An expert system for clearing overloads in transmission systems

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Abstract

An overload is a common problem in modern power systems. In fact, it is impossible to avoid overloads which may lead to a failure or damage of power system equipment as well as to the collapse of the entire system. Therefore, power system operators must take safety measures to clear overloads so that their durations and magnitudes do not exceed the allowable values. This paper describes an expert system application for clearing emergency overloads in power transmission systems. The expert system was developed to provide suggestions to power system operators on control actions to be taken to alleviate a given overload. The expert system utilises the network sensitivity factors to determine appropriate control actions which can include generation rescheduling, line switching and load shedding, and the amount of the required corrections. An overload is classified using answers to the following questions: What is the type of plant? What is the duration of the overload? What is the permissible duration of such an overload? What are the means available for clearing the overload? What measures should be applied first? A prototype expert system for clearing overloads was developed using VP_EXPERT system shell. The proposed technique is demonstrated on the 6-bus power system. The computational speed should meet the demand for real-time applications in control centres. Further development will attempt to apply the expert system in real-time using the data obtained from a SCADA system.
1 Introduction

In steady state operation conditions of a power system, equipment failure or unexpected load demand variations may drive the system into an emergency state of operation at which some transmission equipment (ie. power transmission lines and transformers) loading limits may be violated. In such cases, to avoid a failure or damage of the system equipment as well as a collapse of the entire system, the system operators must take some control actions to clear the overloads so that their durations and magnitudes do not exceed the allowable values. The problem of clearing overloads requires performance of two major tasks in a very short time.

The first task is an overload-conditioning ascertainment which involves the determination of the permissible overload duration for any overload whenever it occurred and acknowledged by a SCADA system. This task can be done by using the existing loading guides and practical experience, or effectively employing an artificial intelligence based approach.

The second task is a decision making procedure. Although mathematical optimisation techniques [1-3] enable a power system operator to perform calculations and obtain a feasible solution, these techniques are slow. Furthermore, the overload clearing process is amenable to formalisation with difficulty and cannot be easily expressed mathematically [4]. Traditionally, the successful performance of the decision making largely depends on an operator's skills and his or her ability to respond reasonably to unpredictable situations. The operator's behaviour under such conditions is essentially determined by the experience obtained in similar situations and his or her ability to use heuristic logic in order to compare a given complex situation with already known emergencies and thereby to make a correct decision [5, 6]. Nevertheless, according to [7-9], major emergencies often occur and extend due to operator mistakes. Under emergency conditions, an operator may act either in a wrong way by violating the guides and instructions or does not act at all due to emotional stress. As experience has shown, there is a strong need for on-line support to assist operators in making prompt and correct decisions under emergency and abnormal conditions. This support can be obtained by employing an expert system based aid which is described in this paper.

2 General principles of overload alleviation

In an overload alleviation, the following tasks are expected to be performed by a system operator [10]:

- identification of the overloaded element and determination of the permissible overload duration;
- selection of the necessary remedial actions for clearing overloads;
- execution of the selected remedial actions;
permanent condition monitoring of the overloaded equipment and, if required, revision and adjustment of the remedial actions to be taken.

Alleviation of emergency line overloads is one of the critical problems for system operators. Under an emergency condition, an operator must determine a strategy to effectively relieve overloads to security limits in a minimum time. However the decision on control actions is always intimately bound up with an increasing sophistication of information and alarms to be examined. The main difficulty is the shortage of time available for making the decision in determining a set of appropriate control actions which must be implemented in a matter of minutes, sometimes even seconds. It is clear that an accurate and effective determination of the permissible duration of an overload would allow a system operator a greater flexibility in decision making and choosing appropriate remedial actions.

Once the permissible duration of an overload is determined, an operator must choose an appropriate plan which includes some of the actions listed below.

### 2.1 Selection of remedial actions

In general, actions directed to relieve overloads can be applied in the following order [11]:

- provide full loading of power stations and other power sources in the receiving part of a power system;
- provide unloading of power stations in the sending part of a power system;
- adjust phase-shift transformers and switch capacitor banks and reactors;
- transfer loads from one part of the system to another;
- increase output of the active and reactive power of generators and synchronous compensators in the receiving part of a power system via their permissible short-term overloading;
- adjust bus voltages in order to decrease the power demand;
- curtail loads of the lowest priority;
- switch off radial transmission lines;
- perform emergency load shedding at selected locations.

Control actions for clearing an overload are not equally effective, and adjustments required for each controller are different. Therefore, it is essential to employ an efficient technique, such as the sensitivity method [10], to determine the relationship between the equipment overloads and the controllers in order to find the most effective corrective actions for a given situation. The actions with higher sensitivity factors are more effective. Note that the execution time and amount of overload relief are the two important factors which should be taken into account in the determination of an appropriate remedial action.
2.2 Alleviation of overloads using the sensitivity method

Based on the decoupling properties [12] shown in Equation (1), the overloads on transmission lines can be relieved by an appropriate change in the voltage angles. The elements which affect VAR flows, e.g. shunt reactances and off-nominal in-phase transformer taps, can be omitted in the determination of the control actions for clearing overloads.

In principle, to remove transmission equipment overloads, shifting real power flows in the system is required. This can be done by controlling the MW generation in the receiving and sending parts of the system, reconfiguration of the transmission network, and load shedding.

\[
[\Delta P] = \left[ \frac{\partial P}{\partial \delta} \right] [\Delta \delta] = [H][\Delta \delta] \tag{1}
\]

The following describes a method of calculating the sensitivity factors which can be employed for shifting real power flows in power systems [10]:

- The generator shift factors can be expressed as:

\[
\alpha_{ij} = \frac{\Delta S_i}{\Delta P_{Gj}} \tag{2}
\]

where \( \Delta S_i \) is the change in MVA flow on element \( i \) when a change in generation, \( \Delta P_{Gj} \), occurs at bus \( j \). If we assume that all other generators remain fixed, then \( \alpha_{ij} \) factor represents the sensitivity of the 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:

\[
\beta_{i,k} = \frac{\Delta S_i}{S^0_k} \tag{3}
\]

where \( \beta_{i,k} \) is the line outage distribution factor when monitoring element \( i \) after an outage on line \( k \); \( \Delta S_i \) is the change in MVA flow on element \( i \); and \( S^0_k \) is the original flow on line \( k \) before it was opened.

- The load shedding factors are obtained as:

\[
\gamma_{ij} = \frac{\Delta S_i}{\Delta P_{Ln}} \tag{4}
\]

where \( \Delta S_i \) is the flow change in MVA on element \( i \) when a change in load, \( \Delta P_{Ln} \), occurs at bus \( n \).
According to [10], overload clearing is a subject to the following security constraints:

\[ P_{Gj}^{\text{min}} \leq P_{Gj} + P_{Gj} \leq P_{Gj}^{\text{max}} \]  
(5)

\[ -S_{k+1}^{\text{max}} \leq S_{k+1}^{0} + \Delta S_{k+1} \leq S_{k+1}^{\text{max}} \]  
(6)

\[ P_{Ln} - \Delta P_{Ln} \geq P_{Ln}^{\text{min}} \]  
(7)

\[ V_{j}^{\text{min}} \leq V_{j} \leq V_{j}^{\text{max}} \]  
(8)

where \( P_{Gj}^{\text{max}}, P_{Gj}^{\text{min}} \) and \( P_{Gj} \) are respectively the maximum and minimum limits, and operating value of the generator MW output at bus \( j \); \( S_{k+1}^{0}, \Delta S_{k+1} \) and \( S_{k+1}^{\text{max}} \) are respectively the original MVA flow, change in MVA flow on line \((k+1)\) after an outage of line \( k \) and long-term rating (or emergency rating) of line \((k+1)\) (with regard that a line flow can be positive or negative); \( P_{Ln}^{\text{min}} \) and \( P_{Ln} \) are respectively the guaranteed minimum load supply and original load at bus \( n \); and \( V_{j}^{\text{max}}, V_{j}^{\text{min}} \) and \( V_{j} \) are respectively the maximum and minimum voltage limits, and actual voltage at bus \( j \).

### 3 Expert system development

This section presents the development of an expert system for clearing overloads in power systems. The expert system was developed based on VP-EXPERT system shell and implemented on IBM personal computers. VP-EXPERT is an effective tool for providing interaction with the load flow analysis software called PSSE to calculate network sensitivity factors and line flows, and other external programs and database files. Figure 1 shows the block diagram of the expert system.

The database of the expert system includes the following data [10]:

- Upper load limit (short-term rating) for each supervised element;
- 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 [13], calculated [14, 15] or employing intelligent systems [16, 17];
- Upper load limit (short-term rating) for each supervised element;
- 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 [13], calculated [14,15] or employing intelligent systems [16,17];
- Upper and lower limits for each power station (or, if required, for each generator);
- Long-term rating (emergency ratings) for each line;
- Guaranteed minimum load supply (or the highest priority load level) at each bus;
- Sensitivity factors for each supervised element and controller, and also the execution time for each controller.

![Figure 1: Block diagram of the expert system.](image)

The above data is stored in dBASE III database files for describing the topology and operating conditions of a power system. Besides, these files are also used for intensive numerical computations and data manipulation between the knowledge base and external programs. Tables 1-3 illustrate the structure of database files "linedata", "gendata" and "loaddata", respectively.

The data associated with lines, generators and loads stored in the database files includes two types. The first one is used to represent constant parameters, such as equipment_type, rating, line_number, load_number, etc. Another type is used to represent variables, such as sensitive_factor and equipment status, which are automatically updated during consultation.

The **knowledge base** of the expert system is developed taking into account the following priorities of control actions:

- generation rescheduling,
- transmission line switching,
- load shedding.
Table 1: Structure of "linedata"

<table>
<thead>
<tr>
<th>Description</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>equipment_type</td>
<td>line</td>
</tr>
<tr>
<td>from_bus</td>
<td>2</td>
</tr>
<tr>
<td>to_bus</td>
<td>6</td>
</tr>
<tr>
<td>rating</td>
<td>25.00</td>
</tr>
<tr>
<td>flow</td>
<td>30.20</td>
</tr>
<tr>
<td>status</td>
<td>overload</td>
</tr>
<tr>
<td>execution_time</td>
<td>5</td>
</tr>
<tr>
<td>sensitive-factor</td>
<td>1.0000</td>
</tr>
<tr>
<td>feasible</td>
<td>no</td>
</tr>
<tr>
<td>line_number</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 2: Structure of "gendata"

<table>
<thead>
<tr>
<th>Description</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>gen_bus</td>
<td>2</td>
</tr>
<tr>
<td>Pmax</td>
<td>60.00</td>
</tr>
<tr>
<td>Pmin</td>
<td>45.00</td>
</tr>
<tr>
<td>output</td>
<td>50.00</td>
</tr>
<tr>
<td>execution_time</td>
<td>8.00</td>
</tr>
<tr>
<td>sensitive-factor</td>
<td>-0.0663</td>
</tr>
<tr>
<td>feasible</td>
<td>yes</td>
</tr>
<tr>
<td>gen_number</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3: Structure of "loaddata"

<table>
<thead>
<tr>
<th>Description</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>load_bus</td>
<td>5</td>
</tr>
<tr>
<td>prio_1</td>
<td>30.00</td>
</tr>
<tr>
<td>prio_0</td>
<td>10.00</td>
</tr>
<tr>
<td>total_load</td>
<td>70.00</td>
</tr>
<tr>
<td>execution_time</td>
<td>1.50</td>
</tr>
<tr>
<td>sensitive-factor</td>
<td>0.1304</td>
</tr>
<tr>
<td>feasible</td>
<td>yes</td>
</tr>
<tr>
<td>load_number</td>
<td>5</td>
</tr>
</tbody>
</table>

This order is based on the consideration of:

- generation rescheduling is highly recommended due to economical reasons and can provide continuous power supply to customers. However, the generation schedule should be adjusted such that the additional power can be produced rapidly and is sufficient to relieve an overload.
• line switching is not highly recommended, and can only be applied when the switching does not cause both an interruption of the power supply and a deterioration of reliability of the power system.
• load shedding should only be recommended as the last resort due to the loss of revenue for the utility as well as creating unsatisfied customers. In order to minimise the degradation of service to customers, load curtailment should not be applied at one location only, but spread over as many customers as possible and must be effective [5]. Furthermore, in applying the load shedding scheme, the loads to be shed are selected based on customer priority level. It is also necessary to continuously supply minimum vital local demands, i.e. the highest priority loads (priority 0), which include auxiliaries of power plants and important industrial customers [6].

The following heuristic rules [10, 11] are implemented in the knowledge base of the expert system:

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 the 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 the 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 the 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 the next element on the list of overloaded elements until the list becomes empty.

The complete knowledge base of the expert system consists of 38 production rules. Some of these rules are illustrated below in the format of \( VP\text{-}EXPERT \).

Rule perform\_initial\_condition
IF initial\_condition = unknown
THEN initial_condition = known

BCALL START; ! call an external program to calculate the initial flows
! and write the result in an external file called initial.

Rule check_overload
IF initial_condition = known
AND update_thermal_rating = performed
AND num_overload = unknown
THEN check_overload = performed

CLOSE linedata
WHILEKNOWN equipment_type
GET ALL, linedata, ALL ! update the initial flows in database, linedata.
RESET flow
RECEIVE initial, new_flow ! get new flows from the external file, initial.
flow = (new_flow)
PUT linedata ! change the flow in the database.
delta_flow = (flow - rating)
RESET new_status
FIND new_status ! find the new status (ie. overload or none) of the line.
RESET status
    status = (new_status)
    PUT linedata ! change the line status in the database.
END
DISPLAY "Overload condition has been checked."

Rule find_new_line_status
IF delta_flow > (0)
AND new_status = unknown
THEN new_status = overload
ELSE new_status = none;

Rule find_clearing_priority
ASK find_clearing_priority: "Which overload do you like to clear first ?";
CHOICES find_clearing_priority: shortest_permmissible_duration,
    highest_overload_maginitude; ! ask the user to select a clearing criterion.

The *external programs* are mainly used to calculate the sensitivity factors
and control adjustments, update the data in the database, and manipulate
input/output data to the knowledge base. Note that the sensitivity factors vary
with different system operating conditions.

The *inference engine* uses the forward chaining strategy to link the rules
given in the knowledge base with the associated data, contained in the database
or input by the user, to solve the overload problem.

Figure 2 shows the solution search strategy of the expert system. The
procedure of the identification and alleviation of overloads is divided into a
number of tasks. An outline of these tasks is presented below:
If the overload is alleviated, then find the next critical overloaded line until all overloads are removed.

- Identify the operating configuration
- Determine the initial flow condition, and identify the overloaded lines

- Select a criterion for clearing overload
- Determine the permissible duration of the existing overloads

Rank overloads and identify the most critical one

Calculate sensitivity factors for the critical overload

- Select the most effective controller
- Calculate the control action required
- Check the controller limits
- Check voltage violations at all buses
- Check overload violations on other lines

Recommend the controller

If the overload problem still exists, then select the next controller

If the overload is alleviated, then find the next critical overloaded line until all overloads are removed.

Figure 2: Solution search strategy of the expert system.
1. Ask the user to select a contingency case. Identify overloads by solving load flows for the selected contingency and compare the results with the thermal limits of transmission lines stored in the "linedata" file.

2. Ask the user whether or not a line switching operation should be considered.

3. Ask the user to select a criterion for clearing the overloads and determine the permissible duration of the existing overloads. Note that two criteria are considered here. The first one is based on the overload magnitude severity, that is the overload with the highest magnitude is alleviated first. The second is based on the permissible overload duration severity. In this case, the overload with the shortest permissible duration is considered first.

4. Monitor the lines with line flow violations.

5. According to the criterion selected by the user, determine the most critical overload and calculate the sensitivity factors for this overload. Update the values of sensitivity factors in the database.

6. Select the most effective generator which has the highest sensitivity factor in the "gendata" database file.

7. Calculate the control action required to remove the overload and check the controller limits. If the required control action exceeds the limits of the controller, fix the controller output. Perform an inspection of overloads and voltage violations to ensure that the adjustment on the controller does not cause a new overload (or an increase in magnitude of the existing overloads) and violation of bus voltages in the system.

8. If the control action has exceeded the limit or the overload does not decrease, then ignore the control measure and chose the controller with the next highest sensitivity factor. Repeat procedure (7).

9. If all generators have been taken but the overload still exists, and if line switching operation is allowed, then select the most effective line which has the highest sensitivity factor in the "linedata" database file. Repeat procedures from (7) to (8) until the overload is removed.

10. If all generators and lines have been used but the overload still exists, then select the most effective load which has the highest sensitivity factor in the "loaddata" database file. Repeat procedures from (7) to (8) until the overload is removed.

11. Recalculate the new line flows after the application of the control actions and display results and recommendations obtained.

12. Repeat procedures from (4) to (11) until all overloads are removed.
Note that, in practice, to minimise an effect of the service degradation, the customer load curtailment is not usually applied to one location only. In the expert system, this aspect is taken into account by repeating the procedure described in step (10) a few times according to the number of priority load levels considered. For instance, if we consider only two load levels, priority 0 and 1, then the procedure in step (10) is repeated twice and only the load specified as priority 1 (lower priority) is to be shed in the first loop.

4 Case studies

Figure 3 depicts a one-line diagram of the six-bus power system [18], which is used to demonstrate an application of the expert system developed. Table 4 shows the power system bus data. Different cases with and without line switching operations are considered.

![One-line diagram of the six-bus power system.](image)

Table 4: Bus data of the six-bus system.

<table>
<thead>
<tr>
<th>Bus</th>
<th>Generation (MW)</th>
<th>Load (MW)</th>
<th>Total_load</th>
<th>Priority 1</th>
<th>Priority 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Actual 0 0 0</td>
<td>Total_load 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>50 45 60</td>
<td>0 0 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>60 55 70</td>
<td>0 0 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0 0 0</td>
<td>70 30 10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0 0 0</td>
<td>70 30 10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0 0 0</td>
<td>70 30 10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
i) Application with line switching: Table 5 shows the line rating limits, initial and final MVA flows of the six-bus system. As can be seen in Column 3, under the base case operating condition, line 2-6 is overloaded at 20.8%. Column 4 represents the flows after applying the corrective actions suggested by the expert system in the form shown in Figure 4. It is assumed that the permissible overload duration of line 2-6 is 12 minutes. According to the recommendation, the following actions can be applied to remove the overload on line 2-6.

- Bus 2, decrease generation on 5 MW;
- Bus 3, increase generation on 10 MW;
- Line 1-2, switch off;
- Bus 6, shed load by 8.6 MW.

Table 6 shows the available actions and their corresponding sensitivity factors for clearing the overload on line 2-6. Note that in the determination of the corrective actions, the actions which have negative sensitivity factors are considered as not applicable because the execution of these actions will result in an increase of the overload magnitude. Furthermore, the equipment with an execution time greater than the permissible duration of the overload (see Column 3) is also considered as not applicable and is not included in the overload clearing scheme.

In order to help the user understand clearly "how" and "why" a control action is recommended or bypassed, the expert system provides a report on the overload clearing process. Figure 5 shows the report for clearing the overload on line 2-6. From this report, for example, we can see that the disconnection of line 1-4 leads to overloads on lines 1-5 and 2-4, and a voltage violation at bus 4.

Table 5: Clearing the overload on line 2-6

<table>
<thead>
<tr>
<th>Line</th>
<th>Rating (MVA)</th>
<th>Initial flow (MVA)</th>
<th>Final flow (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>50.00</td>
<td>32.57</td>
<td>0.00</td>
</tr>
<tr>
<td>1-4</td>
<td>65.00</td>
<td>48.00</td>
<td>56.15</td>
</tr>
<tr>
<td>1-5</td>
<td>50.00</td>
<td>37.34</td>
<td>41.67</td>
</tr>
<tr>
<td>2-3</td>
<td>25.00</td>
<td>12.61</td>
<td>11.97</td>
</tr>
<tr>
<td>2-4</td>
<td>65.00</td>
<td>56.71</td>
<td>55.03</td>
</tr>
<tr>
<td>2-5</td>
<td>35.00</td>
<td>23.45</td>
<td>22.00</td>
</tr>
<tr>
<td>2-6</td>
<td>25.00</td>
<td><strong>30.20</strong></td>
<td>24.99</td>
</tr>
<tr>
<td>3-5</td>
<td>35.00</td>
<td>31.71</td>
<td>31.71</td>
</tr>
<tr>
<td>3-6</td>
<td>85.00</td>
<td>74.86</td>
<td>73.46</td>
</tr>
<tr>
<td>4-5</td>
<td>25.00</td>
<td>6.41</td>
<td>5.44</td>
</tr>
<tr>
<td>5-6</td>
<td>25.00</td>
<td>9.81</td>
<td>10.00</td>
</tr>
</tbody>
</table>
Overload detection
* number of overloads occur: 1
* the critical overload occurs on line: 2-6 { overload = 20.80 % }

Overload alleviation
Action 1: selected controller: generator 3
  change in the output (MW): 60.00 \rightarrow 70.00
  which reduces the overload (%): 20.80 \rightarrow 15.00

Action 2: selected controller: generator 2
  change in the output (MW): 50.00 \rightarrow 45.00
  which reduces the overload (%): 15.00 \rightarrow 14.32

Action 3: selected controller: line 1-2
  switching off the line
  which reduces the overload (%): 14.32 \rightarrow 7.63

Action 4: selected controller: load 6
  change in the load (MW): 70.00 \rightarrow 61.42
  which reduces the overload (%): 8.75 \rightarrow -0.05

** This overload has been cleared.
** All overloads have been removed.

Figure 4: Suggested actions to clear the overload on line 2 - 6.

Table 6: Available actions and sensitivity factors

<table>
<thead>
<tr>
<th>Controller</th>
<th>Sensitivity factor</th>
<th>Execution-time</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>generator 3</td>
<td>0.2394</td>
<td>6.00</td>
<td>generation increase</td>
</tr>
<tr>
<td>generator 2</td>
<td>-0.0663</td>
<td>8.00</td>
<td>generation decrease</td>
</tr>
<tr>
<td>line 3-5</td>
<td>0.1759</td>
<td>6.00</td>
<td>line disconnection</td>
</tr>
<tr>
<td>line 1-2</td>
<td>0.1156</td>
<td>5.00</td>
<td>line disconnection</td>
</tr>
<tr>
<td>line 1-4</td>
<td>0.0433</td>
<td>6.00</td>
<td>line disconnection</td>
</tr>
<tr>
<td>line 2-4</td>
<td>-0.1660</td>
<td>9.00</td>
<td>not applicable</td>
</tr>
<tr>
<td>line 4-5</td>
<td>-0.2118</td>
<td>8.00</td>
<td>not applicable</td>
</tr>
<tr>
<td>line 1-5</td>
<td>-0.2242</td>
<td>7.00</td>
<td>not applicable</td>
</tr>
<tr>
<td>line 2-5</td>
<td>-0.2960</td>
<td>10.00</td>
<td>not applicable</td>
</tr>
<tr>
<td>line 5-6</td>
<td>-0.4221</td>
<td>7.00</td>
<td>not applicable</td>
</tr>
<tr>
<td>line 2-3</td>
<td>-0.5305</td>
<td>8.00</td>
<td>not applicable</td>
</tr>
<tr>
<td>line 3-6</td>
<td>-0.6642</td>
<td>7.00</td>
<td>not applicable</td>
</tr>
<tr>
<td>load 6</td>
<td>0.4161</td>
<td>2.00</td>
<td>load decrease</td>
</tr>
<tr>
<td>load 5</td>
<td>0.1304</td>
<td>1.50</td>
<td>load decrease</td>
</tr>
<tr>
<td>load 4</td>
<td>-0.0210</td>
<td>1.00</td>
<td>not applicable</td>
</tr>
</tbody>
</table>

(ii) Application without line switching: If in a given emergency situation line 1-2 cannot be removed from service, the expert system would provide an alternative recommendation which does not include any line switching action as shown in Figure 6.
According to this recommendation, to remove the overload on line 2-6 the following actions must be applied:

- Bus 2, decrease generation on 5 MW;
- Bus 3, increase generation on 10 MW;
- Bus 6, shed load by 13.6 MW.

**Overload to be removed:** line 2-6

<table>
<thead>
<tr>
<th>Controller</th>
<th>Problem found</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator 3</td>
<td>OK.</td>
</tr>
<tr>
<td>Generator 2</td>
<td>OK.</td>
</tr>
<tr>
<td>Line 3-5</td>
<td>New overload is created on line 3-6.</td>
</tr>
<tr>
<td>Line 1-2</td>
<td>OK.</td>
</tr>
<tr>
<td>Line 1-4</td>
<td>Voltage problem occurs at bus 4, new overload is created on line 1-5, new overload is created on line 2-4.</td>
</tr>
<tr>
<td>Load 6</td>
<td>OK.</td>
</tr>
</tbody>
</table>

Figure 5: Report on the process of clearing the overload on line 2-6.

**Overload detection**

* number of overloads occur: 1
* the critical overload occurs on line: 2-6 { overload = 20.80 % }

**Overload alleviation**

Action 1: selected controller: generator 3
change in the output (MW): 60.00 \(\rightarrow\) 70.00
which reduces the overload (%): 20.80 \(\rightarrow\) 15.00

Action 2: selected controller: generator 2
change in the output (MW): 50.00 \(\rightarrow\) 45.00
which reduces the overload (%): 15.00 \(\rightarrow\) 14.32

Action 3: selected controller: load 6
change in the load (MW): 70.00 \(\rightarrow\) 56.40
which reduces the overload (%): 14.32 \(\rightarrow\) -0.07

** This overload has been cleared.
** All overloads have been removed.

Figure 6: Suggested actions to clear the overload on line 2-6.
Table 7 shows the initial and final flows of the power system without considering line switching corrective action. As can be seen in Column 4, the overload on line 2-6 is removed.

### Table 7: Clearing the overload on line 2-6

<table>
<thead>
<tr>
<th>Line</th>
<th>Rating (MVA)</th>
<th>Initial flow (MVA)</th>
<th>Final flow (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>50.00</td>
<td>32.57</td>
<td>24.53</td>
</tr>
<tr>
<td>1-4</td>
<td>65.00</td>
<td>48.00</td>
<td>43.37</td>
</tr>
<tr>
<td>1-5</td>
<td>50.00</td>
<td>37.34</td>
<td>32.43</td>
</tr>
<tr>
<td>2-3</td>
<td>25.00</td>
<td>12.61</td>
<td>11.61</td>
</tr>
<tr>
<td>2-4</td>
<td>65.00</td>
<td>56.71</td>
<td>58.12</td>
</tr>
<tr>
<td>2-5</td>
<td>35.00</td>
<td>23.45</td>
<td>23.00</td>
</tr>
<tr>
<td>2-6</td>
<td>25.00</td>
<td><strong>30.20</strong></td>
<td>24.98</td>
</tr>
<tr>
<td>3-5</td>
<td>35.00</td>
<td>31.71</td>
<td>32.67</td>
</tr>
<tr>
<td>3-6</td>
<td>85.00</td>
<td>74.86</td>
<td>71.90</td>
</tr>
<tr>
<td>4-5</td>
<td>25.00</td>
<td>6.41</td>
<td>5.12</td>
</tr>
<tr>
<td>5-6</td>
<td>25.00</td>
<td>9.81</td>
<td>9.43</td>
</tr>
</tbody>
</table>

### 5 Conclusion

The development of an expert system for clearing transmission equipment overloads has been successfully completed. The test results show that the expert system provides prompt and feasible solutions for clearing the overloads. Recommendations given by the expert system are flexible and dependent on the permissible overload duration and line switching consideration.

The expert system has a potential to assist system operators alleviate the overloads on their transmission system. The computational speed should meet the demand for real-time applications in control centres. Further development will attempt to apply the expert system in real-time using data obtained from a SCADA system.

### 6 References


