

Crisis management in power systems: a knowledge based approach

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Abstract

In emergency and abnormal conditions, a power system operator has to deal with a large amount of data and apply the most appropriate remedial actions. However, due to emotional and psychological stress, an operator may not be able to adequately respond to critical conditions and make correct decisions. Mistakes can damage very expensive power system equipment or worse lead to the major emergencies and catastrophic situations. The intelligent systems can play an advisory role, suggesting the necessary actions which should be taken to clear a given emergency or abnormal condition. This paper outlines some experience obtained at the Department of Electrical and Electronic Engineering of the University of Tasmania in the development and implementation of the intelligent knowledge based systems. The expert system for clearing overloads was developed using *Leonardo* expert system shell. The system applies the network sensitivity factors to determine appropriate actions which include generation rescheduling, line switching and load shedding, and the amount of the required corrections. The expert system for voltage control was developed based on *VP-EXPERT* shell. It detects voltage violations and provides a set of effective control actions to solve given voltage problems.

1 Introduction

1.1 Power system security and crisis management

Power system security includes measures which intend to keep the system in an operating condition when one or even a few components fail to operate. For example, a generating unit may fail but the remaining units of the system can increase power output to make up the deficit, and thus prevent the load

shedding. Similarly, a power transmission line may be damaged and switched-off by power system protection but the remaining transmission lines can take the increased load.

In order to prevent a power system from collapse, its elements are operated within certain constraints and protected by automatic devices that cause equipment to be taken off if those constraints are violated. However, due to some failures, equipment may still be left in operating with constraints violated. Such conditions may lead in turn to switching of other equipment out of service and if this process continues, large parts or even the entire system can collapse completely.

A major emergency in a power system might start with opening of a single line as a result of a short-circuit. The remaining transmission system takes up the power that was flowing on that line. However, if even one of the remaining lines is now overloaded, it also may open due to a protection operation, and thus an additional load on the remaining network can be imposed. Moreover, a certain transmission line outage can cause some serious voltage problems in the system. Therefore, power system operators are required to take actions to avoid a further deterioration of the situation.

In emergency and abnormal conditions, a power system operator has to deal with a large amount of data and apply the most appropriate remedial actions. However, due to emotional and psychological stress, an operator may not be able to adequately respond to critical conditions and make correct decisions. Moreover, in emergency conditions, a vital decision must often be taken in a matter of minutes, sometimes even seconds. Mistakes can damage very expensive power system equipment or worse lead to the major emergencies and catastrophic situations. There is no time to examine advantages and disadvantages of different approaches to the restoration process and look into long columns of results. Nevertheless, an operator must respond to an emergency and only his or her experience can help to find a right decision. Clearly, there is a strong need for an aid (or decision support system) formalising the operator knowledge.

In recent years, intelligent systems have been successfully applied in power systems; e.g. Dillon & Laughton [1], Tomsovic [16], Srinivasan [14] and Wong [19]. The intelligent systems play an advisory role, suggesting the necessary actions which should be taken to clear a given emergency or abnormal condition. This paper outlines some experience obtained at the Department of Electrical and Electronic Engineering of the University of Tasmania in the development and implementation of the intelligent knowledge based systems for clearing overloads and voltage control in power systems.

1.2 General principles of power system analysis

Modern power control centers are equipped with SCADA systems gathering data on-line which permit to apply real-time methods for power system analysis. Operators have obtained substantial experience using optimal power flows, state

estimation, on-line security estimation and other software packages. The conventional methods employed for power system analysis rely on mathematical models and sophisticated programming techniques. However, the complexity and size of modern power systems such that complete computational solutions usually cannot be obtained in a timely fashion, and thus cannot be used in emergency conditions for decision support.

Therefore, an alternative method called the *decoupled load flow* was introduced by Stott & Alsac [15]. This method is used to improve the computational efficiency and to reduce computer storage requirements. It is also reliable in solving difficult cases for large-scale power transmission systems. The major principles of the decoupled approach are based on two general rules:

- change in the voltage angle δ at a bus primarily affects the real power flow P in the transmission lines;
- change in the voltage magnitude $|V|$ at a bus primarily affects the reactive power flow Q in the transmission lines.

This approach makes possible to develop the intelligent knowledge based systems for real-time applications.

2 Expert system for clearing overloads

2.1 Permissible overloading duration

The accurate determination of the permissible overloading duration allows operators a greater flexibility in decision making and in choosing suitable remedial actions. From an operator point of view, the most hazardous overloads are these which occur on the large system transformers connecting the various voltage level networks, and on the tie power transmission lines connecting different subsystems. Therefore, it is vital to examine factors setting a limit on the loading time of these elements.

The short-term load capacity of transformers depends on the ambient air temperature and the loading time. When the load increases the transformer temperature will rise and the ageing of insulating materials accelerates. Ageing sets certain limits to the load capacity of the transformer. The operation at the rated power and ambient air temperature of $+20^{\circ}\text{C}$ is considered as normal. In this case, the insulating materials will age at the normal speed and a proper maintenance will be provided. In practice, however, the load and temperature can vary according to the power demand and weather conditions. If part of the operation time the transformer loading is lower than its continuous load capacity it can be loaded more at the other times such that the ageing remains normal during the whole time (for example, during the period of 24 hours), e.g. Wong [18]. Therefore, permissible time for clearing transformer overloads should take into account the previous loading of the transformer or its loading history.

For transmission lines, the power limit and permissible duration of an overload in most cases are governed by the conductor temperature increase. In turn, the conductor operating temperature is limited by the conductor ground clearance. As shown in Morgan [8] and Vakili & Viles [17], the loading capacity or thermal rating can be described as a function of conductor temperature, ambient temperature, wind velocity, elevation, ground reflection and solar radiation. In transmission power systems, load currents during and following system disturbances may reach values above of the steady-state thermal rating of the line. Such conditions may be safe for approximately half an hour. This time can then be used to perform the generation rescheduling or load shedding. Therefore, it is necessary to determine how long a conductor can carry an overload without exceeding its maximum permissible operating temperature. This problem can be solved by employing intelligent knowledge based systems, e.g. Le & Negnevitsky [7] and Negnevitsky & Le [9].

2.2 Expert system for the loading capability assessment of transmission lines

The heuristic nature of the short-time loading capability assessment of the transmission lines enables us to use knowledge based or expert systems. The rule-based expert system developed includes the basic components shown in Figure 1.

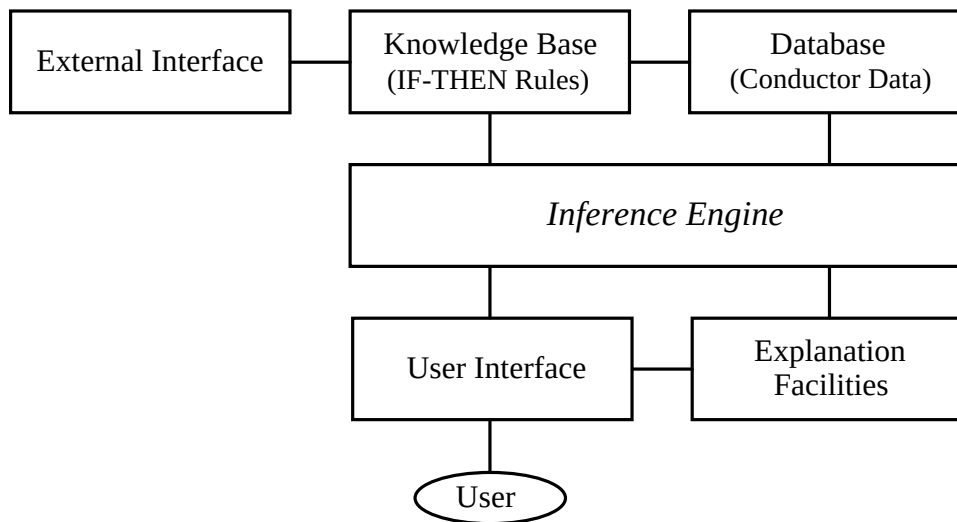


Figure 1: Expert system for the loading capability assessment.

The *knowledge base* contains the domain knowledge in the form of specific facts and heuristics. The knowledge is represented as a set of IF - THEN rules. The *inference engine* carries out the reasoning whereby the expert system reaches a solution. It links the rules given in the knowledge base and associated conditions input by the user with data provided in the database (conductor data).

The *explanation facilities* enable the user to query the system "How" and "Why" a particular solution has been reached. The *database* includes all relevant data for various types of conductors (conductor diameter, conductor resistance, conductor unit weight, specific heat, etc.). The data is represented in the form of a spreadsheet. The *user interface* is the means of communication between a user seeking a solution to the problem and an expert system. The *external interface* allows the expert system to work with external data files and programs written in conventional programming languages including FORTRAN, PASCAL and C. The developed expert system uses external programs written in C. These programs are employed for computing the quantities of heat and adjusting the resistance for temperature changes.

The *Leonardo* expert system shell was chosen among several available software packages for development of the application. *Leonardo* is a complete object oriented tool. The *Leonardo Development System* provides the facilities for building and testing expert systems, the *Leonardo Run System* allows delivery of complete applications to the user and the *Leonardo Productivity Toolkit* provides efficient aids for tailoring the application. The *Leonardo* expert system shell has good interface capability with external data files and programs, easy knowledge encoding and can be implemented on an IBM PC. In addition, *Leonardo* provides a user friendly interface.

The complete knowledge base consists of 43 rules. Details of these rules can be found in Le, Negnevitsky & Piekutowski [5]. The expert system was evaluated against the site tests for both indoor and outdoor conditions. A comparison with actual test results showed that the expert system developed is an accurate model of the actual physical events.

Figure 2 displays an example of the expert system query screen.

A practical application of the expert system can be demonstrated on a power system of the Hydro-Electric Commission (HEC) of Tasmania shown in Figure 3. The example described below examines the winter night loading conditions.

Following the outage of the Palmerston - Liapootah 220 kV transmission line, the current in the Palmerston - Waddamana transmission line increases from 182 to 623 A (196% of the steady state thermal rating). The temperature-time characteristic and short-time ratings evaluated by the expert system are shown in Figures 4 and 5. It can be seen that the conductor temperature increases from 20°C (initial temperature) to 43°C (maximum permissible temperature limited by conductor ground clearance) in 1 minute. Therefore, this overload should be allowed for 1 minute only. This conclusion is displayed on the screen as shown in Figure 6.

2.3 Calculation of sensitivity factors

Based on the decoupling properties, overloads can be maintained within permissible limits by controlling the real power generation in the receiving and sending parts of the system, reconfiguration of the transmission network

This question is asked to assign the specific heat value for the conductor. Consider, for example, the cpecific heat at 20 °C of the following conductors: Aluminium = 900 J/Kg . C degree Copper = 385 Steel = 431			
What is the conductor type?			
<table border="1"> <tr> <td>Aluminium</td> </tr> <tr> <td>Copper</td> </tr> <tr> <td>ACSR</td> </tr> </table>	Aluminium	Copper	ACSR
Aluminium			
Copper			
ACSR			
F keys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review			

Figure 2: The expert system query screen.

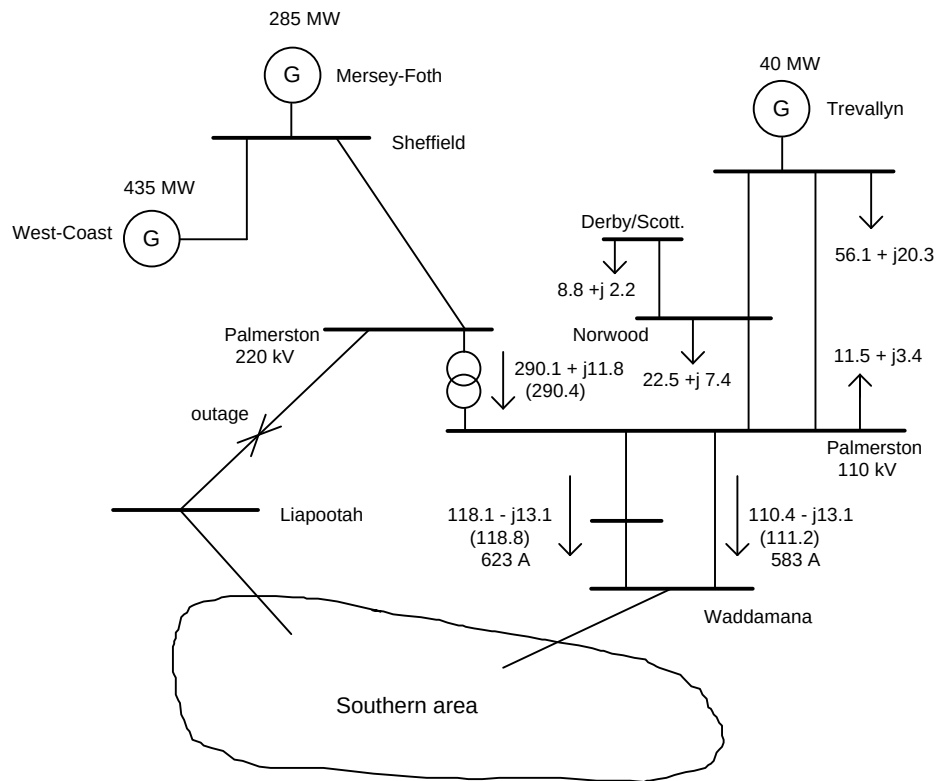


Figure 3: The HEC system: a case study

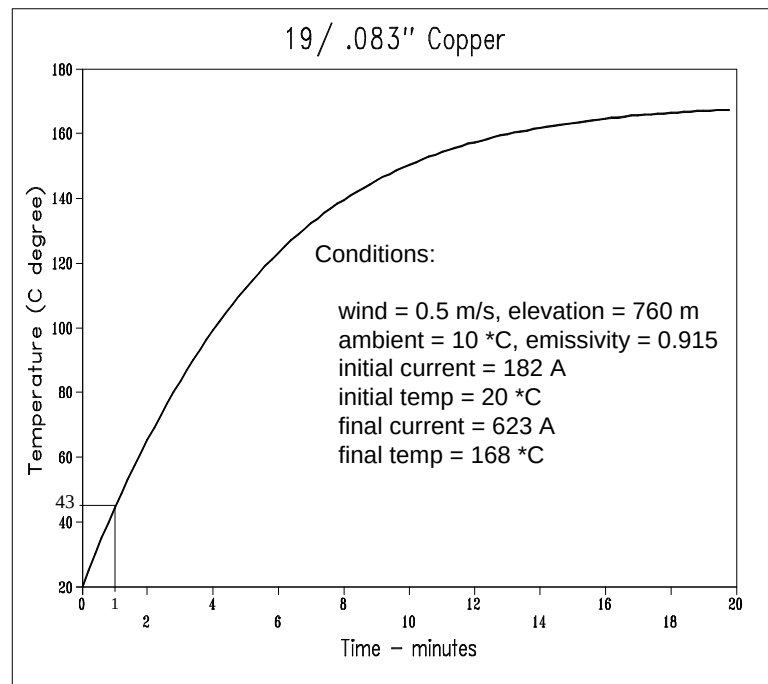


Figure 4: Temperature-time characteristic of the Waddamana-Palmerston transmission lines.

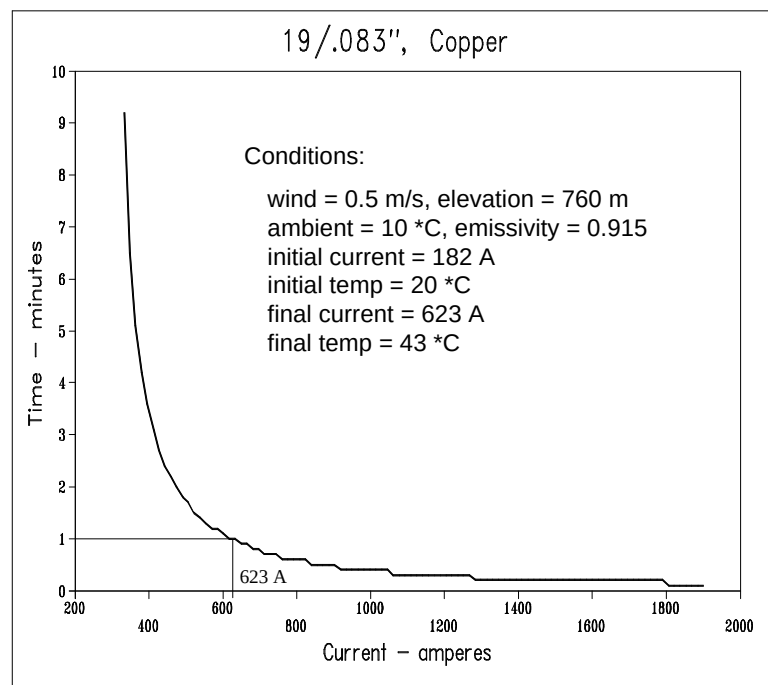


Figure 5: Short time ratings for the Waddamana-Palmerston transmission lines.

LEONARDO (c)1986-1990 Creative Logic Ltd. Knowledge Base: CONDUCTOR	
EXPERT SYSTEM	
Short-Time Thermal Rating of Transmission Lines	
Conclusion	
Conductor type: 19/ .083" Copper	
Operating condition:	
elevation (m): 760	emissivity: 0.915
wind (m/s): 0.5	ambient (*C): 10
Conductor temperature:	
initial (*C): 20	final (*C): 43
Conductor current:	
initial (A): 182	final (A): 623
Steady state thermal rating (A):	317
Permissible overload duration (min.):	1.00
<i>Type any key to see the next screen</i>	

Figure 6: Conclusion screen.

and load shedding as suggested in Negnevitsky [11]. The generator shift factors can be expressed as:

$$\alpha_{ij} = \frac{\Delta S_i}{\Delta P_{Gj}} \quad (1)$$

where ΔS_i is the change in power flow on element i when a change in generation, ΔP_{Gj} , occurs at bus j . If it is assumed that all other generators remain fixed, then the α_{ij} factor represents the sensitivity of the power flow on element i to a change in generation at bus j .

The network reconfiguration factors are used in a similar manner. The line outage distribution factor has the following meaning:

$$\beta_{i,k} = \frac{\Delta S_i}{S_k^0} \quad (2)$$

where $\beta_{i,k}$ is the line outage distribution factor when monitoring element i after an outage on line k ; ΔS_i is the change in reactive power flow on element i ; S_k^0 is the original flow on line k before it was opened.

The load shedding factors can be obtained as:

$$\gamma_{ij} = \frac{\Delta S_i}{\Delta P_{Ln}} \quad (3)$$

where ΔS_i is the change in power flow on element i when a change in load, ΔP_{Ln} , occurs at bus n .

The overload clearing is a subject to the following security constraints:

$$P_{Gj}^{min} \leq P_{Gj} + \Delta P_{Gj} \leq P_{Gj}^{max} \quad (4)$$

$$-S_i^{max} \leq S_i^0 + \Delta S_i \leq S_i^{max} \quad (5)$$

$$P_{Ln} - \Delta P_{Ln} \geq P_{Ln}^{min} \quad (6)$$

$$V_j^{min} \leq V_j \leq V_j^{max} \quad (7)$$

where P_{Gj}^{max} , P_{Gj}^{min} and P_{Gj} are, respectively, the maximum and minimum limits and operating value of the generator output in MW at bus j ; S_i^0 , ΔS_i and S_i^{max} are, respectively, the original MVA flow, change in MVA flow on line i after an outage on line k and long-term rating (or emergency rating) of line i (with regard to that a line flow can be positive or negative); P_{Ln}^{min} and P_{Ln} are, respectively, the guaranteed minimum load supply and original load at bus n ; V_j^{max} , V_j^{min} and V_j are, respectively, the maximum and minimum voltage limits and actual voltage at bus j .

In order to find the most effective corrective actions for the given situation, the sensitivity tree method can be used. It provides relationships between the element load and controllers.

2.4 Knowledge base and database

As proved in Negnevitsky [10], an overload can be classified using the answers to the following questions:

1. What is the type of plant?
2. What is the duration of the overload?
3. What is the permissible duration of such an overload?
4. What are the means available for clearing the overload?
5. What measures should be applied first?

These provide the basis on which the database and knowledge base are organised. The expert system for clearing overloads uses the following data:

- The upper load limit (short-term rating) for each supervised element;
- The permissible overload duration for each supervised element as a function of the load. The permissible time for clearing an overload can be obtained using the data provided in loading guides [4], calculated, e.g. Morgan [8], Smolleck & Sims [13], Vakili & Viles [17], or employing intelligent systems as it was demonstrated above.

- The upper and lower limits for each power station (or, if required, for each generator);
- The long-term ratings (emergency ratings) for each line;
- The guaranteed minimum load supply (or the highest priority load level) at each bus.
- A table of sensitivity factors for each supervised element and controller, and also the execution time for each controller.

2.5 Production rules

The expert system applies the following heuristic rules suggested in Negnevitsky [11] and Negnevitsky & Le [12]:

Rule 1:

IF the real power flow in element i is more than its short-term rating, THEN element i is overloaded.

Rule 2:

IF element i is overloaded, THEN include element i in the list of overloaded elements.

Rule 3:

IF element i is in the list of overloaded elements, THEN determine permissible overload duration t_i for element i .

Rule 4:

IF permissible overload duration t_i is the lowest over all elements in the list of overloaded elements, THEN calculate the sensitivity factors (generator shift, network reconfiguration and load shedding factors).

Rule 5:

IF the generator shift list is not empty, THEN select the most effective controller AND check its limits AND calculate the overload relief on element i .

Rule 6:

IF the overload relief caused by the selected controller application is less than the overload magnitude of element i AND the controller execution time is less than permissible overload duration t_i , THEN include the controller in the list of feasible actions.

Rule 7:

IF element i is still overloaded, THEN select next available controller on the generator shift list until all controllers are taken.

Rule 8:

IF element i is still overloaded AND the network reconfiguration list is not empty, THEN select the most effective controller AND check long-term rating

violations on the other elements after the controller use AND calculate the overload relief on element i .

Rule 9:

IF the selected controller does not cause long-term rating violations on the other elements AND the overload relief is less than the overload magnitude of element i AND the controller execution time is less than permissible overload duration t_i , THEN include the controller in the list of feasible actions.

Rule 10:

IF element i is still overloaded, THEN select next available controller on the network reconfiguration list until all controllers are taken.

Rule 11:

IF element i is still overloaded AND the load shedding list is not empty, THEN select the most effective bus (a bus where the load shedding causes the most significant effect on the overload relief of element i) AND calculate the load shedding required to clear the overload on element i .

Rule 12:

IF the required load shedding is less than the load at the selected bus minus the guaranteed minimum load supply AND shedding execution time is less than permissible overload duration t_i , THEN include the required load shedding at the selected bus in the list of feasible actions.

Rule 13:

IF the required load shedding is greater than the load at the selected bus minus the guaranteed minimum load supply AND shedding execution time is less than permissible overload duration t_i , THEN include the allowable load shedding at the selected bus in the list of feasible actions.

Rule 14:

IF element i is still overloaded, THEN select next bus on the shedding list until the overload on element i is cleared.

Rule 15:

IF the overload on element i is cleared, THEN take next element on the list of overloaded elements until the list becomes empty.

2.6 Numerical example

The expert system was implemented on an IBM personal computer. *Leonardo* expert system shell was used for the development of a prototype application. A six-bus system, shown in Figure 7, is used to demonstrate the performance of the proposed expert system. Table 1 represents bus data of the system.

Table 2 shows line limits and initial MVA flows in the lines. Line 2-6 is overloaded in the initial state. Columns 4 and 5 represent flows after application of the corrective actions suggested by the expert system.

The line flows are determined using ac load flow and according to the recommendations made by the expert system.

Table 3 shows available actions which may be used to clear the overload on line 2-6 and corresponding sensitivity factors. Some actions are not applicable due to security constraint violations. For example, a disconnection of line 1-4 leads to overloads on lines 1-2, 1-5 and 2-5 and a voltage violation on bus 4.

According to recommendations provided by the expert system, the following actions must be applied:

- Case 1:*
- Bus 2, decrease generation on 5 MW;
 - Bus 3, increase generation on 10 MW;
 - Line 1-2, switch off.

However, if in a given emergency situation, line 1-2 cannot be removed from service, the expert system makes the following suggestions:

- Case 2:*
- Bus 2, decrease generation on 5 MW;
 - Bus 3, increase generation on 10 MW;
 - Bus 6, shed load by 6.5 MW.

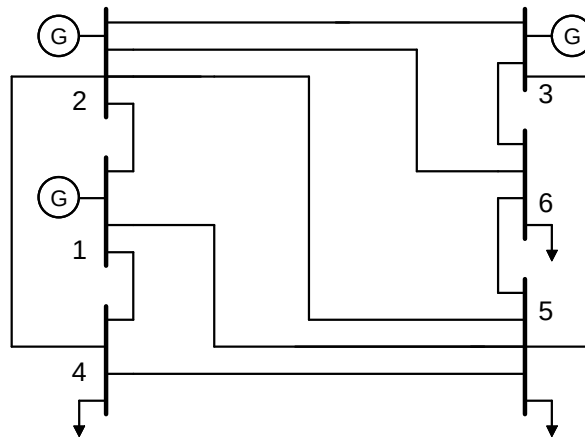


Figure 7: Six-bus power system.

Table 1: Bus data of the system.

Bus	Generation (MW)			Load (MW)	
	Actual	Min	Max	Low priority	Hight priority
1 swing	0	0	0	0	0
2	50	45	60	0	0
3	60	55	70	0	0
4	0	0	0	40	30
5	0	0	0	40	30
6	0	0	0	40	30

Table 2: Case studies.

Line	Line Limit	Initial Flow	Case 1	Case 2
1 - 2	50.0	32.6	0.0	27.7
1 - 4	65.0	48.0	60.6	45.2
1 - 5	50.0	37.3	45.7	33.7
2 - 3	25.0	12.6	11.6	11.5
2 - 4	65.0	56.7	55.1	57.5
2 - 5	35.0	21.9	19.7	21.4
2 - 6	25.0	29.4	25.0	25.0
3 - 5	35.0	30.1	29.8	31.2
3 - 6	85.0	75.1	76.6	74.4
4 - 5	25.0	6.4	5.9	5.4
5 - 6	25.0	9.7	10.8	9.2

Table 3. Available actions and sensitivity factors.

Action	Bus	Sensitivity Factor
Generation Increase	2	-0.0514
Generation Increase	3	0.1824
Load Shedding	4	-0.0148
Load Shedding	5	0.1093
Load Shedding	6	0.3484
Line Disconnection	1 - 2	0.0745
Line Disconnection	1 - 4	not applicable
Line Disconnection	1 - 5	not applicable
Line Disconnection	2 - 3	-0.0977
Line Disconnection	2 - 4	not applicable
Line Disconnection	2 - 5	not applicable
Line Disconnection	3 - 5	0.0297
Line Disconnection	3 - 6	not applicable
Line Disconnection	4 - 5	-0.1287
Line Disconnection	5 - 6	-0.0024

3 Expert system for voltage control

3.1 Problem statement and sensitivity tree method

The objective of voltage control is to maintain power system voltages within specified limits under various load conditions and changes in the transmission network. Classical analytical methods based on different optimisation techniques intend to minimise system losses and improve voltage profiles. However, most of these methods are too complex, provide only analytical solutions and cannot recommend appropriate control actions required to overcome voltage violations in a given emergency condition.

In order to improve the computational performance, a reduced system can be built using the subsystem reduction and equivalencing techniques described in Housos [3]. The reduced system consists of an internal "three-tier" subsystem introducing the voltage problem area, and the external subsystem representing the rest of the power system. This approach allows to minimise the system size and eliminate the less effective voltage controllers. Therefore, voltage magnitudes can be predominantly controlled by the reactive power injections into the internal subsystem. An expert system technique can be used to provide a set of practically effective control actions to solve given voltage problems in real-time.

Voltage controllers can change their values either continuously or in steps, they are not equally effective and the adjustment required from each controller may be different under different power system conditions. The sensitivity tree method can be used to find the effective order of control actions to be applied. It provides the relationship between bus voltages and the controller settings. A sensitivity matrix which relates the changes in the controlled variables, ΔX , to the changes in controller settings, ΔU , may be described as suggested in Hano, Tamura & Narita [2]:

$$[\Delta X] = [S] [\Delta U] \quad (8)$$

where matrix $[S]$ provides sensitivity factors between settings of the controllers and bus voltages. Voltage at any bus in the system can be adjusted by several different controllers. On the other hand, changes in any controller setting result in changes of several bus voltages.

3.2 Database and knowledge base

The expert system was developed based on VP-EXPERT system shell and implemented on IBM personal computers. It interacts with the power flow analysis package, network sensitivity analysis and other external programs and database. The expert system uses the following data:

- Upper and lower limits of voltage at each bus;
- Upper and lower limits of each controller;
- Sensitivity factors for each load bus and each controller.

When a bus voltage exceeds its specified limits, either high or low, a power system operator can adjust transformer taps, change generator bus voltages and switch capacitor banks and reactors.

The voltage control expert system performs the following tasks:

1. Determine the problem area and build an internal "three-tier" subsystem.
2. Calculate the network sensitivity factors and build the sensitivity tree.
3. Identify all buses with abnormal voltages.
4. Select the bus with the maximum voltage violation.
5. Select the most effective controller, estimate control effect and check security constraints.

6. If security constraints are not violated then implement the controller selected. If security constraints are violated then proceed to the next task.
7. If the voltage problem still exists then select the next available controller until all controllers are taken.
8. If the voltage problem still exists and all the controllers have been used then allocate additional shunt capacitor or reactor.
9. If the voltage on the maximum violated bus has become normal then take the next bus with the maximum abnormal voltage and repeat procedures.

Some of the rules implemented in the knowledge base are listed below.

- IF voltage on bus i is below the voltage limit THEN bus i is a low voltage problem bus.
- IF bus i is a low voltage problem bus THEN include bus i in the low problem bus list AND arrange buses in voltage ascending order.
- If all voltage problem buses are determined THEN calculate the sensitivity factors.
- IF the controllers list for a low voltage problem bus is not empty THEN select the most effective controller.

Detailed description of the expert system developed can be found in Le, Negnevitsky & Piekutowski [6].

3.3 Performance evaluation

The purpose of evaluation is to validate the knowledge incorporated in the production rules, and to compare the expert system performance with a conventional approach. Results are demonstrated on the modified IEEE 30-bus test system shown in Figure 8.

The most severe case is an outage of the transformer (T1) connected between buses 27 and 28.

Figure 9 shows a one-line diagram of the reduced system (equivalent) for the outage of transformer T1. In this system, all the control measures in the external areas are retained. The "three-tier" internal subsystem incorporates the following buses:

- First tiers: 27, 28.
- Second tiers: 6, 8, 25, 29, 30.
- Third tiers: 2, 4, 7, 9, 10, 24, 26.

Table 4 provides results (voltage levels and optimal settings of the control measures) given by the expert system for the full 34-bus system and reduced one (equivalent), respectively, in the case of the outage of transformer T1. The results obtained for the equivalent system are very close to those obtained for the entire 34-bus system. It indicates that the proposed approach provides a satisfactory solution.

Advises given by the expert system on voltage control actions to be taken under the outage of transformer T1 are shown in Figure 10.

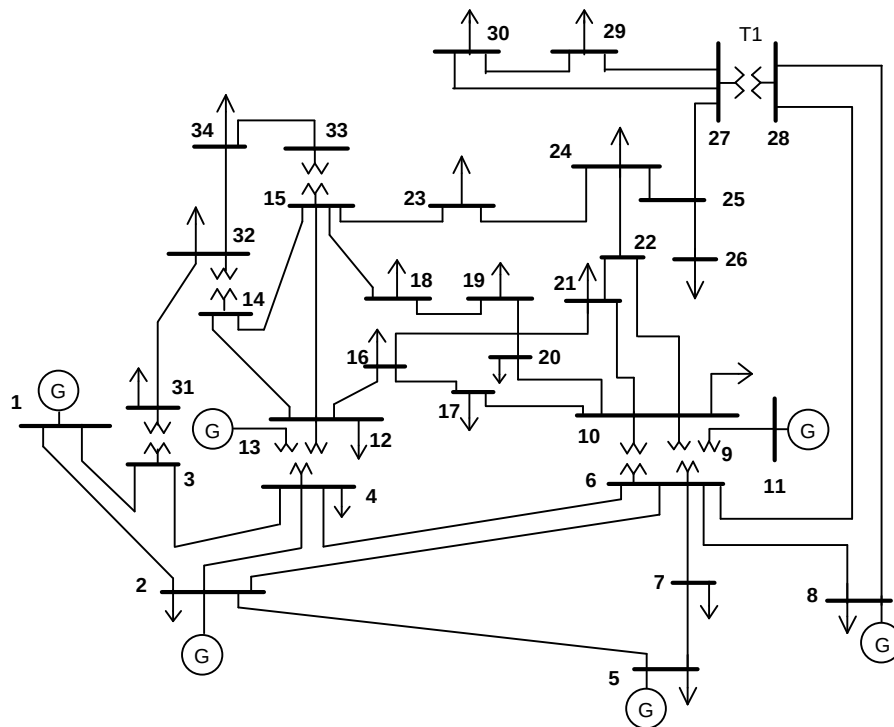


Figure 8: The modified IEEE 30-bus system.

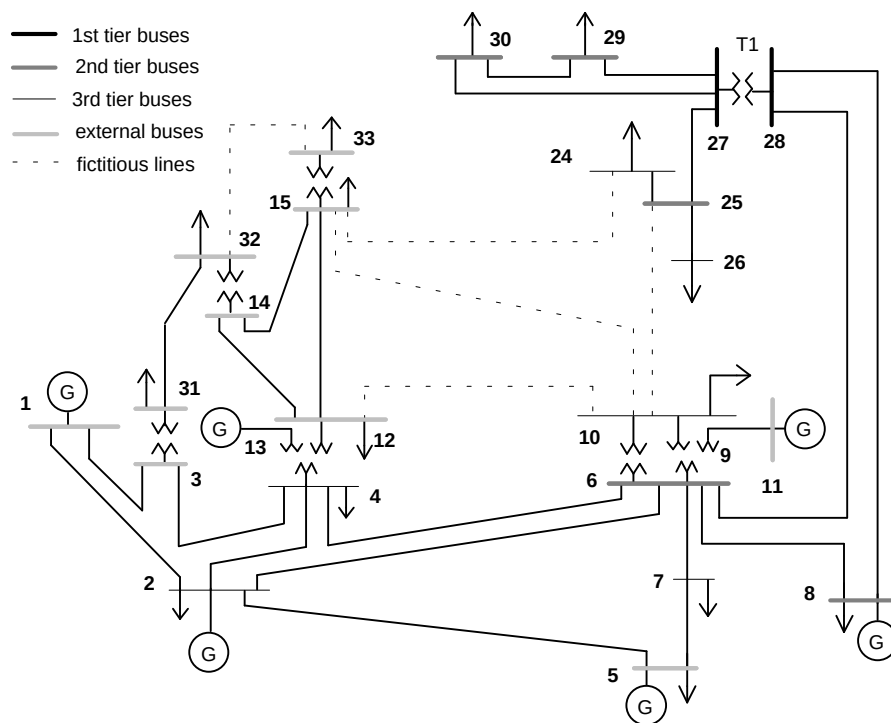


Figure 9: The reduced the modified IEEE 30-bus power system.

Table 4: Bus voltages and optimal control settings.

Remarks	Full system		Equivalent		Remarks	Full system		Equivalent	
	Initial	Final	Initial	Final		Initial	Final	Initial	Final
Load voltages					Load voltages				
V3	1.026	1.014	1.026	1.014	V29	*0.763	0.955	*0.762	0.954
V4	1.020	1.003	1.020	1.003	V30	*0.747	0.950	*0.746	0.950
V6	1.016	0.999	1.016	0.999	V31	0.975	1.027	0.975	1.027
V7	1.005	0.995	1.005	0.995	V32	0.975	1.027	0.975	1.027
V9	0.999	1.059	0.999	1.059	V33	0.982	0.960	0.982	0.960
V10	0.955	1.041	0.955	1.041	V34	0.962	0.978		
V12	0.972	1.051	0.972	1.051	Gen. setting				
V14	0.950	1.023	*0.950	1.020	V1	1.050	1.060	1.050	1.060
V15	*0.943	1.032	*0.943	1.031	V2	1.045	1.045	1.045	1.045
V16	0.957	1.040			V5	1.010	1.010	1.010	1.010
V17	0.950	1.035			V8	1.025	1.025	1.025	1.025
V18	*0.934	1.023			V11	1.050	1.050	1.050	1.050
V19	*0.932	1.021			V13	1.050	1.050	1.050	1.050
V20	*0.937	1.025			Trans. setting				
V21	*0.934	1.026			N:3 - 31	1.069	1.000	1.069	1.000
V22	*0.933	1.025			N:4 - 12	1.032	0.901	1.032	0.901
V23	*0.915	1.013			N:6 - 9	0.978	0.903	0.978	0.903
V24	*0.888	0.998	*0.887	0.998	N:6 - 10	1.069	0.900	1.069	0.900
V25	*0.818	0.974	*0.818	0.973	N:14 - 32	0.950	0.950	0.950	0.950
V26	*0.796	0.955	*0.795	0.955	N:15 - 33	0.950	1.094	0.950	1.094
V27	*0.789	0.971	*0.788	0.970	N:27 - 28	---	outage ---	---	outage ---
V28	1.018	1.001	1.018	1.001					

Note: (*) under voltage bus

Task 1: Calculate the sensitivity factors
Task 2: Detect voltage violations
* number of voltage violations: 13
* the lowest voltage occurs at bus: 30 { V(30) = 0.747 p.u. }
Task 3: Correct voltage violations
Action 1: select controller: transformer 6 - 9
adjust its setting: 0.978 → 0.903 { V(30) = 0.769 p.u. }
Action 2: select controller: transformer 6 - 10
adjust its setting: 1.069 → 0.900 { V(30) = 0.810 p.u. }
Action 3: select controller: transformer 4 - 12
adjust its setting: 1.032 → 0.901 { V(30) = 0.839 p.u. }
Action 4: select controller: generator 1
adjust its setting: 1.050 → 1.060 { V(30) = 0.842 p.u. }
Action 5: select controller: transformer 3 - 31
adjust its setting: 1.069 → 1.000 { V(30) = 0.846 p.u. }
Action 6: select controller: transformer 15 - 33
adjust its setting: 0.950 → 1.094 { V(30) = 0.850 p.u. }
** This voltage violation cannot be corrected by the available controllers
** VAR compensation is required

Figure 10: Voltage control action screen.

The expert system performs well and provides correct decisions. The new approach offers the following advantages:

- The computational performance can be improved by reducing the size of power systems.
- The use of the expert system, steady state equivalent network and power system reduction techniques meets both speed and accuracy requirements for detecting and correcting voltage violations. Hence, the proposed techniques can be used for on-line voltage control applications.
- Analytical results are complemented by description of actions and, hence, are easy to understand.
- The voltage profile can be improved by reallocating the VAR sources. This includes the selection of locations and sizes for the additional VAR compensation to be added in the power system.

4 Conclusion

Prototype intelligent systems for short-time thermal rating of transmission lines, clearing overloads and voltage control in power systems have been developed and successfully evaluated.

The expert system for clearing overloads was developed using *Leonardo* expert system shell. The system applies the network sensitivity factors to determine appropriate actions which include generation rescheduling, line switching and load shedding, and the amount of the required corrections. The expert system for voltage control was developed based on *VP-EXPERT* shell. It detects voltage violations and provides a set of effective control actions to solve given voltage problems.

Further developments of the proposed expert systems will attempt to apply them in real-time using the data obtained from the SCADA system.

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Keywords: intelligent system, power system, clearing overloads, voltage control, sensitivity matrix.

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