A hybrid methodology for the development of intelligent voltage and reactive power control systems

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Abstract: - The reactive power which is entirely different from frequency has local characteristics. In the past, it is managed by the manual operation in a local reactive power control station. 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 used in the real-life situations of developed countries. In this paper, the intelligent system, or expert system for the voltage and reactive power control will be displayed as a prototype that has a simpler structure in terms of MMI and database prior to the development of intelligent system for real-time control. This system makes fully use of the sensitivity matrix that is a numerical analysis technique of control equipment such as generator terminal voltage, 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. The intelligent system has been tested on IEEE 30-bus sample system, and test results applied to the test-bed would be really satisfactory at a steady-state level.

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

1 Introduction

In recent years, the Korean power system has been operated more closely to stability limits because of rapid growth in load-demand as seen in Europe. Obviously, the reactive power demand is continuously going up as reactive power losses are increased due to long-distance transmission lines. Unfortunately, the power system voltage is maintained only by the unit substation since it is not actually easy to find the site for voltage compensation equipment and the regional systematic voltage control framework is not properly installed. Therefore, any real countermeasures against blackout or equipment damage by the voltage collapse need to be taken when it happens in Europe and America very often. Specifically, the voltage stability problem of metropolitan region caused by the northward power flow limits in Korean power system should be urgently settled for improving the efficiency and stability of system operations, where the voltage stability is mainly attributed to unusual reactive power balances, not overall generation reserves.

The reactive power operation has not merely performed by the operator's engineering knowledge and judgment until the hierarchical voltage control system is developed. In the 1970s, the expert system using the expert's heuristic knowledge with computer simulation emerged in step with artificial intelligence. In the 1980s, an expert system for real-time control of voltage and reactive power was proposed based on the sensitivity tree in Canada [1], SEGRE [2] and SETRE [3-4] was successfully applied in Spanish power system. Besides, several advanced countries are operating the voltage and reactive power control system by reflecting inherent characteristics of their power systems [5-6].

In this context, the intelligent system, or expert system for the voltage and reactive power control will be displayed as a prototype that has a simpler structure in terms of MMI and database prior to the development of intelligent system for real-time control. This system makes fully use of the sensitivity matrix that is a numerical analysis technique of control equipment such as generator terminal voltage, 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 is organized as a knowledge base by the expert's knowledge and experience and afforded some functions to infer and judge the current situations, including typical automatic control concept and finally extending to an unmanned automatic control. In other words, the intelligent control is characterized by the mechanical realization of experiential or instinctive knowledge that is not possible to implement by a numerical algorithm. Accordingly, much scholarly work on the expert system has been done on the topics of electric power systems that require complicate operation strategies and the operator's experiential or instinctive knowledge. For example, the expert system will be vigorously applied to the fault detection and diagnosis, recovery, and alarm systems. In the long run, the future large-scale control system will become a hierarchical structure of the decentralized adaptive control and the intelligent control.

2.1 Structure of intelligent voltage/reactive power control system

The structure of intelligent voltage/reactive power control system to be developed in this paper is described in fig. 1. Here the intelligent controller is made up of the numerical calculus module based on the sensitivity matrix, the related control knowledge and the database with a wide variety of information.

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. Databases in the rule-base system by PROLOG are divided by dynamic database and static database. In particular, these databases are composed of immutable truth in a specific domain and temporary truth derived from the inference process. Knowledge base is obtained from the load flow and used in both best-first searches and inference. Database and rule-base will be in the following:

(A) Databases

① The load bus voltage profile calculated by the load flow

② The connection status of transmission lines

③ The upper and lower limits of each bus voltage

④ The upper and lower limits of each reactive power compensation device

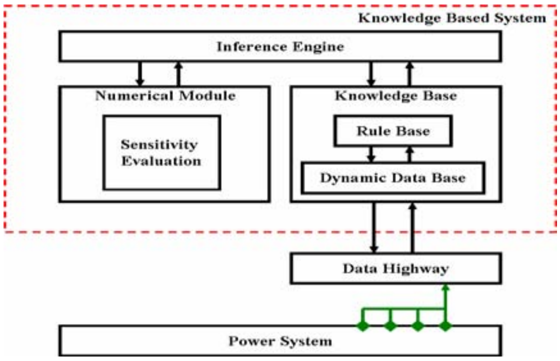

Fig. 1 Structure of intelligent system for voltage control

⑤ The upper and lower limits of each control device (generator terminal voltage or transformer tap)

⑥ The sensitivities of bus voltages with respect to each control device

(B) Rule-base

① Compare the current voltages with their essential limits, and find the buses with voltage violations.

② Check the voltage violation according to the following standards.

- ○ Normal voltage [p.u.]

  $0.95 \leq V \leq 1.05$

- ○ Voltage violation [p.u.]

  $0.95 < V$ or $V > 1.05$

③ Sketch the sensitivity tree for each bus voltage violation, find the most effective (the highest weighted sensitivity) control tool and calculate the control value needed to remove the voltage violation.

④ Check whether or not to satisfy the constraints of the controller. If the control value exceeds the limits, the control limit is set as the control value.

⑤ The control standard of generator terminal voltage is as follows:

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

  $0.95 \leq$ generator terminal voltage ≤ 1.05

⑥ The transformer tap and shunt capacitor/reactor is operated within control limits

⑦ According to the selected control actions, estimate the voltage variations at each bus using the sensitivity tree and recalculate the updated bus voltages by the load flow applied to the control actions.

⑧ Repeat the above procedure for each load bus in the overall system until all bus voltages meet their limits.

3 The Voltage Control using a Sensitivity Matrix

Generally, the sensitivity technique is one of numerical methods for analysis of the linear system. It describes the relationship between the control operation and it's impact. As the power system is a non-linear system, the sensitivity factor between a reactive control measure and the bus voltages can not be a constant value. The first order sensitivity function is commonly used for simplicity especially when non-linearity is negligible. In the practicable intelligent system, there is not enough of a difference in sensitivity over a wide range of system operating conditions [1, 3-6]. This implies that the sensitivity technique can be effectively adopted to analyze the reactive power and voltage control problem.

Assuming an N bus power system with M control measures, the relationship between the bus voltages and the control measures can be represented as shown in fig. 2. It is pointed out that for each bus voltage, several control measures can be used. It can be observed that each control measure affects several bus voltages. For a particular bus voltage violation, it is possible to compute the control action needed to overcome this voltage violation by the sensitivity technique. The control action should neither exceed the specified limits nor incur new voltage violations of other buses.

3.1 The Sensitivity Matrix

Sensitivity matrix is the fundamental parameter for the intelligent voltage control system. It defines the relationship of bus voltages with respect to compensation quantity that is injected into the shunt capacitor/reactor, generator terminal voltage and transformer tap, selects the control method when the voltage violation is created, determines the compensation input.

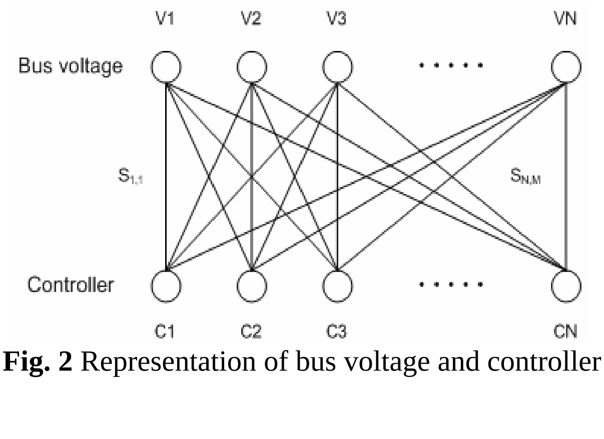

Fig. 2 Representation of bus voltage and controller

The sensitivity matrix is established by the relationship between the voltages and the reactive power and the relationship of the control measures 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 $\Delta\delta \approx 0$, the relationship between the voltage and the reactive power is summarized 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 can estimate the changes of bus voltages against the changes of reactive power. The sensitivity matrix is presented by the control measures as shown in (4).

$$\circ\ \Delta V_i = S_{sh} \bullet \Delta U_{sh}$$
$$\circ\ \Delta V_i = S_{Vg} \bullet \Delta U_{Vg}$$
$$\circ\ \Delta V_i = S_T \bullet \Delta U_T \quad (4)$$

ΔV_i :voltage changes at i bus

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

S_{Vg} :the sensitivity matrix of generator terminal voltage

S_T :the sensitivity matrix of transformer tap

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

ΔU_{Vg} :the quantity changes of generator terminal voltage

ΔU_T :the quantity changes of transformer tap

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

In describing the problem representation used by expert system, two models are most prevalent: state-space representation and problem reduction representation.

(A) State-space Representation
State-space representation involves :

① States. These are snapshots of varying conditions in an environment at one moment in time. All states are unique
② Operators. These act on a state to transform it into another state

A state-space representation the set of all attainable states for given problem.

(B) Problem Reduction Representation
Problem reduction representation stars with a problem statement. From there 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 :

① The initial problem statement
② A set of operators that transform the problem into a set of subproblems
③ Primitive problem statements that are solvable immediately (this is the lowest level of the problem)

State-space representations and problem reduction representations are interchangeable. Problems usually fit better into one representation model than the other. The perception of the problem remains the same in either case. As mentioned above, Any problem can become modeling in these two forms. However, efficiency of the system is greatly different about characteristic of problem. In the power system, problem reduction representations are used in fault diagnosis, restoration system etc., while the voltage control needs the updated sensitivity matrix by the system state with the expert's heuristic knowledge.

In this paper, we intend to formulate the problem using the state space and address the performance index in the voltage control from a numerical control method. Plus, we take advantage of best-first searches that can reduce the searches of state space using a weighted function.

4.1 Modeling of voltage control problem

The voltage control needs the continuously updated sensitivity matrix according to the system state together with the expert's heuristic knowledge. Therefore, the model using the state-space representation is attempted. 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 as shown in fig. 3.

At the bus where the voltage violation is generated, let us assume that the bus voltage of the biggest deviation is V_i, the relationship between this voltage violation and controller is presented as a sensitivity value in the branch and the other bus voltages by this controller are illustrated at the third step in fig. 3.
When the voltage violation is not solved and the voltage deviation of V_K is largest, the control at the second stage is executed, starting from the vertex V_K.

4.2 Searching in the state space

The searches means the process to valuate possible path of solution and to try from initial state to final state. They can be divided into two categories: blind searches and heuristic searches. Searches by heuristic knowledge is a method for searching a solution continuously after removing the path of solution that seems inappropriate by a standard of judgment such as heuristic knowledge or cost function. For instance, heuristic searches are best-first, hill-climbing and branch-and-bound.

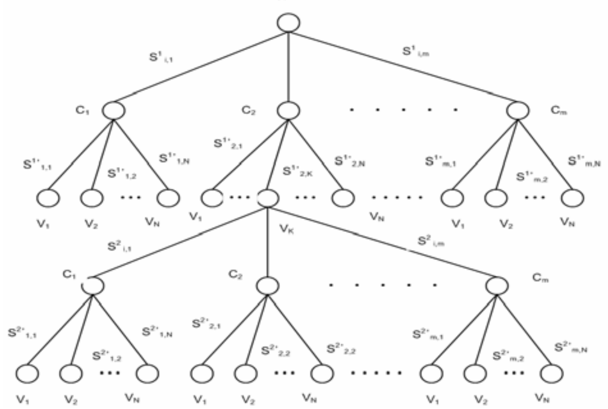

Fig. 3 State space of voltage control

In the voltage control problem, the performance index is originated from a numerical control method. There are performance indices of CSVC, LP, and weighted sum. Performance index of CSVC is used for the voltage control with pilot bus, while performance index of LP is true of the reactive power planning or investment of reactive power facilities due to long calculation times. As mentioned earlier, the aim of this work is voltage control so that the generator terminal voltage is first controlled. When the imbalances of reactive power are experienced due to abrupt disturbances, shunt capacitor/reactor is added and the weighted performance index is introduced 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 are considered.

◯ weighted performance index

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

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

5 Test-Bed

To guarantee the viability of result, accuracy of input data is premised. In the test-bed, the PSS/E raw data are used as the initial input data of system. The accuracy of algorithm built in the test-bed is tested by comparing the results of PSS/E respecting the IEEE 30-bus sample system [7].

In most cases, the test-bed consists of PF module to calculate the load flow and check the overload of lines and bus voltage violation, CONV module to construct Y-bus matrix from PSS/E raw data and form a DB, and GUI module to provide graphical environment so as to be far more user-friendly. The database of this system is divided by both DSK DB that is managed in a file type and DYN DB that is placed in the memory for fast access and renewal.

6 Case study

In the study, the intelligent voltage control is carried out using a test-bed in IEEE 30-bus sample system. Initially, the voltage is violated at a total of 13 buses in this system. Most of all, the bus with the largest voltage violation is searched and then control the terminal voltage of a generator with the largest sensitivity to clear the voltage violation. Voltage (0) step is the voltage profile in the first step. Voltage (1)~(3) steps are the voltage profiles by applying control actions in a sequential manner. The results are given in Table 1 and displayed in fig. 4. These results were verified by incorporating the intelligent voltage control system into the test-bed. Fig. 5 shows the main page of the test-bed in IEEE 30-bus sample system.

Table 1. Voltage profile of load bus by sequential control actions

Bus No.	Voltage(0)	Voltage(1)	Voltage(2)	Voltage(3)
3	0.992	1.007	1.019	1.021
4	0.989	1.007	1.022	1.024
6	0.99	1.018	1.028	1.031
7	0.986	1.003	1.009	1.026
9	0.974	0.989	0.995	0.997
10	0.954	0.97	0.976	0.978
12	0.974	0.984	0.99	0.991
14	0.957	0.968	0.974	0.975
15	0.951	0.963	0.969	0.97
16	0.958	0.97	0.976	0.978
17	0.949	0.964	0.97	0.972
18	0.938	0.952	0.958	0.96
19	0.935	0.949	0.955	0.957
20	0.938	0.953	0.96	0.962
21	0.94	0.957	0.963	0.965
22	0.941	0.957	0.964	0.966
23	0.937	0.952	0.958	0.96
24	0.928	0.946	0.952	0.955
25	0.935	0.959	0.966	0.969
26	0.916	0.94	0.948	0.95
27	0.949	0.977	0.984	0.987
28	0.987	1.019	1.027	1.03
29	0.928	0.956	0.964	0.966
30	0.915	0.944	0.952	0.954

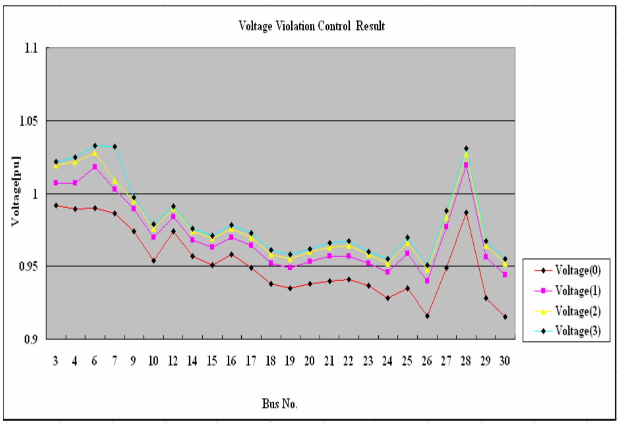

Fig. 4 Trends of load bus voltage profiles by sequential control actions

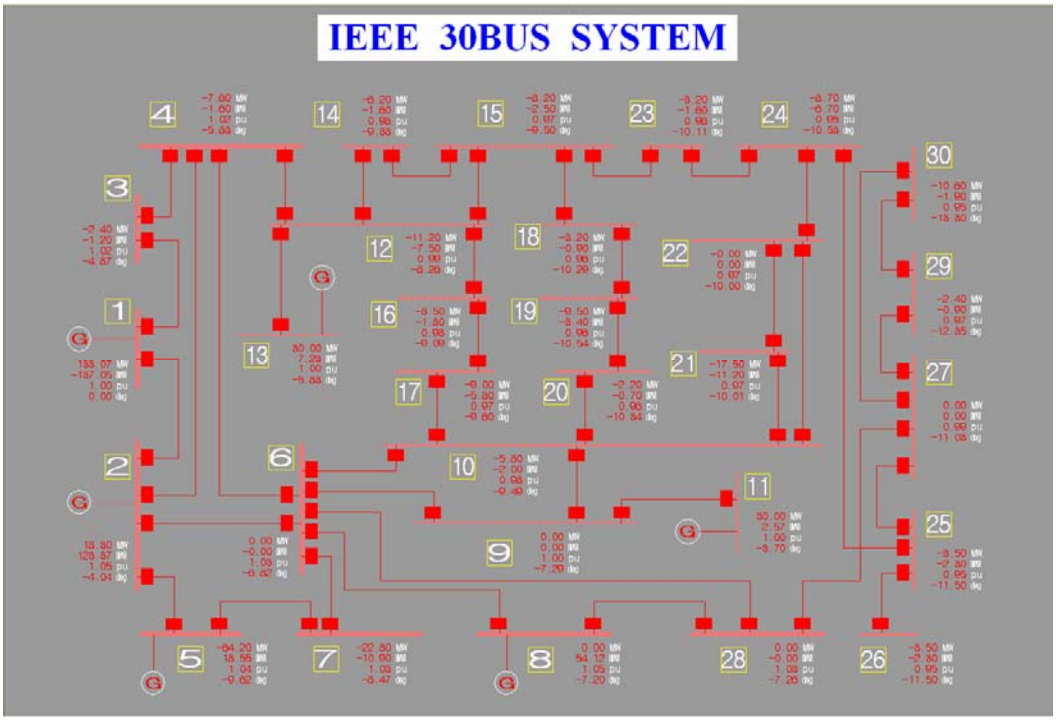

Fig. 5 Test-bed of IEEE 30-bus sample system

7 Conclusion

In this paper, a hybrid type combined with the knowledge base program and a numerical program has been developed using the PSS/E raw file input data. The numerical program is based on the sensitivity matrix indicating the load bus voltage variations by voltage control device such as generator terminal voltage, shunt capacitor/reactor, transformer tap etc. The inference engine of expert system and rule-base for voltage and reactive power control were developed on the sensitivity tree that is fairly connected with load bus and control device. Intelligence program has been developed in PROLOG using an inductive rule-base with a numerical method.

Further, the intelligent system for the voltage and reactive power control will be upgraded by finding control parameters suitable for Korean electric power system based on numerous simulations.

Acknowledgement

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