Chapter 6

Implementation of the Hybrid System

Introduction

The previous chapters dealt with the development of components of active power dispatch and reactive power dispatch using the technique of genetic algorithms, reactive power controller pre-selection and description of some of the existing tools for process data access and conditioning. Power system operators have at their disposal several control actions in order to ensure security of the network. They will rely primarily on control actions of reactive power type (e.g. transformer tap changes) when confronted with voltage problem and active power type (such as generation re-dispatch) to solve thermal overload. In this chapter, a hybridized tool is presented that integrates the beneficial aspects of transparency of symbolic computation (expert system) and robustness of numerical computation based genetic algorithm in order to provide a strategy to assist the power system operator in improving the network state when it is operating outside the normal state. Such innovative approach incorporating superior decision in effect makes use of these components coordinated by an expert system to evaluate the actual system situation and, based on the operators' intuition lodged in the knowledge base, selects the appropriate tools to bring the system back to normal state if there is any operating limits violation. The entire hybrid system was implemented on an existing operator training simulator, based on the GDL process data system as discussed in chapter 3; this provided the opportunity for verification with different scenarios under operational realism. Furthermore, on the simulator autonomous execution of the suggested actions could be implemented as an option, which gives a taste of future intelligent power system control. For autonomous execution, the remote controllability of certain control devices is presupposed, and the expert system thus operates in a closed loop fashion without operators' intervention. Also, the system is ready to be finally integrated into an existing comprehensive restoration expert system; after the goal of this system - re-supply of all consumers with some adequate reserve whereby more tolerant margins of voltage profile and loading of components must be admitted - has successfully been met, the functionality developed in this work is intended to care for recovery to normal system state with regard to these margins. This can easily be achieved by incorporating the rules module developed here into the existing knowledge base of the restoration expert system. Thus, the modular structure used in [50,51] was equally adopted in this work.

6.1 Network State Assessment and Enhancement Strategy

Figure 6.1 depicts a flow diagram of the steps and the sequence of the processes involved in the detection and correction of the existence of nodal voltage limits violation and branches overloads in a power system. It reflects the way a system operator actuates when confronted with a situation in which the network is operating outside the normal state. Specifically, it comprises the tasks of:

- identification or assessment of the network state;
- selection of appropriate tools for state enhancement;
- interpretation of the results of evaluation programs;
- determination of the availability of reactive power controllers and active power margins of generators;
- recommendation of corrective measures for the elimination of voltage problems and branches limit violations, and
- optional autonomous execution of recommended control actions.

The first step in the solution strategy involves the detection of the existence of any network operating limits violations which could be in the form of branches and/or voltage related. The numerical external routine of **network state assessment** (see chapter 3) uses its voltage profile and branches apparent power flow limit violation checking functions to establish the existence of any operating limits violations. If the result of evaluation is negative, the process is exited, otherwise the nature of violations (i.e. whether it is overloads or nodal voltage related) is determined.

If an overload related problem has been established, the allowable maximum number of overloads problem iterations is checked. If this value is exceeded, it is necessary to establish whether there is any outstanding voltage problem to relieve overloads of branches (transmission lines, cables and transformers) through reactive power dispatch. Otherwise the tools of numerical computation of **GA based real power dispatch** (see chapter 4) is required to reschedule the generating units' real power output in order to remove the overloads while at the same time operating at minimum production cost. The results obtained through pre-evaluation in the form of optimal real power scheduled are executed for the corresponding generating units, and the above described procedure is repeated to check for the existence of further violations.

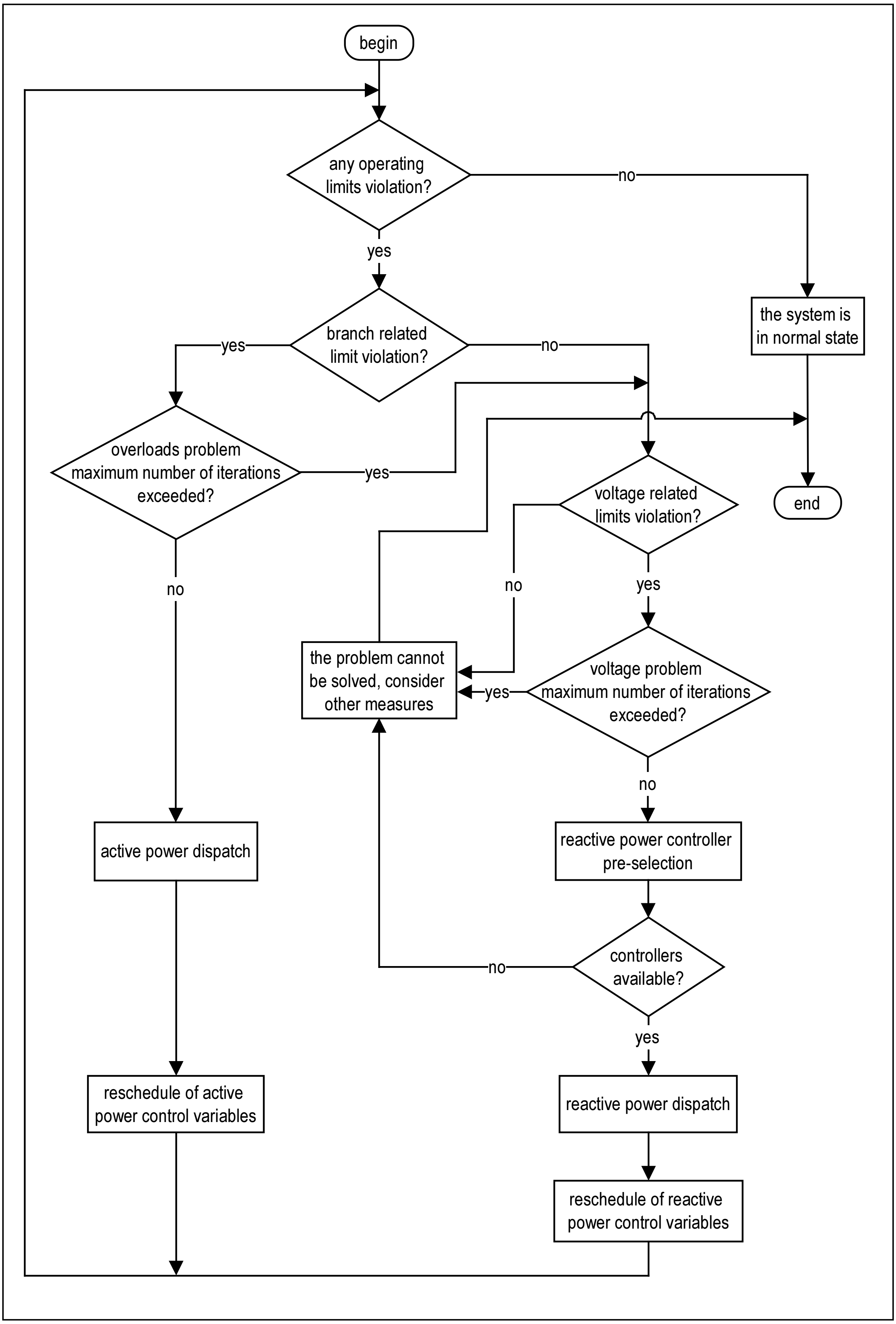

Figure 6.1 Operating limits violation detection and removal strategy

If the violations of operating limits are not branch overloads related, then there is a need to establish whether the problem is voltage related. Once voltage limits violation is found to exist, in the same way as for overloads problem, the allowable maximum number of voltage problem iterations is checked. If this value is exceeded, then there is no solution to the problem; an appropriate message is displayed to the user and the process is exited; otherwise the **reactive power controllers pre-selection mechanism** (see chapter 5) determines the availability of relevant reactive power controllers by selecting only generating units and on-load tap changing transformers electrically closest to the nodes experiencing voltage problems, and all the available shunt switching elements. If no such controller is available, a corresponding message is presented to the user and the process is exited, otherwise the tool of **GA based reactive power dispatch** (see chapter 5) is called in order to optimally adjust the pre-selected reactive power controllers as remedial actions for the elimination of voltage limits violation. The results of the pre-evaluation in the form of optimal settings of reactive power controllers are executed for the respective devices. Again, the existence of any further operating limits violation is then checked. If none exists, the process is exited, otherwise the above described process continues until the system is restored to normal state with regard to overloads and voltage profile.

6.2 Knowledge Base Development

6.2.1 Rule Based Structure

The knowledge base contains the set of rules of the hybrid system. These rules are represented in the form of “if **condition** then **conclusion**” format. Within these rules and on the basis of logical values ‘positive’ and ‘negative’ as well as their conjunction and disjunction among themselves, the entire sequence necessary for the field of knowledge required for state assessment and enhancement strategy is lodged. The text oriented structure of the rules in the form of natural language text elements also facilitates the interaction with the power system operator. This rule format as well as the inference engine which have already been described in detail and found to work satisfactorily in [40,50,51] are adopted in this work and briefly described in appendix B.1.

6.2.2 Knowledge Organization for the Hybrid System

The development of a knowledge based support system requires the determination of the knowledge to perform the task of network state assessment and its enhancement. The rules to perform these tasks can be identified as follows:

- checking for existence of branches (transformers and lines) overloads and/or voltage problems;
- voltage problem identification;
- branches (transformers and lines) overloads identification;
- *a priori* selection of reactive power controllers and hence their availability;
- elimination of branches overloads;
- elimination of nodal voltage limits violation;
- optional autonomous execution of controllers' action by expert system or manual adjustment by the user/power system operator.

These rules are respectively classified under network state assessment and enhancement and are discussed below:

6.2.2.1 Network State Assessment

In order to monitor the state in which the power system is operating, five rules are designed for this task. These rules deal with the detection of existence of nodal voltage limits violation and/or branches (lines and transformers) overloads in the form of apparent power flow limit violations, and the identification of appropriate corrective tools to be employed.

- ***Rule for checking the existence of any operating limits violations***

This rule for detection of existence of any operating limits violations is evaluated by calling the numerical routine of state assessment through the corresponding FORTRAN-interface of the prolog interpreter. Under this condition, the numerical computation of state assessment uses the current power system data to run the load flow program. The predefined nodal voltage limits obtained from the SCADA process database - or the default values in case they are not specified - are then compared with the actual voltage profile procured by the load flow in order to establish the existence of voltage problems. Similarly, for branches (lines and transformers) overloads detection, the thermal limits obtained from the process database are compared with the actual apparent power flows calculated by the load flow program. The detected violations, their values and locations are then mapped into voltage limits violation and branches overloads lists until they are required by the decision making process. The result of evaluation is eventually terminated with a logical value of positive or negative.

- ***Rule for determination of voltage related limits violation***

Once operating limits violation(s) is (are) found to exist, the task of this rule is to identify whether the limits violation type is voltage related. The result of evaluation is eventually terminated with a logical value of positive or negative.

- ***Rule for determination of branch overloads related violation***

The task of this rule is similar to the above rule except that it identifies the type of limits violation as branches overloads related. The result of evaluation is eventually terminated with a logical value of positive or negative.

- ***Rule for maximum number of allowable iterations in voltage problem elimination***

The task of this rule is to determine whether the maximum number of allowable iterations in the voltage problem elimination process is exceeded. The results of evaluation is eventually terminated with a logical value of positive or negative.

- ***Rule for maximum number of allowable iterations in branch overloads problem elimination***

The rule is similar to the rule for the voltage related problem except that its task involves the determination if the maximum number of allowable iterations in the overloads problem elimination process is exceeded. The result of the evaluation is eventually terminated with a logical value of positive or negative.

6.2.2.2 Network State Enhancement

After it has been established by the network state monitoring that the power system is not in the normal state, it is necessary to provide a measure to eliminate the problem thus enhancing the state of the network. Based on the type of problem, the knowledge based system must then decide on the appropriate corrective tool (active power, reactive power or voltage control) to be used in the problem elimination process. By taking the advantage of the existence of good decoupling between the real power flow distribution in a network (voltage angle difference between buses), and the reactive power flow distribution (bus voltage magnitudes) - see chapter 2, section 2.2 -, the appropriate tools are determined. If the problem is branch overloads related, the real power control tool is used while a voltage violation requires application of the reactive power dispatch tool. Rules to carry out the task of this state enhancement can be classified as follows:

- ***Rule for selection and determination of the availability of reactive power controller(s)***

  If a voltage problem is detected, the rule for *a priori* selection of controllers is invoked. This rule reflects the way experienced power system operators act when voltage limits violations occur by selecting the electrically closest controller(s) with respect to node(s) experiencing voltage limit violation(s). The numerical computation of the reactive power controller pre-selection mechanism (see chapter 5, section 5.1) is communicated with in order to determine the number of controllers to be applied. These selected on load tap changing transformer and generating unit lists together with all the available switching elements are then accessed by the GA reactive power dispatch module to determine their optimal settings. Based on the total number of controllers, their availability is then determined by testing if this number is not equal to zero. If no such controller is available for optimization, the evaluation of the rule thus fails.

- ***Rule for voltage limits violation remedial actions***

  This rule is invoked if voltage limits violation was detected and it has been established that reactive power controllers are available for the state enhancement process. The objective here is to adjust the selected reactive power controllers in such a way that the voltages of nodes experiencing voltage problems are corrected. The numerical computation of the GA reactive power dispatch (see chapter 5) is communicated with through the expert system's external interface in order to determine the required setting of the controllers. The aspired setting of reactive power controllers and their identifiers are then mapped into their corresponding lists for either autonomous execution by the expert system or manual adjustment by the operator. The evaluation of this rule must always succeed.

- ***Rule for eliminating branch overloads***

  This rule is invoked if there is any branch overloads. The objective here is to re-dispatch generating units' real power output in such a way that branches experiencing overloads are relieved. The numerical computation of the GA active power dispatch (see chapter 4) is communicated with through the external interface to determine the appropriate schedule of generating unit's real power output with the secondary aim of minimizing the production cost while fulfilling other constraints of power balance, generating units power output and branches apparent power flows. The results obtained through pre-evaluation in the form of generating units' real power scheduled and their identifiers are then mapped into a list. This list is then accessed by the expert system for optional autonomous execution or presentation to the operator for manual adjustment. The rule is positive terminated as its evaluation is found to always succeed.

6.3 Structure of the Hybrid Scheme

Figure 6.2 depicts the architecture of the realized hybridized network state assessment and enhancement scheme showing the basic components:

- The numerical computation component **(State Assessment and Enhancement Routines, "SAER")** developed within the scope of this work which in turn consists of:

  - the network state assessment module that uses its voltage profile limits violation and branch overloads checking functions to determine the actual state of the network;
  - subsystem of genetic algorithm (GA) based active power dispatch to redistribute generating units' power output to relieve branches (lines and transformers) overloads as described in chapter 4;
  - subsystem of GA based reactive power dispatch to optimally adjust the settings of reactive power control devices in order to correct violations of voltage magnitude limits (see chapter 5);
  - reactive power controller pre-selection mechanism to select *a priori* voltage sensitive reactive power control devices for the reactive power dispatch module (see chapter 5, section 5.1).

  The existing data setup packets (generation observer, load observer and topology evaluation) [50] were used in this work to provide all the necessary power system data (see chapter 3; tables 3.1, 3.2a and 3.3) for the above enumerated modules.

- The super-ordinate **central control mechanism**; the existing set of calling predicates and external routine interface declarations of the restoration expert system [51] was augmented by those predicates specifically required by the hybrid system of network state assessment and enhancement developed in this work. The tasks include among other:

  - evaluation of individual **conditions** of the rules as part of the problem solution proceeding, stored in the knowledge base;
  - tactical adaptation to the power system under consideration and to its current state;

- invocation and coordination of the access to the individual numerical computation programs;
- procurement of information from the pre-evaluation of the numerical routines, in order to derive a logical response (positive or negative);
- furnishing this information back to the inference engine; and
- through optional autonomous execution of control devices, encroaching on the functional process of the power system operator.

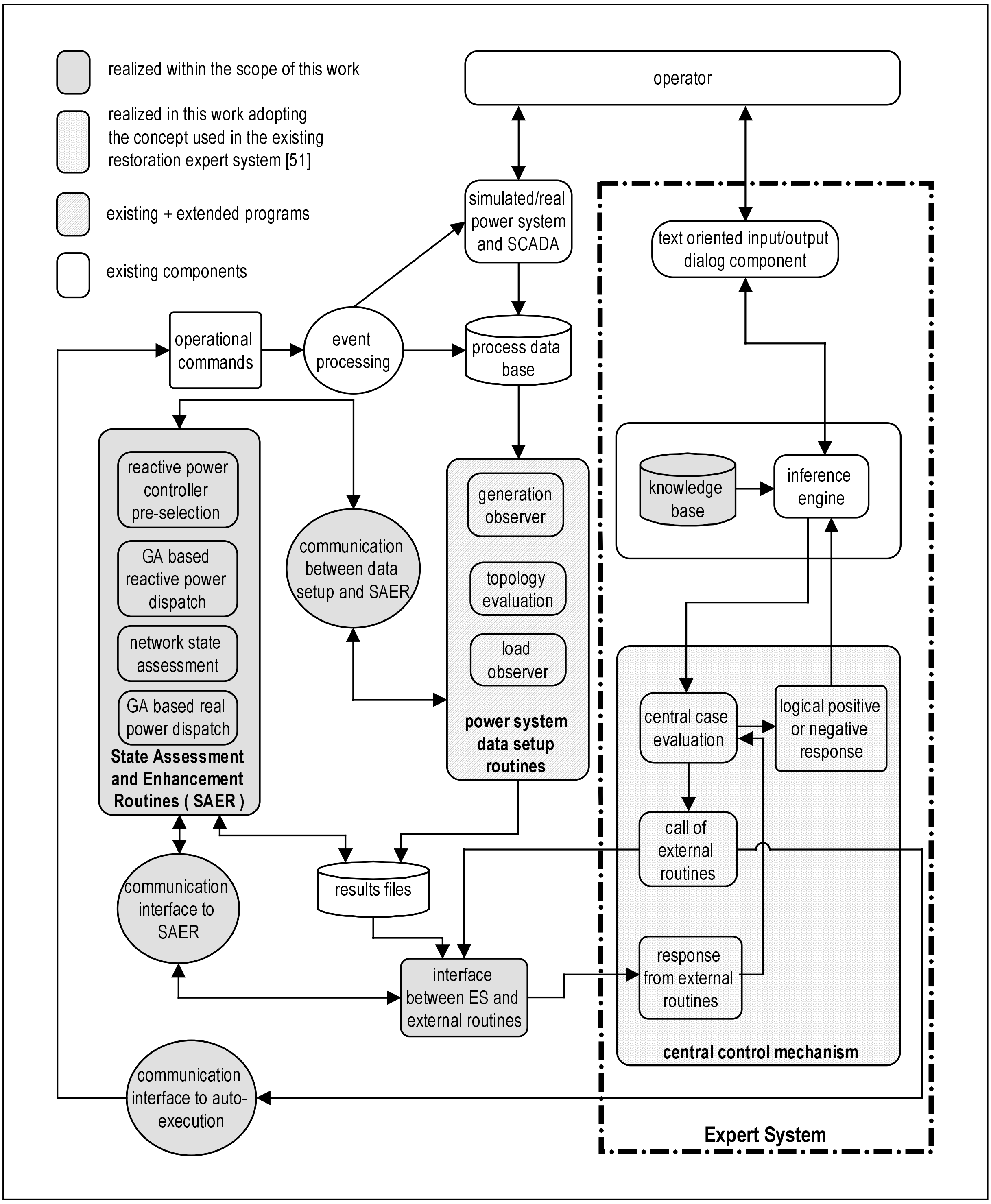

Figure 6.2 Architecture of the hybrid system

- **Interface for communication** with the other system components outside the expert system. This is involved in linking the predicates in the control mechanism already declared above and the corresponding numerical routines. Further interfaces for sending and accomplishment of necessary information are:

    - a direct interface for communication between state assessment and enhancement routines and data setup packages for the accomplishment of the required power system data;
    - communication interface between control mechanism and corresponding autonomous execution of control commands routine. In this case, the GDL description of the control variable together with the intended status as event element are formulated in the control mechanism and as command automatically routed through the simulator's event processing to the model of the corresponding power system component as discussed in chapter 3; and
    - a shared communication interface through which individual components of the control mechanism dealing with symbolic information communicate with each of the numeric components of state assessment and enhancement routines. The communication format determined by the control mechanism can be in the form of numerical information, lists or their combination.

- The **inference engine** used here is that of the existing restoration expert system [50,51], and the knowledge base as part of this work was described in section 6.2. To evaluate a rule, the inference engine matches the condition part of the rule with the corresponding pattern already lodged in the central control mechanism and therefore deduces a logical conclusion by means of combining knowledge evaluated from the rule base and case data from the pre-processing external programs whose results are stored in the results files, or through the user dialog in the case of manual execution. The inference engine repeatedly applies production rules from the knowledge base until an ultimate end is reached (see figure 6.1).

The numerical computations were coded in Fortran, while the symbolic computations were coded in Prolog. Prolog stands for ***Pro****gramming in* ***log****ic* - an idea that emerged in the early 1970s to use logic as language. Specifically the chosen prolog system was Modular Prolog (MProlog) because of its support for an external language interface as essential feature for coupling the necessary numerical programs with the symbolic computations [71].

6.4 Functionality of Network State Assessment and Enhancement Scheme

A closer look at the process of the network state assessment and enhancement scheme described in section 6.1 revealed that there are some logical decisions involved, hence the control by the super-ordinate expert system. Based on the flow chart of figure 6.1 and the procedure previously described in section 6.2, and using the rule syntax as outlined in appendix B.1, the entire knowledge base was encoded into 8 production rules (see appendix B.2).

Figure 6.3 depicts the process of rule's evaluation with an example. With the invocation of a rule named **limit_detection** (top rounded rectangle), the inference engine matches the text elements **'there', 'is', 'any limits violation'** of the condition part of the rule with the corresponding calling predicate **'there&is&any_limits_violation'** lodged in the central control mechanism. The central control mechanism then passes a string NETWORK_PATH through its external predicate named **state_det** to the corresponding FORTRAN interface subroutine of the same name and number of arguments. A message in telegram form is then sent to the external routine of **network state assessment** which in turn obtained all the applicable data from the power system data setup routines retrieved from the process database. The results of the processing of this external routine are mapped into a data storage result file, and a return message is sent back to the interface routine which in turn accesses the data already mapped in the result file and passes an integer value TOTAL_VIOL as the numeric argument part to the calling predicate of the central control mechanism. Based on this factual information, a logical positive or negative response is derived and then passed on to the inference engine for conclusion on the success or failure of rule's evaluation. The above described procedure is clearly shown with bold curved lines in figure 6.3 and is applicable as general solution.

After the evaluation of this rule which deals with the existence of any operating limits violations as exemplified in more detail above, depending on its result the process is either exited - if the evaluation was negative -, or another rule named **overload_detection** is invoked to determine if the problem is overload related (see figure 6.1).

If it has been established that the problem is overloads related, the user is provided with the summary of the lists of branches experiencing apparent power flow violations in predefined GDL format (see chapter 3), and a rule named **overload_iteration** is activated to check whether the maximum number of allowable iterations in the overloads problem elimination process, in this case a maximum value of 2, is exceeded. If so, then ES checks whether there is any outstanding voltage problem to relieve the overload problem through reactive power dispatch; otherwise, a rule with the name **branch_overload** is activated. The numerical computation of GA real power dispatch (see chapter 4) is communicated with to re-schedule the generating units' real power output in order to remove the overloads. The results obtained through pre-evaluation in the form of generating units' corrected real power schedule and their identifiers are mapped into a list and then accessed by the interface routine which then passes them to the central control mechanism as arguments for optional autonomous execution or for presentation to the operator for manual execution.

For (optional) closed loop operation, the computed **real power set-points** of the generating units and their identifiers in GDL format are entered by the central control mechanism into the **automatic database entry routine**. This first checks for the validity of the assigned values, and through the communication interface directly routes them to the event processing part of the training simulator, and the corresponding power unit models respond accordingly.

For each of the commands executed autonomously, a waiting time of 10 seconds was provided before further proceeding in order to allow to respond to changes in state since the internal clock rate of the training simulator used is 10 seconds which is similar to typical cycle rates for SCADA measurement transmission of real power system control. The (individual) ramping time of the generating units is waited for by remaining in the loop between the rules named **limit_detection** and **branch_overload**.

If the limits violation is not branch overloads related, a rule named **voltage_detection** is activated to establish whether the problem is voltage related. Once a voltage limits violation is found to exist, in a similar manner, a rule named **voltage_iteration** is activated to check whether a maximum number of allowable iterations in the voltage problem elimination process is exceeded. This value was set at 2 iterations. If so, the process is exited with the appropriate message to the user; otherwise a rule with the name **control_selection** is activated, and by pattern matching of the condition part of this rule with the corresponding calling predicate in the central control mechanism the availability of reactive power controller(s) electrically closest to the nodes violating the voltage limits is determined. This is achieved by communicating through the appropriate interface with the numerical computation of the reactive power controllers pre-selection routine (see chapter 5) to select generating units and/or tap changing transformers closest to node(s) experiencing voltage problems. The existence of shunt capacitors and reactors in the network is also determined by retrieving them from the process database. The results obtained are then mapped into 3 lists of selected generating units, tap changing transformers and total

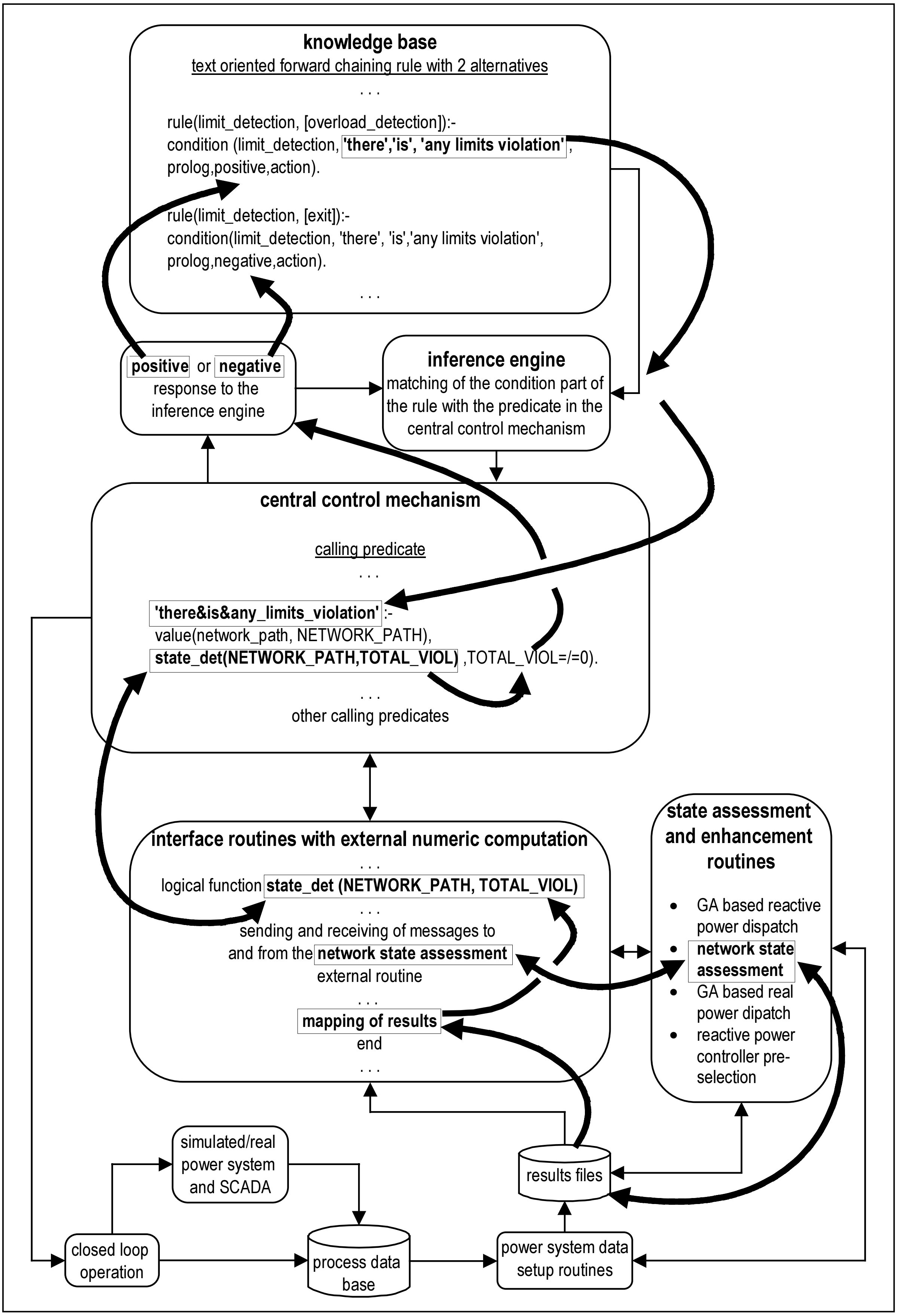

Figure 6.3 Process of evaluation of condition part of a rule as solution strategy (see text)

number of controllers respectively until they are accessed by the reactive power dispatch module to determine their optimal settings. Based on the factual information of total number of controllers as argument passed on to the central control mechanism, it then procures a decision on the controllers' availability for the inference engine.

If the result of the rule's evaluation is negative, a message "consider other measures" is presented to the operator and the process exited; otherwise a rule with the name **voltage_problem** is invoked to provide remedial action for the elimination of voltage limits violation. Accordingly, the numerical computation of GA reactive power dispatch is communicated with through the interface to optimally adjust the pre-selected reactive power controllers in order to eliminate the voltage problem (see chapter 5). The GA reactive power dispatch module first accesses the selected controllers already mapped into the lists and then determines the optimal settings of these controllers. The results of the pre-evaluation in the form of optimal and initial settings of reactive power controllers and their identifiers are additionally mapped into the 4 lists of **generating units, on load tap changing transformers, capacitors** and **reactors** respectively. These lists of control devices are then accessed by the appropriate interface routine and passed on to the calling predicate of the central control mechanism for optional autonomous or manual execution.

If the option of autonomous execution was chosen, the expert system operates in a closed loop fashion without the operators' intervention and the following possibilities exist:

- The computed **generating unit terminal voltage set-points** in the form of commands are entered through the communication interface directly into the process database of the training simulator using the existing automatic database entry program after the validity of each pre-set value has been checked for, and the simulation model responds accordingly; this process anticipates future perspectives of external power unit control which is not given in today's practice.
- In case of **on load tap changing transformers**, the computed tap position setting commands before autonomous execution are checked by a utility program with respect to the remote controllability of the particular transformer as well as the physical feasibility of the intended tap position. The commands are then passed on to the simulator's event processing in the form of integer values of transformer steps. Should the above mentioned check not succeed, a message in form of text is presented to the operator for manual adjustment, as well as the reason for the refusal.

- Concerning the **shunt switching elements (capacitor banks and reactors)**, the same principle applies except that the command to be passed on to the event processing is in the form of switching ‘on’ or ‘off’ commands to the breakers of the banks. This also presupposes the remote controllability of the switches.

In manual operation mode, each of the controller’s identification and their suggested settings are presented to the user/operator for manual adjustment.

The rule named **limit_detection** is activated again in order to detect the existence of any remaining operating limits violations. If there is no more violation existing, the process is exited with success and the system restored to normal state; otherwise further measures such as load shedding remain possible options left to the operator so far.

6.5 Integration into the Existing Restoration Expert System

Because of the modular set-up of the knowledge base and functional structure of the constituent algorithms of the existing restoration expert system [51], the hybrid system developed in this work is intended to be integrated into this restoration system to cater for the recovery of the network to the normal state after the main goal of re-supplying the consumers affected with disturbances has been met. This is made possible because of the modular construction of the hybrid system.

For verification purpose, the system was built as a separate module in this work but it can easily be integrated into the existing restoration expert system. In this way, after the main goal of restoration process has been achieved the restoration expert system in effect calls the corresponding module containing the set of rules of network state assessment and enhancement developed in this work to bring the system back to normal state.