and P_{loss} are the minimum voltage, the maximum voltage, and the active power loss of the distribution network, respectively. Given that the voltages of the distribution network were already maintained within their operating limits, only the APLM was performed in the VVO. Consequently, the active power loss of the distribution network was reduced by about 5.8%.

Table 1. Distribution system state for case 1

	V_{min}	V_{max}	P_{loss}
RPF	0.970 p.u.	1.00 p.u.	475.2 kW
VVO	0.999 p.u.	1.04 p.u.	447.8 kW

The power factor references for the DGs ($PF_{ref,\ DG}$) as calculated by the VVO are shown in Table 2. Because the power factor references were lagging, the DGs supplied reactive power to the distribution network; thus, the voltages were increased compared to those of the RPF, as shown in Figure 4.

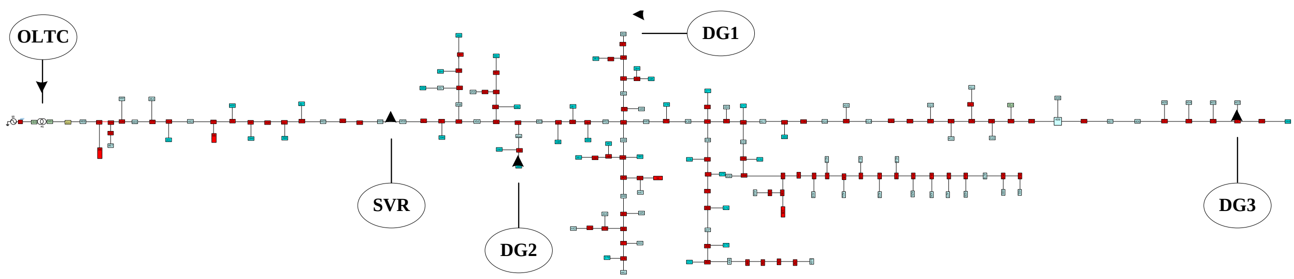

Figure 3. Test distribution network

Table 2. Power factor references of DGs for case 1

	$PF_{ref, DG1}$	$PF_{ref, DG2}$	$PF_{ref, DG3}$
RPF	1	1	1
VVO	lagging 0.74	lagging 0.97	1

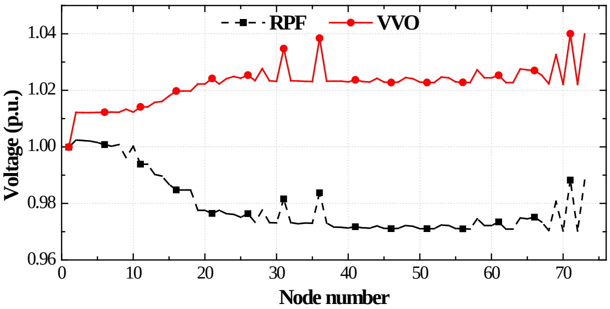

Figure 4. Voltage profiles of RPF and VVO for case 1

Case 2

In case 2, an over-voltage violation occurred; thus, the ELM, the SOM, and the APLM were sequentially executed in the VVO. The references calculated at each step and the major states when the calculated references were applied are summarized in Table 3. The voltage profile of the distribution system with respect to the references calculated by the VVO is shown in Figure 5.

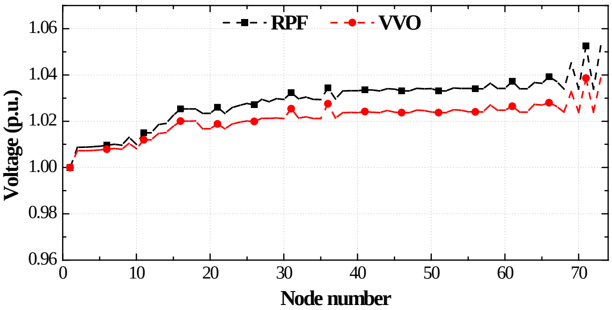

Figure 5. Voltage profiles of RPF and VVO for case 2

The emergency level of the violation was zero, which means that the voltages remained within their normal operating range. The over-voltage violation was eliminated without a switching operation. As shown in Table 3, the tap position of the OLTC (T_{OLTC}) was decreased by the ELM but it recovered to its initial tap position by the SOM. Because the active power loss was not considered in the SOM, the active power loss increased remarkably in the SOM. However, the increased active power loss was minimized to 531.8 kW by the APLM.

CONCULSIONS

The objectives of the prototype VVO for the K-SDMS are classified according to their priority levels as eliminating violations, minimizing switching operations, and minimizing the active power loss of the distribution. In order to achieve these objectives with consideration of a looped topology and a bidirectional power flow, the VVO determines the references for volt/var control devices while utilizing three different OPFs. In this paper, the OPFs are presented and results from a case study that illustrate the effects of the VVO are reported.

Acknowledgments

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Table 3. Calculated references and corresponding network sates of case 2

	Distribution network state			Reference for volt/var control devices				
	V_{min}	V_{max}	P_{loss}	T_{OLTC}	T_{SVR}	$PF_{ref, DG1}$	$PF_{ref, DG2}$	$PF_{ref, DG3}$
RPF	1.000 p.u.	1.053 p.u.	519.7 kW	12	15	1	1	1
ELM	0.997 p.u.	1.038 p.u.	536.5 kW	11	15	lagging 0.90	lagging 0.98	leading 0.90
SOM	0.965 p.u.	1.000 p.u.	673.5 kW	12	15	leading 0.94	leading 0.90	leading 0.90
APLM	1.000 p.u.	1.039 p.u.	531.8 kW	12	15	1	1	leading 0.98