Chapter 7

Testing and Verification of the Hybrid System

Preliminary Remarks

The hybridized genetic algorithm / expert system based network state assessment and enhancement scheme developed in the preceding chapters is a tool dedicated to assist the power system operators to detect and remove any nodal voltage and branch overload problems occurring in the power systems. Before any simulation tests are discussed, two important notions should be carefully addressed: A distinction is drawn here between **verification** and **validation**. Testing, validation and verification of a knowledge based system are very important for expert system research and development. Testing is necessary during the development phase. Since a knowledge based system represents human reasoning and knowledge, it is necessary to justify its representation level through validation. **Validation** refers to building the right system which means that a system performs a given task with an acceptable level of accuracy while **verification** means that the system correctly fulfils its specifications. Validation is achieved through comparing the model's performance and simulation results against known performance and results, usually from a real life equivalent. In the case of a hybrid system, validation is not possible, so careful verification of the simulation model is important. For testing and verification purposes, the hybrid system was coupled with an existing power system operator training simulator. This thus enables one to preset a variety of scenarios on any network modeled on the simulator, and the hybrid system can then be used to restore the network back to the normal state. Verification on two different real German power systems (Duisburg municipal 110/25/10 kV system and a part of the high voltage 400/230/110 kV transmission system), both of them replicated on the operator training simulator in full operational detail, are presented in this chapter. The results of the application proved that the system is able to intelligently detect and remove the operating limits violation in a transparent manner. Depending upon the chosen mode (see chapter 6, section 6.4), the suggestions made by the hybrid system are either presented for manual execution or performed autonomously.

7.1 Testing and Verification on Duisburg Municipal Power System

7.1.1 Description of the Duisburg Power System

For verification of the hybrid system, the Duisburg municipal 110/25/10 kV system was first considered. The system is replicated on the operator training simulator in full operational detail - see example of substation diagram shown in figure 7.2 - and briefly described as follows: 5 generating units (4 thermal units and a gas turbine unit), 46 transformers, 43 of which are equipped with tap changers, and 5 compensation reactors (pure cable network) which can be remotely controlled, 2 tie connections with the neighboring utilities, 208 loads most of which are concentrated at the 10 kV distribution level. Realistic generating units cost coefficients given as quadratic curves obtained from [24,34,39] are assumed as presented in table A.1 (see appendix A); the power system parameter data can be found in [20]. The survey diagram for this particular power system as represented on the training simulator is as shown in figure 7.1.

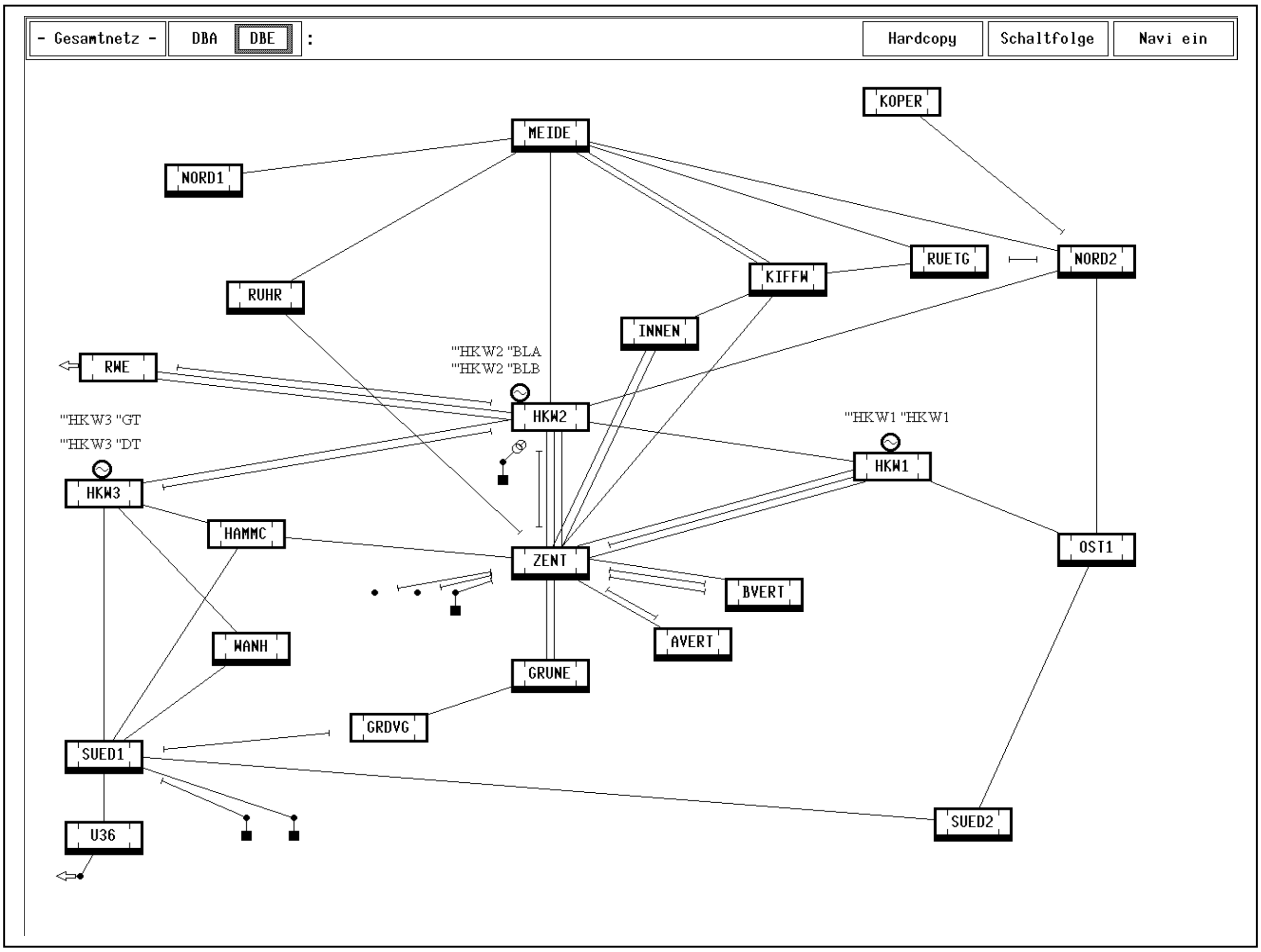

Figure 7.1 Survey diagram of Duisburg power system

In order to create different scenarios of voltage and overload problems in the system, the following means were adopted:

- modifications in the topology and load situation in the network,
- removal or addition of transmission lines, and
- adjustment of operational values of some selected control devices.

7.1.2 Scenarios on Duisburg Power System

Among the various studies conducted on this power system, the following five samples are presented to illustrate the effectiveness of the approach developed in this work:

<u>Scenario 1:</u> Modification of Load Pattern and Adjustment of Transformer Taps

The system was operating in the normal state with all the loads connected except two loads at substation U36. These loads were then reconnected, and 110/25/10 kV transformer at substation MEIDE step was wrongly tapped from 13 to 3. These actions led to the violation of operating limits, and the hybrid system was used to restore the system back to normal state; in doing so, the following steps were taken:

State Assessment

The expert system tried to establish the existence of any operating limit violations using the external component of state assessment, and
- no branch overload was observed,
- over - and under - voltages were observed at four nodes and the summary presented to the user in the following form:

Node '''MEIDE ''25 'TR3	high voltage limit exceeded by 18.2%
Node '''MEIDE ''10 'TR3	high voltage limit exceeded by 15%
Node '''U36 ''10 'TRAFO1	low voltage limit exceeded by 6%
Node '''U36 ''10 'TRAFO2	low voltage limit exceeded by 6%

Figure 7.2 shows the 110, 25 and 10 kV switchyards of substation MEIDE affected by the voltage limit violation.

This figure at the same time exemplifies the grade of detail in which both of the regarded power systems are represented on the training simulator.

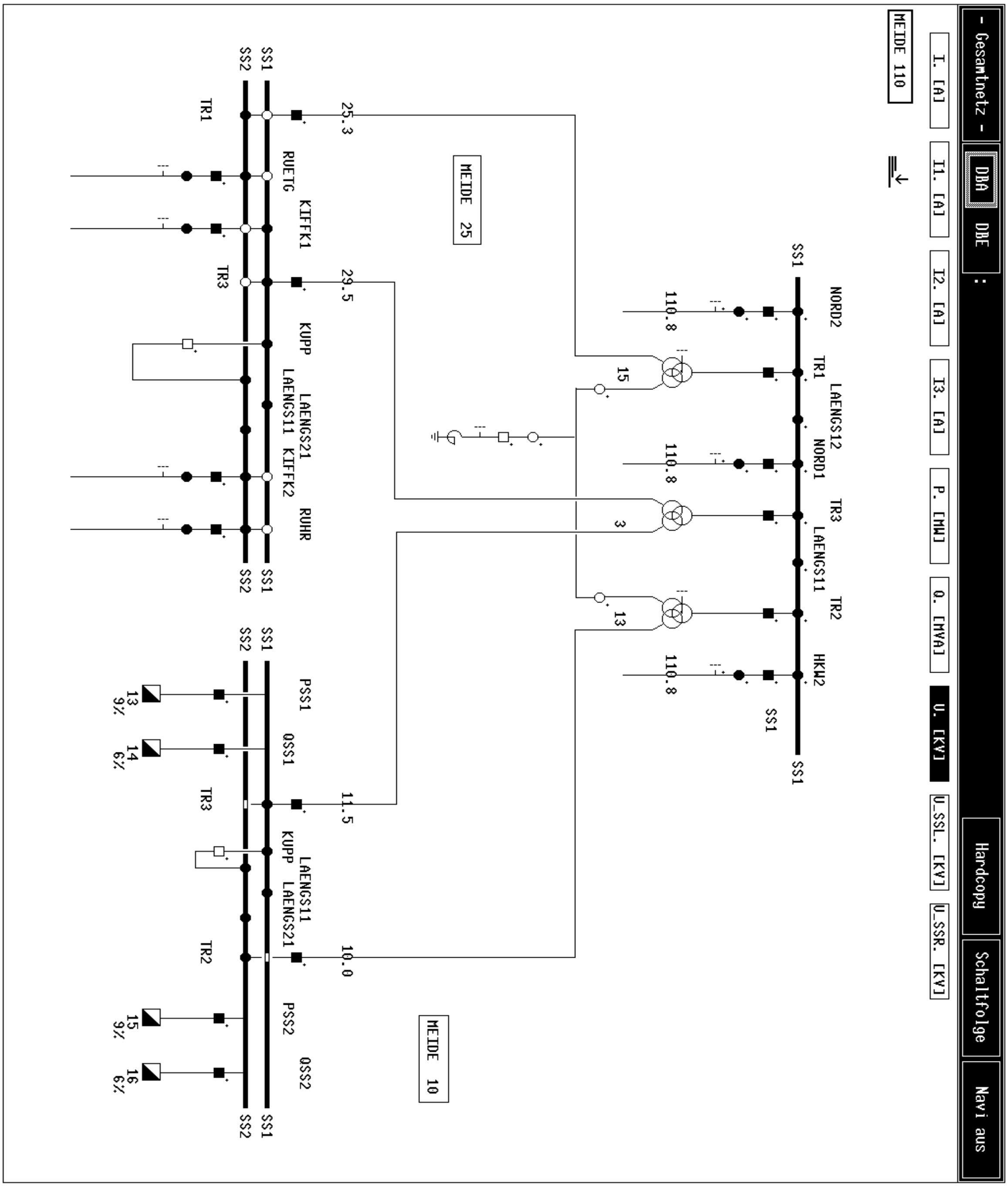

Figure 7.2 Switchyard diagram of substation MEIDE (hardcopy from operational surface of the training simulator

Controller Pre-Selection Mechanism

Two generating units at substations HKW2 and HKW3, and three on-load tap changing transformers - one at substation MEIDE and two at substation U36 - were selected by this mechanism and passed on to the reactive power dispatch to determine their optimal settings for corrective control.

Control Actions

The GA reactive power dispatch module used the above selected controllers and all the 5 available reactors as input to provide a corrective control to the above problem. The following control actions were procured by the expert system to be executed manually or autonomously:

1. Adjust the generating unit ’’’HKW2 ’’BLB terminal voltage from 104% to 105%.
2. Adjust the generating unit ’’’HKW3 ’’DT terminal voltage from 104% to 105%.
3. Adjust the transformer ’’’MEIDE ’’TRAF ’TR3 tap from 3 to 13.
4. Adjust the transformer ’’’U36 ’’TRAF ’TRAFO1 tap from 13 to 9.
5. Adjust the transformer ’’’U36 ’’TRAF ’TRAFO2 tap from 13 to 8.

After the above suggested actions had been executed, the expert system used the component of state assessment to determine whether any operating limits violation were still existing. It was observed that the four voltage limits violations have been alleviated and no other new operating limits violations were caused by the control actions.

Scenario 2: Shutting Down of Generating Unit and Removal of Transmission Line

In this illustrative example, with the power system operating in the state achieved in scenario 1 and one of the parallel cables between substations HKW2 and HKW3 out of service, the generating unit ’’’HKW2 ’’BLA was shut down and a forced outage was introduced in the operating one of the two parallel cables connecting substations HKW2 and HKW3, thus fully disrupting the direct connection between the two substations. These actions led to cable overload in the system. This problem was overcome by the hybrid system in the following manner:

State Assessment

In order to establish the existence of any operating limits violation, the ES called the state assessment module, and a branch overload (3.8%) was detected in the cable connecting substations HKW1 and OST1. The thermal rating for this particular line is 58.0 MVA and the actual flow was 60.2 MVA.

Control Actions

The overload was primarily caused by large active power flows. The active power re-dispatch option was therefore considered by the ES in the removal process by calling the GA active power dispatch module to determine the adjustment to be made to all the three actually synchronized generating units' power output. The following control actions were procured by the expert system to be executed manually or autonomously:

1. Adjust the generating unit '''HKW2 ''BLB power output from 140 MW to 79.8 MW.
2. Adjust the generating unit '''HKW3 ''DT power output from 8.2 MW to 79.8 MW.
3. Adjust the generating unit '''HKW1 ''HKW1 power output from 48 MW to 28.8 MW.

Execution of these changes in generating units' power output resulted in the elimination of the overload without introducing any new operating limit violations.

<u>Scenario 3:</u> Disconnection of Tie Network

Here, the system was initially operating in the normal state achieved in scenario 2 and generating unit '''HKW2 ''BLA was again re-synchronized. Interrupting the tie connection to the external system (RWE) resulted in voltage limits violations at 12 nodes. The following steps were however taken by the hybrid system to restore the power system back to normal:

State Assessment

The expert system established that

- no branch overload was observed, and
- over voltages were observed at 12 nodes, and presented to the user in the form:

Node '''GRUNE ''10' SS1	high voltage limit exceeded by 1%
Node '''MEIDE ''25 'TR3	high voltage limit exceeded by 0.6%
Node '''MEIDE ''10 'TR2	high voltage limit exceeded by 1%
Node '''HKW2 ''110' HO_SUED	high voltage limit exceeded by 2.2%
Node '''NORD2 ''10 'SS2	high voltage limit exceeded by 1%
Node '''NORD2 ''10 'L_SPULE	high voltage limit exceeded by 1%
Node '''WANH''10 'SS2	high voltage limit exceeded by 1%

Node ’’’WANH’’10’ SS1	high voltage limit exceeded by 1%
Node ’’’SUED2 ’’10 ’L_SPULE1	high voltage limit exceeded by 1%
Node ’’’SUED2 ’’10 ’L_SPULE2	high voltage limit exceeded by 1%
Node ’’’OST1 ’’10 ’TR2	high voltage limit exceeded by 2%
Node ’’’OST1 ’’10 ’TR1	high voltage limit exceeded by 2%

Controller Pre-Selection Mechanism

Since the problem was voltage related, the ES used the controller pre-selection mechanism first to select the most voltage sensitive controllers. Four generating units and 12 on-load tap changing transformers were selected by this mechanism and passed on to the GA reactive power dispatch module to determine their optimal settings for corrective control.

Control Actions

The GA reactive power dispatch module used the selected controllers and all the 5 available reactors as input to provide a corrective control to the above problem. At the end of the solution process, the total number of controllers considered was further curtailed to 10 (i.e. 2 of the 4 selected generating units, 8 of the 12 selected transformers and no reactor). The control actions procured by the expert system to be executed manually or autonomously are summarized thus:

1. Adjust the generating unit ’’’HKW2 ’’BLA terminal voltage from 104% to 100%.
2. Adjust the generating unit ’’’HKW1 ’’HKW1 terminal voltage from 106% to 100%.
3. Adjust the transformer ’’’GRUNE ’’TRAF ’TRH tap from 9 to 13.
4. Adjust the transformer ’’’KIFFW ’’TRAF ’TR2 tap from 8 to 10.
5. Adjust the transformer ’’’HKW2 ’’TRAF ’TRHN tap from 11 to 9.
6. Adjust the transformer ’’’HKW2 ’’TRAF ’TRBLBAN tap from 10 to 9.
7. Adjust the transformer ’’’NORD2 ’’TRAF ’TR2 tap from 9 to 13.
8. Adjust the transformer ’’’WANH ’’TRAF ’TR1 tap from 9 to 13.
9. Adjust the transformer ’’’OST1 ’’TRAF ’TR1 tap from 9 to 13.
10. Adjust the transformer ’’’RUHR ’’TRAF ’TRS tap from 12 to 13.

After the above suggested actions had been executed, it was established by the expert system that the voltage problem was solved and no new operating limits violations were caused by these control actions.

Scenario 4: Modification of Load Pattern

A number of loads at substations AVERT, BVERT and INNEN were deactivated in order to modify the load situation in the network from 249 MW to 197 MW. A voltage problem was induced in the power system at three nodes as a result of these actions. The process taken to solve this problem was:

State Assessment

The expert system established that
- no branch overload was observed, and
- over voltages were detected at 3 nodes with a violations summary as follows:

Node '''HKW2 ''6 'BLBAN	high voltage limit exceeded by 5%
Node '''INNEN ''10 'TRM	high voltage limit exceeded by 2%
Node '''INNEN ''10 'TRN	high voltage limit exceeded by 2%

Controller Pre-Selection Mechanism

One generating unit and three on-load tap changing transformers were selected by this mechanism for GA reactive power dispatch to determine their optimal settings for corrective control.

Control Actions

The GA reactive power dispatch module used the above selected controllers and all the 5 available reactors as input to provide a corrective control to the above problem. At the end of the solution process, 3 transformers and a reactor were used to eliminate the problem. The control actions procured by the expert system were:

1. Adjust the transformer '''INNEN ''TRAF 'TRM tap from 12 to 13.
2. Adjust the transformer '''INNEN ''TRAF 'TRN tap from 12 to 16.
3. Adjust the transformer '''HKW2 ''TRAF 'TRBLBAN tap from 9 to 13.
4. Switch the reactor'''SUED2 ''10 'L_SPULE2 breaker and isolator on.

After the above suggested actions had been executed, the expert system used the component of state assessment to determine whether any operating limits violation would still exist. It was observed that the voltage violations had been alleviated and no other new operating limits violations were caused by the control actions.

Scenario 5: Wrong Transformer Tap Setting

All the loads and cables of the power system removed in the above scenarios were restored to their original state, with the transformer steps remaining in the states procured in the previous scenarios, thus making the situation different from that of scenario 1. As a result of wrong tap setting of transformer ’’’MEIDE ’’TRAF ’TR3 at substation MEIDE from 13 to 3 (see figure 7.2), both voltage and overload problems were induced in the power system at 27 nodes and in a transmission cable respectively. The steps involved in the detection and elimination of these problems were:

State Assessment

The expert system first established that
- there was a branch overload in one of the cables connecting substations MEIDE and KIFFW (actual flow was 18.31 MVA and thermal rating is 18.0 MVA), and
- there were over voltages ranging between 1% and 11% at 27 nodes.

Control Actions

The module of GA active power dispatch used the four actually synchronized generating units’ power output to provide a corrective control for the overload problem. At the end of the solution process, the control actions procured by the expert system were:

1. Adjust the generating unit ’’’HKW2 ’’BLB power output from 71.4 MW to 71.2 MW.
2. Adjust the generating unit ’’’HKW3 ’’DT power output from 71.4 MW to 71.2 MW.[1]

After the above suggested actions had been executed, the expert system used the component of state assessment to find out whether any operating limits violation would still exist. It was observed that the overload problem was still persisting even after the maximum allowable iterations number of 2 had been exceeded. The ES then checked for the existence of an outstanding voltage problem (see chapter 6, figure 6.1), and over voltages were detected at 27 nodes.

[1] Identical technical data and cost coefficients of both generating units, see appendix A, table A.1.

Controller Pre-Selection Mechanism

Three generating units and ten on-load tap changing transformers were selected by this mechanism for GA reactive power dispatch to determine their optimal settings to alleviate the
voltage problem.

Control Actions

The above 13 selected controllers and all the available five reactors served as input to the GA reactive power dispatch module to provide a corrective control to the above problem. At the end of the solution process, the total number of controllers for corrective control was further curtailed to nine (i.e. 1 of the 3 selected generating units, 8 of the 10 selected transformers and no reactor). The control actions procured by the expert system to be executed manually or autonomously are summarized thus:

1. Adjust the generating unit '''HKW2 ''BLB terminal voltage from 105% to 102.5%.
2. Adjust the transformer '''MEIDE ''TRAF 'TR3 tap from 3 to 13.
3. Adjust the transformer '''KIFFW ''TRAF 'TR1 tap from 8 to 10.
4. Adjust the transformer '''ZENT ''TRAF 'TRANFA tap from 3 to 4.
5. Adjust the transformer '''GRUNE ''TRAF 'TRI tap from 12 to 14.
6. Adjust the transformer '''INNEN ''TRAF 'TRM tap from 13 to 18.
7. Adjust the transformer '''INNEN ''TRAF 'TRN tap from 16 to 17.
8. Adjust the transformer '''RUHR ''TRAF 'TRN tap from 12 to 18.
9. Adjust the transformer '''RUHR ''TRAF 'TRS tap from 13 to 18.

After the above suggested controller actions had been executed, both overloads - and voltage - problems were successfully eliminated.

7.2 Testing and Verification on 400/230/110 kV Transmission System

7.2.1 Description of Transmission System

In order to further verify the capabilities of the hybrid system, a part of the German high voltage 400/230/110 kV transmission system was also considered. This system is equally replicated on the operator training simulator in operational detail and briefly described below:

The system consists of 24 generating units (16 thermal, 7 gas turbines and one pressurized water reactor), 85 transformers equipped with tap changing facilities of which 77 can be remotely controlled, 12 tie connections with neighboring utilities, and 53 loads. Realistic generating units cost coefficients given as quadratic curves were obtained from [24,34,39] as presented in table A.2 (see appendix A), and the power system data can be obtained from [20]. The survey diagram for this particular power system, as represented on the training simulator is as shown in figure 7.3.

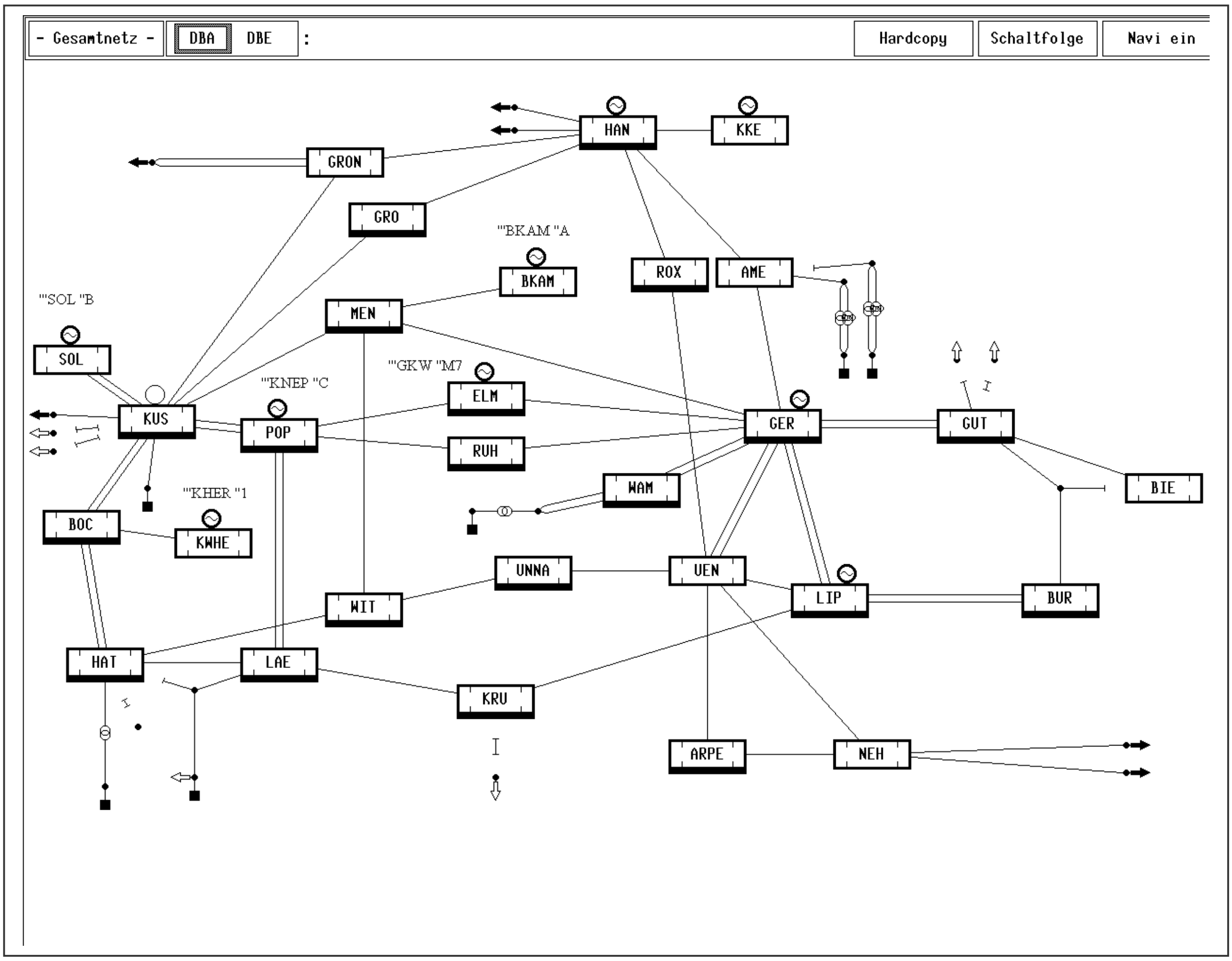

Figure 7.3 Survey diagram of high voltage transmission system

7.2.2 Scenarios on Transmission System

<u>Scenario 1:</u> Modification of Load Pattern and Wrong Setting of Transformer Tap

Loads at substations ARPE, MEN, ROX and UNNA were deactivated in order to modify the load situation in the network, and the transformer '''ELM ''TRAF '212 at substation ELM step was wrongly adjusted from 26 to 7. A voltage problem was induced in the power system at a node as result of these actions. The process taken to solve this problem was:

State Assessment

The expert system established that
- there was no branch overload, and
- over voltage was detected at a node with the violations summary as follows:

Node '''ELM ''110 '212   high voltage limit exceeded by 1.5%

Controller Pre-Selection Mechanism

A generating unit '''GKW ''M7 and an on-load tap changing transformer '''ELM ''TRAF '212 were selected by this mechanism.

Control Actions

The GA reactive power dispatch module used the controllers selected by the controller pre-selection mechanism as input to provide a corrective control to the above problem. At the end of the process only the transformer was used to eliminate the voltage problem. The control action procured by the expert system was:

1. Adjust the transformer '''ELM ''TRAF '212 tap from 7 to 26.

After the above suggested action had been executed, the expert system by means of the state assessment determined that the voltage problem had been solved and no other new operating limits violations were caused by this control action.

Scenario 2: Outage of a Transmission Line

The system was in normal operating condition when a transmission line connecting substations UEN and NEH (see figure 7.3) was de-energized as a result of forced outage. An over voltage problem was however provoked as a result of this action. The process taken by the hybrid system to solve this problem was:

State Assessment

Using this module the expert system established that

- there was no branch overload, and
- over voltage was detected at a node with following violation summary:

Node '''UNNA ''110 '411 high voltage limit exceeded by 2.5%

Controller Pre-Selection Mechanism

Generating unit '''BKAM ''A and transformer '''UNNA ''TRAF '411 were selected by this mechanism for GA reactive power dispatch to determine their optimal settings for corrective control.

Control Actions

The GA reactive power dispatch module used the 2 selected controllers as input to provide a corrective control to the above detected problem. At the end of the optimization procedure, only one on-load tap changing transformer was used to eliminate the problem. The following action was suggested:

1. Adjust the transformer '''UNNA ''TRAF '411 step from 1 to 5.

After execution of the suggested control action, the expert system by the use of the state assessment established that the voltage problem had been removed and no other new operating limits violations were caused.

Scenario 3: Forced Outage of Transmission Lines

The system was in normal operating condition when the transmission lines connecting substations WIT and MEN and that connecting substations WIT and UNNA (see figure 7.3) were disconnected as a result of forced outage. Under voltages ranging between 1.1% and 17% were provoked at 10 nodes as a result of these actions. The process taken by the hybrid system to solve this problem was as follows:

State Assessment

It was established by the expert system that

- there was no branch overload, and
- under voltages were detected at 10 nodes with the violations summary as follows:

Node '''SOL ''220 'S1	low voltage limit exceeded by 1.5%
Node '''KUS ''220 'S3	low voltage limit exceeded by 1.8%
Node '''POP ''220 'S1	low voltage limit exceeded by 0.9%
Node '''BOC ''220 'S1	low voltage limit exceeded by 1.1%
Node '''RUH''30 '231	low voltage limit exceeded by 0.7%
Node '''HAT ''380 'S1	low voltage limit exceeded by 8%
Node '''WIT ''380 'S1	low voltage limit exceeded by 8.6%
Node '''WIT ''110 '412	low voltage limit exceeded by 17%
Node '''WIT ''110 'TEW_WI_W	low voltage limit exceeded by 8.5%
Node '''LAE ''30 '231	low voltage limit exceeded by 2%

Controller Pre-Selection Mechanism

Three generating units and nine on-load tap changing transformers were selected by this mechanism.

Control Actions

The GA reactive power dispatch module used the 12 selected controllers as input to provide a corrective control to the above detected problem. At the end of voltage problem elimination procedure, 3 generating units and 8 on load tap changing transformers were used to eliminate the problem with the following control actions:

1. Adjust the generating unit '''SOL ''B terminal voltage from 100% to 102%.
2. Adjust the generating unit '''KNEP ''C terminal voltage from 107.5% to 110.0%.
3. Adjust the generating unit '''KHER ''1 terminal voltage from 107.5% to 100%.
4. Adjust the transformer '''SOL ''TRAF 'B tap from 10 to 19.
5. Adjust the transformer '''KUS ''TRAF '212 tap from 14 to 19.
6. Adjust the transformer '''POP ''TRAF '211 tap from 11 to 9.
7. Adjust the transformer '''BOC ''TRAF '211 tap from 9 to 16.
8. Adjust the transformer '''RUH ''TRAF '231 tap from 12 to 10.
9. Adjust the transformer '''HAT ''TRAF '421 tap from 4 to 26.
10. Adjust the transformer '''LAE ''TRAF '231 tap from 9 to 4.
11. Adjust the transformer '''WIT ''TRAF '411 tap from 14 to 24.

After the above suggested actions had been executed, the expert system, using the state assessment module established that the voltage problem has been removed and no other new operating limits violations were caused as a result of the control actions.

7.3 Concluding Remarks

From the foregoing diverse scenarios on both the municipal and transmission power systems, the hybrid solution combining GA and ES technology has successfully proved to be a good platform to solving overload and voltage problems. It has provided the flexibility and ease-of-use to allow an incorporation of the relevant power system operation expertise as well as the functionality to procure meaningful solutions in transparent manner. Implementation in the training simulator control environment gave the opportunity of testing and verification under operational realism; furthermore, the incorporated optional mode of autonomous execution of control command anticipates a taste of future power system operation.