Hybrid Intelligent Voltage and Reactive Power Control System For Jeju Power System 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. Accordingly, the voltage and reactive power control system is also required in Korea. In this paper, the intelligent system for the voltage and reactive power control will be developed and its performance will be verified on Jeju Island in Korea with PSCAD/EMTDC. The proposed system particularly takes advantage of the sensitivity matrix that is a numerical analysis technique with respect to control facilities such as generator terminal voltage, switched shunt capacitor/reactor, transformer tap as well as the best-first searches to adopt sensitivity coefficients as the cost function, leading to the development of a true hybrid type.

Key-Words: Sensitivity matrix, Expert system, Best-first searches, Voltage and reactive power control, Hybrid

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 SEGRE [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 context, the intelligent system for the voltage and reactive power control will be developed and simulated on Jeju Island in the Korean Power system by the aid of PSCAD/EMTDC. This system makes fully use of the sensitivity matrix that is a numerical analysis technique of control equipment such as generator terminal voltage, switched shunt capacitor/reactor, transformer tap as well as the best-first searches to use sensitivity coefficients as the cost function, leading to the development of a hybrid type expert system.

2 Intelligent Control System

The intelligent control means that the controller plays a leading rule in inferring and judging the current situations based on the knowledge base formed by the experts' knowledge and experience. Plus, it covers typical automatic control concepts and extensively an unmanned automatic control scopes. On the whole, the intelligent control has been vigorously researched in the area of large-scaled power systems required of complicated operation strategies and experts' experiences since it is characterized in terms of the mechanical realization of experts' experimental or instinctive knowledge that is not possibly implemented by a numerical algorithm alone. For example, the expert system is widely studied in the fault detection and diagnosis, fault recovery, system state estimation and alarm system. In the long run, the futuristic large-scale control system will be well organized by a hierarchical structure of both the decentralized adaptive control and the intelligent control.

2.1 Fundamentals of intelligent voltage and reactive power control system

The structure of intelligent voltage and reactive power 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.

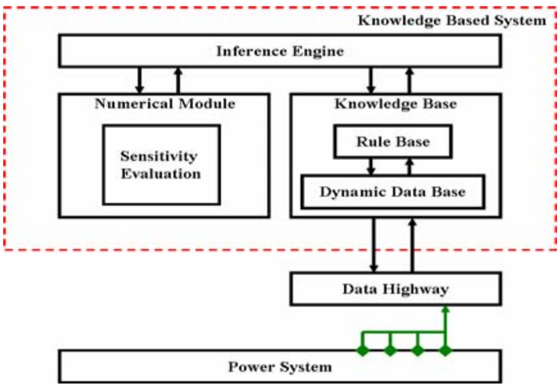

Fig. 1 Structure of intelligent voltage control system

2.2 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. 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

The load bus voltage profile calculated from the load flow

The open/closed status of transmission lines

The upper and lower limits of each bus voltage

The upper and lower limits of each reactive power compensation device

The upper and lower limits of each control device

The sensitivities of bus voltages with respect to each control device

(B) Rule base

Compare the current voltages with their specified limits, and find the buses with voltage violations.

Check the voltage violation according to the following criteria.

○ Normal voltage [p.u.]

$0.95 \le V \le 1.05$

○ Abnormal voltage [p.u.]

$0.95 < V$ or $V > 1.05$

Establish the sensitivity tree for each abnormal bus voltage, find the most effective (the highest weighted sensitivity) control in the bus with the worst voltage violation, and calculate the controls needed to remove the voltage violation.

Check the operation of controller considering the its constraints. If the controls exceed the limits, the control value is fixed to the control limit.

The criteria of generator terminal voltage are as follows:

○ Upper and lower limits of generator terminal voltage [p.u.]

$0.95 \le$ generator terminal voltage ≤ 1.05

The transformer tap and switched shunt capacitor/reactor are operated in the range of control limits

According to the selected control actions, estimate voltage variations at each bus using the sensitivity tree and refresh the bus voltages recalculated by the load flow under the appropriate control actions.

Repeat the above procedures for each load bus in the overall system until all bus voltages satisfy their own limits.

3 Voltage Control using Sensitivity Matrix

Normally, the sensitivity technique is one of numerical methods for analysis of the linear system. It describes the relationship between the control actions and their effects. As the power system is nonlinear, the sensitivity factor between reactive control actions and bus voltages cannot be constant. The first order sensitivity function is commonly used for simplicity especially when non-linearity is negligible. In the intelligent system put to practical use, there is not enough of a difference in sensitivity over a wide range of system operating conditions when using the first order sensitivity function [1, 3-6]. This implies that the sensitivity technique may be effectively adopted to analyze the voltage and reactive power control problem.

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.

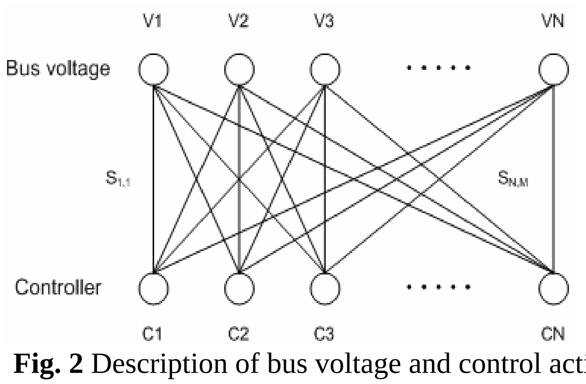

Fig. 2 Description of bus voltage and control actions

3.1 Sensitivity Matrix

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.

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.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \vdots & \frac{\partial P}{\partial V} \\ \cdots & \cdots & \cdots \\ \frac{\partial Q}{\partial \delta} & \vdots & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (1)$$

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).

$$[\Delta Q] = \left[\frac{\partial Q}{\partial V}\right][\Delta V] \quad (2)$$

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

$[\partial Q / \partial V]$ is the Jacobian matrix of load flow calculation in (2). That is, $[\partial Q / \partial V]^{-1}$ is the inverse matrix of $[\partial Q / \partial V]$ 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).

$$\begin{aligned} &\circ\, \Delta V_i = S_{sh} \bullet \Delta U_{sh} \\ &\circ\, \Delta V_i = S_{Vg} \bullet \Delta U_{Vg} \\ &\circ\, \Delta V_i = S_T \bullet \Delta U_T \end{aligned} \quad (4)$$

ΔV_i : voltage changes at *i* bus

S_{sh} : sensitivity matrix of reactive power compensation device

S_{Vg} : sensitivity matrix of generator terminal voltage

S_T : sensitivity matrix of transformer tap

ΔU_{sh} : quantity changes of reactive power compensation device

ΔU_{Vg} : quantity changes of generator terminal voltage

ΔU_{T} : quantity changes of transformer tap

4 Modeling of Voltage Control Problem and Searches in the State Space

The problem formulation in the expert system is composed of the state-space representation and the problem reduction representation.

(A) State-space Representation

State-space representation involves :

States. These are snapshots of varying conditions in an environment at one moment in time. All states are unique

Operators. These act on a state to transform it into another state

A state-space is the set of all states available for a given problem.

(B) Problem Reduction Representation

Problem reduction representation starts with the division of a problem statement. At first, the statement is broken apart into subproblems. Repeatedly, the subproblems are broken down until a solution is immediate, in other words, until no further subdivision is necessary. The concept is simple: reduce the problem down to workable subproblems.

Problem reduction representation consists of :

The initial problem statement

A set of operators that transform the problem into a set of subproblems

Primitive problem statements that are solvable immediately (this is the lowest level of the problem)

State-space representation and problem reduction representation are interchangeable. Problems usually fit better into one representation model than the other. As mentioned above, any problem can be modeled by these two forms. However, efficiency of the system is greatly influenced by characteristics of problem. In the power system, problem reduction representation is used in fault diagnosis, fault restoration, and so on, while the voltage control needs the updated sensitivity matrix by the system state in accordance with the experts' heuristic knowledge.

In this paper, we intend to formulate the problem using the state-space representation and apply the performance index in a numerical control method to the voltage control. Also, we will introduce best-first searches that can tremendously reduce the searches of state-space using a weighted function.

4.1 Modeling of voltage control problem

The voltage control needs continuously updated sensitivity matrix, depending on the system state together with the experts' heuristic knowledge. Consequently, the model using the state-space representation has been provided. Given that the system consists of N load buses and M controllers and the abnormal voltages at some buses happen, the state-space is constructed in Fig. 3.

At the bus where the voltage violation is created, let us suppose that the bus voltage with the largest deviation is V_i. The relationship between the bus voltage and control action is presented as a sensitivity value in the branch and the other bus voltages by this control action are illustrated in the third step in Fig. 3.

When the voltage violation still exists and the voltage deviation of V_K is the largest, the control at the second stage is executed, starting from the vertex V_K. In this manner, the voltage control problem is reduced to the path detection which finds the path to reach the steady state starting from the bus with abnormal voltage through various control actions.

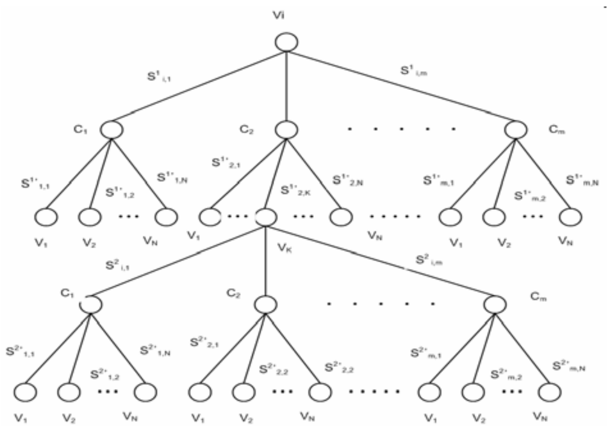

Fig. 3 State-space model of voltage control

4.2 Searches in the state space

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 searches by heuristic knowledge 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. For instance, heuristic searches is best-first, hill-climbing and branch-and-bound.

In the voltage control problem, the performance index is originated from a numerical analysis. There are performance indices of CSVC, LP, and weighted sum. Performance index of CSVC is used for the voltage control with a pilot bus, while performance index of LP is true of the reactive power planning or investment of reactive power facilities because of taking too much calculation time. As mentioned earlier, the aim of this work is the voltage control so that the generator terminal voltage is first controlled. When the unbalances in reactive power are detected due to abrupt disturbances, switched shunt capacitor/reactor is then added and the weighted performance index is implemented for this formulation. In the state space of Fig. 3, the bus with the largest voltage deviation is found and the control action with the largest sensitivity is chosen. Consequently, the best-first searches using the sensitivity coefficients as the cost function is utilized.

weighted performance index

$$\min(\sum \alpha |\Delta Q_i| + \sum \beta |\Delta V_{gi}| + \sum \gamma |\Delta T_K|)$$

$$where, \alpha > \gamma > \beta$$

5 PSCAD/EMTDC

The PSCAD/EMTDC is used for the analysis of various situations in power system, consisting of PSCAD module to provide the GUI (Graphic User Interface) and the EMTDC module as a simulation engine. In addition, it will be able to reproduce and implement a number of cases in power systems since power electronic elements, synchronous and rotary machines, an induction machine, and control system models have been built in PSCAD/EMTDC.

The power system configuration as close as the real systems needs to be constructed for carrying out intelligent voltage and reactive power control using PSCAD/EMTDC. Once it is completed, the technical parameters in generator, exciter, and governor and line parameters are simultaneously input. Then, we will identify the model type of generator, exciter, and governor from the PSS/E dynamic data and check whether or not the same model is used in PSCAD/EMTDC. The power system schematic of Jeju Island was displayed in Fig. 4 and reproduced for PSCAD/EMTDC simulations under the permission of KEPCO and KPX.

6 Case Study Results

In the case study, we found the abnormal bus voltage in case of a transmission line outage in Jeju Island using PSCAD/EMTDC. For the transmission line outage joining North Jeju TP (120) bus and Jocheon (350) bus amongst all (n-1) transmission line outages, the voltage violations happened at Jocheon (350) bus and Seongsan bus (200) bus as seen in Table 1. The Jocheon (350) bus with the largest voltage deviation has been selected and the control actions have been taken by the generator with the largest sensitivity, which finally overcame the voltage problem.

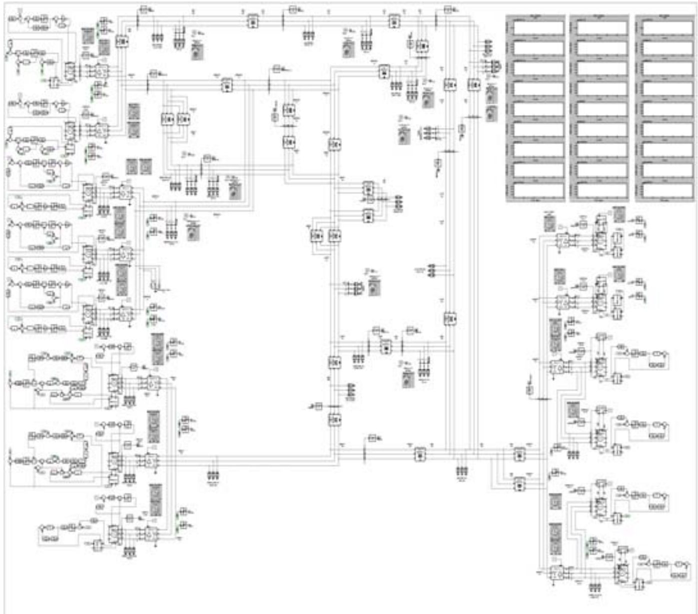

Fig. 4 Power system configuration in Jeju Island for PSCAD/EMTDC simulation

The scenario with PSCAD/EMTDC has been laid down by power system operation manual in Korea as can be seen in Table 2.

The voltages of Jocheon (350) bus before and after the voltage control has been executed by the generator terminal voltage are portrayed in Fig. 5 and Fig. 6.

Table 1. Voltage profile of bus in case of a transmission line outage joining North Jeju TP (120) bus and Jocheon (350) bus (Bold style: voltage violated)

us number	Bus name	oltage [p.u.]
120	North Jeju TP	1.004614
121	North Jeju CS	1.004614
122	North Jeju TS	1.004613
130	East Jeju	1.003642
140	New Jeju	0.998226
150	Hanrim CC	1.0075
160	Andeok	0.995925
170	South Jeju TP	0.996792
180	New Seogwi	0.976921
190	Hanra	0.973811
200	**Seongsan**	**0.938745**
210	Pyoseon	0.98019
220	Sanji	1.003352
330	Hanrim	1.005726

350	**Jocheon**	**0.931945**

Table 2. Scenario in case of a transmission line outage

[Sec]	h
	-phase short circuit fault happened
	t breaker on
	nal voltage of generator chosen by ltage controller increased

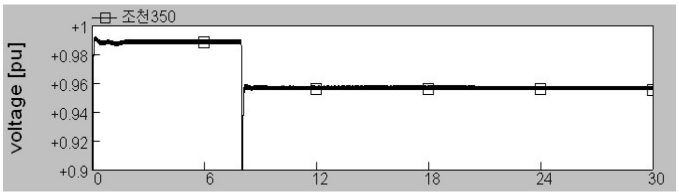

Fig. 5 Voltages of Jocheon (350) bus by elapsed time before the voltage control has been applied

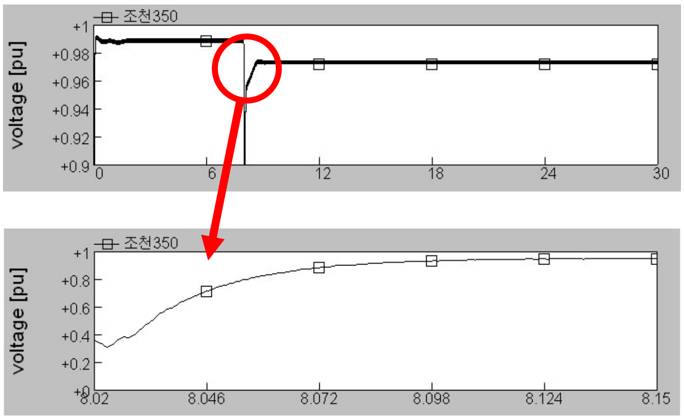

Fig. 6 Voltages of Jocheon (350) bus by elapsed time after the voltage control has been applied

7 Conclusion

In this paper, a hybrid type integrated with the numerical based analysis program and intelligent program has been developed. The numerical based analysis program is coded with C language based on the sensitivity matrix predicting the load bus voltage variations by the injection of voltage control device such as generator terminal voltage, switched shunt capacitor/reactor, transformer tap as well as the load flow to guarantee the effects of voltage control. Besides, the rule base and inference engine for expert voltage and reactive power control system were developed in the basis of the sensitivity tree that is fairly connected with load bus voltage and control actions. The intelligent program has been formulated by PROLOG using an inductive rule base with a numerical and logical computation method.

The viability of the proposed hybrid system was verified on Jeju Island by performing the dynamic simulation with PSCAD/EMTDC in case of a transmission line outage. In the near future, the performance of the proposed intelligent system for the voltage and reactive power control will be tested using RTDS (Real Time Digital Simulator) and upgraded to be suitable for Korean electric power system based on numerous simulations.

Acknowledgement

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