

Implementation of a Power System Dynamic Security Assessment and Early Warning System

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Abstract—A real time dynamic security assessment and early warning (DSAEW) system for the purpose of keeping interconnected power systems operating in security region, monitoring dynamic security margin constantly and ensuring system operation reliability is proposed in this paper. The framework of the DSAEW system is designed in accordance with Client/Server and Browser/Server models based on the TCP/IP protocol. In this paper, the overall system architecture, function design and technology used of such tool including TSA- Transient Stability Assessment, VSA- Voltage Stability Assessment is presented. Furthermore, the calculation of some operation limits involving the bus voltage limits, the branch/corridor transfer power limits and the P-load limit of the whole system is introduced in this paper as well. On one hand, the DSAEW system can easily and conveniently integrate with existing Energy Management System (EMS) to implement the real time dynamic security assessment. On the other hand, the DSAEW system can make intensive dynamic analysis related to the specified case study as an off-line simulation platform.

Index Terms—voltage stability analysis, transient stability analysis, energy management system, security early warning, real time mode, training mode, operation limits

I. INTRODUCTION

IN recent years, power systems have become more complex due to the continuous upgrading of equipment. Specially, with introduction of the deregulated and unbundled power market operational mechanism, the electricity supply industry was compelled to make full use of available facilities in pursuit of economical management. Consequently, it is likely that power systems will be operated under increasingly stressed conditions. Accordingly, the critical dynamic behaviour and the stability issues are posing great challenges to the operation of interconnected power systems. Consider that the interconnected power systems are complex large-scale, long-distance, high-voltage and heavily loaded transmission

systems, and the installation of FACTS (Flexible ac transmission systems) devices, which increases the system complexity further, it is important to keep interconnected power systems operating in security region and monitor dynamic security margin constantly under normal operation conditions so as to ensure system operation reliability [1], [2]. Therefore, developing a dynamic security assessment and early warning (DSAEW) system to analyze and simulate possible contingencies in order to classify potential harmful situations and to indicate and even operate preventive and/or corrective remedial actions is significant and necessary.

This paper presents the overall architecture and some fundamental physical concepts which involve how to determine system operation limits constrained by voltage security / transient security numerically. The dynamic security assessment scope is to provide Energy Management System (EMS) operators with a tool for transient/voltage stability analysis to be used on-line during the normal cycle of real time operation and off-line with the purpose of study and research. The main DSAEW technical functions are to provide system operation limits which involve bus voltage limits, branch/corridor transfer power limits, active power loading limit of the whole system et al, under a certain load-generation increasing pattern with respect to an usual contingency set. Specially, the voltage separation between the real operating condition and the operation limit is represented as the system dynamic-security-constrained margin, which can be visualized for dispatcher to monitor the current operation state of power system.

This paper is organized as follows. Section II presents the operation functions and architecture of DSAEW system. In Section III, the key module design philosophy is discussed. The calculation of operation limits is described in Section IV. Section V details the preliminary results. The conclusions are summarized in Section VI.

II. SYSTEM ARCHITECTURE AND FUNCTION DESCRIPTION

In the DSAEW system, the following two operating modes can be available: (i) Real time mode, (ii) Training mode. In the real-time mode, the EMS feeds DSAEW system with network data and solutions periodically for dynamic security analysis. Once the real-time mode is triggered, the whole operating process is automatic. In the training mode, the dispatcher can make the further intensive analysis for the specific historical data. On the other hand, the dispatcher can perform the dynamic security assessment for the future

This work was supported in part by the National Natural Science Foundation of China (Project 50337010), the National Key Basic Research Special Foundation of China (Project 2004CB217900) and the Key Laboratory of Power System Protection and Dynamic Security Monitoring and Control Ministry of Education (KWO2003)

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operating condition for the planning purpose.

The DSAEW system runs in a distributed environment with the Client/Server (C/S) and Browser/Server (B/S) operating modes. The corresponding system configuration is shown in Figure 1.

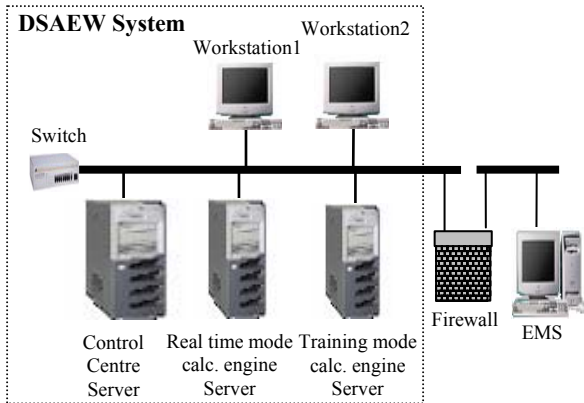


Fig. 1. Overall DSAEW system architecture.

Figure 2 shows the calculation flow chart.

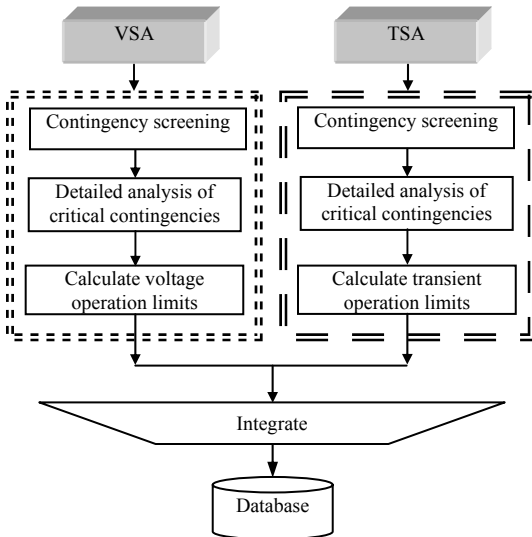


Fig. 2. DSAEW system calculation flow chart.

In accordance with the DSAEW architecture and the system calculation flow chart shown in Fig. 2, total 6 system functional modules can be designed as follows. (i) TSA [3], [4] real time mode; (ii) TSA training mode; (iii) VSA [5] real time mode; (iv) VSA training mode; (v) TSA & VSA real time mode; (vi) TSA & VSA training mode. Each mode can run in parallel simultaneously as well as operating independently.

III. KEY MODULE DESIGN PHILOSOPHY

The advanced technologies are widely used in the design and development of DSAEW system, which include (i) C/S and B/S models based on the TCP/IP protocol; (ii) Programming with Visual C++, Visual Basic, SourceSafe and OOP (object-oriented programming), component technology

[6]; (iii) Data Access Objects (DAO), Open Database Connectivity (ODBC) and ActiveX® Data Objects (ADO) [7]; (iv) Process mode based parallel computing, Shell programming et al. In the DSAEW system, the TSAT/VSAT commercial software [8], [12] is embedded as API interface to calculate the corresponding voltage and transient security operation limits.

A. Real time Operating Mode

In this mode, the required system data including the current operating conditions and the real time power flow data are periodically transferred from SCADA/EMS to the DSAEW system using the specified channel and the specific transfer mechanism. Once the real time operating mode is triggered, the whole operating process is automatic. The corresponding data and execution flow chart is shown in Figure 3.

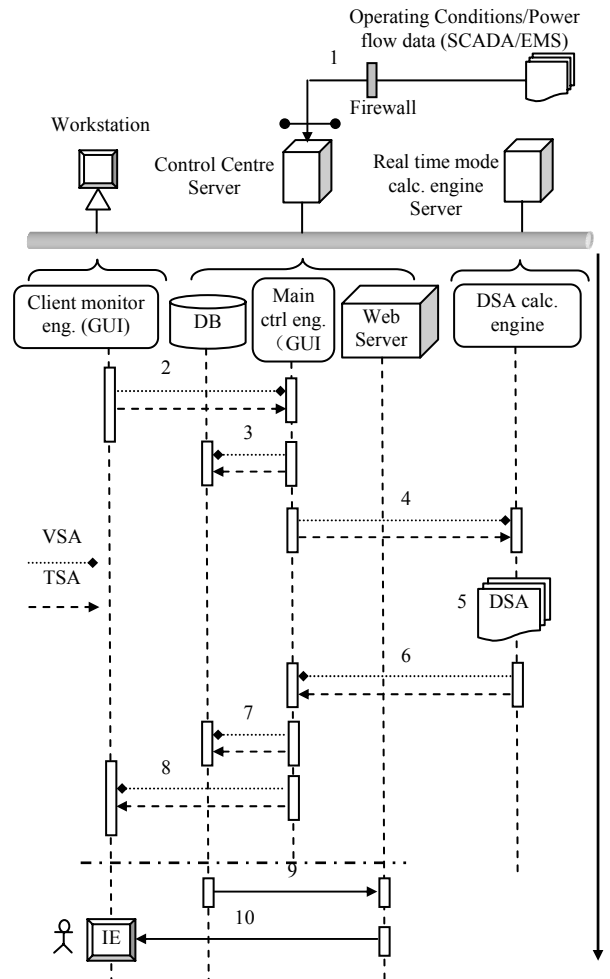


Fig. 3. DSAEW system real time operating mode flow chart.

- (1) Transfer the real time operating conditions and power flow data from SCADA/EMS to the DSAEW system;
- (2) Trigger the real time operating mode using the Client Monitor Engine;
- (3) Monitor the latest SCADA/EMS data and backup;
- (4) Send the latest power flow data to Calculation Engine Server;

- (5) Make dynamic security analysis using process mode based parallel computing technique with multi-CPU support;
- (6) Return the results to the Control Centre Server;
- (7) Analyze the results and record useful information to database;
- (8) Inform dispatcher the current system dynamic security assessment finished;
- (9) Retrieve the latest result information from database;
- (10) Browse the results using IE.

B. Training Operating Mode

In this mode, there are two kinds of implementation modes can be available.

Mode I: The dispatcher can make intensive off-line dynamic security assessment with respect to the specified historical data.

Mode II: For the planning purpose, the dispatcher perform the predicative analysis for the future system operating conditions according to the historical data, and compare with the results from real time operating mode.

Figure 4 shows the data and execution flow chart.

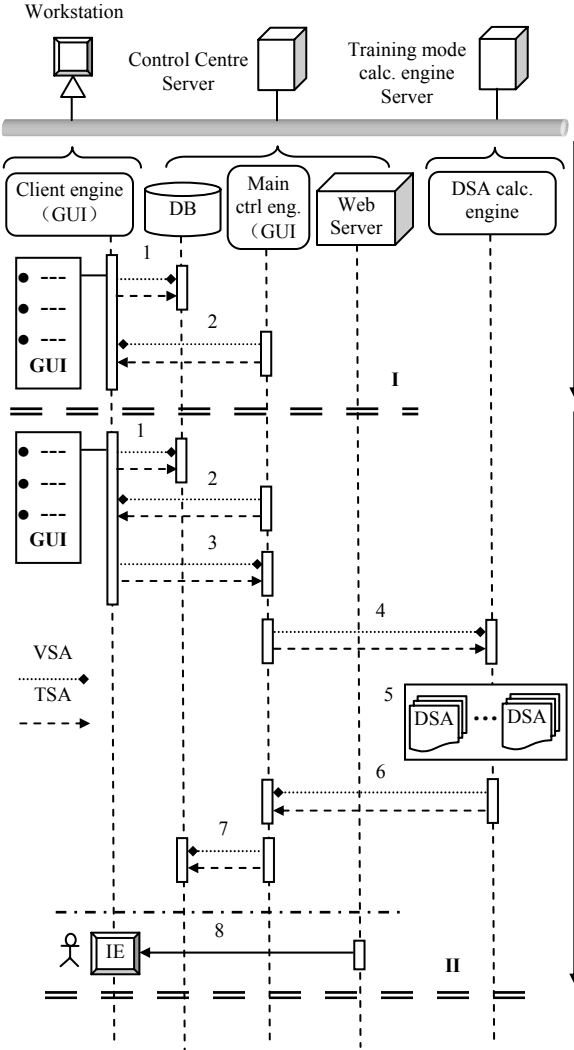


Fig. 4. DSAEW system training operating mode flow chart.

- (1) Form the off-line analysis data list using client-side tool;
- (2) Download these data files from Control Centre Server to the local workstation for further intensive analysis;
- (3) Upload the adjusted data files to the Control Centre Server;
- (4) Transfer these data files to the Training mode Calculation Engine Server further;
- (5) Make dynamic security analysis for the queued data files using process mode based parallel computing technique with multi-CPU support;
- (6) Return the results to the Control Centre Server;
- (7) Analyze the results and record useful information to database;
- (8) Browse the results using IE.

C. Web Client GUI

In the DSAEW system, the corresponding resulting display is based on the B/S model. The dispatcher can intuitively, rapidly and dramatically observe the current system operating condition and know how far the current operation state is from dynamic security region boundary through the web client GUI. In order to review the system operation state more fully and intensively, the man-machine interaction mode is designed in the DSAEW system. The details are shown in Table I.

TABLE I
MAN-MACHINE INTERACTION MODE BASED ON THE WEB CLIENT GUI

Type	Date/Time	Op.	Date/Time Selection		Auto Refresh	Voltage/Trans. Stability	N-1/N-2 Spec. Ctg
			Client	Server			
Chart	Auto	Real	×	√	Y	√	√
	Man.	Real	Date	Time	Time only		
	Man.	Hist.	√	×	×		
Table	Hist. only		√	×	×	√	√

From Table I, for chart resulting display, if the date/time selection is 'Auto' and the operating condition is 'Real', the dynamic security assessment results can be displayed based on the current time and refresh automatically. Similarly, if the date/time selection is 'Manual' and the operating condition is 'Real', the dispatcher needs to set the specific date on the web client GUI. Once the date is selected, the corresponding resulting display can automatically refresh with the specific date. If the date/time selection is 'Manual' and the operating condition is 'Historical', the dispatcher must select the specific date and time to review the results.

IV. CALCULATION OF OPERATION LIMITS

Just as mentioned earlier, the main aim of the developed DSAEW system is to provide system operation limits under a certain load-generation increasing pattern with respect to an usual contingency set. Usually, applying analytical methods [9]-[11] to determine security regions of the large-scale power systems which include many dynamic elements such as HVDC links, FACTS devices et al., is very difficult and almost infeasible. Naturally, the numerical simulation based approaches seem to be alternative, and the corresponding obtained power system security region is called as *power*

system numerical security region. Specially, the one-dimension security limit is defined as *power system operation limit*.

The calculation of the operation limits is based on a given power transfer under all critical contingencies. A power transfer is defined as a set of power flow dispatches in which the generation and/or loads are changed to meet specific system dispatch conditions. The power transfer is with respect to the source-and-sink concept (in general, Source refers to as generation and Sink refers to as load), as shown in Figure 5 in which a combination of generation and load dispatches in the Source is applied to meet the load increase in the Sink.

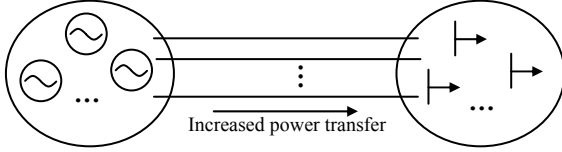


Fig. 5. Description of a power transfer.

Suppose a given source-sink pattern is as follows

$$\mathbf{P}_{\text{source}} = \mathbf{P}_{\text{source}(0)} + k\mathbf{h}_{\text{source}}, k=1,2,3,\dots \quad (1)$$

$$\mathbf{P}_{\text{sink}} = \mathbf{P}_{\text{sink}(0)} + k\mathbf{h}_{\text{sink}}, k=1,2,3,\dots \quad (2)$$

where $\mathbf{P}_{\text{source}}$ and \mathbf{P}_{sink} are the Source and Sink vectors, respectively; $\mathbf{h}_{\text{source}}$ and \mathbf{h}_{sink} are the step sizes for Source and Sink, respectively.

The critical contingency set is defined as

$$\mathbf{c} = \{c_1, c_2, \dots, c_n\} \quad (3)$$

A. Operation Limit Solutions

In Eqs.(1-2), with increasing of the specified step size, all critical contingencies described in Eq.(3) are analysed at each step. If any security criteria violations (e.g., voltage stability or transient stability) occur, the operating point (transfer level) at that time is deemed as insecure. The value of the transfer at the last secure point is reported as the transfer security limit.

Let the Sink value be the independent variable. With increasing of the variable, some relationships between the Sink variable and the operating parameters which include the bus voltage magnitude, branch transfer power et al., under base case and post-contingency can be depicted. And the corresponding relationship can be described using the following implicit function expression:

$$\mathbf{s} = f(P_{\text{sink},k}) \quad (4)$$

where \mathbf{s} represents the operating parameter vector; $P_{\text{sink},k}$ is the increase of Sink value at k th step. Under base case (pre-contingency) operating condition, the following three situations need to be addressed.

(i) The Eq.(4) is monotonously increasing function as shown in Figure 6(a). An upper limit for the operating parameter can be found as

$$\mathbf{s}_{\text{limt}}^u = f(P_{\text{sink},\text{limt}}) \quad (5)$$

$\mathbf{s} < \mathbf{s}_{\text{limt}}^u$ and $\mathbf{s} \geq \mathbf{s}_{\text{limt}}^u$ correspond to secure (stable) and

insecure (unstable) conditions respectively.

(ii) The Eq.(4) is monotonously decreasing function as shown in Figure 6(b). A lower limit for the operating parameter can be found as

$$\mathbf{s}_{\text{limt}}^l = f(P_{\text{sink},\text{limt}}) \quad (6)$$

$\mathbf{s} > \mathbf{s}_{\text{limt}}^l$ and $\mathbf{s} \leq \mathbf{s}_{\text{limt}}^l$ correspond to secure (stable) and insecure (unstable) conditions respectively.

(iii) The Eq.(4) is not monotonously increasing or decreasing function. There is no operation limit can be available.

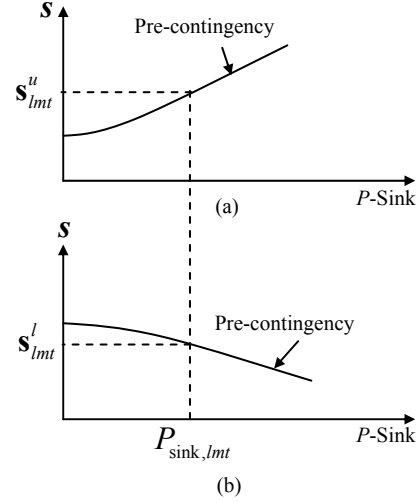


Fig. 6. The relationships between the Sink variable and the operating parameters.

B. Typical Operation Limits

Three kinds of typical operation limits are addressed in this section. The corresponding visualization technology is used to help dispatcher understand the system operation limits better.

(i) Bus voltage limits. In general, the bus voltage limits are solved as the lower limits which correspond to the base case under the most critical contingency. In the DSAEW system, the so-called spider chart is used to visualize the voltage limits.

(ii) Branch transfer power limits. The branch transfer power limits can be the upper limits or the lower limits in accordance with the different situations as shown in Figure 6. In the DSAEW system, the bar chart is used to visualize the branch transfer power limits.

(iii) Load limit (system margin). It is related to the different load-generation increasing pattern. Usually, the minimum separation between the Sink limit value and the Sink initial value for all critical contingencies. In the DSAEW system, the histogram is used to visualize the load limit.

To implement overall DSAEW system efficiently, some advanced and commercial power system simulation software with contingency scanning function can be used as the numerical calculation engine [8], [12]. However additional programming, analysis and data processing are required for DSAEW purpose.

V. PRELIMINARY RESULTS

A real-sized modified Chinese power system of 1101 buses, 97 generators and 5 areas was used for test. The following results can be available in the DSAEW system.

(i) Top critical contingencies. The contingency name, P-load limit value, fault information, critical buses, critical branches et al., can be available. The number of the critical contingencies can be set by dispatcher.

(ii) Critical buses. Combining the critical buses related to each critical contingency can form the final required critical bus set. The corresponding voltage limits can be available. The number of critical buses for each critical contingency can be set by dispatcher.

(iii) Critical branches. Similar as the critical buses mentioned above. Combining the critical branches related to each critical contingency can form the final required critical branch set. The branch transfer power limits can be available.

(iv) Corridors. The corridors consist of the tie lines or the specified branch set. The corridor transfer power limits as well as each tie line transfer power limit can be available.

(v) Special monitored buses/branches. The corresponding operation limits with respect to these specified buses/branches must be solved and displayed on the web client GUI.

Figure 7 shows the whole monitoring GUI of dynamic security assessment with respect to a certain operating condition.

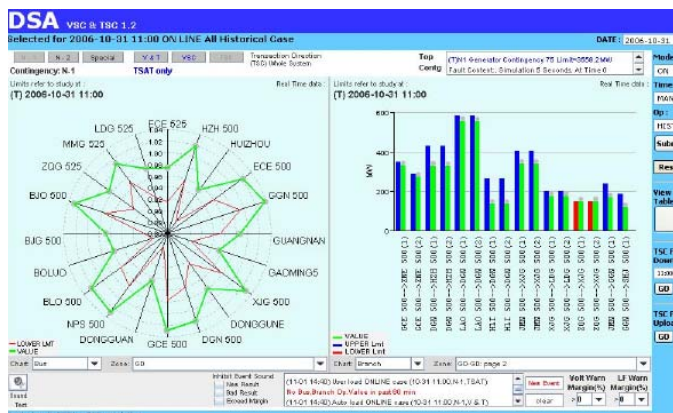


Fig. 7. DSA Monitoring GUI with respect to a certain operating condition.

In Fig.7, the left half window shows the critical buses using spider chart. The real time operating condition is represented by the outer envelope curve marked with green color. The corresponding voltage limits is represented by the inner envelope curve marked with red color. The security margin for a critical bus can be seen intuitively and dramatically on the spider chart. The right half window shows the critical branches using bar chart.

The monitoring GUI related to the corridors and system margin is shown in Figure 8.

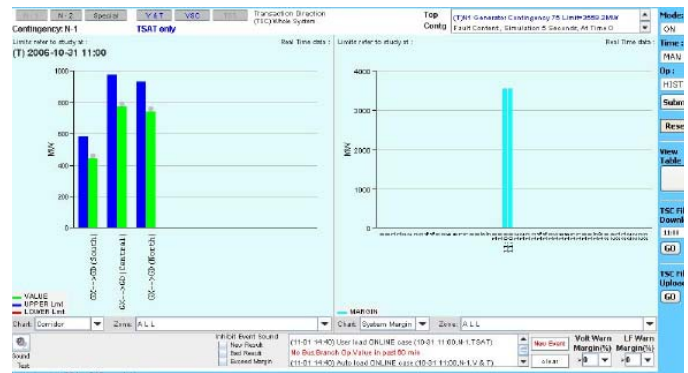


Fig. 8. DSA Monitoring GUI with respect to the corridors and system margin.

Figure 9 shows the security assessment dynamic process with respect to the specified bus or branch.

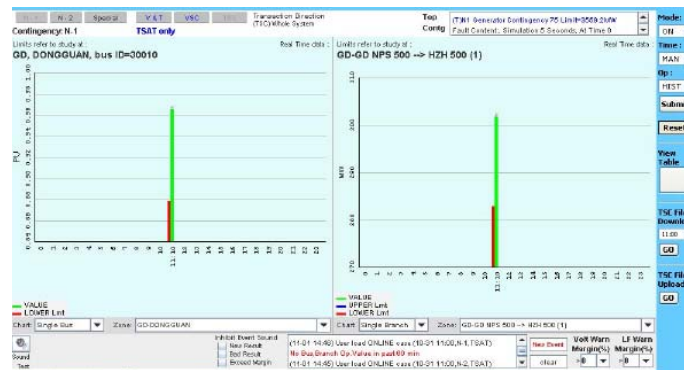


Fig. 9. Security assessment dynamic process with respect to the specified bus or branch.

In the DSAEW system, once the real operating condition is lower or higher than the operation limit, the system will warn the dispatcher through the audible and visual alarm. Furthermore, if there exists at least one contingency in the pre-defined contingency set (N-1, N-2, user-defined et al.), which violates the system security criteria based on the base case operating condition, the result of DSA for the system related to the specific contingency is defined as unstable state. Figure 10 details such situation.

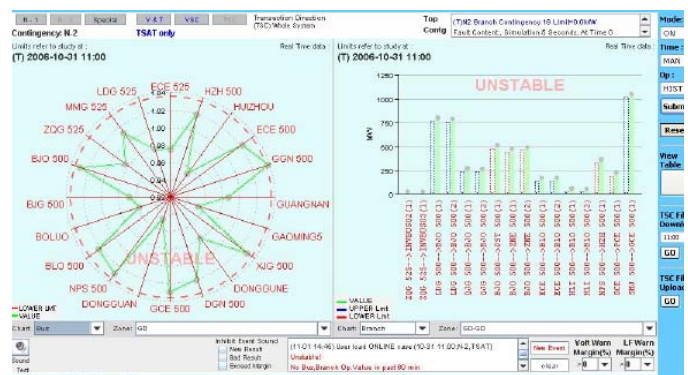


Fig. 10. DSA Monitoring GUI with respect to the unstable case.

In order to obtain the more details about the critical buses and branch circuits as well as the corridors, some tables are designed to assist operators get more useful information. Figure 11 shows the corresponding GUI.

No	Name	System	Phase	Fault	Comment	Status
1	N1 Branch Contingency 355MHW	355MHW		At Time 0 Seconds, Three Phase Fault On Line :J31062, J35111, L16 /HCB525-1 Q1N 823		22.09
2	N1 Generator Contingency 73	355MHW		At Time 0 Seconds, Disconnect Generator :J35370, L1 / SHANTOU2G, Nansore		25.06
3	N1 Generator Contingency 72	355MHW		At Time 0 Seconds, Disconnect Generator :J35369, L1 / SHANTOU2G1, Nansore		26.06
4	N1 Generator Contingency 75	355MHW		At Time 0 Seconds, Disconnect Generator :J35372, L1 / J31010, Romore		26.57
5	N1 Branch Contingency 31	355MHW		At Time 0 Seconds, Three Phase Fault On Line :J30065, J30033, J216 /J300 509 LDC 556		28.24
6	N1 Branch Contingency 32	355MHW		At Time 0.1 Seconds, Clear Three Phase Fault On Line At Near End, Clear Three Phase Fault On Line At Far End		28.29
7	N1 Generator Contingency 31	355MHW		At Time 0 Seconds, Disconnect Generator :J31245, L1 / LAIDIN20, Nansore		28.35

Fig. 11. DSA GUI related to the table information.

In summary, the visualization of buses/branches/corridors can provide more detail and important information for the power system engineers.

VI. CONCLUSION

This paper presents the design philosophy and implementation of a dynamic security assessment and early warning system. The system architecture, the operation functions, the system key modules and the calculation of operation limits are described in detail. In the real time mode, the dispatcher can rapidly, intuitively and accurately acquire the current system dynamic security operating level. In the training mode, the dispatcher can make intensive dynamic analysis with respect to the historical cases of interest. The DSAEW system can easily integrate with the existing EMS as a real time digital simulation tool. On the other hand, the DSAEW can instruct dispatcher to understand the essential of power system dynamic security assessment as an off-line training platform. Some visualized results are given to provide critical information in different detail levels.

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VIII. BIOGRAPHIES

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