Development of an Intelligent Voltage Control System for Jeju Island in Korea

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Abstract – The reactive power, unlike frequency, has local characteristics and it has relied on the manual operation in a local reactive power control station so far. Since coordination or integrated control was possible due to the recent advances in computers and communication networks, the hierarchical voltage control system, consisting of primary, secondary, and tertiary, has been already applied to the real-life situations of several developed countries in Europe. Recently, the Korea power system has been operated more closely to stability limits because of rapid growth in load-demand as seen in Europe. For this reasons, KEPCO recognized the need of the voltage control system and developed the voltage control system. In this paper, we developed intelligent voltage control system for domestic system using numerical algorithm based on the sensitivity matrix and expert system, and dynamic response characteristics of the developed system investigated as a preliminary step for interfacing RTDS(Real Time Digital Simulator). In addition, the developed system performance was verified.

Keywords: Sensitivity matrix, Expert system, Intelligent voltage control system, RTDS

1. Introduction

Recently, massive power outages in Europe and North America were caused by unbalances in reactive power, resulting in voltage collapse. Furthermore, the consolidated regional selfishness such as NIMBY (Not In MY Back Yard) phenomenon makes it difficult to construct large-scaled generation plants and reinforce transmission line facilities even though the demand rapidly increases. Obviously, reactive power losses are increased due to the installation of long-distance transmission lines since the generation power plants are located far from the load-demand regions. Many countries around the World are now experiencing this situation. In fact, any appropriate voltage and reactive power control contributes to preventing blackout or equipment damage by the voltage collapse, reducing the reactive power losses, and eventually enhancing the transmission transfer capability.

The operation in reactive power has been merely performed by the operators’ engineering knowledge and judgment until the hierarchical voltage control system is developed. In the 1970s, the expert system using the experts’ heuristic knowledge with computer simulation emerged in step with artificial intelligence. In the 1980s, an expert system for real-time voltage and reactive power control was proposed based on the sensitivity tree in Canada [1], and at the same time SEGREG [2] and SETRE [3-4] were successfully applied in Spanish power system. At this moment, several advanced countries are operating the voltage and reactive power control system by taking into account inherent characteristics of their own power systems [5-6].

Most of all, the Korean power system has been operated more closely to stability limits because of rapid growth in load-demand as seen in Europe, and more reactive power demand will in turn be needed. Unfortunately, the power system voltage is maintained only by individual substations since it is not actually easy to secure the site for voltage compensation equipment and the regional systematic voltage control framework is not really prepared. Therefore, any real countermeasures against blackout or equipment damage by the voltage collapse need to be taken as it is highly probable for such events to happen in Korean power system. Specifically, the voltage stability problem in metropolitan region incurred by the northward power flow limits in the Korean power system is regarded as one of the critical issues for improving the efficiency of power system
operations and stability, where unusual reactive power balances mainly accounted for the voltage instability, irrespective of overall generation reserves.

In this paper, we developed intelligent voltage control system for domestic system using numerical algorithm based on the sensitivity matrix and expert system, and dynamic response characteristics of the developed system investigated as a preliminary step for interfacing RTDS (Real Time Digital Simulator). In addition, the developed system performance was verified.

2. Intelligent Voltage Control System

The structure of intelligent voltage control system to be explored in this paper is described in Fig. 1, where the intelligent controller is made up of the sensitivity matrix based numerical module and the knowledge base including a wide variety of information related with power system status and control knowledge.

2.1 Knowledge base

The knowledge in a specific problem domain is classified by truth and rule and then stored in the database and rule base, respectively. Database in the backward rule base system, for instance PROLOG, is divided by static database and dynamic database, and stored as immutable truth in a specific domain or hypothetic truth derived from the inference process.

Fig. 1. Structure of intelligent voltage control system.

Here, the knowledge base stores the system information obtained from the load flow and uses it for both searches and inference. Database and rule base will be in the following:

(A) Database
① Upper and lower limit of each bus voltage
② Upper and lower limit of the voltage regulation
③ Upper and lower limit quantity of compensation devices
④ Priority of compensation devices
⑤ Quantization level of generator terminal voltage

(B) Rule base
① If the bus voltage exceed upper and lower limit of each bus voltage the system operate the controller
② If abnormal voltage occurred, firstly controller constitute sensitivity tree.
③ Controller select the compensation device of largest sensitivity
④ If selected reactive power compensation device's capacity is lack, controller select the second highest compensation device
⑤ Controller operate the specified priority of compensation devices
⑥ If abnormal voltage occurred in several bus, controller operated based on the greatest abnormal bus voltage.
⑦ If a bus voltage don’t adjust within voltage regulation by using compensation device of first ranking, compensation device of next ranking is committed.
⑧ Reactive power compensation amount determined Linear Prediction method.
⑨ The controller solved power flow to identify control effect

2.2 Sensitivity Matrix

Assuming an N bus power system with M control actions, the relationship between the bus voltages and the control actions can be represented as shown in Fig. 2. It is pointed out that the changes in each control action have significant impacts on the voltage in some buses. For a particular voltage violation, it is possible to compute the control action needed to remove this voltage violation by the sensitivity technique. It is worthy to mention that the control action should neither exceed the specified limits nor incur new voltage violations of other buses.

The sensitivity matrix is a fundamental parameter in the intelligent voltage control system. By defining the relationship of changes in bus voltages according to compensation changes in the generator terminal voltage, shunt capacitor/reactor, and transformer tap, it selects the control actions when the voltage violation occurs and determines the quantity of compensation requirement.
Fig. 2. Description of bus voltage and control actions.

The sensitivity matrix is reestablished by the relationship between the voltages and the reactive power in the Jacobian matrix constructed from the load flow equation.

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\
\frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta V
\end{bmatrix}
\]  \hspace{1cm} (1)

Assuming that the voltage angle is negligible in the relation with the reactive power, the relationship between the voltage and the reactive power is encapsulated in (2).

\[
\Delta Q = \left[ \frac{\partial Q}{\partial V} \right] \Delta V
\]  \hspace{1cm} (2)

\[
\Delta V = \left[ \frac{\partial Q}{\partial V} \right]^{-1} \Delta Q
\]  \hspace{1cm} (3)

\[
\left[ \frac{\partial Q}{\partial V} \right]^{-1}
\]  is the Jacobian matrix of load flow calculation in (2). That is, \( \left[ \frac{\partial Q}{\partial V} \right]^{-1} \) is the inverse matrix of \( \frac{\partial Q}{\partial V} \) and called the sensitivity matrix which estimates the changes of bus voltages against the changes of reactive power. The sensitivity matrix is given by the control actions as shown in (4).

- \( \Delta V_i = S_{sh} \cdot \Delta U_{sh} \)
- \( \Delta V_i = S_{sh} \cdot \Delta U_{sh} \)
- \( \Delta V_i = S_{g} \cdot \Delta U_{g} \)
- \( \Delta V_i = S_T \cdot \Delta U_T \)

3. State-space model of the Intelligent voltage control problems

This paper applied the weighted evaluation function such as expression (1) when all the compensation devices use discrete control quantity.

\[
\min_{V_{vio}} \left( a \sum \Delta V_{gi} + \sum \beta \left| \Delta X_{K} \right| + \sum \gamma \left| \Delta Q_{i} \right| \right)
\]  \hspace{1cm} (1)

\( V_{vio} \) is newly occurred abnormal bus voltage in normal bus

Basically, the transformer Tab and the switched shunt used discrete quantity. But, compensation device such as generator terminal voltage used continuous quantity. Therefore, continuous quantity such as generator terminal voltage must be converted to a discrete quantity through the quantization process. The following Fig. 3 is in partly expanded state-space model of discrete effect quantity in power system composed of each 2 devices (generator, transformer, switched shunt).

3.1 Least-cost search

After a given problem define the representation model, to solve the problem we need a several strategy and one of the key strategies is search. The searches will be defined by the trial process to assess possible solution paths and reach from initial state to final state. It may be divided into two categories: blind searches and heuristic searches. The blind searches divided to breadth-first search and depth-first search. But, this method is not good in case that state-space is large due to it do not contain intelligent decision. The heuristic searches is a method to continuously search a solution after getting rid of the solution path that seems inappropriate by judgment such as heuristic knowledge or
cost function. This method could reduce state-space but might be occurred that do not solve.
This paper used least-cost search to minimize weighted evaluation function such as expression (1). The search process following:

•Step 1:
About the bus where the abnormal bus voltage, a v1 node that the largest effect quantity (sensitivity value × control quantity) was selected by the system. And the system expands v1 node as three quantized effect quantity. Using three quantized effect quantity, the system calculated liner prediction and weighted evaluation function about all the bus voltage. Evaluation function quantities of expanded node are 11,9,10 as seen figure 2. The system selected v1_2 node that the smallest of evaluation function value and progress a selection of compensation device of step 2.

•Step 2:
The system performs liner prediction by using effect quantity of v2. As a result, the system selected transformer tap t1 because abnormal bus voltage occurred in normal bus. And through the same process of v1 node, the system selected t1_3 node that the smallest of evaluation function quantity. Finally, if abnormal bus voltage is dissolved, the system selected compensation device of step 3. Conversely, if abnormal bus voltage is solved, the system finished the search process.

4. PSCAD/EMTDC Dynamic Response Characteristic
As the preliminary step for interface with RTDS, dynamic response characteristics of the developed system investigated the case of transmission line outage using PSCAD/EMTDC[7].
The voltages of Jocheon bus before and after the voltage control has been executed by the generator terminal voltage are portrayed in Fig. 4 and 5.
The scenario with PSCAD/EMTDC has been laid down by power system operation manual in Korea as can be seen in Table 1.

Table 1. Scenario in case of a transmission line outage

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.00</td>
<td>Three-phase short circuit fault happened</td>
</tr>
<tr>
<td>8.02</td>
<td>Circuit breaker on</td>
</tr>
<tr>
<td>8.10</td>
<td>Terminal voltage of generator chosen by the voltage controller increased</td>
</tr>
</tbody>
</table>

5. RTDS Interface
Fig. 6 shows the basic structure of interface system between RTDS and the intelligent voltage system.
RTDS system generated power system information data file for a specified period. As MMI Client for communication with RTDS system, it is stored the data in VMS’s DB. Also, it receives a signal to adjust the bus voltage and to adjust the control quantity of control target device. VMS (Voltage Management System) is the parent system to interfacing the intelligent voltage system and RTDS. The operating conditions of the intelligent voltage control system can be set on the HMI.
Fig. 7 shows the HMI display of the intelligent voltage control system.

And intelligent voltage control system operating conditions as follow:

① Upper and lower limits of abnormal bus voltage:
The user can specify the abnormal voltage range over a wide range of the controller were to be applied.

② Upper and lower limits of voltage regulation:
This rule means that not adjust the control action within the upper/lower limits of abnormal voltage but calculate the control action within the upper/lower limits of voltage regulation for the buses occurred abnormal voltage.

③ Upper and lower limits of generator terminal voltage:
The intelligent voltage control system adjusts bus voltage using a generator terminal voltage within the setting range.

④ Priority of compensation devices:
For an effective and efficient voltage-control a user could set control devices(generator terminal voltage, shunt capacitor, transformer tap) Priority.

⑤ Quantization level of generator terminal voltage:
A continuous Control value such as the generator terminal voltage is converted into discrete control value, thereby it is a rule for minimize aforementioned weighted evaluation function.

⑥ The controller execution cycle:
Because of the controller don’t execute on transient state, the controller execution cycle setting is important issue.

6. Case Study

In the case study, we found the abnormal bus voltage in case of a transmission line outage and a transmission line restoration in Jeju Island using RTDS.

The controller operation condition is as follow:

① Upper and lower limit of abnormal bus voltage [p.u.]: 0.95 > V or V > 1.05

② Upper and lower limit of the voltage regulation [p.u.]: 0.97 < V < 1.03

③ Upper and lower limits of generator terminal voltage [p.u.]: 0.95 ≤ generator terminal voltage ≤ 1.05

④ Priority of compensation devices:
Generator > shunt capacitor > transformer tap

⑤ Quantization level of generator terminal voltage: 5[step]

⑥ The controller execution cycle: 90 [sec]

Figure 8 show 154[kV] bus voltage profile in Jeju power system and Table 2 is a bus voltage before the controller execution.

Looking at figure 8, the voltage violation happened at several buses after a transmission line outage. The controller is performed voltage control about a largest abnormal bus voltage[Sanji(210)].

After voltage control, the Sanji(210) bus adjusted within voltage regulation. But the North Jeju TP bus is adjusted by the controller. The controller is performed voltage control again at the controller execution cycle.

The North Jeju TP(170) bus voltage could not adjust within voltage regulation. The reason the controller doesn’t occurred new voltage violation in another buses by linear prediction of controller.

Finally, the voltage violation happened at the South Jeju bus(170) after transmission line restoration. The controller adjusted all the bus voltages within voltage regulation at the controller execution cycle.
Table 2. A bus voltage profile before the controller execution

<table>
<thead>
<tr>
<th>BUS NO.</th>
<th>BUS NAME</th>
<th>First control before</th>
<th>Second control before</th>
<th>Final control before</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>North Jeju TP</td>
<td>1.051344</td>
<td>1.058798</td>
<td>1.04125</td>
</tr>
<tr>
<td>121</td>
<td>North Jeju CS</td>
<td>1.051343</td>
<td>1.058797</td>
<td>1.04125</td>
</tr>
<tr>
<td>122</td>
<td>North Jeju TS</td>
<td>1.051343</td>
<td>1.058797</td>
<td>1.04125</td>
</tr>
<tr>
<td>130</td>
<td>East Jeju</td>
<td>0.941803</td>
<td>0.971353</td>
<td>1.040724</td>
</tr>
<tr>
<td>140</td>
<td>New Jeju</td>
<td>0.9623</td>
<td>0.991398</td>
<td>1.041826</td>
</tr>
<tr>
<td>150</td>
<td>Hanrim CC</td>
<td>0.999744</td>
<td>1.025911</td>
<td>1.058213</td>
</tr>
<tr>
<td>160</td>
<td>Andeok</td>
<td>1.008411</td>
<td>1.038311</td>
<td>1.061596</td>
</tr>
<tr>
<td>170</td>
<td>South Jeju TP</td>
<td>1.013565</td>
<td>1.045016</td>
<td>1.066134</td>
</tr>
<tr>
<td>180</td>
<td>New Seogwi</td>
<td>1.005808</td>
<td>1.029971</td>
<td>1.045863</td>
</tr>
<tr>
<td>190</td>
<td>Hanra</td>
<td>1.01381</td>
<td>1.033414</td>
<td>1.04169</td>
</tr>
<tr>
<td>200</td>
<td>Seongsan</td>
<td>1.019621</td>
<td>1.033073</td>
<td>1.029228</td>
</tr>
<tr>
<td>210</td>
<td>Sanji</td>
<td>0.941176</td>
<td>0.97075</td>
<td>1.040172</td>
</tr>
<tr>
<td>220</td>
<td>Jochen</td>
<td>1.037213</td>
<td>1.04742</td>
<td>1.036721</td>
</tr>
<tr>
<td>230</td>
<td>Hanrim</td>
<td>1.000012</td>
<td>1.02677</td>
<td>1.058658</td>
</tr>
</tbody>
</table>

8. Conclusion

In this paper, we developed intelligent voltage control system for domestic system using numerical algorithm based on the sensitivity matrix and expert system, and dynamic response characteristics of the developed system has been investigated as a preliminary step for interfacing RTDS. In addition, the developed system performance was verified. In future, we will improve the performance of the intelligent voltage control system by parameter tuning and modification of control algorithms.

Acknowledgements

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References


Fig. 8. 154[kV] bus voltage profile in Jeju power system.


[7] H. J. Lee et al., “Hybrid Intelligent Voltage and Reactive Power Control System For Jeju Power System in Korea” 8th WSEAS International Conference on POWER SYSTEM (PS 2008), Santander, Cantabria, Spain, September 23-25, pp118-123

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