論 文
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상정사고를 고려한 무효전력/전압 제어 전문가 시스템

A Knowledge Based System for Reactive Power/Voltage Control Including Contingency

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요 약

본 논문은 계통의 무효전력/전압 제어 문제를 해결하기 위한 전문가 시스템을 제시한다. 상정사고로 인해 계통이 비상상태가 되었을때 전압제한치를 위반한 모선을 보다 더 신속하게 해소할 새로운 방법에 대한 필요성이 요구된다. 이런 목적에 적합하도록 무효전력 보상 우선 순위를 나타내는 모선서열 배열을 만드는데 사용되는 인덱스 집합 개념을 도입한다. 전체 계통의 상태에 입각한 인덱스 집합은 정상상태 안정도 인덱스, 무효전력 전달 인덱스, 전압 심각도 인덱스 및 발전기 연료비 인덱스로 구성된다. 이러한 체계와 전문가로 부터 얻어지는 지식에 대한 경험적 규칙으로 인하여, 전압이 위배 되었을때 전문가 시스템에서 추론에 의해 단지 무효전력원의 양만을 결정하기 때문에 빠른 의사결정을 내릴 수 있다. 본 연구에서는 커패시터와 리액터, 변압기 탭, 발전기 전압을 무효전력 조정기기로 사용하였으며, 가중항에 대한 사용자의 선택에 따라 조정량을 최소로 하거나 발전기 연료비용을 최소로 할 수 있는 전문가 시스템을 개발하였다. 사례연구에 대한 결과도 제시한다.

Abstract- This paper presents a knowledge based system to solve reactive power/voltage control problem in a power system.

A need is recognized for new methods to alleviate a bus voltage limit violation more quickly when a power system becomes an emergency state due to contingency. To cope with this object, a set of indices concept which is used to make bus order list of reactive power injection priority is introduced. A set of indices, based on the overall system conditions, consists of steady state stability index, reactive power transmittance index, voltage severity index and generator fuel cost index. This scheme and empirical rules of the knowledge on the basis of the human expert result in fast decision-making of the reactive power compensation devices since only the amount of devices is determined by the inference in the knowledge based system when the voltage violation is detected.

In this approach, control devices such as shunt capacitor(reactor), transformer tap settings and generator voltages are utilized. Also the developed system herein can be used to minimize control action taken or generator fuel cost according to the user's option on the weighting factor. The results of a case study are also presented.

1. INTRODUCTION

Reactive power and voltage control plays an important role in modern interconnected power system which has become more and more complicated. In this reactive power and voltage control area, many researches using optimization technique such as linear programming or gradient projection method were developed in the past[1, 2, 3, 4, 5]. But they are not always efficient for modern large-scale power system. That comes mainly from discreteness of control variables and nonlinearity among the variables. Also the fact that many factors to be considered exist in modern power system is making the reactive power and voltage control problem more difficult for a systematic and algorithmic methods, such as those presented in [2, 3, 4, 5, 6, 7]. Especially, It is very important to alleviate the detected voltage problem within a quick time period (critical clearing time) when a system becomes an emergency state by contingency. Therefore, more efficient and suitable methods for power system control are expected to be realized. Recently, the knowledge based system, a branch of artificial intelligence (A.I), provides one method for such a demand.

This approach can be used by integration with algorithmic methods for finding more efficient solution. An application of knowledge based system to the planning, operation and training area in a power system has become an active research area. The strength of knowledge based system is the way of incorporation in problem solving with the heuristics, rules and deep knowledge obtained from human expert who has worked in the area for a long time.

From the reactive power and voltage control problem point of view, there already exist several knowledge based systems developed since many heuristic rules and knowledge are in this area.

[8, 9, 11, 12] The knowledge based system by Liu and Tomsovic[8], employed the production rules(IF-THEN structures) to express the knowledge required to perform the given task. This implementation was written in the production system language, OPS-5, which utilizes a forward chaining mechanism for inference. More severe voltage problems are alleviated with the help of a linear programming technique. The paper developed by William, R.W. at al.[9] uses network decomposition concept which requires having only the network information local to the bus with a voltage limit violation. The work done by Kenneth Wilhelmsson and Goran Andersson[11] makes use of frame based representation of knowledge and production rules. The knowledge of system is implemented by the language LISP. X.P. Zhang and Y.S. Hai[12] reported the A.I approached system which used pattern recongnition technique to increase the decision-making speed and PROLOG to implement knowledge and heuristic rules.

In this paper, the knowledge based system is utilized to obtain the feasible control actions to alleviate reactive power and voltage control problem in a power system with contingency. In the most of papers reported using A.I. approach, both the location and amount of reactive power compensation devices are determined in the knowledge based system. However this approach shows the typical drawback of knowledge based system. The larger power system becomes, the more inference time is needed to find the suitable control actions. Hence, the important idea of this paper is to develop the knowledge based system which finds only the amount of reactive power compensation sources such as shunt capacitor, shunt reactor, transformer tap position and generator voltage. This job is done by the conception that the bus order list representing priority for the location of reactive power sources to be switched on can be determined in advance. The bus order list is constructed by the use of a set of indices concept[13, 14]based on information on the jacobian and sensitivity matrices obtained from power flow routine. A set of indices in this paper is composed of steady state stability index which represents a capability to withstand violation of bus voltage before the onset of system instability, reactive power transmittance index which is related to the

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接受日字 : 1990年 4月 13日
1次修正 : 1990年 7月 13日

knowledge of transmission path of the reactive power changes, voltage severity index which indicates the degree of voltage violation of a bus and generator fuel cost index which represents the effect of reactive power changes on the generator fuel cost. Also VAR supporting bus list at an arbitrary bus is introduced to reduce the inference time in the knowledge based system. The VAR supporting bus list is made up of the buses of which can give the arbitrary bus the effect of reactive power injection most significantly. Rules were written to describe the logic sequence that would be utilized to maintain the desired voltage profile. Also the adjustments to the control devices needed to alleviate voltage limit violations are determined by the sensitivity coefficients among variables.

The proposed system in this paper was written in two kinds of computer languages, FORTRAN and PROLOG.

The organization of this paper is as follows : In section 2 the problem is described. The outline for circuit contingency is introduced in section 3. In section 4 sensitivity coefficients used for finding control actions in the developed system are formulated. Section 5 discusses bus order list making algorithm based on a set of indices and VAR supporting bus list concept. Knowledge base, inference engine, data structure, production rules required for constructing knowledge based system are described in section 6. Case study and conclusions are dealt with in section 7 and 8, respectively.

2. PROBLEM DESCRIPTION

When a power system becomes a voltage emergency state by contingency, control actions must be initiated to alleviate the violations such as over and undervoltages within a critical clearing time. This state can be alleviated by adjusting the reactive power compensation devices such as shunt capacitors/reactors, transformer taps and generator voltages. In a case that the reaction time to adjust reactive power compensators is critical, the conventional methods are not suitable for improving the system state performance. Thus a method using knowledge based system has been described and is presented.

3. CONTINGENCY ANALYSIS

Over the years, contingency analysis has become more and more sophisticated, primarily because of the development of the fast and large-capacity digital computer[15, 16, 17, 18, 19]. In principle, all the events that cause trouble on a power system should be considered, however the remedial actions to correct the possible consequence caused by the one of the major types of failure events, or transmission line outages, are focused. Transmission line outages cause changes in the flows and voltages on the transmission equipment remaining connected to the system. Therefore, the analysis of transmission failures requires methods to predict these flows and voltages so as to be sure they are within their respective limits.

In order to consider the voltage problem only in this paper, It is assumed either the line overload is not caused by the single line outage since most power systems are designed to have sufficient redundancy to withstand singel line failure events or the overload problem is already cleared. Because contingency analysis is only a tool for detecting possible abnormal conditions requiring study by the operation personnel, computational speed and ease of detection are paramount considerations. Fast straight foreward technique, such as the popular DC power flow method, considers only the real power loading of circuits while ignoring the effect of system contingency on system bus voltages and, hence, on reactive power flow. Thus most of these techniques can only be applied to MW limit security problem[15, 16]. On the other hand, voltage problems were also found to be a very important aspect of security assessment. It has become the target of many research projects. [17, 18, 19] An efficient and effective AC power flow methods today, although they are frequently computationally unattractive and too demanding of engineering time for use in contingency studies, is required for a case that system voltage is concerned.

In this paper, it is assumed that those potentially critical contingency cases are already ranked by the severity of their impacts on a power system using the technique developed.[19] After the initial state of a power system is calculated by using AC power flow method, a more reliable formula based on the modified matrix inverse lemma is applied to update the bus voltage and angles of the system with line outage appearing on the top of ranked list. To solve any votage problem caused by contingency, the knowledge based system is initiated.

4. SENSITIVITY COEFFICIENTS

Sensitivity coefficient calculation method needed in solving the reactive power and voltage control problem is introduced here. Based on the Newton-Raphson power flow, the following matrix equation can be obtained :

$$\begin{vmatrix} \Delta P_G \\ \Delta P_L \\ \Delta Q_G \\ \Delta Q_L \end{vmatrix} = \begin{vmatrix} \cdot\ \cdot\ \cdot\ \cdot & J_{PVGG} & J_{PVGL} & J_{PGT} \\ \cdot\ \cdot\ \cdot\ \cdot & J_{PVLG} & J_{PVLL} & J_{PLT} \\ \cdot\ \cdot\ \cdot\ \cdot & J_{QVGG} & J_{QVGL} & J_{QGT} \\ \cdot\ \cdot\ \cdot\ \cdot & J_{QVLG} & J_{QVLL} & J_{QLT} \end{vmatrix} \begin{vmatrix} \Delta\theta_G \\ \Delta\theta_L \\ \Delta V_G \\ \Delta V_L \\ \Delta T \end{vmatrix} \tag{1}$$

The sensitivity matrix S defined herein is of the dimension $p \times m$ where p is the number of dependent variable and m is the number of each control variable.

sensitivity due to generator voltage changes

$$S_{QV} = \frac{\Delta Q_G}{\Delta V_G} = J_{QVGG} - J_{QVGL}\, J_{QVLL}^{-1}\, J_{QVLG} \tag{2}$$

$$S_{VV} = \frac{\Delta V_L}{\Delta V_G} = -J_{QVLL}^{-1}\, J_{QVLG} \tag{3}$$

sensitivity due to capacitor/reactor changes

$$S_{VQ} = \frac{\Delta V_L}{\Delta Q_L} = J_{QVLL}^{-1} \tag{4}$$

sensitivity due to transformer tap changes

$$S_{VT} = \frac{\Delta V_L}{\Delta T} = -J_{QVLL}^{-1}\, J_{QLT} \tag{5}$$

$$S_{QT} = \frac{\Delta Q_G}{\Delta T} = J_{QGT} - J_{QVGL}\, J_{QVLL}^{-1}\, J_{QLT} \tag{6}$$

5. BUS ORDER MAKING ALGORITHM

5.1 A SET OF INDICES

An approach in this paper is to asssume preassigned locations for reactive power compensation based on a set of indices[13], and then try to improve the system voltage profile by the inference in the knowledge based system, while minimizing the number of locations, the amount of reactive power and generator fuel cost. Savulesch [13] proposed a set of indices concept related to steady state stability, power loss and reactive power transmittance index. Also. the optimal reactive power allocation based on a similar concept about a set of indices was presented by A. verkataramana[14]. Since the indices are based on heuristic techniques, these indices coupled with ohter experiences supported by knowledge based system can give better reactive power allocation. Based on these indices concepts with some modifications, steady state stability and reactive power transmittance index are analyzed. And a new voltage severity and generator fuel cost index are proposed. Taking into consideration the above four factors, load buses are ordered for a possible reactive power and voltage control.

5.1.1 STEADY STATE STABILITY INDEX

It is well-known the fact that the steady state stability of a power system can be verified by the results of power flow analysis.[20] In a word, the term $\partial Q/\partial V$ (the changes of reactive power with respect to those of voltage) gives stability information. For small changes in ΔQ and ΔV, the diagonal elements $(\partial Q/\partial V)_{ii}$ represent steady state stability index.[14] That is, the buses which have higher values of $(\partial Q/\partial V)_{ii}$ can withstand more variation of reactive power before the onset of system instability compared to the buses which have lower values of $(\partial Q/\partial V)_{ii}$. Using this fact, the load buses can be arranged to the ascending order according to the diagonal jacobian elements. The result be the index that accounts for steady state stability.

$$SSSI=[B_1\ B_2\ B_3\ B_4, \cdots\cdots\cdots\cdots, B_{n1}]$$

where $\partial Q_{B1}/\partial V_{B1} < \partial Q_{B2} <, \cdots < \partial Q_{Bn1}/\partial V_{Bn1}$; B_1 $B_2, \cdots\cdots, B_{n1}$ are load bus number and subscript nl is the number of load buses.

The corresponding vector of weighting factors is

$$W_{SSSI}=[W_{S1}\ W_{S2}\ W_{S3}\ W_{S4}, \cdots\cdots, W_{Sn1}]$$

where $W_{S1} > W_{S2} > W_{S3} > W_{S4} > \cdots\cdots, > W_{Sn1}$.

5.1.2 REACTIVE POWER TRANSMITTANCE INDEX

When the reactive power injection is varied at a given bus, it is important to know which bus voltage magnitude is affected by this injection. This is related to the knowledge of transmission paths of the reactive power changes, known as the reactive power transmittance index[13]. The location of the reactive power compensation devices for voltage control should be decided in such a way that the result affects as many buses as possible. For this purpose, the reactive power transmittance index is defined as follows:

$$RPTI=[C_1\ C_2\ C_3\ C_4, \cdots\cdots, C_{n1}]$$

where C_1 $C_2, \cdots\cdots, C_{n1}$ represent bus numbers and the order of buses is determined according to decreasing value of the sum of the i-th column of matrix S_{VQ}. That is, the higher the value of sum of the i-th column of matrix S_{VQ}, the better is its voltage control capability.

The corresponding vector of weighting factors is

$$W_{RPTI}=[W_{C1}\ W_{C2}\ W_{C3}\ W_{C4}, \cdots\cdots, W_{Cn1}]$$

where $W_{C1} > W_{C2} > W_{C3} > W_{C4} >, \cdots\cdots, > W_{Cn1}$.

5.1.3 VOLTAGE SEVERITY INDEX

The main objective of reactive power/voltage control is to maintain a desired voltage profile on the system as soon as possible even though the system become voltage emergency state due to contingency which may be caused by a destructive storm or automatic relaying. Thus it is reasonable to alleviate the buses with severe voltage violation more quickly than the buses with light voltage violation. Calculating the violation of bus voltage at i-th bus,

$(Dev)_i = |V_i -$ upper voltage limit$|$ if upper limit violation

$(Dev)_i = |V_i -$ lower voltage limit$|$ if lower limit violation

$(Dev)_i = 0.0$ if no violation.

The voltage severity index is defined as follows:

$$VSI=[E_1\ D_2\ D_3\ D_4, \cdots\cdots, D_{n1}]$$

where D_1 $D_2, \cdots\cdots\cdots, D_{n1}$ represent bus numbers and the order of buses is determind according to decreasing value of $(Dev)_i$. That is, the larger the value of $(Dev)_i$ the more suitable is the location for reactive power compensation.

The corresponding vector of weighting factors is

$$W_{VSI}=[W_{D1}\ W_{D2}\ W_{D3}\ W_{D4}, \cdots\cdots, W_{Dn1}]$$

where $W_{D1} > W_{D2} > W_{D3} > W_{D4} >, \cdots\cdots, > W_{Dn1}$.

5.1.4 GENERATOR FUEL COST INDEX

imizing the system losses is employed. In this paper, however, the effect of reactive power injection at the load buses on generation fuel cost is considered.[3,7] Thus it is assumed that there is a linear relationship between reactive power injection and generator fuel cost. Without loss of generality, the fuel cost function is given by the total summation of generator fuel cost which can be expressed as the quadratic function of generating power output P_K for all $k \in G$.[7]

$$f(P)=\sum_{k\in G}(A_K + B_K P_K + C_K P_K^2) \qquad (7)$$

where A_k, B_k, C_k : fuel cost coefficients of k-th generator

G : set of all generator buses.

The change of generator fuel cost with respect to that of reactive power($\Delta f/\Delta Q$)is derived as follows :

$$\frac{\Delta f}{\Delta Q}=\beta J_A \qquad (8)$$

where β : $[B_1+2C_1P_1,\ B_2+2C_2P_2, \cdots\cdots, B_{NG}+2C_{NG}P_{NG}]$

$_{NG}$: total number of generator buses.

J_A : $J_{PVGL}\ J_{QVLL}^{-1}$

The generator fuel cost index, taking into consideration the magnitude of $\Delta f/\Delta Q_i$ which means the i-th element of vector($\Delta f/\Delta Q$), is defined by :

$$GFCI=[E_1\ E_2\ E_3\ E_4, \cdots\cdots, E_{n1}]$$

where $E_1\ E_2, \cdots\cdots, E_{n1}$ represent bus numbers and the order of buses is determined according to decreasing value of $\Delta f/\Delta Q_i$. That is, the larger the value of $\Delta f/\Delta Q_i$ the more suitable is the location for reactive power compensation.

The corresponding vector of weighting factors is

$$W_{GFCI}=[W_{E1}\ W_{E2}\ W_{E3}\ W_{E4}>, \cdots\cdots, >W_{En1}]$$

where $W_{E1}>W_{E2}>W_{E3}>W_{E4}>, \cdots\cdots, >W_{En1}$.

5.2 BUS ORDER LIST MAKING ALGORITHM

Based on the indices discussed above, steady state stability index, reactive power transmittance index, voltage severity index and generator fuel cost index, final location vector for reactive power injection can be determined by the following steps.

step1) Make total weighting vector by adding the elements of four weighting vectors corresponding to the same bus number in the indices. In this time, each weighting vector need not be the same weighting for all indices, particular index can be given more weight than others according to the user's option. For example, more weight on the RPTI can be given if user wants to minimize the number of location of reactive power compensation. And more weight on the CFCI if to optimize the total system operation cost, more weight on the VSI if to alleviate the bus with voltage violation more quickly.

step2) Make the final bus order vector using the corresponding bus number according to the decreasing value of the element of final weighting vector. In the element of bus order list, there is a possibility that the chosen bus number is not feasible for reactive power compensation. This defect, however, can be easily deleted with the help of the VAR supporting bus list concept explained in the next section.

5.3 VAR SUPPORTING BUS LIST

In case that the selected bus(old bus) for the reactive power control is infeasible, other bus(new bus) should be selected to replace the function of that bus. The new bus is selected such a way that the effect of new bus is almost same as that of the old one. The selection can be done with ease by considering buses whose reactive power changes can affect most to the changes of voltage of the old bus in the bus order list. To obtain an efficient inference in the knowledge based system, the list which contains the buses supporting reactive power to alleviate voltage problem for the each bus is put in the knowledge base. This list can be easily constructed by the elements of each row of sensitivity matrix S_{VQ}, named 'VAR supporting bus list'.

6. THE KNOWLEDGE BASED SYSTEM

A knowledge based system is a computer software that behaves like a human expert in narrow, specific domain of application. The system has knowledge in a particular domain and is capable of solving problems that require the knowledge obtained in the domain.[21] The developed knowledge based system, generally, consists of three main modules, i.e., a knowledge base, an inference engine and a man machine interface. The knowledge base contains knowledge that is specific to the domain of application, including such things as simple facts about the domain, rules

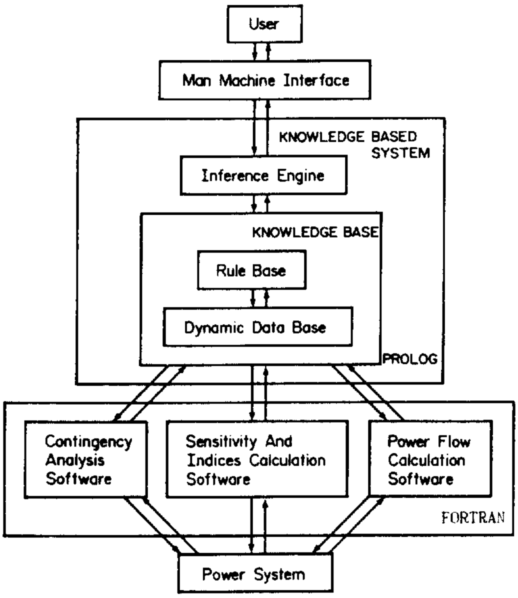

Fig. 1 schematic diagram of the knowledge based system for reactive power/voltage control

that describe relations or phenomena in the domain, and possibly methods, heuristics and ideas for solving problems in this domain. The inference engine actively utilizes knowledge, rules, heuristics and ideas in the knowledge base to chain a set of rules to form a line of reasoning. The man machine interface provides smooth communication between the user and the system. The structure of the knowledge based system in a block diagram form is shown in Fig. 1.

6.1 KNOWLEDGE BASE

It is obviously clear that a successful knowledge based system relies on a high quality knowledge base. All known knowledge for a complete description of the power system form the knowledge base. That is, the knowledge base comprises facts about the power system components, parameters, topology data, operational constraints and sensitivities of power system rules that describe relations between phenomena in the power system and methods for solving problems in the power system. The following empirical rules are well identified for the reactive power and voltage control problem.[8, 12].

(a) If a load bus voltage drops below(or rises above)the operating limit, control devices such as shunt capacitors, shunt reactors, transformer tap changers and generator voltages can be switched or adjusted to restore the voltage profile.

(b) If a load bus voltage drops below(or rises above) the operating limit, it is most efficient to apply the reactive power compensation locally. If the capacity of local compensators is insufficient to resolve the voltage problem, then compensators with next highest sensitivities should be chosen.

(c) If the voltage is low(high)at a bus, the tap position of the local transformer tap changer can be raised (lowered) to correct the problem. However, increasing(decreasing) the tap position may cause other load bus voltages to drop(rise).

(d) Generator bus voltages can be raised (lowered) to solve the low(high) load bus voltage problems.

(e) The usage priority of reacitve power control devices to solve the voltage problems from high to low is shunt capacitors/reactors, transformer tap changers and generator voltages.

In addition, the knowledge base in this paper was developed in the list format for convenience. The knowledge base consists of rule base and dynamic data base which is updated every time the system infers new control action. The dynamic data base is composed of bus order list, generator bus data(gen_data), load bus data(bus_data), capacitor data(cap_data), reactor data(rea_data), transformer data(tap data) and various sensitivity matrices (sen_mat, tsen_mat) and the rule base is made up of production rules developed on the basis of the above empirical rules. The load bus data includes information concerning bus number (name), type, voltage, demand(MW, MVAR), VAR supporting bus list and voltage limit. The generator bus data contains information as to bus number(name), type, rated voltage, actual real and reactive power generation, maximum and minimum real and reactive power generation, power factor based upon plant efficiency. The capacitor(reactor) data contains information about bus name, number of banks, number of banks in service and size of each bank. Finally, transformer data comprises tap position at present time, number of steps and size of each step.

6.2 INFERENCE ENGINE

The inference engine is used to chain the facts given in the knowledge base and empirical rules. The search procedure of the proposed knowledge based system makes use of the "depth-first" search strategy. This strategy provides the most efficient utilization of the reactive power control sources. This is because the search space is formed in such a way that the most weighted sensitive controller has the highest priority. The inference engine involves a series recursive search procedure. This is the main reason the PROLOG language is chosen in this knowledge based system. PROLOG language provides very powerful automatic back-tracking, pattern matching and tree-based data structuring capabilities. Therefore the recursive search procedures can also be easily realized by the PROLOG language.

6.3 DATA STRUCTURE

The general form of the data representation is given by type, name, status, attributes and characteristics. The above form is explained explicitly below for various data types.

(1) Load buses
[Name, Type, Voltage, MW demand, MVAR demand, [VAR supporting bus list], Voltage limit]

(2) Generator buses
[Name, Type, rated voltage, MW generation, MVAR generation, MW limit, MVAR limit, Power factor]

(3) Shunt capacitors or reactors
[Bus name, Number of banks, Number of banks in service, Size of each bank]

(4) Transformer
[Name, Current tap position, Number of steps, Size of each step]

6.4 PRODUCTION RULES

In principle, any consistent formalism in which we can express knowledge about some problem domain can be considered for use in an expert system. However, the language of if-then rules, also called production rules, is by far the most popular formalism for representing knowledge and will be used here. If-then rules usually turn out to be a natural form of expressing knowledge, and have the desirable features, that is, modularity, incrementability, modifiability and transparency. Also, by recursively using predicate calculus rules in cooperation with numerical and logical calculations, all rules in this paper are realized in PROLOG language. Of course, the rule structure is flexible, such that rules can be modified, added and deleted easily by the operator. The major rules used for the reactive power and voltage control are summarized here.

Rule1 : If there exists a bus with voltage violation, then select bus on the top of bus order list which depends on user's option.

Rule2 : If the problem bus is selected, then check whether or not the bus is feasible for reactive power compensation.

Rule3 : If not feasible, then select in the VAR supporting bus list other bus which can support most significantly the reactive power needed in the problem bus.

Rule4 : If the feasible bus with compensator to be used for reactive power reallocation is selected, then compute the increment of various controllers :

$$\Delta U_i = S_{ij}^{-1} \Delta V_j$$

where S_{ij} is the i, j-th element of sensitivity matrix defined in equations (2)-(6), ΔV_j is the magnitude of voltage violation and ΔU_i is the available control actions.

Rule5 : If the reactive power compensator can provide the necessary control, then implement the necessary compensation.

Rule6 : If the controller is at full output and there remain other controllers to be used, then select next bus on the bus order list.

Rule7 : If all bus voltages are now within limits, then verify with power flow.

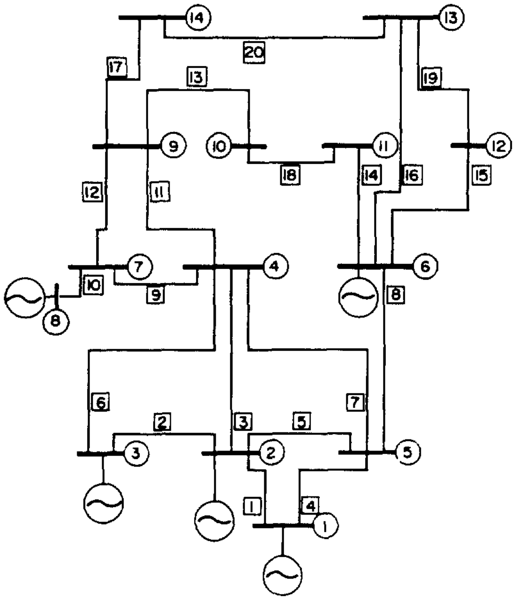

Fig. 2 one line diagram of IEEE 14 bus system

Table 1 Line data for IEEE 14 bus system

line number	bus number from	bus number to	impedance R	impedance X	tap ratio	line charge
1	1	2	0.0194	0.0592		0.0264
2	2	3	0.0470	0.1980		0.0219
3	2	4	0.0581	0.1763		0.0187
4	1	5	0.0540	0.2230		0.0246
5	2	5	0.0570	0.1739		0.0170
6	3	4	0.0670	0.1710		0.0173
7	4	5	0.0134	0.0421		0.0064
8	5	6	0.0000	0.2520	1.000	
9	4	7	0.0000	0.2091	0.975	
10	7	8	0.0000	0.1762		
11	4	9	0.0000	0.5562	0.9625	
12	7	9	0.0000	0.1100		
13	9	10	0.0318	0.0845		
14	6	11	0.0950	0.1989		
15	6	12	0.1229	0.2558		
16	6	13	0.0662	0.1303		
17	9	14	0.1271	0.2704		
18	10	11	0.0821	0.1921		
19	12	13	0.2209	0.1999		
20	13	14	0.1709	0.3480		

7. CASE STUDY

The suggested Knowledge-based system has been tested on the modified IEEE 14 bus system to demonstrate the usefulness. The system has 14 buses, 20 lines, 5 generators, 3 tap-changing transformers and 3 shunt capacitor/reactor banks. Fig. 2 shows one line diagram of the system.

Table 1 summarizes the line data for the IEEE 14 bus system on 100 MVA base, while Table 2 gives bus data.

The operating limits of generators are summarized in Table 3, and fuel cost coefficients are given in Table 4.

Also the limits of other control variables needed in simulating are shown in Table 5.

CASE 1

Problem : Line outage at line 12, low voltages at

Table 2 Bus data of IEEE 14 bus system (in p.u.)

bus number	Generation P	Generation Q	Load P	Load Q
1	0.000	0.000	0.000	0.000
2	0.600	0.424	0.217	0.127
3	0.700	0.234	0.942	0.190
4	0.000	0.000	0.478	−0.039
5	0.000	0.000	0.276	0.116
6	0.800	0.122	0.112	0.075
7	0.000	0.000	0.000	0.000
8	0.600	0.174	0.000	0.000
9	0.000	0.000	0.295	0.066
10	0.000	0.000	0.290	0.058
11	0.000	0.000	0.235	0.018
12	0.000	0.000	0.261	0.016
13	0.000	0.000	0.135	0.058
14	0.000	0.000	0.149	0.050

Table 3 Operating limits (in p.u.) of generators

bus number	*P*min	*P*max	*Q*min	*Q*max	*V*min	*V*max
1	0.0	0.900	−0.20	0.500	0.95	1.05
2	0.0	0.700	0.00	0.400	0.95	1.05
3	0.0	0.800	0.00	0.400	0.95	1.05
6	0.0	0.900	0.00	0.500	0.95	1.05
8	0.0	0.650	0.00	0.300	0.95	1.05

bus 9, $V=0.920$, at bus 10, $V=0.914$, at bus 11, $V=0.940$, at bus 14, $V=0.918$.

Solution : Taking into account all four indices discussed above, bus order list is; [14, 11, 10, 12, 9, 13, 7, 4, 5].

In this case, all the four indices are given the same weighting. The various indices used to find bus order list are shown in Table 6, VAR supporting bus list in Table 7. Also, a part of dynamic data base is shown in Table 8. Rule 1 selects bus 14 on the first of bus order list. Bus 14 is feasible bus by rule 2. Rule 4 chooses capacitor bank at bus 14 as reactive power compensator and compute reactive power increase.

Rule 5 : Implement. Rule 7 : Voltage problem is not cleared. Rule 6 : Select bus 11 on the second in the list. Bus 11 is not feasible bus by rule 2. Rule 3 : Select other bus, bus 10, on the VAR supporting bus list for bus 11. Rule 4 computes reacitve power increments. Rule 5 : Implement. Rule 7 : Voltage problem is not cleared. Rule 4 chooses as controller capacitor bank located on bus 9 which is the next element in VAR supporting bus list for bus 11. Rule 5 : Implement. Rule 7 : Voltage within limits.

Table 4 Fuel cost coefficients of generators

bus number j	A_j \$/hr	B_j \$/hr · Kw	C_j \$/hr · Kw^2
1	0.00	1.75	0.0175
2	0.00	1.00	0.0625
3	0.00	3.25	0.0083
6	0.00	3.00	0.0250
8	0.00	3.00	0.0250

Table 5 Limits of other control variables(p.u.)

(i) Transformer tap ratio

$1.0-0.0125\times NT\le Ti\le 1.0+0.0125\times NT$

NT=number of steps, i=transformer bus

0.0125=step size of transformer

(ii) Load bus voltage

$0.95\le Vi\le 1.05$ i=total load bus

(iii) VAR sources

$-0.10\le Q5\le 0.0$

$0.0\le Q9\le 0.10$

$0.0\le Q10\le 0.20$

$-0.10\le Q12\le 0.0$

$-0.10\le Q13\le 0.0$

$0.0\le Q14\le 0.15$

Table 6 Index and bus order list

[1] STEADY STATE STABILITY INDEX
[14, 12, 11, 7, 13, 10, 9, 5, 4]
[2] REACTIVE POWER TRANSMITTANCE INDEX
[14, 9, 10, 11, 13, 12, 7, 4, 5]
[3] VOLTAGE SEVERITY INDEX
[10, 14, 9, 11, 4, 5, 12, 13, 7]
[4] GENERATOR FUEL COST INDEX
[12, 13, 11, 14, 10, 9, 4, 5, 7]

[5] BUS ORDER LIST
[14, 11, 10, 12, 9, 13, 7, 4, 5]

Table 7 VAR supporting bus list

bus number	capacitor	reactor
4	[9, 10]	[5]
5	[9, 10]	[5]
7	[9, 10]	[5]
9	[9, 10, 14]	[13]
10	[10, 9, 14]	[13]
11	[10, 9, 14]	[13]
12	[14, 9, 10]	[12, 13]
13	[14, 9, 10]	[13, 12]
14	[14, 9, 10]	[13]

CASE 2

Problem : Line outage at line 14, low voltages at bus 10, $V=0.928$, at bus 11, $V=0.901$, at bus 14, $V=0.940$.

Solution : Taking into account all four indices discussed above, bus order list is; [11, 14, 10, 12, 13, 9, 4, 7, 5].

Table 8 Contents of dynamic data base

```
system_conf(14, 20, 5, 9, 3)
icl_data([4, 5, 7, 9, 10, 11, 12, 13, 14])
isg_data([1, 2, 3, 6, 8])
    .          .

sen_mat(4, [.0447, .0277, .0208, .0180, .0051, .0077, .0011, .0027, .0115])
sen_mat(5, [.0277, .0459, .0129, .0112, .0093, .0048, .0007, .0016, .0071])
sen_mat(7, [.0208, .0129, .1053, .0084, .0070, .0036, .0005, .0012, .0053])
    .          .

tsen_mat(4, [.1051,   .1269, .0644])
tsen_mat(5, [.1740,   .0785, .0399])
tsen_mat(7, [.0489, -.4062, .0300])
    .          .

gsen_mat(4, [.1148, .3663, .2272, .1587, .1173])
gsen_mat(5, [.1902, .3734, .1406, .2117, .0726])
gsen_mat(7, [.0534, .1704, .1057, .0739, .5942])
    .          .

cap_data(2, 10, 4, 0, 0.05)
    .          .

rea_data(3, 13, 2, 0, 0.05)
    .          .

tap_data(1, 1.0000, 7, .0125)
    .          .
```

In this case, all the four indices are given the same weighting. In a similar sequence to the case 1, bus 10 and bus 9 are chosen as controllers. Results are shown in Table 9.

CASE 3

Problem : Line outage at line 16, low voltages at bus 12, $V=0.933$, at bus 13, $V=0.900$, at bus 14, $V=0.916$.

Solution : Taking into account all four indices discussed above, bus order list is ; [13, 14, 12, 11, 10, 9, 4, 7, 5].
In this case, all the four indices are given the same weighting. In a similar sequence to the case 1, bus 14, bus 9 and bus 10 are chosen as controllers. Also the tap ratio of transformer at line 8 and the voltage of generator at bus 6 are adjusted to alleviate the voltage problem. Results are summarized in Table 9.

8. CONCLUSIONS

A new method using knowledge based system technique for reactive power/voltage control on a system with contingency is introduced. The proposed system is developed on the basis of the various indices, bus order and VAR supporting bus list concepts. This scheme is advantageous when the system is required to alleviate the voltage problem within critical time for keeping voltage stability. In the developed system, the power flow, sensitivity and contingency algorithms are the basis, and the way of integrating them with heuristic knowledge is performed successfully.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the finan-

Table 9 Results for the IEEE 14 bus system

Variable	Base case	Case 1		Case 2		Case 3	
		initial	final	initial	final	initial	final
$V1$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
$V2$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
$V3$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
$V4$	0.9800	0.9750	0.9800	0.9750	0.9820	0.9780	0.9940
$V5$	0.9820	0.9760	0.9800	0.9800	0.9850	0.9810	1.0000
$V6$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0100
$V7$	0.9870	0.9930	0.9960	0.9760	0.9990	0.9810	1.0100
$V8$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
$V9$	0.9750	0.9200	0.9910	0.9550	1.0000	0.9650	1.0160
$V10$	0.9620	0.9140	0.9870	0.9280	0.9910	0.9530	1.0120
$V11$	0.9670	0.9400	0.9770	0.9010	0.9660	0.9610	0.9960
$V12$	0.9640	0.9600	0.9670	0.9630	0.9660	0.9330	0.9640
$V13$	0.9740	0.9640	0.9780	0.9690	0.9750	0.9000	0.9500
$V14$	0.9550	0.9180	0.9800	0.9400	0.9690	0.9160	0.9910
$Q1$	−0.1420	−0.1198	−0.1348	−0.1412	−0.1603	−0.1426	−0.2000
$Q2$	0.2280	0.2880	0.2387	0.2662	0.2001	0.2485	0.0493
$Q3$	0.3510	0.3800	0.3502	0.3772	0.3363	0.3636	0.2700
$Q6$	0.3012	0.4403	0.1232	0.2580	0.1859	0.2883	0.3864
$Q8$	0.1051	0.0705	0.0565	0.1681	0.0394	0.1377	0.0000
$Q9$	0.0000	0.0000	0.1000	0.0000	0.1000	0.0000	0.1000
$Q10$	0.0000	0.0000	0.2000	0.0000	0.2000	0.0000	0.2000
$Q14$	0.0000	0.0000	0.1000	0.0000	0.0000	0.0000	0.1500
$T1$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0875
$T2$	0.9750	0.9750	0.9750	0.9750	0.9750	0.9750	0.9750
$T3$	0.9625	0.9625	0.9625	0.9625	0.9625	0.9625	0.9625
Fuel cost [$ /hr]	1447.052	1458.53	1456.39	1454.84	1453.39	1455.65	1454.04

cial assistance contributed by the Korea Science and Engineering Foundation.

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