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An expert system for teaching voltage control in power systems

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Abstract

Recent advances made in the development of expert systems lead to the major impact in teaching and learning environments. This paper describes an expert system for teaching voltage control in power systems. The expert system was implemented using a commercially available expert system shell *Level5 Object*. The major objective of the tool developed was to demonstrate the use of artificial intelligence in the field where practical knowledge and experience are very important. Voltage control in power systems provides this opportunity. The expert system calculates power load flows and bus voltages, simulates the system disturbances including changes in the power demand and network configuration, detects and corrects voltage violations and provides recommendations and explanations. The expert system is used to advise a user on appropriate actions required to improve the voltage profile by adjusting transformer taps, changing generator voltages and switching reactive power compensators. It also helps to determine the optimal location and size of the additional reactive power compensation to be installed in the power system. The expert system can serve both academic and industrial training needs.

1 Introduction

Expert systems have found a number of successful applications in business and industry, e.g. Harmon & Sawyer [4]. As indicated in Durkin [2], although the major role in contribution to the development of expert system applications is played by educational institutions, there is still a very few applications in the teaching area. Meanwhile, recent advances made in the development of expert systems will lead to the major impact in our teaching and learning environment. The use of interactive expert system based tools, e.g. McFarlane & Parker [10],

is intended to supplement, but not replace, traditional teaching techniques such as lectures and laboratory sessions. An employment of different educational tools and materials provides better understanding of a subject. Simply applying theory, as indicated in Gibbs & Habeshaw [3], is ineffective. Also Lesgold showed in [7], that examples can influence learning process much more than the presentation of concepts and even rules.

This paper describes an expert system for teaching voltage and reactive power control in power systems. The expert system was implemented using a commercially available expert system shell *Level5 Object* [8]. The major objective of the tool developed was to demonstrate the use of artificial intelligence in the field where practical knowledge and experience are very important. Voltage control in power systems provides this opportunity.

Power utilities must maintain the system voltage within allowable limits. However, with the growth of power systems in their size and complexity, the voltage control tends to be more complex and difficult to handle. The voltage differs in the network from one node to another. Moreover, any change in the power demand or network configuration may lead to voltage variations and even voltage violations.

Power utilities have accumulated an expertise in different operational conditions. This expertise is stored in manuals and guidance, but the most significant part of knowledge can be obtained through the practical experience only. Often in order to correct voltage problems, an operator must choose an appropriate control action among conflicting options, and responsible decisions must be taken very rapidly. Mistakes can cause major emergencies, and even lead to a voltage collapse and system blackout. In recent years, intelligent decision support systems have been introduced to help power system operators to keep the voltages within allowable limits, e.g. Liu & Tomsovic [9] and Cheng [1].

The expert system developed can perform the following tasks:

- calculate power flows and system voltages;
- simulate the system disturbances including changes in the power demand and network configuration;
- detect and correct voltage violations in the power system;
- display results, recommendations and explanations.

2 Reactive power and voltage control

Power system steady state conditions can be described by the power flow equations. These equations are then solved to obtain bus voltages and angles using given power system topology, generation, load demand and impedances of generators, transformers, transmission lines and other elements.

The power flow equations are non-linear and, therefore, analytical solutions usually may not be obtained. Numerical solutions even for simple power systems can be produced with the aid of a digital computer only. Such solutions

are iterative in nature and thus time consuming. The power flow equations, however, can be approximated by decoupled equations introduced by Stott & Alsac [11] exploiting the fact that the real power (W) flows are more sensitive to voltage angles and the reactive power (VAR) flows are mainly dependent on voltage magnitudes.

Based on the decoupling relation, bus voltage magnitudes can be maintained within appropriate upper and lower limits by controlling the reactive power injections into the power system.

In power systems, variations in the power demand or changes occurring in the network configuration may result in voltage violations. The effect of these changes may be reduced by adjusting the settings of the controllers. This includes the use of tap-changing transformers and voltage boosters, as well as a suitable allocation of VAR sources such as static capacitors and synchronous condensers.

The controllers have both upper and lower permissible limits. The limits for transformer taps, generator voltages and switchable shunt VAR sources are, respectively

$$n_{ij}^{min} \leq n_{ij} \leq n_{ij}^{max} \tag{1}$$

$$Q_G^{min} \leq Q_G \leq Q_G^{max} \tag{2}$$

$$D_i^{min} \leq D_i \leq D_i^{max} \tag{3}$$

where n_{ij}^{max}, n_{ij}^{min} and n_{ij} are, respectively, the maximum, minimum and current tap position (turns ratio) settings of the transformer between bus *i* and bus *j*; Q_G^{max}, Q_G^{min} and Q_G are, respectively, the maximum, minimum limits and operating value of the reactive power output of the generator at bus G; D_i^{max}, D_i^{min} and D_i are, respectively, the maximum and minimum VAR limits and current VAR output of the switchable shunt VAR source at bus *i*.

The above controllers can change their values either continuously or in steps. The controllers are not equally effective and, therefore, required adjustments are different for each control device. To find the effective order of control actions to be taken to correct voltage violations, the sensitivity tree method can be used. Figure 1 represents relations between bus voltages and controllers applied for the N bus power system with M controllers, where $S_{i,k}$ are the sensitivity factors between the controllers and the load bus voltages. It may be seen that voltage adjustment on any bus can be achieved by the application of a number of controllers. It should also be noted that changes in any controller setting result in changes of a number of bus voltages.

Then the sensitivity matrix suggested by Hano [5] is employed to select the most effective controllers and determine their adjustments required to correct the voltage problem. The controllers are sequentially adjusted starting from the most effective one, which has the largest factor in the sensitivity matrix row corresponding to the violated bus. When the controller is activated, its effect on

all other buses of the power system is determined using the sensitivity matrix column corresponding to the adjusted controller. This procedure ensures that the controller application will not create other violations. If the most effective controller is not sufficient to correct the voltage problem, the next controller is activated.

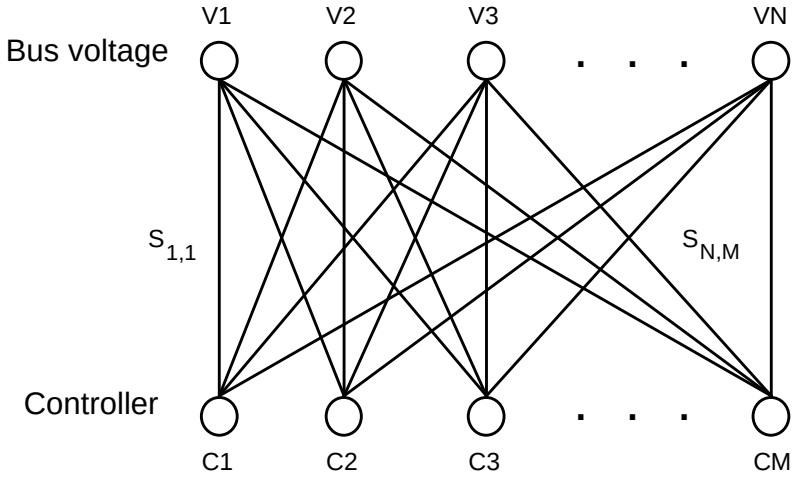


Figure 1: Sensitivity tree for voltage control studies.

3 Expert system development

The expert system was developed based on *Level5 Object* expert system shell and implemented on IBM personal computers. *Level5 Object* is an object oriented complete tool which facilitates interactions with external databases, programs, texts files, timers and user interfacing options. Knowledge can be represented using graphical editors and stored in the form of Methods, Rules and Demons [8]. The graphical depiction allows the user to display and modify the knowledge tree and decision process easily.

The block diagram of the expert system developed is shown in Figure 2. It contains the *Level5 Object* expert system shell, load flow analysis package, external programs to calculate the sensitivity factors and correct voltage violations, and also database dBASE III with power system parameters.

3.1 Database and knowledge base

The expert system applies the following data:

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

Note that the sensitivity factors vary with different system operating conditions.

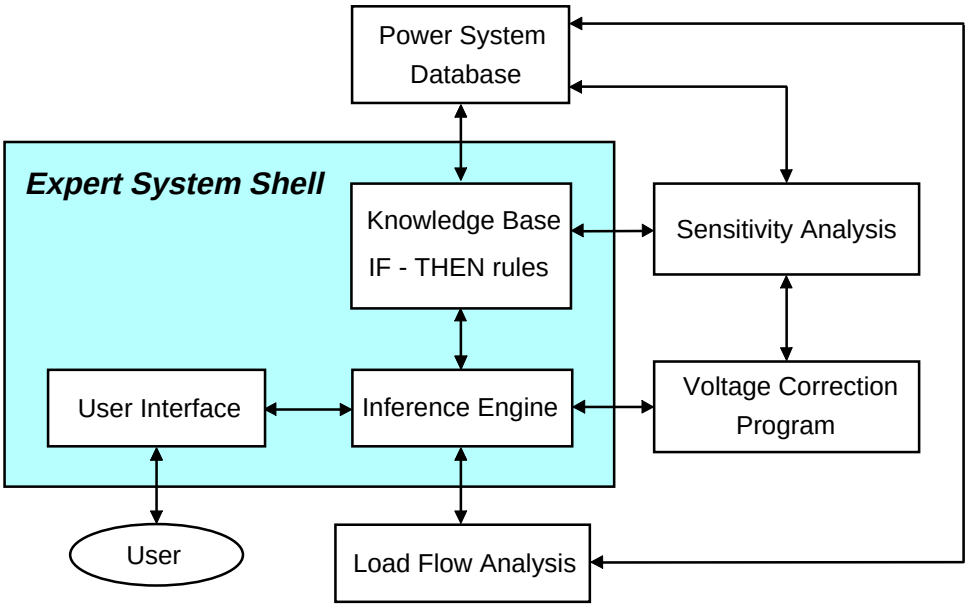


Figure 2: Block diagram of the expert system.

When a bus voltage exceeds its specified limits, either high or low, the usual actions to be taken by a system operator are either to switch a capacitor bank, adjust the tap positions of transformer tap changers or vary the generator bus voltage in order to restore a normal voltage profile. For instance, when a low voltage occurs on a load bus, a capacitor bank or synchronous condenser can provide additional reactive power to the power system thus raising bus voltages. The tap changer can adjust the turns ratio of a transformer, and hence increase the secondary voltage magnitude.

Empirical and heuristic rules specified in Liu & Tomsovic [9] and Le, Negnevitsky & Piekutowski [6] are implemented in the knowledge base of the expert system developed. Some of the key rules are given below.

Rule 1: IF initial OF voltages < lower_limit
THEN voltage violation IS 'under_voltage'

Rule 2: IF initial OF voltages > upper_limit
THEN voltage violation IS 'over_voltage'

Rule 3: IF voltage violation IS 'under_voltage'
THEN ACTIVATE "IPU, EXTERN, ADJUDR.EXE"

Rule 4: IF voltage violation IS 'over_voltage'
THEN ACTIVATE "IPU, EXTERN, ADJOVR.EXE"

Rules 1 and 2 are used to detect the voltage violation problem. Once the voltage violation is detected, rules 3 and 4 are used to activate the external programs "adjudr.exe" and "adjovr.exe" in order to correct the problem. If,

however, the voltage violation problem cannot be solved by adjusting the existing reactive power sources, the additional reactive power compensation may be allocated and added to the power system as suggested in Le, Negnevitsky & Piekutowski [6].

3.2 Inference engine

The main purpose of the inference engine is to link rules given in the knowledge base and the conditions input by the user with data stored in the database. It also activates the external programs in order to solve a voltage violation problem. The expert system employs a mixed mode inferencing method. The backward chaining is used to pass through the available controllers to find the most effective one, using IF-THEN rules. The backward chaining mechanism can access and modify information in the database. On the other hand, forward chaining demons are used to propagate the effect of any change in the power demand or network configuration.

Figure 3 shows the main menu of the expert system. The user can select the icon *Loadflow* to activate the load-flow analysis package in order to determine the initial operating condition (bus voltages and power flows) or to initiate an outage condition by selecting the icon *Contingency*. The contingency conditions include outages of transmission lines, transformers and generators.

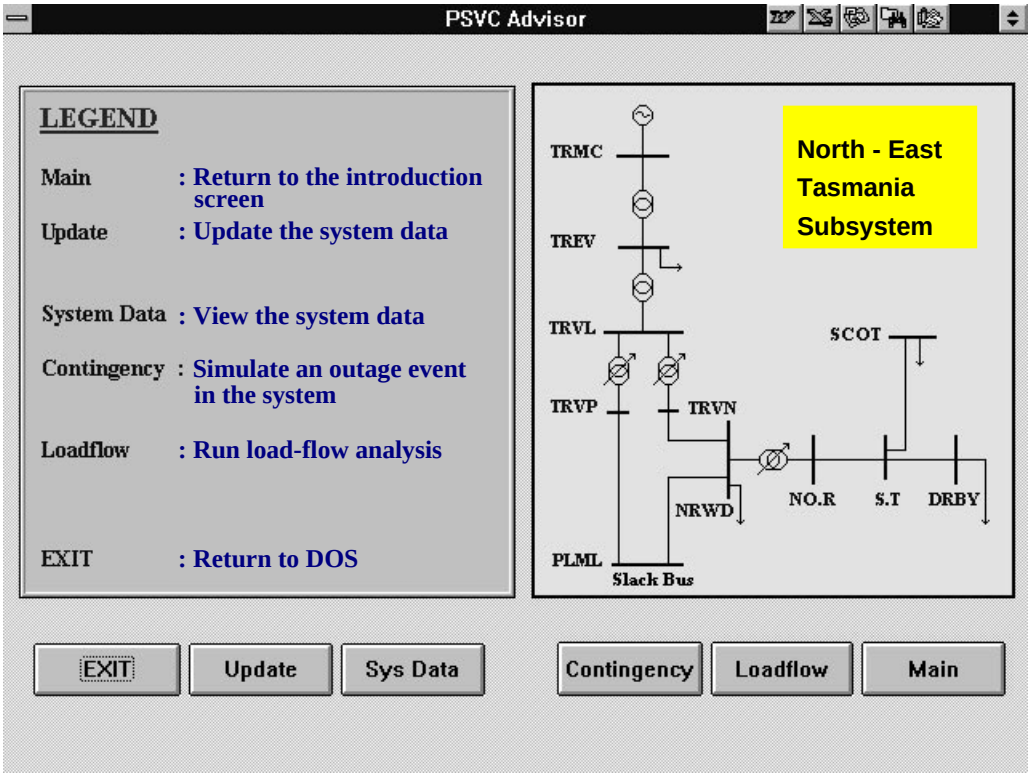


Figure 3: Main menu of the expert system.

The system also offers other options, such as *Update* (update the system data), *Sys Data* (view the system data), *Main* (return to the introduction screen) and Exit (return to DOS).

When the icon *Update* is selected, the screen shown in Figure 4 appears. The user is allowed to append, edit and print the system data. The main menu to view the system data is shown in Figure 5. This menu is displayed if the user selects the icon *Sys Data*. Then he or she can view data for generators, transformers, capacitors, buses and transmission lines. Figures 6 and 7 show windows to view the generator data and to edit the bus data, respectively.

4 Case studies

The purpose of the developed expert system is essentially tutorial. It intends to present a practical problem to students, and examine how the expert system techniques can be applied. It was very important to give the user an active role, and opportunity to examine the power system by changing the system parameters and initiating events that cause voltage problems. The user also can create and study outage events in the system with potential out-of-limit voltages. The man-machine interface is user-friendly and requires minimum inputs.

Consider an application of the expert system on a simple example. The North-East Tasmania subsystem shown in Figure 3 serves this purpose.



Figure 4: Main system data menu.

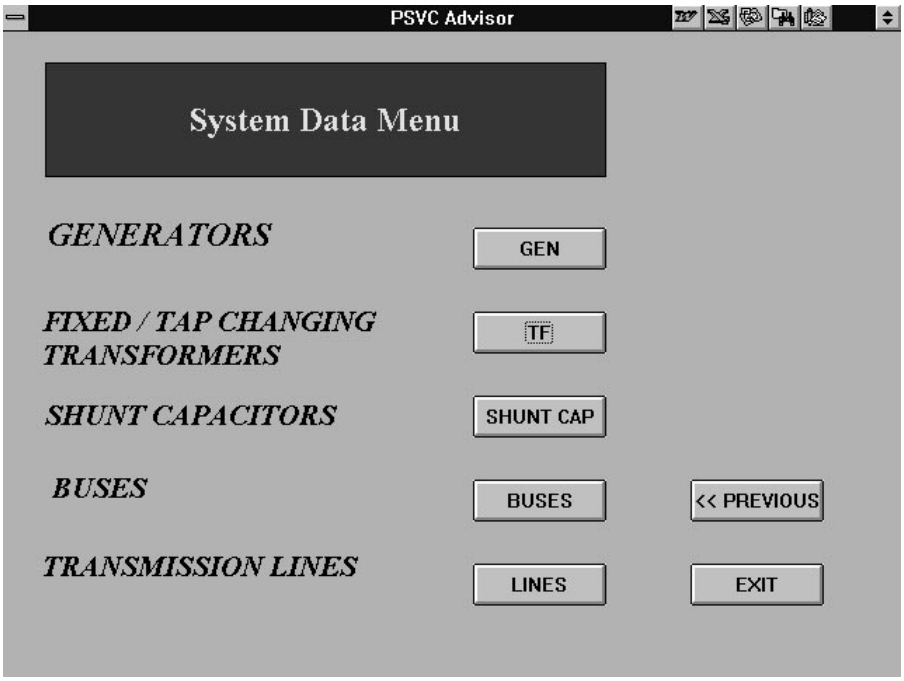


Figure 5: System data view menu.

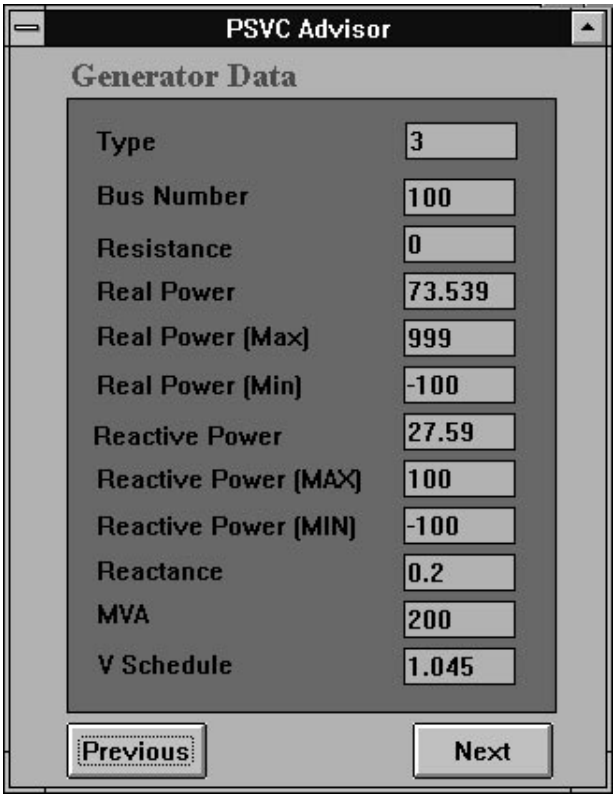


Figure 6: Generator data view window.

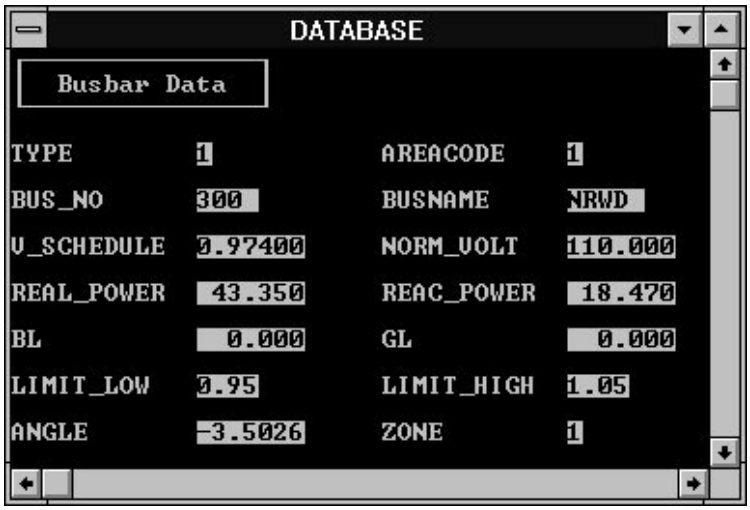


Figure 7: Bus data edit window.

Suppose the user selects the icon *Contingency* on the main menu screen, and then causes the outage of the transmission line between bus 300 and bus 500. The load-flow analysis is automatically carried out and when completed, the initial power system condition is displayed as shown in Figure 8. The line connecting bus 300 to bus 500 becomes dashed and red in colour to indicate the outage. Actual bus voltages, upper and lower voltage limits and bus violation status (Under, Over and None) are also shown. As can be seen, there are three low voltage buses, 900, 1000 and 800. Now the user can activate the icon *Advice* in order to alleviate the voltage problem. The window shown in Figure 9 appears. It presents an extract of the problem created and asks the user to make an appropriate selection. If the icon *Yes* is chosen, then the voltage problem will be corrected automatically starting from the most violated bus (bus 900). This is the common procedure accepted by power system utilities. However, if the user activates the icon *No*, he or she can correct the voltages manually in a different order and may even find a better solution. Figure 10 displays a list the control actions recommended by the expert system when the icon *Yes* was selected. As can be seen, two control actions are required to correct the voltage problem. Figure 11 shows the conclusion screen which demonstrates new settings of the controllers and final bus voltages. All voltages are now within their limits, and thus the voltage problem has been solved successfully.

5 Conclusion

The expert system for teaching voltage control in power systems was developed. The knowledge base consists of a number of production rules which control the execution of the load flow and other external programs and data manipulation through the expert system shell *Level5 Object.*

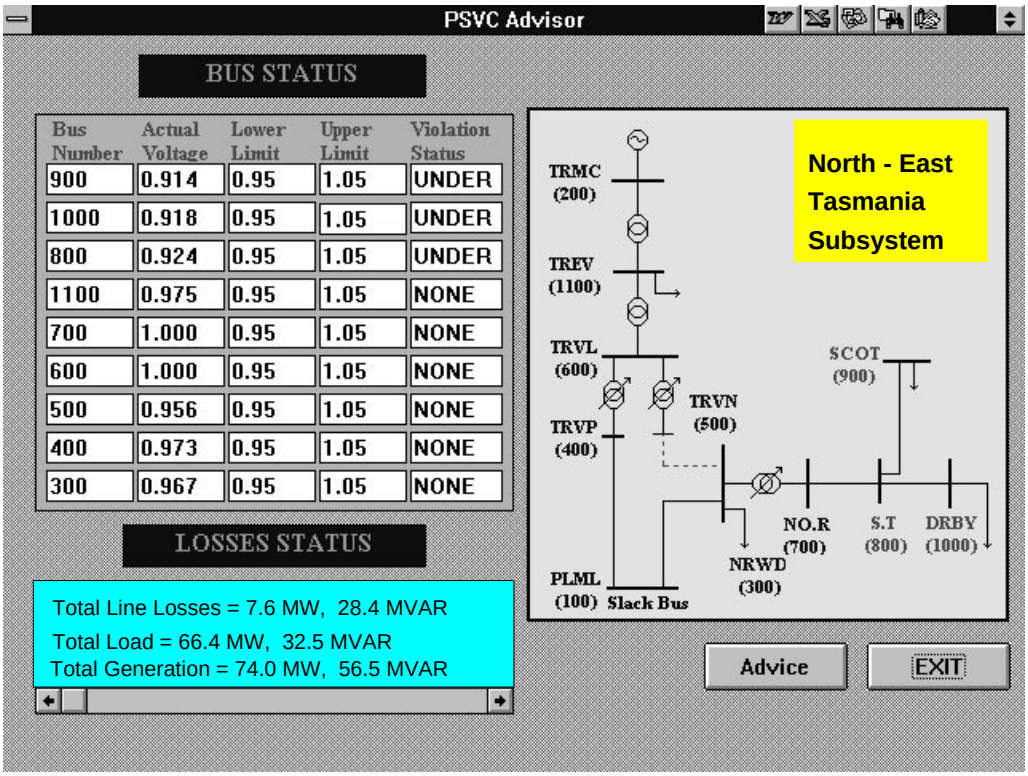


Figure 8: Initial operating condition under the outage of the transmission line.

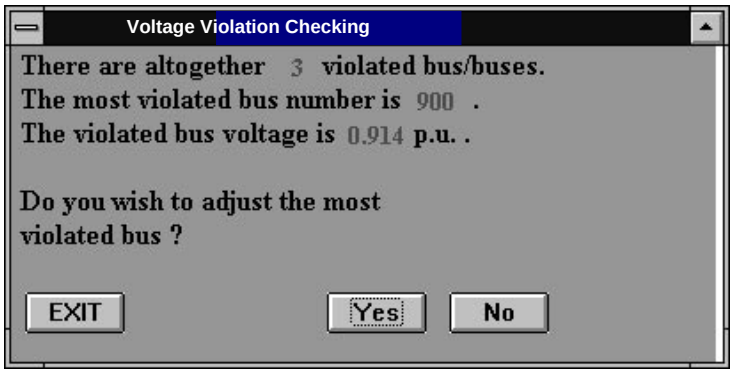


Figure 9: Voltage violation check window.

The expert system is used to detect voltage violation problems and to advise on the appropriate actions required to improve the voltage profile by the suitable allocation of VAR sources throughout the power system, i.e., by adjusting transformer taps, changing generator voltages and switching VAR compensators. It also can help to determine the optimal location and size of the additional VAR compensation to be installed in the power system in order to maintain an acceptable level of system security.

The expert system can serve both academic and industrial training needs.

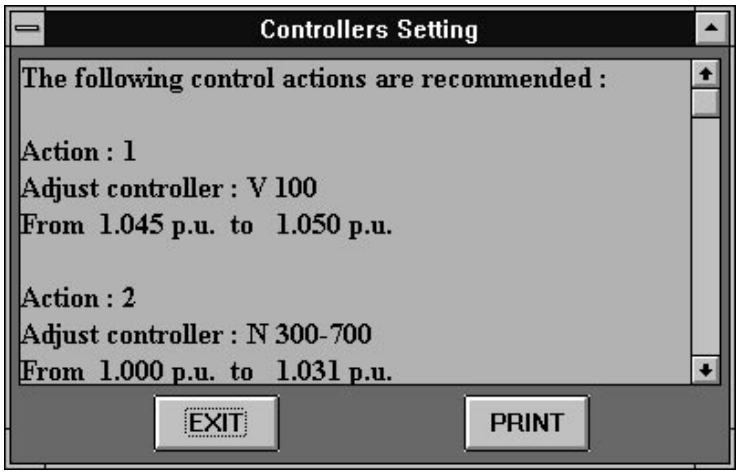


Figure 10: Control action window.

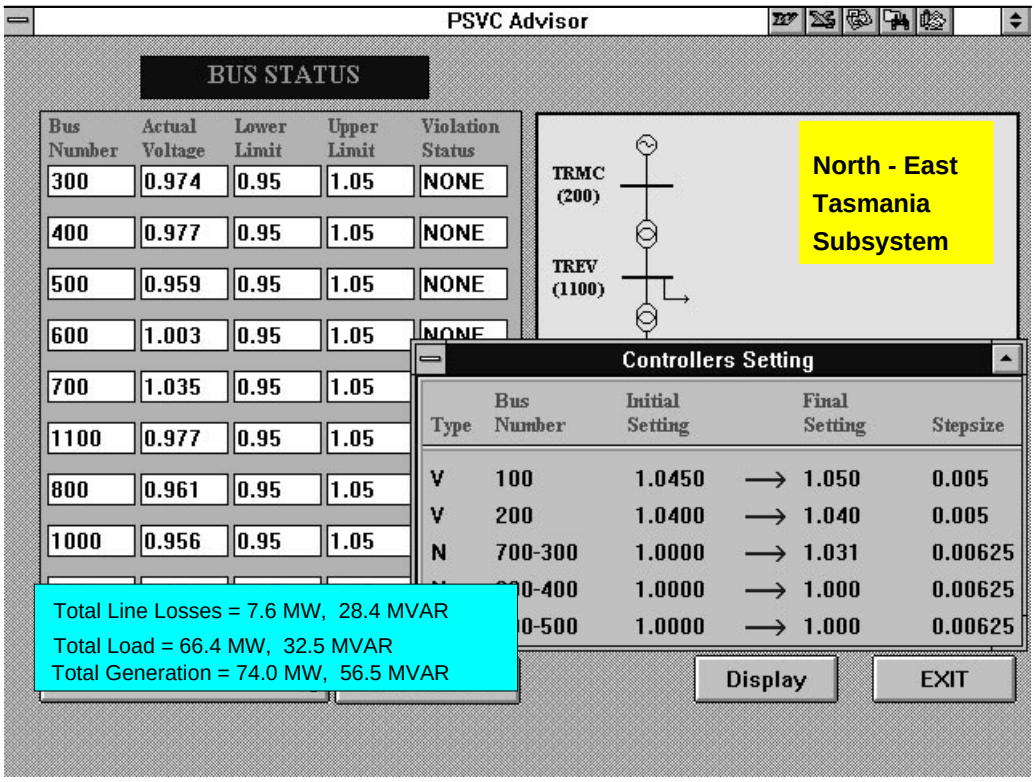


Figure 11: Final operating conditions after alleviation of the voltage problem.

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Electrical & Electronic Engineering Department, Mr. Yew Kwong Wong and Mr. Kok Wei Koh, for their contribution.

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