Computational Intelligence Applications to Crisis Management in Power Systems

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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 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 major emergencies and catastrophic situations. Intelligent systems can play an advisory role suggesting the necessary actions, which should be taken to deal with a given emergency or abnormal condition as well as identifying failures of protection systems and circuit breakers. This paper outlines some experience obtained at the School of Engineering of the University of Tasmania in developing intelligent systems for power systems security. An expert system for clearing overloads applies the network sensitivity factors to determine appropriate actions, which include generation rescheduling, network reconfiguration and load shedding. An expert system for voltage control is developed and used for detecting voltage violations and providing a set of effective control actions to solve voltage problems in real-time. An artificial neural network is used to identify multiple failures of protection relays and circuit breakers. This system uses information received from protection systems in the form of alarms and is able to deal with incomplete and distorted data.**

Keywords—-*computational intelligence; power system; emergency condition; crisis management*

I. INTRODUCTION

Computational intelligence can be considered as a successor of artificial intelligence [1-3]. It uses advanced heuristic search algorithms, artificial neural networks, the theory of fuzzy sets and evolutionary computation. Computational intelligence also employs such techniques as swarm intelligence, chaos theory, artificial immune systems, wavelet analysis, etc.

Since the early 1990s, computational intelligence techniques have been successfully applied in power systems [4-7]. Applications related to power system security are of particular interest in this paper.

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 the 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 the operating state with constraints violated. Such conditions may lead in turn to switching-off 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-off 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 an operation of the protection system, and thus an additional load is imposed on the remaining network. Moreover, a certain transmission line outage can cause some serious voltage problems as well. Therefore, power system operators are required to take immediate 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 even catastrophic events. 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) formalizing the operator's knowledge.

This paper outlines some experience obtained at the School of Engineering of the University of Tasmania in developing intelligent systems for power system security.

II. BASICS OF POWER SYSTEM ANALYSIS

Modern power control centers are equipped with *Supervisory Control And Data Acquisition* (SCADA) systems gathering data on-line. SCADA systems enable a power system operator to apply real-time methods for power system analysis. Power operators have substantial experience in utilizing 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* [8] is often used in emergency conditions. This method improves a computational efficiency and reduces computer storage requirements. It is reliable in solving difficult cases for large-scale power transmission systems. The major principles of the decoupled approach are based on two general rules:

- Real power flow P between two busses connected through a power transmission line is primarily affected by the change in voltage angle δ between these busses.

- Reactive power flow Q between two busses connected through a power transmission line is primarily affected by the change in the voltage magnitude $|V|$ at these busses.

This approach makes it possible to develop intelligent systems for real-time applications.

III. INTELLIGENT SYSTEM FOR CLEARING OVERLOADS

A. Background

An accurate determination of permissible overloading durations for power system equipment 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 large system transformers connecting the various voltage level networks, and on the tie power transmission lines connecting different power subsystems. Therefore, it is vital to examine factors setting limits on the overloading time of these elements.

Short-term loading capabilities of transformers depend 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 loading capability of a transformer. Operating conditions at the rated power and ambient air temperature of +20°C are considered normal. In such cases, insulating materials will age at a normal speed and a proper maintenance can be provided. In practice, however, the load and temperature can vary according to the power demand and weather conditions. If part of the operating time the

transformer loading is lower than its continuous loading capacity it can be loaded more at the other times such that the ageing remains normal during the whole period (for example, during a 24-hour period). Therefore, permissible time for clearing transformer overloads should take into account the previous loading of the transformer or its loading history.

For transmission lines, both the power limit and the permissible duration of an overload in most cases are governed by the conductor temperature increase. On the other hand, the conductor operating temperature is limited by the conductor ground clearance. As shown in [9, 10], the loading capacity or thermal rating of a conductor can be described as a function of its temperature, ambient temperature, wind velocity, elevation, ground reflection and solar radiation. In a power transmission system, line currents during and following a system disturbance may reach values above of the steady-state thermal ratings of power lines. Such conditions may be safe for a period of up to 30 minutes. This time can be used to perform the generation rescheduling or load shedding in order to clear or at least reduce overloading. 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. [11].

B. Loading Capability Assessment of a Transmission Line

A heuristic nature of the short-time loading capability assessment of power transmission lines enables us to use an expert system approach. The rule-based expert system includes the basic components shown in Fig. 1.
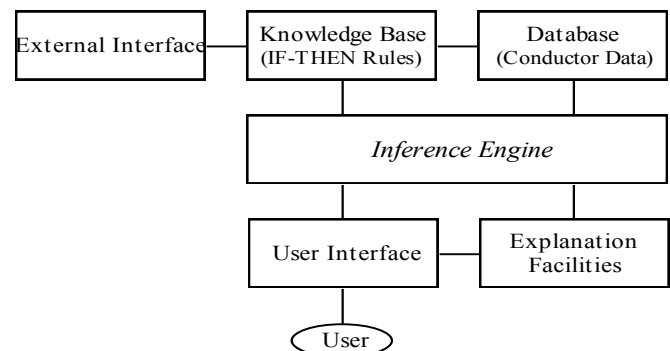

Fig. 1. Expert system for the loading capability assessment

The *knowledge base* contains the domain specific knowledge in the form of IF - THEN rules. The *database* includes all relevant data (conductor diameter, conductor resistance, conductor unit weight, specific heat, etc.) for various types of conductors. The data is represented in the form of a spreadsheet. 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. The *explanation facilities* enable the user to query the system "*How*" a particular solution has been reached. 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 C. These programs

are employed for computing the quantities of heat and adjusting the resistance for temperature changes.

The complete knowledge base consists of 43 rules. Details of these rules can be found in [12]. The expert system was evaluated against the site tests for both indoor and outdoor conditions. A comparison with actual test results demonstrates that the expert system represents an accurate model of the actual physical events.

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

A practical application of the expert system is demonstrated on a power system of Hydro Tasmania shown in Fig. 3. The example described below examines the winter night loading conditions.

Following the outage of the Palmerston - Liapootah 220 kV transmission line, the current on 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 Figs 4 and 5. It can be seen that the conductor temperature increases from 20°C (initial temperature) to 43°C (the maximum permissible temperature limited by the 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 Fig. 6.

This question is asked to assign the specific heat value for the conductor. Consider, for example, the cpecific heat at 20°C ofthe following conductors:
Aluminium= 900 J/Kg . C degree
Copper   = 385
Steel   = 431

What is the conductor type?

Aluminium
Copper
ACSR

F keys: 1 Help 2 Quit 3 Why? 5 Volunteer 6 Backup 7 Expand 8 Review
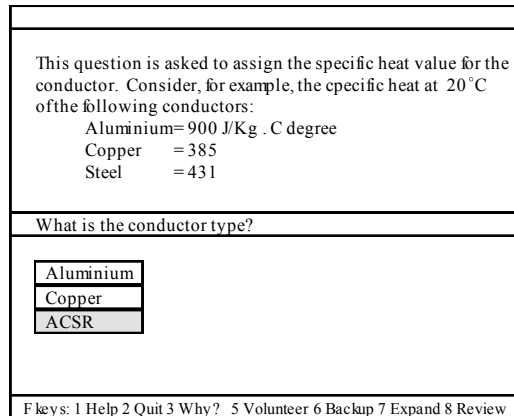
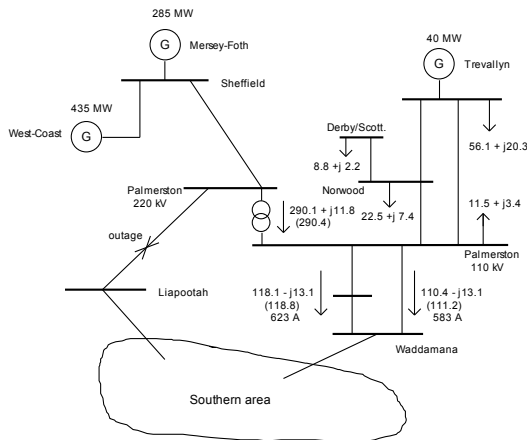Fig. 2.   The expert system query screen
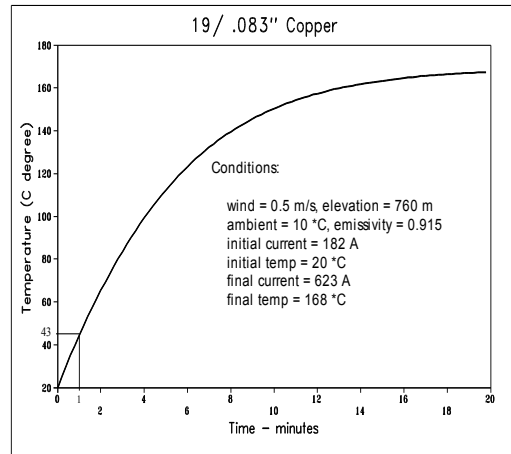
Fig. 3.   The HEC system: a case study

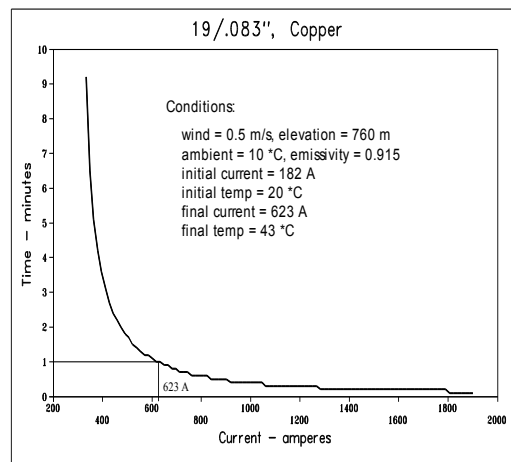Fig. 4.   Temperature-time characteristics of the Waddamana-Palmerston transmission line

Fig. 5.   Short time ratings for the Waddamana-Palmerston transmission line
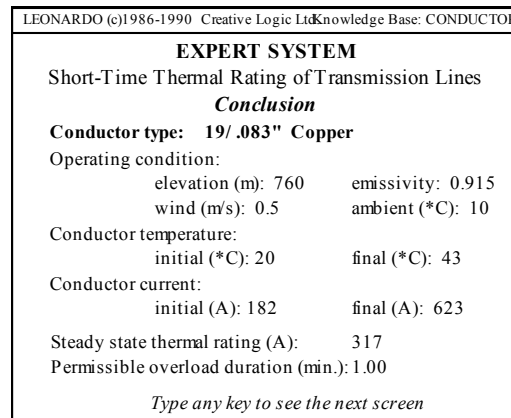
LEONARDO (c)1986-1990 Creative Logic Ltd   Knowledge Base: CONDUCTOR

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

Type any key to see the next screen

Fig. 6.   Conclusion screen

C. Sensitivity Factors

Permissible loading of power transmission lines can be maintained by controlling the real power generation in receiving and sending parts of the system, reconfiguration of the transmission network and load shedding as suggested in [13]. Generator shift factors can be expressed as:

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

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:

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

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 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:

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

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:

$$P_{Gj}^{min} \le P_{Gj} + \Delta P_{Gj} \le P_{Gj}^{max} \qquad (4)$$

$$-S_i^{max} \le S_i^0 + \Delta S_i \le S_i^{max} \qquad (5)$$

$$P_{Ln} - \Delta P_{Ln} \ge P_{Ln}^{max} \qquad (6)$$

$$V_j^{min} \le V_j \le V_j^{max} \qquad (7)$$

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

In order to find the most effective corrective actions for a given overload, the sensitivity tree method is used. The tree provides relationships between an overloaded power line load and available controllers.

D. Knowledge Base and Database

Any overload can be classified using answers to the following questions [13]:

1) What is the type of plant?
2) What is the overload duration?
3) What is the overload permissible duration?
4) What are the means available for clearing the overload?
5) What is the action to be applied first?

This provides the basis on which the database and the knowledge base are organized. The expert system for clearing overloads uses the following data:

- The upper load limits (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 [14], calculated, e.g. [9, 15, 16], or employing intelligent systems as it was discussed above.

- The upper and lower limits for each power station (or, if required, for each generator).

- The long-term ratings (emergency ratings) for each power transmission line.

- The guaranteed minimum load supply (or the highest priority load level) at each bus.

- The sensitivity factors for each supervised element and controller, and also the execution time for each controller.

E. Production Rules

The expert system applies the following heuristic rules specified in [13]:

Rule 1:

IF the real power flow on 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).

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 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 is applied 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 the 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 the 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 the overloaded elements until the list becomes empty.

F. Case Study

A six-bus system shown in Fig. 7 is used to demonstrate the performance of the developed expert system. Table 1 represents bus data of the system.
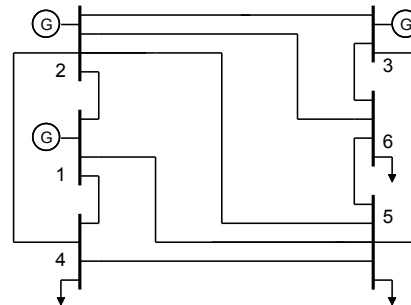

Fig. 7. Six-bus power system

TABLE I. 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 shows line limits and initial MVA flows on the lines. Line 2-6 is overloaded in the initial state. Columns 4 and 5 represent flows after corrective actions suggested by the expert system have been applied.

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 constraints. 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.

TABLE II. 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 III.   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

According to recommendations provided by the expert system, the following actions are to 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 due to security constraints, the expert system makes the following recommendations (Case 2):

- Bus 2, decrease generation on 5 MW;

- Bus 3, increase generation on 10 MW;

- Bus 6, shed load by 6.5 MW.

IV.   EXPERT SYSTEM FOR VOLTAGE CONTROL

A. Problem Statement and Sensitivity Tree Method

The main objective of voltage control is to maintain power system voltages within specified limits under various loading conditions and changes in the transmission network. Classical analytical methods based on different optimization techniques intend to minimize system losses and improve voltage profiles. However, most of these methods are too complex, provide analytical solutions only, 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 [17]. The reduced system consists of an internal "three-tier" subsystem that introduces the voltage problem area, and the external subsystem that represents the rest of the power system. This approach allows to minimize 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 a given voltage problem in real-time.

Voltage controllers can change their values either continuously or in steps, they are not equally effective and adjustments required from an individual controller are different under different power system conditions. The sensitivity tree method is 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 the controller settings, ΔU, may be described as suggested in [18]:

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

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, a change in any controller setting results in voltage changes on several buses.

B. Database and Knowledge Base

The developed voltage control expert system interacts with the power flow analysis package, network sensitivity analysis and other external programs and databases. 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 on or off.

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 level of voltage violation.

5) Select the most effective controller, estimate controller 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 on the maximum violated bus has become normal then take the next bus with the maximum abnormal voltage and repeat the procedures.

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

Rule 1:

IF voltage on bus i is below the voltage limit THEN bus i is a low voltage problem bus.

Rule 2:

IF bus *i* is a low voltage problem bus THEN include bus *i* in the low voltage problem bus list AND arrange buses in the voltage ascending order.

Rule 3:

If all voltage problem buses are determined THEN calculate the sensitivity factors.

Rule 4:

IF the controller 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 [19, 20].

C. 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 Fig. 8. The most severe case is an outage of transformer T1 connected between buses 27 and 28.

Fig. 9 shows the one-line diagram of the reduced system (equivalent system) 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 controllers) given by the expert system for the full 34-bus system and the equivalent system, 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.
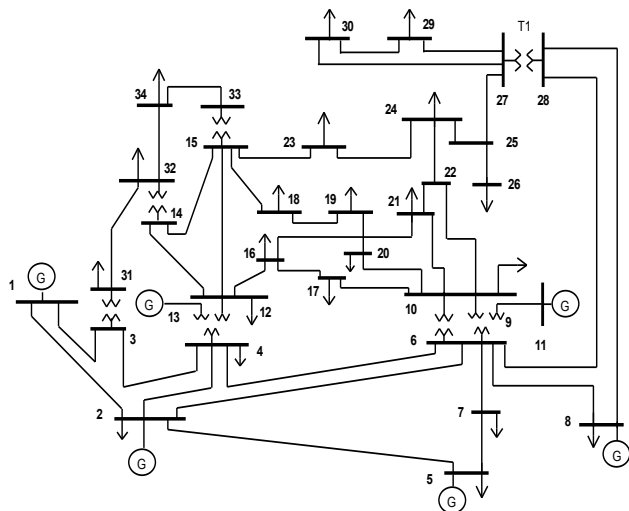

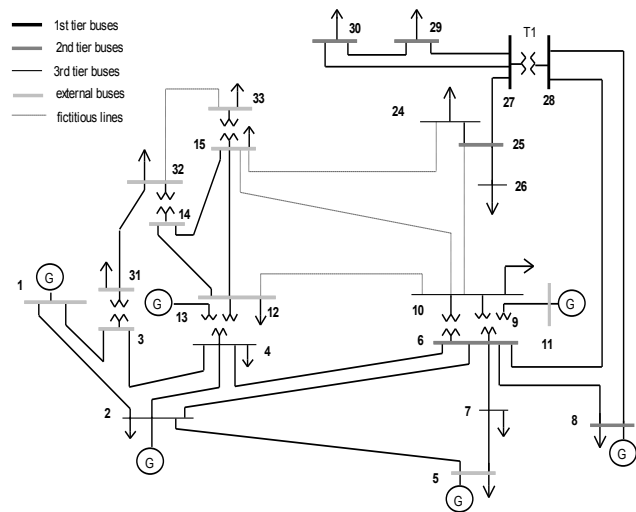Fig. 8. The modified IEEE 30-bus system

Fig. 9. The equivalent IEEE 30-bus power system

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

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.

TABLE IV. 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					
V14	0.950	1.023	*0.950	1.020	Gen. setting				
V15	*0.943	1.032	*0.943	1.031	V1	1.050	1.060	1.050	1.060
V16	0.957	1.040			V2	1.045	1.045	1.045	1.045
V17	0.950	1.035			V5	1.010	1.010	1.010	1.010
V18	*0.934	1.023			V8	1.025	1.025	1.025	1.025
V19	*0.932	1.021			V11	1.050	1.050	1.050	1.050
V20	*0.937	1.025			V13	1.050	1.050	1.050	1.050
V21	*0.934	1.026			Trans. setting				
V22	*0.933	1.025			N:3 - 31	1.069	1.000	1.069	1.000
V23	*0.915	1.013			N:4 - 12	1.032	0.901	1.032	0.901
V24	*0.888	0.998	*0.887	0.998	N:6 - 9	0.978	0.903	0.978	0.903
V25	*0.818	0.974	*0.818	0.973	N:6 - 10	1.069	0.900	1.069	0.900
V26	*0.796	0.955	*0.795	0.955	N:14 - 32	0.950	0.950	0.950	0.950
V27	*0.789	0.971	*0.788	0.970	N:15 - 33	0.950	1.094	0.950	1.094
V28	1.018	1.001	1.018	1.001	N:27 - 28	--- outage ---		--- outage ---	

Note: (*) bus with voltage constraints violated

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

Fig. 10. Voltage control action screen

V. NEURAL NETWORK FOR ON-LINE IDENTIFICATION OF MULTIPLE FAILURES

A. Fault Identification Problem

In complex emergency situations, failed protection relays and circuit breakers (CB) have to be identified in order to begin the power system restoration process. In fact, re-energizing defective or unprotected equipment can expand the damage and spread the problem, and it is often the cause of cascading blackouts [21].

Studies of large emergencies in power systems indicate that failures of protection relays are involved in 75% of cases [22]. An identification of faulted sections and malfunctions of protection relays and CBs requires an extensive knowledge of the behavior of protection systems during various conditions [23-27]. Due to the fact that this problem is non-linear, large-scale and often has a combinatorial nature, various artificial intelligence techniques have been explored and successfully used. In particular, expert system and neural network approaches have proved to be the most effective in dealing with this level of complexity.

However, the primary aim of the previous work was to locate faulted sections rather than to identify failures of protection systems and CBs. Such failures were considered as noise, which just complicated the process of locating a faulted section. The task of identifying failures of protection relays and CBs itself was considered too complex as one needed detailed and reliable data to start with. Unfortunately, such data may not always be available. In addition, protection system analysis is time consuming and requires a complex reasoning process. During a complex emergency the number of possible situations is often enormous, which makes the operator's job of making decisions very difficult. As a result, complex emergencies often lead to large system blackouts and serious damages to power equipment. From a practical point of view, it is also desirable to be able to analyze complex emergencies with multiple cascading failures [28].

An emergency in a power system can be represented by a set of three vectors:

$$E = \langle S, R, F \rangle \tag{9}$$

Where vector *S* includes one or more sections of a power system where a fault occurs, vector *R* is a set of relays that have operated and CBs that have tripped as a result of the fault; and vector *F* is a set of protection devices and CBs that should have operated during the fault but failed to do so. Emergency *E* is considered complex if vector *F* has two or more elements.

Pattern *P* of emergency *E* (referred to as P^E) is usually observed in a control centre; it is represented by a set of alarms. In fact, this pattern is a mapping of vector *R*. Pattern P^E can also be expressed as a set of statements in the form: <Alarm name, Alarm value>. In general, the number of statements equals to the maximum number of alarms provided by the SCADA system. If the alarm has been received then its value is 1, and if the alarm has not been received then its value is 0. Pattern *P* of emergency *E* can be represented as a binary vector:

$$P^E = \left| A_1^E, A_2^E, \ldots, A_m^E \right| \tag{10}$$

Where A_i^E is the value of alarm *i* (either 0 or 1), and *m* is the pattern dimension.

A perfect pattern of emergency *E*, P_O^E, is a complete set of alarms (without any errors in the SCADA system) for a single pre-fault configuration of a power system. The perfect pattern is, in fact, the set of devices that have operated ($P_O^E = R^E$).

Corrupted pattern of emergency *E*, P_C^E, is an incomplete and/or distorted pattern. The same emergency can, in fact, be described by a set of corrupted patterns, $<P_C^E>$. This set is called the pattern space of emergency *E*, and can be defined as:

$$\left\langle P_C^E \right\rangle = \begin{vmatrix} A_{1,1}^E, & A_{2,1}^E, & \ldots, & A_{m,1}^E \\ A_{1,2}^E, & A_{2,2}^E, & \ldots, & A_{m,2}^E \\ \ldots, & & \ldots & \\ A_{1,N^E}^E, & A_{2,N^E}^E, & \ldots, & A_{m,N^E}^E \end{vmatrix} \tag{11}$$

Where $A_{i,j}^E$ is the value of alarm *i* (either 0 or 1) for corrupted pattern *j* of emergency *E*, and N^E is the total number of corrupted patterns of emergency *E*.

The goal now is to find a set of failed protection devices and CBs - set F^E - based on corrupted pattern P_C^E. The problem can be formulated as a pattern classification problem. In this case, an emergency situation (represented by pattern $P_{C,j}^E$) has to be classified into one of several possible classes, where each class corresponds to a single combination of failed devices (vector F^E). Neural networks offer a practical approach to solving such complex pattern classification problems [3].

B. The Problem Decomposition

A single emergency may generate up to 500 different alarms. However, each section of a power system produces its own set of alarms. The maximum number of such alarms for a single section does not normally exceed 35-40. Thus, in order to reduce the problem dimensionality, a neural network should

be constructed individually for each section. The solution can be expressed as following [29]:

1) Simulate the response of protection systems in the case of two failures.

2) Form a set of all possible alarms, and a set of all relays and CBs that fail to operate.

3) Form a pattern space of an emergency and creating a training set.

4) Construct and train a NN.

Simulation of emergency situations is demonstrated on the 110 kV power system shown in Fig. 11. It has two power plants, five substations, 10 transmission lines, and 14 buses. The protection system consists of 304 relays.

Fig. 12 represents a graph of all possible emergencies when a fault occurs on line L0. As can be seen, there are 25 possible emergencies that can be caused by this fault. There are three emergencies with a single failure (the first level of the graph) and 22 complex emergencies with two cascading failures of protection relays and/or CBs (the second level of the graph). A detailed analysis of each emergency is given in

Table 5. Fig. 13 shows the NN used. It has 32 inputs and 20 outputs. The number of inputs corresponds to the number of alarms. The number of outputs corresponds to the number of devices that failed to operate – set *F* in *Eq.* (9).

C. Structure of the Neural Network Identification System

Preliminary simulations demonstrated that using only perfect patterns of emergencies in a training set leads to large recognition errors. To improve the NN performance, errors of the SCADA system are simulated by inserting a single random alarm error into a perfect pattern. Also the data loss is simulated by removing a single random alarm from a perfect pattern. As a result, a set of 5072 corrupted patterns is generated and then used to train and test the NN.

To estimate a similarity between the 25 emergencies shown in Fig. 12, the Hamming distance between different classes is calculated. The distance between classes E_X and E_Y representing emergencies *X* and *Y*, respectively, is determined as [30]:

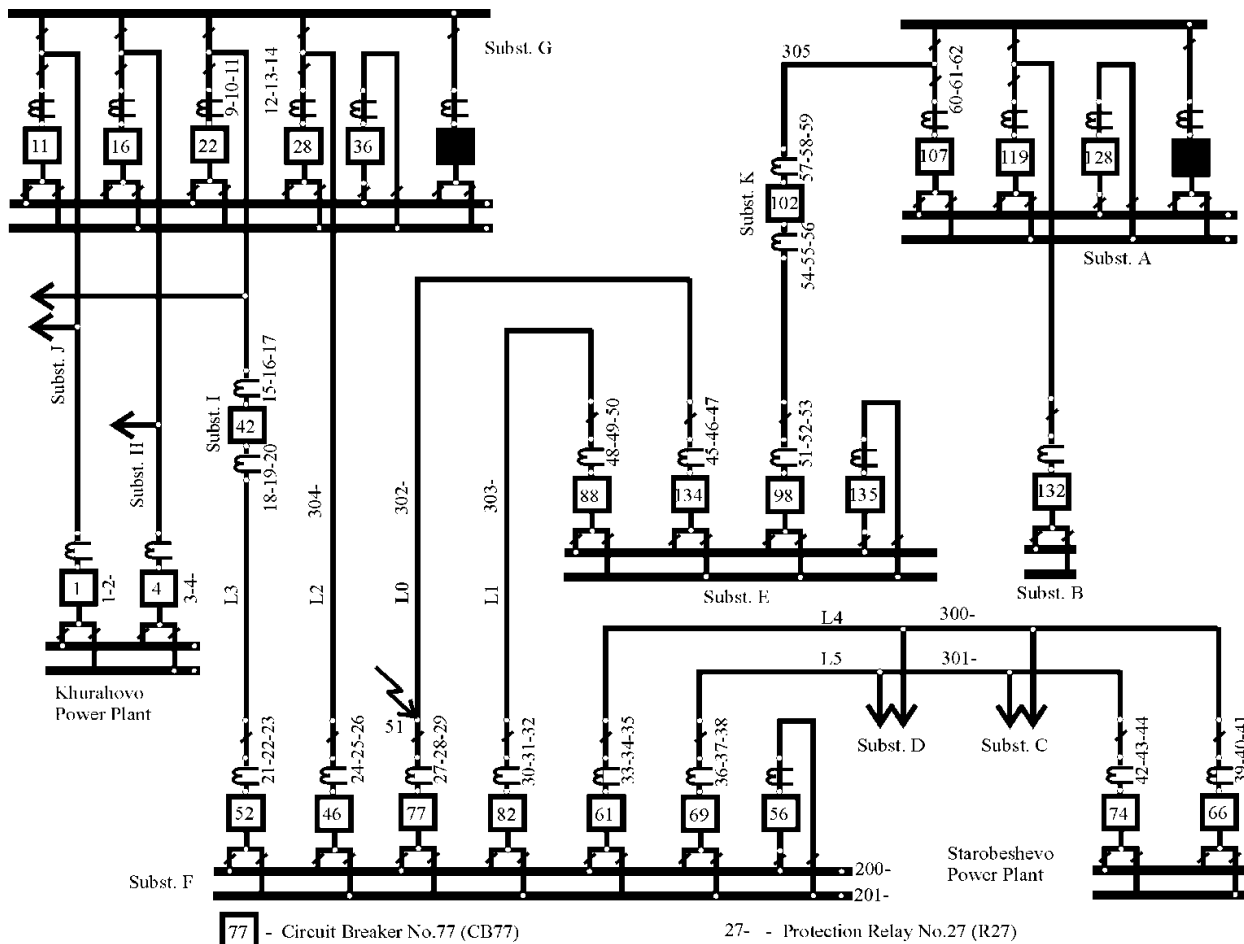$$d(E_X, E_Y) = \frac{1}{N^X} \sum_{i=1}^{N^X} \frac{1}{N^Y} \sum_{j=1}^{N^Y} \frac{1}{m} \sum_{k=1}^{m} \left| A_{k,i}^X - A_{k,j}^Y \right| \quad (12)$$

Fig. 11. The 110 kV power system

TABLE V.   SIMULATED EMERGENCIES

| Emergency	S	Operated relays and tripped CBs, (R)	Failed devices, (F)
E_1	L0	R27,CB77,R46,CB134	R302
E_2	L0	R302,CB77,R46,R32,CB82,R47,R56,CB102	CB134
E_3	L0	R302,CB134,R27,R19,CB42,R49,CB88,R13,CB28,R40,CB66,R43,CB74	CB77
E_4	L0	R27,CB77,R46,R32,CB82,R47,R56,CB102	R302,CB134
E_5	L0	R27,R19,CB42,R49,CB88,R13,CB28,R28,R40,CB66,R43,CB74,R46,CB134	R302,CB77
E_6	L0	R302,R27,R19,CB42,R49,CB88,R13,CB28,R28,R40,CB66,R43,CB74,R46,R47,R56,CB102	CB134,CB77
E_7	L0	R19,CB42,R49,CB88,R13,CB28,R28,CB77,R40,CB66,R43,CB74,R46,CB134	R302,R27
E_8	L0	R27,CB77,R32,CB82,R47,CB134	R302,R46
E_9	L0	R302,CB77,R32,CB82,R47,R56,CB102	CB134,R46
E_{10}	L0	R302,CB77,R46,R47,R14,CB28,R20,CB42,R41,CB66,R44,CB74,R56,CB102	CB134,R32
E_{11}	L0	R302,CB77,R46,R32,R47,R14,CB28,R20,CB42,R41,CB66,R44,CB74,R56,CB102	CB134,CB82
E_{12}	L0	R302,CB77,R46,R32,CB82,R47	CB134,R56
E_{13}	L0	R302,CB77,R46,R32,CB82,R47,R56	CB134,CB102
E_{14}	L0	R302,CB134,R19,CB42,R49,CB88,R13,CB28,R28,R40,CB66,R43,CB74	CB77,R27
E_{15}	L0	R302,CB134,R27,R49,CB88,R11,CB22,R13,CB28,R28,R40,CB66,R43,CB74	CB77,R19
E_{16}	L0	R302,CB134,R27,R19,R49,CB88,R11,CB22,R13,CB28,R28,R40,CB66,R43,CB74	CB77,CB42
E_{17}	L0	R302,CB134,R27,R19,CB42,R13,CB28,R28,R40,CB66,R43,CB74,R29,R50,CB88,R56,CB102	CB77,R49
E_{18}	L0	R302,CB134,R27,R19,CB42,R49,R13,CB28,R28,R40,CB66,R43,CB74,R29,R50,R56,CB102	CB77,CB88
E_{19}	L0	R302,CB134,R27,R19,CB42,R49,CB88,R28,R40,CB66,R43,CB74,R14,CB28,R29	CB77,R13
E_{20}	L0	R302,CB134,R27,R19,CB42,R49,CB88,R13,R28,R40,CB66,R43,CB74,R104,CB16,CB36	CB77,CB28
E_{21}	L0	R302,CB134,R27,R19,CB42,R49,CB88,R13,CB28,R40,CB66,R43,CB74	CB77,R28
E_{22}	L0	R302,CB134,R27,R19,CB42,R49,CB88,R13,CB28,R28,R43,CB74,R29,R41,CB66	CB77,R40
E_{23}	L0	R302,CB134,R27,R19,CB42,R49,CB88,R13,CB28,R28,R40,CB66,R29,R44,CB74	CB77,R43
E_{24}	L0	R302,CB134,R27,R19,CB42,R49,CB88,R13,CB28,R28,R40,R43,CB74,R29,R41	CB77,CB66
E_{25}	L0	R302,CB134,R27,R19,CB42,R49,CB88,R13,CB28,R28,R40,CB66,R43,R29,R44	CB77,CB74
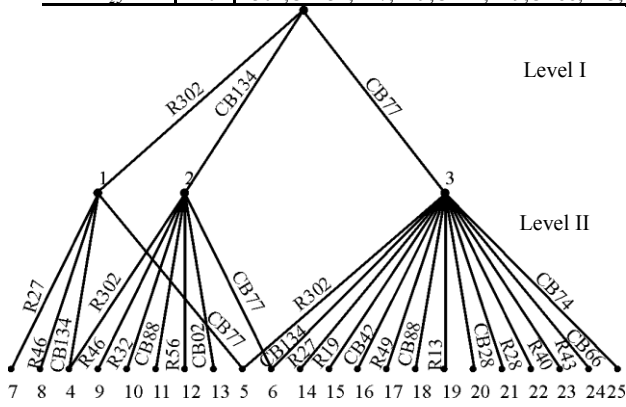
Fig. 12. The emergency graph for section L0

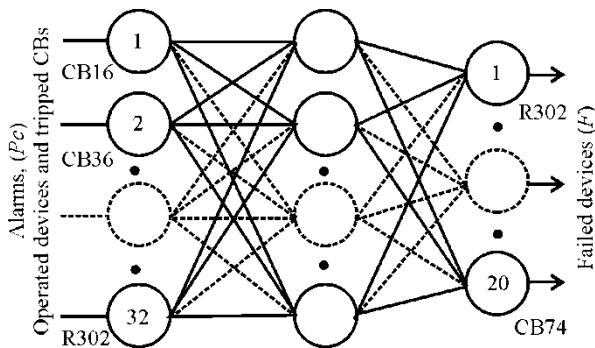

Fig. 13. The multi-layer perceptron

Where N^X is the number of corrupted patterns in class E_X, N^Y is the number of corrupted patterns in class E_Y, $A^X_{k,i}$ is the value (either 0 or 1) of alarm k in corrupted pattern i of emergency X, and $A^Y_{k,j}$ is the value (either 0 or 1) of alarm k in corrupted pattern j of emergency Y.

The NN-based identification system is shown in Fig. 14. Neural network NN-0 separates emergencies into two classes. *Class* 1 represents emergencies with one failed device and *class* 2 emergencies with two failed devices. If a pattern is classified as an emergency of *class* 1 then NN-1 is used. However, if a pattern is classified as an emergency of *class* 2 then NN-2 is used. NN-1 and NN-2 are trained with patterns describing emergencies with one and two failures, respectively.
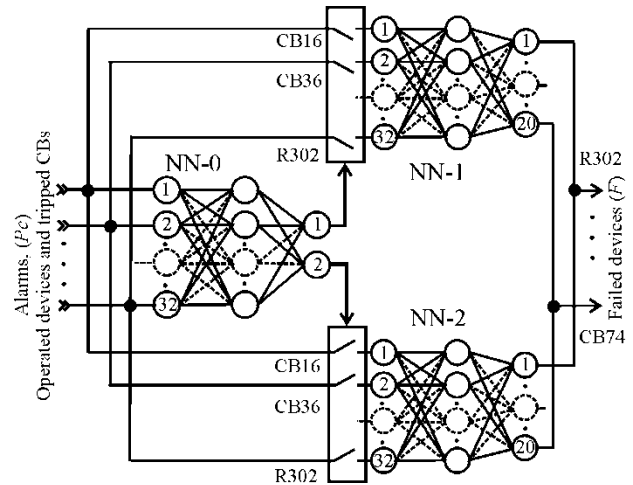

Fig. 14. The NN-based identification system

The entire set of 5072 corrupted patterns is randomly divided into training, test and evaluation sets. The training set includes 2536 training samples and is used for training NN-0. A training example is represented as:

$$\left\langle \left\langle A^E_{1,j}, \quad A^E_{2,j}, \ ..., A^E_{32,j} \right\rangle, \left\langle O_1{}^E, O_2{}^E \right\rangle \right\rangle \quad (13)$$

Where $A_{i,j}^{E}$ is the NN input represented by the value of alarm i (either 0 or 1) for corrupted pattern j of emergency E; O_1^{E} and O_2^{E} are the NN desired outputs. If O_1^{E} is 1 and O_2^{E} is 0, then E is an emergency with a single failed device. If O_1^{E} is 0 and O_2^{E} is 1, then E is a complex emergency with two failed devices.

To train NN-1 and NN-2 the following data sets were created:

$$\left\langle \left\langle A_{1,j}^{E},\quad A_{2,j}^{E},\ ...,A_{32,j}^{E} \right\rangle, \left\langle F_1^{E}, F_2^{E}, ...,F_{20}^{E} \right\rangle \right\rangle \qquad (14)$$

Where F_i^{E} is the desired value of NN output i for emergency E. If F_i^{E} is 1, then device i fails to operate during emergency E, but if F_i^{E} is 0, then device i operates successfully. An optimal number of hidden neurons is determined based on the analysis of the network performance. Results are given in Table 6.

TABLE VI.   EVALUATION RESULTS

		NN-0	NN-1	NN-2
Neurons	Input	32	32	32
	Hidden	7	13	15
	Output	2	20	20
Examples	Training	2536	2132	4050
	Test	1268	1066	2025
	Evaluation	1268	1066	2025
MSE	Training	0.0009	0.0009	0.0210
	Test	0.0010	0.0012	0.0211
	Evaluation	0.0023	0.0013	0.0220
Epoch		600	250	1000

D. Case Studies

For emergencies with two failures, the NN-based identification system can produce three possible outcomes: correct recognition, inadequate recognition and incorrect recognition. In the case studies presented here, emergency patterns are corrupted by both distorted (one alarm is false) and incomplete (one alarm is missing) signals.

- *Case 1: Correct recognition.*

This case is illustrated in Fig. 15. Emergency E_{18} occurs as a result of a short circuit on transmission line L0 (near Substation F, point 51). The primary transmission line protection R302 operates and sends tripping signals to breakers CB77 and CB134. Breaker CB134 trips while the other breaker, CB77, fails to operate. Substation F is then de-energized by tripping CBs on adjacent substations.

Remote backup protection systems on line L0 (R19, R49, R13, R43 and R40) operate and send tripping signals to respective CBs (CB42, CB88, CB28, CB74 and CB66). All CBs except CB88 trip. Circuit breaker CB88 on substation E fails to trip. As a result of this failure, the 3rd zone of distance relay R56 on substation K causes breaker CB102 to open. It results in de-energizing both substations, F and E. All devices that operated in emergency E_{18} are shown in Table 5.
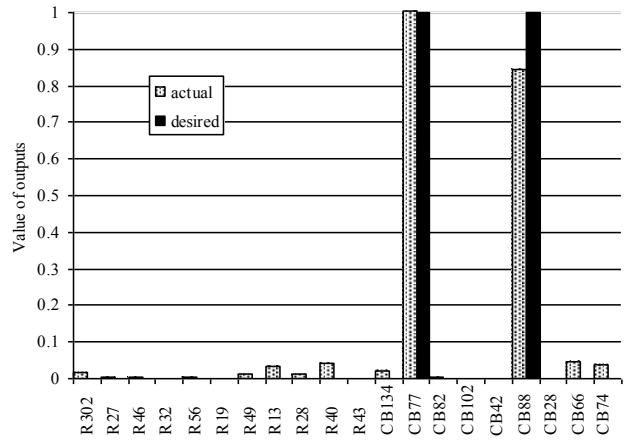

Fig. 15.   Case 1: Correct identification

- *Case 2: Inadequate recognition.*

Fig. 16 illustrates a situation when the system cannot identify emergency E_{16}. This emergency is caused by two failed devices CB77 and CB42. The first device, CB77, is identified, but the second one, CB42, is not. The maximum values of the NN outputs indicate failed devices CB77 and R19. The reason for an inadequate recognition is the similarity between patterns of these two emergencies. (the Hamming distance between classes E_{16} and E_{15} is 2.2, which is relatively small). Thus, an operator should obtain some additional information before making the final diagnosis in this situation.
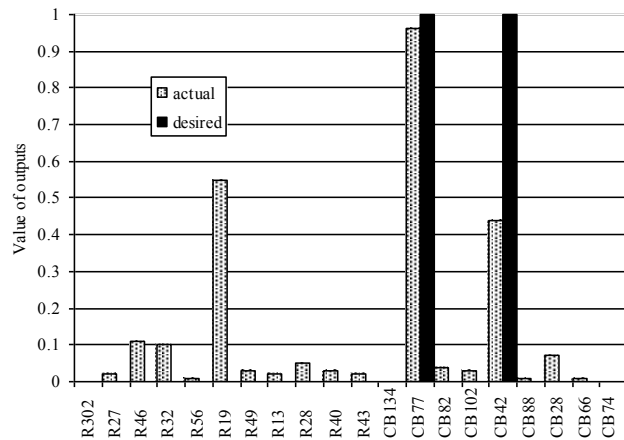

Fig. 16.   Case 2: Inadequate identification

- *Case 3: Incorrect recognition.*

The corrupted pattern of complex emergency situation E_7 cannot be recognized. This emergency is a result of a double failure: primary protection R302 and local backup protection R27 on line L0. The corrupted pattern also includes false alarm R20 and missing alarm R49. The NN response is shown in Fig. 17.
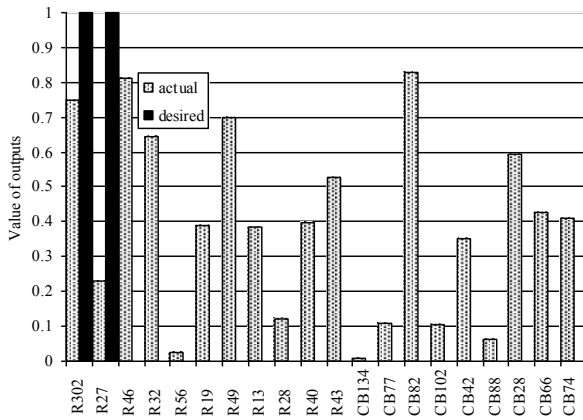
Fig. 17. Case 3: Incorrect identification

VI. CONCLUSION

Prototype intelligent systems for clearing overloads, voltage control and multiple failure identification in power systems have been developed and successfully evaluated. The expert system for clearing overloads applies the network sensitivity factors to determine appropriate actions, which include generation rescheduling, network reconfiguration and load shedding. The expert system for voltage control is used for detecting voltage violations and providing recommendations for solving voltage problems in real-time. The multiple failure identification system is based on artificial neural networks. It is used to identify failures of protection relays and circuit breakers during emergency conditions. This system uses information received from protection systems in the form of alarms and is able to deal with incomplete and distorted data.

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