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An Expert System for Power System Restoration

In-Su Wang, Heung-Jae Lee
Department of Electrical Engineering
Kwangwoon University
Seoul 139-701, Korea
e-mail: hjlee {at} kw.ac.kr

Abstract— **This paper introduces a power system restoration guidance system that assists the decision of power system operators for reliable and fast restoration processes when a blackout happens in a power system. This system consists of three major subsystems, that is a topology processor, main restoration guidance expert system and another expert system for voltage control. The topology processor identifies the real-time embedded topology structure between power system components and determines the power outage section. The expert system for voltage control deals with abnormal voltages that may be incurred during a restoration process. This system is developed based on voltage sensitivity analysis. The power system restoration guidance expert system determines the optimal restoration path to prevent overloads and real power flow. Case studies demonstrate a promising possibility of practical application.**

Keywords-component; formatting; power system restoration guidance expert system; topology processor; voltage control expert system

I. INTRODUCTION

Recently unexpected power system blackouts have frequently occurred in many counties, leading to great socio-economic losses. When the blackout happens in the bulk power system, it is very important to provide high-quality and reliable restorative operation while preventing cascading blackouts in power system.

The self-healing is a high-end technology that accurately recognizes power network disturbances and maintains the optimal state. Also, it is the final goal of the smart grid project which is currently in the progress of being developed worldwide. In order to have the ability of self-healing, numerous precision sensors, advanced operations in each hierarchy, and automatic control systems are ultimately required.

However, due to the fact that not only performance improvement of hierarchical operations system but cooperative operations of hierarchical control systems have not been matured, power system restoration have entirely relied on the operator's heuristic knowledge and judgment. Because of non-linear characteristics of power system, it is extremely difficult to set out reliable restoration plans. Allowing for the re-trip of switches caused by overvoltages or overloads during restoration processes, analytical verifications are often required since it may enormously delay restoration time. Therefore, restoration guidance systems that may uphold power system operator's judgment during restoration processes should be taken into account. Some countries had already developed the restoration guidance systems and applied them to the transmission-substation-distribution system. In Korea, basic researches for distribution systems and 154kV substations had been performed but few basic researches in the level of transmission system had been executed so far. In recent years, necessity of restoration guidance systems for power system has been invoked since several blackout incidents broke out in Korean power system.

In this paper, the power system restoration guidance systems are presented. This system consists of three major subsystems such as a topology processor, main restoration guidance expert system, and voltage control expert system. The topology processor identifies the real-time embedded topology structure between power system facilities and at the same time determines the power outage section. The voltage control expert system adjusts abnormal voltages that may happen during restoration processes, which is especially developed based on the voltage sensitivity analysis. The power system restoration guidance expert systems establish the optimal restoration path by taking advantage of overloads and real power flow. The Human Machine Interface (HMI) is built by combining three major subsystems with simulator.

II. POWER SYSTEM RESTORATION GUIDANCE SYSTEM

A. *Topology processor*

A power system is generally made up of generation, transmission and substation facilities. It is very vital to identify the topology structure between transmission and substation facilities when power system disturbances are created by malfunctions or non-operations of power system devices.

Topology structure identification of transmission lines and substations is regarded as a step of implementing mechanisms, where power system operators intuitively detect each component's connection relationship represented in a single-line diagram, via a computer program. Expert system based topology processors for electric substations have been proposed by Lee [1-3], and they are applied in this expert system. A double bus, one and half breaker scheme of 345 [kV] bulk power substations is shown in Figure 1.

Under such a complicated switching structure condition, the topology processor enables computers to identify the transmission network connections. In order to find topology structure of transmission network, data structures are effectively defined. Furthermore, the dual searching strategy is adopted to represent the topology structure of transmission facilities.

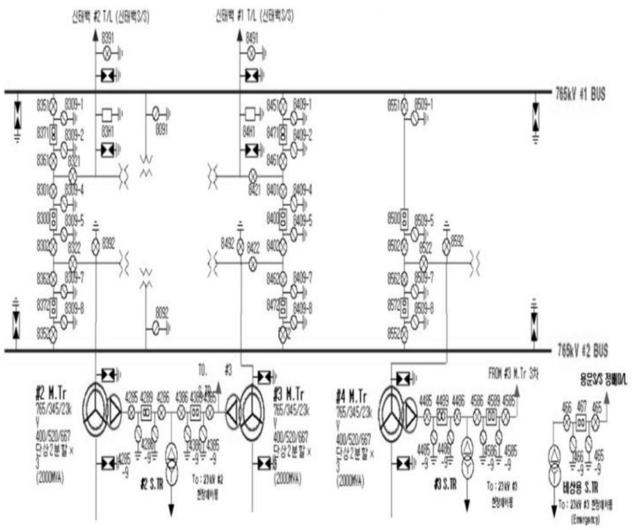

Figure 1. Structure of a bulk power substation

1) Definition of aggregated switch

As shown in Figure 1, each unit devices are connected complicatedly through circuit breaker, disconnecting switch and ground switch. If these switches are used in topology processor, topology identification is very difficult because the possible combination of switches increase exponentially. The new aggregation technique to reduce possible combination of switches is represented in Figure 2.

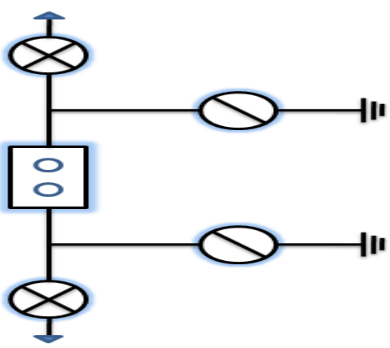

Figure 2. Structure of a switching group

As shown in Figure 2, a circuit breaker composes a switching group with two series disconnecting switches and two parallel ground switches. The switches of switching group are interlocked. We define newly a switching group as aggregated circuit breaker in order to reduce the searching space and to enhance the efficiency of the representation of connection structure and the topology identification [1].

The predicate of an aggregated circuit breaker is defined as follows.

a_cb (CB_name, DS_name_list, ES_name_list, status)

Here, 'CB_name' describes the name of circuit breaker and 'DS_name_list' describes a set of disconnecting switch connected to circuit breaker. 'ES_name_list' describes ground switch. 'status' describes ON/OFF status of aggregated circuit breaker. 'status' is determined by the status of circuit breaker and disconnection switches. To determine the ON/OFF status of aggregated circuit breaker, PROLOG rules are used [1]. We changed the complex connection structure of 765kV substation to simple connection structure using the aggregated circuit breaker as shown in Figure 3.

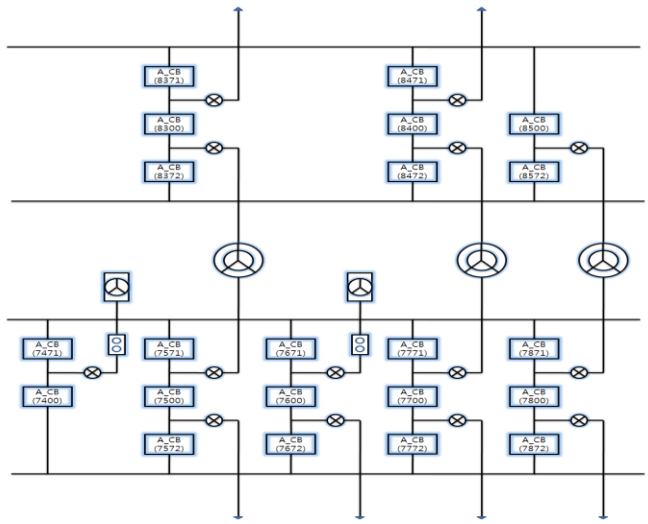

Figure 3. Structure of an aggregated substation

2) Data Representation

Data representation is closely related with proposed topology processor. For efficient data representation, we describe unit devices and switches. The predicates of unit devices and switches are as follows.

htl_ data(name, voltage, capacity)

ltl_data(name, voltage, capacity)

mtr_data(name, voltage_list, capacity)

shr_data(name, capacity)

cb(name, phase, status)

ds(name, phase, status)

es(name, phase, status)

Here, 'name' describes the name of each unit device and 'voltage' describes the voltage of each unit device. 'capacity' describes the capacity of each unit device and 'voltage_list' in predicate mtr is a set of voltage connected to transformer. 'status' is ON or OFF status of switches.

Also, the connection structure between unit devices is described. The predicate of connection structure between unit devices is as follows.

a) A predicate of connection structure between 765kV transmission line and bus.

Tl_hbus_dat(tl_name, ds_name, a_cb_list)

b) A predicate of connection structure between 345kV transmission line and bus.

lbus_tl_dat(tl_name, ds_name, a_cb_list)

c) A predicate of 765kV and 345kV bus.

hbus_daa(hbus_name, a_cb_list)
lbus_daa(lbus_name, a_cb_list)

d) A predicate of connection structure between 765kV bus and transforme.

Hbus_mtr_dat(tr_name, ds_name, a_cb_list)

e) A predicate of connection structure between 345kV bus and transforme

mtr_lbus_dat(tr_name, ds_name, a_cb_list)

3) Topology identification

The proposed topology processor identifies topology through the two steps inference process. The first is determination of the status of aggregated circuit breaker. The second step is topology identification using the aggregated circuit breaker. In the first step, topology processor uses the PROLOG rules and the status data of switch such as circuit breaker, disconnecting switch and ground switch. In the second step, topology processor uses the duplex searching method. Figure 4 shows duplex searching method including all possible topology of 765kV substation.

B. Restoration guidance expert system

Expert system based restoration guidance systems have been proposed mainly in Japanese researchers [4-8]. In fact, power system restoration is a very complex problem. The operation rules are different in each country due to the network topology and configurations. Therefore development of appropriate rule base is a most important part of the expert system restoration rules. The rule base are developed using empirical rule of human expert and emergency operation rules of Korean electrical reliability council and Korea power exchange corporation.

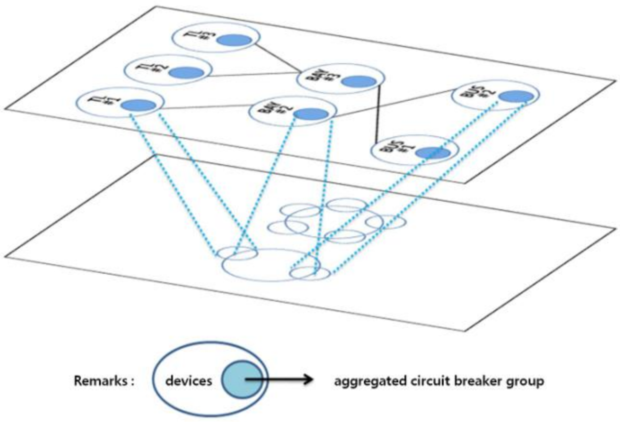

Figure 4. Duplex searching method

The main restoration guidance expert system is the core expert system that determines the restoration path when a blackout occurred in power system. The knowledge base comprises the rule base that stores if-then type of knowledge and the database that retains static data and dynamic data as well. The inference engine is a process that solves given problems and derives a solution from the rules of knowledge base and the facts accumulated in the database [9].

Major rules are developed as follows.

1) Rules for recognizing blackout section

2) Rulse for restoration from massive blackout

a) Rulse for using the blackstart generator in blackout region [2 rules]

b) Rules for blackout restoration procedure by Korea Power Exchange [10 rules]

3) Rules for power supply to load from non-blackout region [6 rules]

4) Rules for partitioning load in blackout region [3 rules]

5) Rules for increasing reserve power to supply blackout region [8 rules]

There are two problem representation methods - the state space representation and the problem reduction technique. In general, the problem reduction technique has been frequently used in power system. However the power system restoration guidance system was developed by making use of the state space model due to the nature of problem. State space of power system restoration problem is briefly expressed in Figure 5. For the efficient search, the best-first search method was chosen to search an optimal combination of switching.

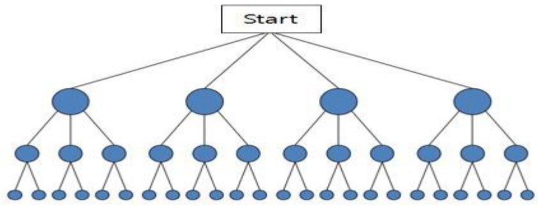

Figure 5. State space representation of restoration problem in power system

C. Voltage control system

During the restoration processes, overvoltages may arise by Ferranti effect, supposing that the light-loaded high voltage transmission line is energized. If there are no proper controls, the unbalanced reactive power give rise to the nationwide blackouts accordingly.

In the 1980s, an expert system for real-time voltage and reactive power control was proposed based on the sensitivity tree in Canada [10], and two practical expert systems [11-13] were successfully applied in the Spanish power system. Recently an efficient voltage control system is proposed [14], and it is applied in this expert guidance system.

The structure of voltage control expert system is explained in Figure 6. It is primarily based on reactive power facilities and, most of all, consists of the sensitivity matrix using numerical module as well as knowledge base with a wide variety of information related to power system state and control knowledge.

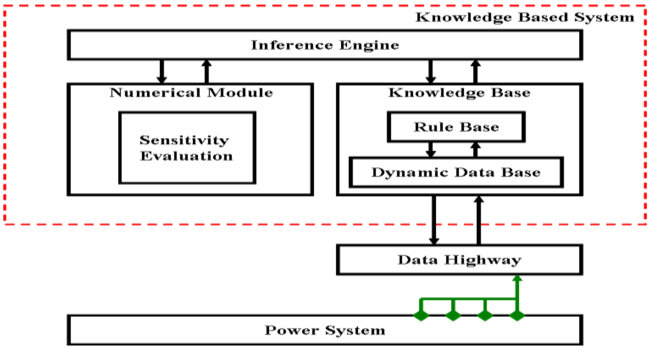

Figure 6. State space of restoration problem in power system

1) 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 Figure 8. 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.

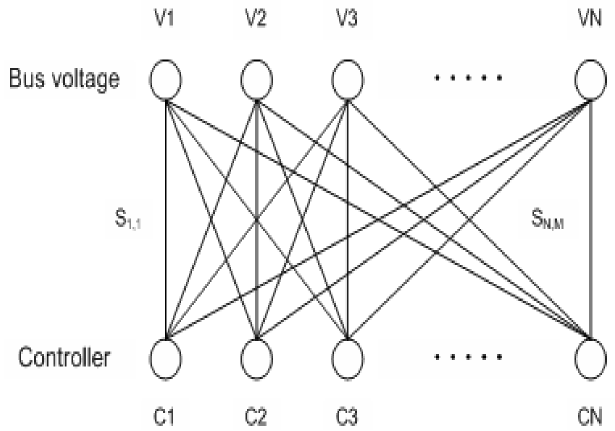

Figure 7. Description of bus voltage and control actions

The sensitivity technique is one of the numerical methods for analysis of the linear system. The sensitivity matrix is the fundamental parameter for the relationship of bus voltages with respect to compensation quantity that is injected into the generator terminal voltage, shunt capacitor and transformer tap. Sensitivity matrix is established by the relationship between the voltage and the reactive power. Assuming that the voltage angle is negligible in the Jacobian matrix, the relationship between the voltage and the reactive power is encapsulated in equation (1)

$$[\Delta V] = \left[\frac{\partial Q}{\partial V}\right]^{-1} [\Delta Q] \tag{1}$$

The sensitivity matrix is presented by the control actions as shown in equation (2)

$$\begin{aligned} &\circ\, \Delta V_i = S_{sh} \bullet \Delta U_{sh} \\ &\circ\, \Delta V_i = S_{Vg} \bullet \Delta U_{Vg} \\ &\circ\, \Delta V_i = S_T \bullet \Delta U_T \end{aligned} \tag{2}$$

ΔVi : the voltage change at the i bus

S_{sh}, S_{Vg}, S_T : the sensitivity matrix of the compensation devices

ΔU_{sh}, ΔU_{Vg}, ΔU_{T} : the quantity changes of the compensation devices

2) *Knowledge base*

The knowledge in a specific problem domain is classified by facts and rules which are stored in the database and rule base respectively. Database is consists of static database and dynamic database. These databases are composed of immutable facts in a specific domain or hypothetic truth derived from the inference process.

The knowledge base stores the system information obtained from the load flow and uses it for both search and inference. The major database and rule base are as follows.

a) Database

① The load bus voltage profile calculated from the load flow

② The open/closed status of the transmission lines

③ The upper and lower value limits of each bus voltage and control device

④ The upper and lower limit of the voltage regulation

⑤ The priority of the compensation devices

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

b) Rule base

① Rules for checking the voltage violation

- *Abnormal voltage [p.u.] : 0.95 < V or V > 1.05*

② Rules for checking the control limits of the generator terminal voltage

- *0.95 ≤ upper and lower limits of generator terminal voltage [p.u.] ≤ 1.05*

③ Rules for establishing the sensitivity tree for each abnormal bus voltage

④ Rules for finding the most effective control for the bus with the worst voltage violation

⑤ Rules for calculating the control value needed to remove the voltage violation

⑥ Rules to selecting the control actions and estimate the voltage variations

III. Human Machine Interface (HMI) and Power System Restoration Simulator

The setting of developed dynamic coloring can be divided by static attribution settings for representing constant values and dynamic attribution settings for representing continuously changed values [15]. Attribution of facilities is obviously represented by setting of tag values, type and width of lines, characters and circles. Dynamic attribution is represented by the flicker or change of colors according to the pre-defined rules. The power system restoration simulator using dynamic coloring is vividly demonstrated in Figure 8.

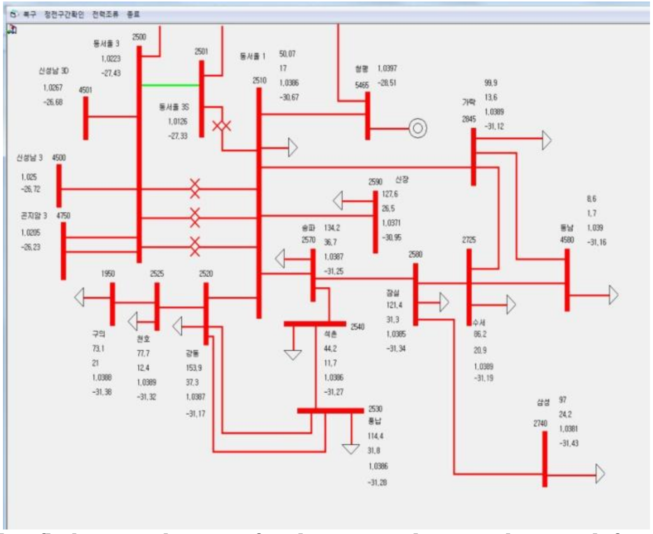

Figure 8. Displays of power system restoration simulator

IV. Conclusion

In this paper, the power system restoration guidance systems have been addressed for power system operator's reliable and fast restoration in case of the power system outages.

As mentioned earlier, the topology processor accurately recognized the power system outage section. The power system restoration guidance expert systems are integrated with the voltage control expert system and then the restoration path for preventing overvoltages and overloads is proposed for power system operators.

Performance of the proposed restoration guidance system is verified through various case studies. Results showed a promising possibility of practical application.

Acknowledgment

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