



On-Line Transient Stability Assessment Scoping Study

Final Project Report

Power Systems Engineering Research Center

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Power Systems Engineering Research Center

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Scoping Study**

Final Project Report

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Power Systems Engineering Research Center

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Executive Summary

With the increase in transactions on the bulk power system, there is a critical need to determine transient security in an on-line setting, and to perform preventive or corrective control if the analysis indicates that the system is insecure. In recent years the industry has seen the development of large generation projects near locations of fuel supplies. As a result, the stability properties of the system have been altered. Unfortunately, the developers of the new “non-utility” plants are not cognizant of the impact of the plants on system stability. In this environment, new stability conditions may actually reduce available transfer capability. Stability problems may not occur frequently, but when they occur, their impact can be enormous. Most of the time, off-line studies are performed to determine conservative estimates of stability limits. In today’s bulk power market, the responsibility for monitoring system stability may be vested with an independent system operator. On-line stability monitoring may be even more necessary than in the past as power system operators try to facilitate as many economic transactions as possible.

This project’s objectives were to review the state of art in on-line transient stability assessment; evaluate promising new technologies; and identify technical and computational requirements for calculating transient stability limits and corrective and preventive control strategies for operating situations that are transiently insecure.

Six on-line transient stability package vendors were identified by conducting a literature survey. A detailed questionnaire which addressed several pertinent issues relating to on-line transient stability assessment was prepared. All six vendors responded to the questionnaire. The responses received were carefully analyzed. This analysis provided a detailed overview of the capabilities of available tools, performance metrics, modeling features, and protective and corrective control measures.

An elaborate questionnaire was then prepared and sent to all PSERC member companies. This questionnaire addressed specific needs in terms of required features, preferred performance, and control capabilities. A detailed analysis of the responses received provided a clear picture of the desired features and performance specifications of an on-line transient stability assessment tool.

A comparison of the analysis conducted on the vendor responses and the PSERC member company responses identified areas and topics that needed further development and research. This information will be useful in soliciting new research proposals and providing vendors a guide to the features that need to be developed and implemented.

A literature survey was also conducted on new analytical developments in on-line transient stability analysis. Based on this review, novel concepts based on quadratized models for power system components were explored to investigate whether there would be a significant advantage in accuracy and computational efficiency in using quadratized models. A summary of the literature survey is given in Appendix A. The proposed quadratized model based approaches to transient stability analysis and security

assessment is described in Appendix B. The proposed new modeling approach promises to facilitate improved transient stability analysis and dynamic security assessment.

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1. Introduction

With the increase in transactions on the bulk power system there is a critical need to determine transient security in an on-line setting and also perform preventive or corrective control if the analysis indicates that the system is insecure. In recent years the industry has seen the development of large generation projects at concentrated areas of available fuel supplies. The stability properties of the system have been altered, while the new “non-utility” plants are not cognizant of their impact on system stability. In this environment, stability issues may affect available transfer capability. Stability problems may not happen frequently, but their impact, when they do happen, can be enormous. Most of the time, off-line studies are performed to determine conservative limits. In the new environment, the responsibility of monitoring system stability may be vested with the RTO and on-line stability monitoring may be necessary.

This project aims at reviewing the current state of the art in the area of on-line transient stability assessment, evaluating promising new technologies, and identifying technical and computational requirements for calculating transient stability limits and corrective and preventive control strategies for cases that are transiently insecure.

1.1 Approach

This scoping study to ascertain the current state of the art in on-line transient stability assessment capabilities and arrive at specifications for on-line transient stability analysis tools is comprised of three main components:

- a. On-line transient stability analysis vendor survey and analysis
- b. Member survey and analysis
- c. Technical survey of the state of the art and suggested new developments in modeling and analytical approach

The first step in the project consisted of conducting a literature survey to determine current vendors who provide on-line transient stability tools. Six vendors who have fully developed tools and market these tools were identified. A detailed questionnaire that specifically addressed the capabilities of the tools and performance was developed. This questionnaire was distributed to the six vendors identified and a response was received from all of them. The responses obtained were carefully analyzed to identify modeling capabilities, analytical techniques, real time functionality, and performance.

The next step in the project consisted of developing a questionnaire for all member companies to determine their requirements and needs in terms of an on-line transient stability tool. A detailed questionnaire was prepared and sent to all member companies. A total of ten companies responded to the questionnaire. The responses were carefully analyzed to determine the desired capabilities and performance requirements. A base line capability specification was then developed using this analysis.

The results of the analysis conducted on the vendor survey and the member survey were compared to identify specific topics or areas in which further development and research

were needed. This aspect of the scoping study will potentially generate new research topics for future projects and also identify topical areas for member companies to support.

1.2 Objective

With the increasing stress on the transmission system, electric utilities are actively pursuing analytical tools that will enhance their ability to improve system security and operate the system more reliably. With systems becoming more susceptible to large disturbances as evidenced by the August 14th 2003 North East Blackout, a critical need exists to conduct transient stability studies closer to real time. This would necessitate an on-line transient stability assessment tool. Currently several vendors advertise on-line transient stability analysis tools. One of the objectives of this research project is to survey the vendors and determine the capabilities of the on-line transient stability tools. This survey is specifically aimed at determining the modeling features, ability to interface with the energy management systems (EMS), preventive control capabilities, corrective control capabilities, and performance metrics.

The other important objective of this project is to survey member companies and determine their needs in terms of an on-line transient stability analysis tool. The results of this survey are aimed at providing a base line specification for an on-line transient stability tool.

The final objective of the project is to examine the analytical basis for the modeling of various components and to determine if a quadratized model of the various components will provide a more efficient tool. A quadratized model is proposed for energy function based dynamic security assessment of power systems. The quadratized model is presented in Appendix B. The advantages of the proposed model are: (a) an improved method for determining the post disturbance equilibrium point of the system, and (b) an improved method for determining a model preserving energy function. From the computational point of view these are the two major tasks in dynamic security assessment. Improvements in these two tasks will improve the overall efficiency of dynamic security assessment procedures. The evaluation of the proposed approach was outside the scope of this project. This evaluation will be pursued in future projects.

1.3 Report Organization

The first section of this report provides the introduction and outlines the objectives of the report. In Section 2, the on-line transient stability package vendor survey is detailed and the analysis of the survey is presented. The vendor responses are discussed and the current state of the art in available tools is identified. Section 3 outlines the survey sent to member companies to determine individual requirements of the various companies with regard to on-line transient stability. The responses of the various companies are detailed and a base line specification for transient stability tools is developed. The results of the two surveys are also used to develop a list of topics for future research and development. A summary of the literature survey is given in Appendix A. In Appendix B, the proposed quadratized models for several power system components are examined and their role in

making on-line transient stability analysis more efficient evaluated. Appendix C contains a list of references.

2. Vendor Survey – On-Line Transient Stability Tools

A literature survey was conducted to determine vendors who currently deliver on-line transient stability packages. Six vendors were identified with products that were advertised and demonstrated at various forums. These vendors include:

- Areva T&D Corporation
- Bigwood Systems
- Powertech Labs Inc.
- Siemens EMIS
- University of Liege, Belgium
- V&R Energy System Research Inc.

2.1 Vendor Survey

A detailed survey was prepared to evaluate the capabilities of the various tools and to determine their specified performance in a real time setting. The survey questionnaire is presented below and the intent of each question in the survey is also discussed.

Name of Vendor _____

Please circle the most appropriate answer

1. The basis for the DSA Tool is

Full Scale Time Domain Simulation

Extended Equal Area Criterion

Transient Energy Function Method

Other _____ (Please Specify)

This question was designed to determine the specific analytical tools used to perform the transient stability analysis. Several approaches have been reported in the literature. The three approaches listed above are the mostly widely used and reported.

2. The DSA tool has a pre-filter to determine critical contingencies given a selected list of contingencies to analyze using a full blow time domain simulation program.

Yes

No

The pre-filter is an important requirement in any on-line security assessment tool. The number of contingencies to be considered could be very large and the sample has to be appropriately pruned to meet real time analysis requirements.

3. The DSA tool interfaces with network data obtained from the real time system using a state estimator

Yes

No

In an on-line setting system updates are obtained via the SCADA system and state estimation is performed to determine the current operating conditions. In order to perform the on-line analysis on the most current system, the stability analysis tool has to interface with the data obtained from state estimation. This is a critical capability for an on-line tool.

4. The DSA tool has the ability to be automatically triggered following a network topology change

Yes

No

In an on-line setting the stability limits will change following a network topology change and the limits will have to be reevaluated. Hence, the on-line system has to have the capability to be automatically triggered following a network topology change. This is an important capability for any on-line tool.

5. The DSA tool can be triggered manually by the operator for a specified condition and list of contingencies

Yes

No

In many instances the operator will require the ability to perform “what if” kind of analysis to determine the capabilities of the system. This necessitates the ability to trigger the tools for a desired scenario.

6. The DSA tool is triggered on a regularly scheduled cycle

Yes

No

Most EMS analysis tools are triggered on a regularly schedule cycle. This is an important characteristic to ensure that analysis is done on a regular basis and all system changes are incorporated in the analysis.

7. The DSA tool has capabilities to represent the dynamics of the external equivalent

Yes

No

In most analyses conducted in an EMS setting the external system representation is represented mainly in terms of it steady state characteristics and the net flows exchanged with the external area. However, in the case of dynamic analysis the characteristics of the external equivalent have to be accurately represented. This is critical in terms of obtaining limits that are accurate.

8. The DSA tool has all modeling capabilities available in a conventional time domain simulation package

Yes

No

If No Please Specify what is not available.

The modeling capabilities are a critical element of any transient stability analysis tool. A wide range of modeling capabilities is needed and the system has to be tested using appropriate models to guarantee the accuracy of the results.

9. The DSA tool uses a database structure to facilitate performance

Yes

No

This structure has been found to greatly enhance the real time performance. In a computationally intensive application like transient stability it is imperative to have this capability. This feature becomes particularly important when several contingencies have to be evaluated for the same operating condition.

10. The DSA tool converts the traditional EMS bus name – breaker format to a bus number format for analysis

Yes

No

The network data in a traditional EMS scheme appears in the bus name – breaker format because the network topology changes have to be tracked as switching operations occur. In any dynamic analysis the network power flow model has to be interfaced with the dynamic data through a bus number format. In order to facilitate the process an automatic transformation between the two formats should be provided.

11. The DSA tool uses a multiprocessor architecture to analyze multiple contingencies at the same operating condition

Yes

No

This is another critical feature for an on-line transient stability tool. Multiple contingencies have to be evaluated at a given operating point. In order to meet real time requirements the availability of a multiprocessor architecture becomes critical.

12. The DSA tool has capabilities to stop the simulation if the case is considered to be either stable or unstable

Yes

No

This is a feature which greatly enhances the real time performance. For contingencies where the stability characteristic is clear cut, the computational efficiency can be significantly enhanced by stopping the simulation.

13. The DSA tool has capabilities to analyze faults other than three phase faults

Yes

No

In many reliability areas in North America the limiting contingencies are not necessarily three phase faults. As a result, any on-line transient stability tool should have the capability to determine the appropriate fault impedance that should be inserted in a conventional positive sequence time domain simulation to represent the effects of unsymmetrical faults.

14. The DSA tool has capabilities to represent relay operations and hence subsequent switching following an initiating disturbance

Yes

No

In transient stability analysis, relay representation following large disturbances is essential to ascertain whether an initiating disturbance could lead to cascading failures. This modeling aspect is an essential component of the analysis.

15. The DSA tool has capabilities to calculate critical operating limits in terms of plant generation or critical interface flows

Yes

No

In an operation's setting it is critical to determine limits on critical parameters identified by the existing reliability criteria. It is not sufficient to determine whether a given scenario is transiently stable or unstable. Quantitative information regarding the limits in terms of the limiting parameters is essential. An on-line tool must provide this kind of information

16. The DSA tool has capabilities to represent preventive control and corrective control strategies

Yes

No

This question specifically addresses additional capabilities that are desirable in an on-line transient stability tool. If a particular scenario is deemed transiently unstable, then the operator should have the flexibility to maneuver the system to an acceptable condition using either corrective or preventive control.

17. Please specify the preventive control strategies that can be represented

This question follows up on the previous question and determines the types of options available for preventive control strategies

18. Please specify the corrective control strategies that can be represented

This question follows up on question 16, and determines the types of options available for corrective control strategies

19. The DSA tool has capabilities to represent special protection systems

Yes

No

If Yes please specify the capabilities

Special protection schemes play an important role in preventing transient instability and their incorporation in the analysis is essential in key situations.

20. The DSA tool has sensitivity based or similar analytical tools to account for change in parameters and operating conditions

Yes

No

Under many operating scenarios it becomes important to determine the change in stability limits with change in operating conditions. Repeating the entire analysis could be computationally burdensome. Sensitivity analysis has proven to be a useful tool in considering changes in parameters and operating conditions. Availability of this option will significantly enhance the capability of the on-line tool.

21. The DSA tool has the capability to detect voltage problems during transient swings

Yes

No

Sort of (explain):

Voltage dips during transient swings are important aspects of reliability criteria in many reliability regions in North America. Availability of this option which is essentially a by product of the transient stability analysis greatly enhances the ability of the operator to assess the performance of the system.

22. The DSA tool can analyze systems of the following size in the following amount of computation time for one run:

System size (buses): _____

System size (generators): _____

Typical computation time for one run: _____

These questions assess the performance capabilities of the tool in terms of size of the system that can be analyzed and the computation time required to run a single scenario

23. The following companies are using our DSA tool:

This question determines if the tools has been adopted by any utility.

2.2 Responses from Survey

All six vendors identified responded to the survey. Their responses are provided in Table 2.1. In order to protect the identity of the responder the responses are included in random order.

2.3 Analysis of Vendor Survey

The analysis of the vendor survey indicates the following features among available products provided by the six vendors:

- Most vendors use a full-scale, time domain simulation computational engine together with either an extended equal area criterion approach or a transient energy function approach to perform transient stability assessment. One vendor uses a specialized approach called the Single Machine Equivalent method.
- All but one tool provide the ability to pre-filter critical contingencies from a given list of contingencies.
- All the tools provide an interface to real time data using a state estimator.
- All the tools except one provide the ability to be automatically triggered following a network topology change.
- All the tools can be triggered manually by the operator for a specified condition and list of contingencies.
- All the tools are triggered on a regularly scheduled cycle.
- All the tools except one have the capabilities to represent the dynamics of the external equivalent.
- All the tools provide the complete set of modeling capabilities available in a conventional time domain simulation package.
- Three of the tools utilize a database structure to facilitate performance.
- All the tools except one convert the traditional EMS bus name-breaker format to a bus number format for analysis.
- All the tools except two use a multiprocessor architecture to analyze multiple contingencies at the same operating condition.
- All the tools have the ability to stop the simulation for cases that are clearly stable or clearly unstable.
- All the tools except one have the ability to analyze faults other than three phase faults.
- All the tools except one have the ability to represent relay operations and hence analyze subsequent switching following an initiating disturbance.
- All the tools have the capability to calculate critical operating limits.
- Three of the tools have the capability to represent preventive control and corrective control strategies.
- Three of the tools have the capability to represent special protection systems.
- Five of the tools use sensitivity-based techniques to account for change in parameters and system operating conditions.

Table 2.1 Responses from Vendor Survey

Vendor # Question	1	2	3	4	5	6
1	Full Scale Time Domain Simulation Extended Equal Area Criterion	Full Scale Time Domain Simulation Transient Energy Function Method	Other : SIME (for Single-Machine Equivalent) method. It combines the functionalities of a conventional time-domain simulation package and of direct methods applied to one-machine systems	Full Scale Time Domain Simulation	Full Scale Time Domain Simulation Transient Energy Function Method	Hybrid Version (Full time domain with EEAC)
2	Yes	Yes	Yes	No	Yes	Yes
3	Yes	Yes	Yes	Yes	Yes	Yes
4	Yes	Yes	Yes	No	Yes	Yes
5	Yes	Yes	Yes	Yes	Yes	Yes
6	Yes	Yes	Yes	Yes	Yes	Yes
7	Yes	Yes	Yes	No	Yes	Yes
8	Yes	Yes	Yes	Yes	Yes	Yes
9	No Database is used on EMS side for management of data files, but data on application side is in files	No – We experience better performance using data files	Yes	Yes	Yes	No The DSA tool receives from the EMS side the proper set of files to activate the functions. The files are updated with the latest SE snapshot and the desired output and desired monitored devices

Vendor #	1	2	3	4	5	6
Question						
10	Yes	Yes	Yes	No	Yes	Yes The EMS updates the bus-branch model for DSA every time it is called for execution
11	Yes	No	Yes	No	Yes	Yes
12	Yes	Yes	Yes	Yes	Yes	Yes
13	Yes	No	Yes	Yes	Yes	Yes
14	Yes	Yes	Yes	Yes	No	Yes
15	Yes	Yes	Yes	Yes	Yes	Yes
16	Yes	No -Future	Generation rescheduling (shifting) Potentially also load-shedding can be implemented	No –Under development	No	Yes, it may use an OPF or sensitivities for this but it is not currently part of our delivery
17	For VS : ULTC Tapping, Shunt switching, generator v scheduling	None	Generation shedding	None	None	None
18	For VS: Load shedding. For TS Gen tripping is easily simulated using multiple scenario	None	Yes Same with the conventional time-domain (TD) package used Since SIME uses a powerful TD simulator, it implicitly has the capability of modeling protection systems included in the package	None	None	None

Vendor #	1	2	3	4	5	6
Question						
19	Yes – Rule Based	No	Yes	No – Under Development	Yes	None
20	Yes – Don’t Understand the question	Yes	Yes . in principle some monitoring for voltages may be implemented	Yes	No	Yes
21	Yes - And frequency excursion and relays margin violations	Yes		Yes	Yes	Yes
22	System size (buses): 100,000 System size (generators): 12,000 Typical computation time for one run: Depends on model size, model dynamics, disturbance type, simulation time, and type/number of processors, and whether transaction analysis is being conducted (Note that it is generally insufficient to determine if the system is secure – it is necessary to determine how close it is to being insecure. Therefore results are checked against criteria and also a margin may have to be computed). Typical complete cycle time for one DSA pass would be between 5 and 15 minutes. (all scenarios)	System size (buses): 20,000 System size (generators): 5,000 Typical computation time for one run: Not Given	System size (buses): 1000-1500 System size (generators): 300 Typical computation time for one run: Full DSA reasonably within 15 minutes	System size (buses): _6000 System size (generators): _1400 Typical computation time for one run: _10 sec of dynamic process in 13 sec of computation time (on Pentium 4 CPU 2 GHz; 256 MB of RAM)	System size (buses): 10,000 System size (generators):1,000 Typical computation time for one run: 10 minutes	System size (buses):100,000 System size (generators): 15,000 Typical computation time for one run: _____ 5000 buses, 400 gens, 3Ghz CPU, 1GB memory VSAT, 500 contingencies in 30 sec TSAT, 1 contingency, 5 sec simulation in 5 sec (keeps up with real-time)

Vendor #	1	2	3	4	5	6
Question						
23	On-line licnesees (all may not have tools installed yet) ERCOT Entergy BPA ATC TVA Southern Company Services MAIN MISO GuangXi Electric Company Approximately 45 entities (commercial and educational) are using the same tools for off-line analysis.	Tokyo Electric Power Company, ABB-NM (ABB is a BSI software reseller: BSI's DSA application is integrated sold as an option in their Ranger EMS), CFE (the National Power Company of Mexico), and Commonwealth Edison	Test facilities have been set-up at HTSO (Hellenic Transmission System Operator) and at CESI with remote connection to GRTN (Italy)	None	The function was installed at NSP (now XCEL Energy). The tool was demonstrated to the industry. However, the tool is no longer in use.	Voltage stability has been delivered to the following utilities: ENTERGY, MISO, ATC, BPA and ESB Ireland. Transient stability has been delivered to ERCOT. Voltage and transient stability has been delivered to ERCOT and is scheduled for delivery to TVA later in 2004

- Five of the tools have the capability to detect voltage problems during transient swings.
- The tools provided by the six vendors vary in their capabilities with regard to system size and performance. The range of system sizes that can be handled by the various tools are from 1500 buses to 100,000 buses, and 300 generators to 15,000 generators. The time performance provided by all vendors for a complete cycle of analysis ranged from 5 - 15 minutes.
- All but one tool have been implemented at a utility company.

3. Member Survey – On-Line Transient Stability Tools

A user survey was prepared and sent to all PSERC member companies. Ten member companies responded to the survey. These member companies included:

- ABB
- Arizona Public Service Company
- IREQ
- MidAmerican Energy Company
- NYISO
- PJM
- Southern Company
- TVA
- TXU Electric Delivery
- WAPA

3.1 Industry Member Survey

A detailed survey was prepared to evaluate the needs of the members companies survey with regard to a on-line transient stability tool. The survey questionnaire is presented below and the intent of each question in the survey is also discussed.

Name of Member Company. _____

Name of responder (optional): _____

Please circle the most appropriate answer

1. We would prefer the tool to run on (In this case you could circle more than one if needed)

Off line operations planning data

Off line system planning data

Real time EMS data

Don't need the tool at all

Other _____ (Please Specify)

This question is aimed at determining the preferred choice in terms of a transient stability tool for the member company.

2. We prefer the DSA tool to have a pre-filter to determine critical contingencies given a selected list of contingencies to analyze using a full blown time-domain simulation program.

Yes

No

Don't care

This question determines the need for a contingency pre-filter to identify critical contingencies.

3. The DSA tool should interface with network data obtained from the real time system using a state estimator

Yes

No

Don't care

This question identifies the need for real time data to be used in the analysis.

4. The DSA tool should have the ability to be automatically triggered following a network topology change

Yes

No

Don't care

The nature of the trigger for the on-line tool is determined.

5. The DSA tool should have the capability to be triggered manually by the operator for a specified condition and list of contingencies

Yes

No

Don't care

The nature of the trigger for the on-line tool is determined.

6. The DSA tool should have the capability to be triggered on a regularly scheduled cycle

Yes

No

Don't care

The nature of the trigger for the on-line tool is determined.

7. The DSA tool should have the capabilities to represent the dynamics of the external equivalent

Yes

No

Don't care

This question is aimed at determining the nature of the system represented in the members' EMS representation.

8. The DSA tool should have all modeling capabilities available in a conventional time domain simulation package

Yes

No

If No, please specify what is not necessary.

Don't care

This question is aimed at determining the capabilities of the tools preferred by the member companies.

9. The DSA tool should use a database structure to facilitate performance

Yes

No

Don't care

This question determines the special needs required by the member companies in terms of aids to enhance real time performance.

10. The DSA tool should convert the traditional EMS bus name – breaker format to a bus number format for analysis

Yes

No

Don't care

This question determines specific format requirements to interface the dynamic analysis with real time EMS data.

11. The DSA tool should use a multiprocessor architecture to analyze multiple contingencies at the same operating condition

Yes

No

Don't care

This again deals with a feature which would greatly enhance performance.

12. The DSA tool should have capabilities to stop the simulation if the case is considered to be either stable or unstable

Yes

No

Don't care

This is a feature that significantly enhances performance.

13. The DSA tool should have capabilities to analyze faults other than three phase faults

Yes

No

Don't care

This question aims to determine special needs in terms of types of disturbance that should be analyzed.

14. The DSA tool should have capabilities to represent relay operations and hence subsequent switching following an initiating disturbance

Yes

No

Don't care

This question determines the needs of member companies in terms of specific requirements in the transient stability analysis.

15. The DSA tool should have capabilities to calculate critical operating limits in terms of plant generation or critical interface flows

Yes

No

Don't care

This is an important issue that addresses specific reliability criteria requirements for each member company.

16. The DSA tool should have capabilities to represent preventive control and corrective control strategies

Yes

No

Don't care

This is another important issue that addresses specific reliability criteria requirements for each member company.

17. Please specify the preventive control strategies that you would like the package to have

18. Please specify the corrective control strategies that you would like the package to have

The two questions above examine specific preventive and corrective control options that member companies would like as options in the tool.

19. The DSA tool should have capabilities to represent special protection systems

Yes

No

If Yes please specify the capabilities

Don't care

This is an important issue that addresses specific requirements for each member company in terms of special protection schemes preferred.

20. The DSA tool should have sensitivity based or similar analytical tools to account for change in parameters and operating conditions

Yes

No

Don't care

This question addresses an issue of specific choices regarding the need to analyze changing conditions in the system.

21. The DSA tool should have the capability to detect voltage problems during transient swings

Yes

No

Sort of (explain):

Don't care

This is an important issue that addresses specific reliability criteria requirements for each member company.

- 22 The DSA tool should have the capability to analyze systems of the following size in the following amount of computation time for one run (i.e. one contingency):

System size (buses): _____

System size (generators): _____

Typical computation time for one run: _____

Any other capabilities that you would like to see in a DSA tool of your choice:

This question ascertains the needs of member companies in terms of performance requirements.

23. If you already have a DSA tool that you are using, we would very much appreciate any comments that you might have on your satisfaction with the tool. Please describe the tool in the context of the questions asked above.

This question determines if the member company is already using an on-line transient stability tool and a brief description of their experiences with the tool.

3.2 Responses from Survey

Ten member companies responded to the survey. Their responses are provided in Tables 3.1 and 3.2. The structure of the two tables is identical except that each table contains five responses to facilitate the display in a table. In order to protect the identity of the responder the responses are included in random order.

Table 3.1 Summary of PSERC Member Survey Replies

PSERC Member	1	2	3	4	5
Question					
1	Off line system planning data Real time EMS data (assuming this data is a real-time state estimator)	Off line system planning data Real time EMS data	Off line operations planning data	Off line system planning data Real time EMS data	Real time EMS data
2	Yes	Yes	Yes	Yes	Yes
3	Yes	Yes	Yes	Yes	Yes
4	Don't care (should be configurable)	Yes	Yes	Yes	Yes
5	Yes	Yes	Yes	Yes	Yes
6	Yes	No	Yes	Yes	Yes
7	Yes	Yes	Yes- maintenance of the external equivalent (with both real-time and through time considerations) may be an issue. What type of equivalencing would be used? A reduced network retaining discrete machine models, or a dynamic equivalencing process? May need the capability to retain discrete representations close-in for modeling	No	Yes

			scheduled/forced outages near the inter-Area boundary.		
8	Yes	Yes	No - Assuming that the DSA is intended to be a limited application study tool for near real-time assessment, it does not need the detailed modeling capabilities required for engineering analysis. The DSA should support standard models and modeling techniques, with some additional capability for representation of non-standard models (FACTS, HVdc controls) where appropriate. We would be concerned that in trying to replicate too much of the capability of a “full-blown” stability modeling program would compromise the performance (and complicate the maintenance) of the model.	Yes	Yes

9	Yes	Don't Care	No - This would only facilitate model building or maintenance, it is not likely to enhance performance of the actual analysis process.	Yes	Yes
10	Yes (should be configurable)	Yes If you need to use in Planning studies, have to	Yes - The data translation I/O processes should support ASCII raw data format in either bus number (bus/branch model) or bus name/breaker (nodal network model) formats.	No	Yes
11	Yes	Don't Care	Yes- It should be capable of taking advantage of multiple processor or hyper-threading technology but use of that architecture should not be pre-requisite to efficient use of the program.	Yes	Yes
12	Yes	Yes	Yes User should be able to set optional triggers to terminate the simulation based on monitored performance parameters (e.g., generator angle,	Yes	Yes

			acceleration, transmission-line loading, bus voltage, etc.) and report the limiting condition(s) that resulted in the termination.		
13	Yes (should calculate and use default negative and zero sequence impedances if not supplied; automatically determine worst contingency for machine(s) of interest)	Yes Many criteria fault limits we see are for delayed clearing of phase to ground faults	No - All the program needs is to allow the definition of fault admittance at the point of the fault for the simulation. Has consideration been given to fault location other than at the bus?	Yes	Yes
14	Yes	Yes	Yes- To the extent that this does not compromise performance, the capability should be there to accurately represent the action of special protections or remedial action schemes (SPS or RAS).	Yes	Yes
15	Yes	Yes- This would be the main reason to have a DSA tool	No - We're not sure the business is ready for automatic updating of transient stability limits in real-time. DSA should provide the basis to	Yes	Yes

			perform the assessment and provide timely results to enable the system operators to make an informed judgement of the system conditions and let the operator(s) decide what action(s) are appropriate.		
16	Yes	No – Let us do one thing well, and then move to extras	Yes - It would be assumed that the DSA would be capable of modeling (within reason) the appropriate SPS, RAS, or Dynamic Control Systems that are available.	Yes	Yes
17	<p>Prior to a limit violation:</p> <ul style="list-style-type: none"> • alarming capability as a defined limit is approached • configurable remedial action options (such as least-cost, minimized number of control actions, etc.) to observe limits 	Unit output limits, min. MVAR limits	In addition to SPS/RAS/DCS, in study mode the DSA should be able to model line or generator (or control function) outages to “pre-study” an anticipated system condition (e.g., study a scheduled line outage prior to releasing the switching order) or model redispatch of generation to mitigate projected	<p>Network Reconfiguration</p> <p>Curtailement of non firm schedules</p>	Capability to implement a corrective action for a given contingency

			(or actual) overloads.		
18	<u>After a limit violation (assuming a steady-state stable system prior to critical contingency):</u> - refer to response given in Question 17 above	Unit rejection	As above DSA should allow the user the capability to study corrective actions including system generation redispatch, opening transmission lines to mitigate overloads, in addition to modeling SPS/RAS/DCS actions and under/over-frequency responses (load shed, generator tripping due to severe system frequency excursion).	Generation redispatch Load shedding Emergency switching	Switching action; Generation change
19	<u>Yes - New tool should provide easy configuration and validation of any SPS</u>	Yes – Generation rejection	Yes - The model should be capable of providing the input (sensing) quantity(ies) that trigger the operation of the SPS/RAS and correctly model the resultant event (branch/element trip, generation rejection, etc.)	Yes	Yes - Switching actions and Generation change
20	Yes	Yes	Yes - To the extent that it does not	Yes	Yes

			compromise performance. The functionality should not be viewed as an engineering design tool, but provide the necessary analysis for system operations to perform “what if” type sensitivities. The facility to change operational parameters should be within the state capability of the power system equipment (i.e., don’t allow generation to be redispatched above/below maximum/minimum operating points.		
21	Yes	Yes -Should detect extreme swings that may cause unit trips. Should be able to use post disturbance steady-state voltages from LF type analysis to determine feasible acceptable minimum VAR limits, and from that determine acceptable MW limits	Yes - Report instantaneous and peak-to-peak oscillation and compare with transient and steady-state voltage limits; provide input(s) to over/under-voltage relay models.	Yes	Yes
22	System size (buses):		System size	System size	System size

	20,000 System size (generators): 5000-10,000 Typical computation time for one run: 30 seconds		(buses): 2500 System size (generators): 500 Typical computation time for one run: < 1minute for a 7-10sec simulation	(buses): 800 System size (generators): 150 Typical computation time for one run: 60s	(buses): 20,000 System size (generators):1,000 Typical computation time for one run: < 10 minutes
23	Graphical display of results for wide-area view; data archiving capabilities; scenario creation and simulation for operator training purposes		If based on a nodal/breaker model, would the network topology function be able to identify additional elements that must be tripped as a result of a breaker failure contingency event or correctly model bus fault or breaker fault contingencies?		Present results in a graphical format that is easy to understand
24	Our Company has purchased the on-line version of the Transient Security Assessment Tool (TSAT) from Powertech Labs, Inc. and we are presently working to integrate this application within our system control center. This TSAT application has many of the capabilities mentioned in this questionnaire, such as an interface with real-time EMS state estimator data, contingency		No		

	<p>ranking prior to full time-domain simulation, scheduling capabilities for flexible study cycles, distributed computation architecture, full dynamics modeling capabilities for power systems up to 100,000 buses and 15,000 generators, transient voltage criteria monitoring, system damping monitoring through use of Prony analysis, early termination options for stable and unstable cases, automatic fault impedance calculation, flexible power transfer analysis using a source-sink approach, automated stability limit search strategies, multiple scenario management, case archiving capabilities, etc. Any new DSA tool developed should maintain data format compatibility with and embody many of the concepts and analytical techniques utilized within the TSAT application.</p>				
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Table 3.2 Summary of PSERC Member Survey replies

PSERC Member	6	7	8	9	10
Question					
1	Off line system planning data Real time EMS data	Off line operations planning data Off line system planning data Real time EMS data	Off line operations planning data Real time EMS data	Real time EMS data - We have a GE product (TSM) up and running.	Off line operations planning data Off line system planning data Real time EMS data
2	Yes	Yes	Yes	Yes	Yes
3	Yes	Yes	Yes	Yes	Yes-(also in study mode using a Power flow case)
4	Yes	Yes	Yes	Don't Care	Yes - (also for any significant change in analog measurements)
5	Yes	Yes	Yes	Yes	Yes
6	Yes	Yes	Yes	Yes	Yes
7	Yes	Yes	Yes	Yes	Yes - (but simplified representation?)
8	Yes	Yes	Yes	Yes – at least be able to take a snapshot and put into a data format compatible with PTI or some other powerflow software program	Yes - (only the ones that impact significantly the results)
9	Yes	Don't Care	Yes	Yes	Yes
10	Don't Care	Yes If you need to use in Planning studies, have to	Yes	Yes – Would make it easier to compare to a static powerflow	Don't Care

				simulation.	
11	Don't Care	Don't Care	Yes	Don't Care	Don't Care
12	Yes	Yes	Yes	Yes	Yes
13	Yes	Yes	Yes	Yes	Yes
14	Yes	Yes	Yes	Yes	Yes
15	Yes	Yes	Yes	Yes	Yes
16	Don't Care	Yes	No	Yes	Yes
17		Generator VAR control, Transformer tap control, Capacitor switching control, SVC control, Statcon control AND ALLOW THE USER TO SPECIFY CONTROL STRATEGIES/PRIORITIES		Ability to model existing RAS and operating procedures for dynamically and thermally constrained paths.	Drop loads and reduce the loading
18		ABOVE CONTROLS plus LOAD SHED CONTROLS (under voltage, under frequency, etc)		None at this time.	Series capacitor switching, Braking resister, fast steam valving
19	Yes – Should model all SPC	Yes – Model under voltage, under frequency, automatic generation runback schemes etc.	Yes	Yes - as stated above in No. 17 - the ability to apply known RAS actions or other predetermined operational procedures for specified contingencies.	Yes
20	Yes	Yes	Yes	Don't care – don't understand issue here.	No

21	Don't Care	Yes	Yes	Yes	No
22	System size (buses): 20,000 System size (generators): 2000 Typical computation time for one run: Not a factor	System size (buses): 50,000 System size (generators): Typical computation time for one run: 15 minutes	System size (buses): 1000 System size (generators): 200 Typical computation time for one run: 30 sec	System size (buses): should be expandable System size (generators): Typical computation time for one run: We run 574 outages in 15-20 seconds on TSM with 2800 buses modeled today.	System size (buses): 5000 System size (generators):300 Typical computation time for one run: 1 minute
23			<ul style="list-style-type: none"> • Identification of limiting equipment (line, SVC, SC, inductances) and corresponding sensitivity factors. • Identification of worst contingencies according to used acceptance criteria. 		Sort selected list of contingencies (in item 2) based on severity and provide a measure of severity. Compare this list for two base cases. Support multiple islands cases (base case as well as contingency causing the island)
24	Do not have a tool.		Presently, we are using a DSA system where the operation strategies and the corresponding transmission limits are established by off-line studies	The most difficult issues in priority are: Data integrity – bad telemetry Model maintenance Model expansion	

			<p>(operation planning group) and stored in a data base (LIMSEL). The acceptance criteria used to define these limits are coming from NPCC with the addition of TransÉnergie special criteria. The LIMSEL data base is used for maintenance planning, operation scheduling and real time operation purposes. For each possible configuration, the data base will provide secure limits. At the control center level, these limits are used on-line to control the secure operation and to generate alarms to the operators if they are bypassed.</p> <p>We are presently working to optimize and to accelerate the computation of the limits provided by</p>	<p>Model topology exchange with other Reliability Centers User interface needs improvement Continuing training Receiving routine topology updates from Control Areas in the footprint</p>	
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			this DSA tool for reducing cycle time. Those efforts will ultimately lead to a computation of transfer capacities directly in the control room.		
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3.3 Analysis of PSERC Member Survey

The analysis of the PSERC member survey clearly outlines the following aspects:

- An on-line transient stability tool that uses both off line data either planning or operations planning, and real time EMS data is preferred.
- A pre-filter to determine critical contingencies is essential.
- Interfacing with the real time data using a state estimator is essential.
- Different modes of triggering the on-line transient stability analysis tool are preferred.
- The representation of the dynamics of the external equivalent is preferred by most members. Some of the members have provided a detailed description of their needs.
- The members prefer detailed modeling capabilities available in a conventional time simulation package.
- The data base to enhance performance is preferred by most members.
- The conversion to the traditional EMS bus name – breaker format is preferred by most members.
- Most of the PSERC members preferred the use of a multiprocessor architecture to improve the real time performance of the tool.
- The option to stop clearly stable or unstable cases was also preferred by most members.
- A clear majority of the responders wanted the ability to analyze faults other than three phase faults. One responder wanted the ability to analyze faults that did not occur only at buses.
- There was unanimous agreement among the responders regarding the need to represent relay operation in the tool.
- There was strong agreement among the member companies with regard to the ability of the tool to calculate critical operating limits.
- A majority of the responders expressed the need for the tool to represent preventive and corrective control strategies.
- Several of the responders provided a list of the corrective and preventive control strategies needed.
- There was unanimous agreement among all member companies regarding the need to represent special protection systems.
- Several companies expressed the need to evaluate limit changes with changing operating conditions or parameters without repeating the entire exercise.
- The need to detect voltage problems during the transient swings was also deemed important.
- The system size required by the member companies ranged from 500 buses to 50,000 buses, 200 generators to 10,000 generators, and a single run computation time of less than a minute.
- Two companies currently have tools which they are testing.
- Several companies identified desirable features in tools they would consider.

3.4 New Directions for Research and Development

The analysis of the vendor survey and PSERC member survey clearly indicates a need for on-line transient stability tools. The member companies have clearly identified a need for the tool. In addition, the responses from the survey clearly indicate a need for research and development in the following areas:

Research Requirements

- Protective Control strategies in conjunction with limits derived from on-line transient stability analysis.
- Optimization of the protective control strategies.
- Corrective Control strategies in conjunction with limits derived from on-line transient stability analysis.
- Optimization of the corrective control strategies.
- Representation of generalized special protection schemes.
- Options for a wide range of preventive and corrective control schemes should be incorporated in the tool.

Development Requirements

- Ability to represent faults other than three phase faults is important
- Ability to locate faults at locations other than at buses is needed.
- Dynamics of the external equivalent needs to be incorporated in some detail.
- Flexibility in terms of relating transient stability limits to system operating parameters should be provided.
- Graphical display of results for wide-area view; data archiving capabilities; scenario creation and simulation for operator training purposes should be developed.
- Ability to identify additional elements that must be tripped as a result of a breaker failure contingency event.
- Correctly model bus fault or breaker fault contingencies.

The above list of desirable features coupled with the fact that energy function approaches are more efficient for dynamic security assessment translates to the need to further develop structure preserving energy function approaches. In this sense, Appendix B presents some new ideas towards the goal of improving the structure preserving energy function methods. The basic idea is to use detailed quadratized models to represent the system and use this structure to compute equilibrium points and energy functions. This approach is promising for two reasons: (a) the computation of the equilibrium points is more efficient since quadratized models converge quickly to the solution – using Newton’s type algorithms and (b) the construction of the energy function is simpler and permits more efficient calculation of stability regions. The proposed approach needs to be evaluated and its merits be proven.

Appendix A: Literature Review of the Current Research on On-Line Transient Stability Assessment

This Appendix presents a brief literature survey on the state of the art of on on-line transient stability assessment (TSA). The literature on the topic of on-line transient stability analysis and assessment is extremely extensive. The area is a very active area of theoretical research and in addition many practical implementations of on-line TSA algorithms have been recently developed or are currently under development. Here only a very brief and general review is performed, concentrating mainly on recently reported developments and applications. A short, compared to the total, number of references is included in Appendix C. Apart from some fundamental papers the majority of the references are recent publications, dated within the last 15 years. Some important books that present the fundamental concepts on the topic are also listed at the beginning of the list. No detailed explanations are given on the way each approach works, since this is assumed to be known. More details on the fundamentals on on-line TSA methods or generally on power system transient stability can be found in [1-4]. Reference [4] contains extensive information on transient stability and a relatively brief and explanatory section on the fundamentals of the direct methods which are the most popular and superior techniques used for TSA in an on-line environment. An interesting literature survey on the topic has been also presented in [57]. Important issues on the current and future research on TSA are discussed in [42,56,91,92,97,99]. Finally, for completeness, several publications on the broader topic of dynamic security analysis and assessment (DSA) are also involved, since the two topics are very closely related. Some general comments on the existing literature are given next.

The key issue of the topic of on-line transient stability assessment is the requirement for on-line operation. This imposes the requirement of fast and efficient calculations. Nonetheless, this should not have a negative effect on the precision of the analysis. However, the complexity of the dynamic model of a bulk power system makes the fulfillment of this requirement a difficult challenge. Several approaches have been proposed and used to deal with the problem efficiently, without, however, compromising the accuracy of the results.

The most common tool for transient stability analysis is the time domain dynamic simulation. The power system is modeled as a set of nonlinear differential-algebraic equations and the equations are solved using numerical integration. This approach is very common in practice and yields very accurate results. However, it involves a huge computational burden, which makes its use in an on-line application difficult, especially since extensive and exhaustive simulations are usually required. Simulation is very commonly used in offline studies. Nonetheless, it is also an important tool for on-line studies and all the on-line stability analysis applications also involve dynamic simulation, or combine dynamic simulation with some other technique. Frequently, some other method is used to conclude on the stability or instability of the system at early stages of simulation, reducing therefore the required simulation time.

By far the most important approach to on-line stability analysis is the energy function methods. These methods are much faster than full scale simulations, and thus more suitable for on-line

studies, and they also have the advantage that they can provide stability regions around an operating point. All these methods are based on Lyapunov's direct method for stability analysis. The use of Lyapunov's method in power systems has been proposed since the late 40's and 50's [5,6]. The first systematic application in power systems was presented in the late 60's [7].

The application of Lyapunov's direct method to power systems is referred to as the transient energy function method (TEF). This technique has proved to be a practical tool in transient stability analysis and dynamic security assessment. The main idea of the method is to use a Lyapunov-type function, called TEF, to compute the region of stability around the post disturbance equilibrium point of the system. The boundary of the region of stability allows the assessment of the stability of an equilibrium point qualitatively as well as quantitatively via the computation of critical clearing times, critical energies and stability margins. Although several different function have been tested as candidate Lyapunov functions the sum of kinetic and potential energies of the post-disturbance system seem to have provided the best results, and it is therefore almost exclusively used. Some approaches using a corrected TEF have been also proposed and used [72, 98,107] in stability assessment studies. Different or modified types of Lyapunov functions have been also recently investigated [103, 127].

There are three main methods of stability analysis that make use of the TEF concept: (1) the lowest energy unstable equilibrium point method (u.e.p) [7], (2) the Potential energy boundary surface method (PEBS) [8] and the controlling unstable equilibrium point (u.e.p.) method. The latter category includes the boundary-controlling u.e.p. method (BCU) which is quite popular in the current research. These methods were initially applied to simplified models of power systems, but have been extended to more complex and realistic models, that preserve the actual structure of the power network and involve detailed generator models [9,10,22,25,53,136,141]. The application of the TEF methods also involves the simulation of the system, at least during the fault period, so combinations of TEF methods with time domain analysis are very common in literature and provide results of increased accuracy. Apart from the simulation time a difficult and computationally intensive part of the TEF methods is the calculation of the equilibrium points of the post-disturbance system. Nevertheless, these methods are by far more efficient compared to full time domain analysis and can provide more information (i.e. degree of stability or stability via the computation of critical energy values of critical clearing times).

Related to the TEF methods is also the extended equal area criterion method (EEAC). This type of methods is also associated with the Lyapunov's direct method. The method has been also extensively investigated and used in current literature [11,18,47,112,117,128]. A similar approach referred to as generalized equal area criterion (GEAC) is discussed in [28]. In many cases the application of EEAC involves the transformation of the system to an equivalent single-machine system [12,28,73,105,111] usually connected to an infinite bus (SMIB) and the application of the EAC to it. Combination with time domain simulation is also important in these methods, as well.

Hybrid methods that combine time-domain transient simulation and some TEF method (included EEAC) have evolved as a natural extension combining the advantages of the time domain

simulations with the benefits that can be obtained by the use of an energy function method (like the computation of stability margins and other indices and limits etc). These hybrid approaches have become a very active area of research and many hybrid implementations have been proposed and tested [26,47,48,52,59,61,63,65,104, 112,117,119,128]. In most cases, apart from additional information that an energy function provides, the TEF method is also used as an early stopping criterion for the time-domain simulation. The second kick method is another approach that has been proposed and investigated as a stopping criterion for the numerical integration [62,76]. Hybrid methods combining the accuracy of time-domain simulation and the advantages of an energy function method are currently the state of the art in on-line TSA applications.

Energy methods have also been applied for the study of voltage behavior, along with transient stability assessment. References [25,27,85,86] are indicative of such approaches. Furthermore, contingency screening and ranking algorithms have been proposed based on TEF methods [64,71,78,93,117,119,140]. Moreover, TEF methods have been used along with sensitivity analysis mainly to indicate preventive or emergency control remedial actions for dynamic security [11,24,50,67,69,80,95,115,117,132,139] or even for optimal system operation with dynamic security considerations [38,77,132].

Apart from the analytical methods described so far, computational intelligence methods have been also recently proposed for TSA or DSA [13,20,21,34,39,46,55,58,60,83,94,102,109,110, 114,120,123,125,135,142,143]. The high computation speed of such methods makes them good candidates for on-line applications. These methods involve either some expert system or heuristic based method, or some learning-based or pattern recognition method. By far, artificial neural networks (ANN), belonging to the learning or training-based methods, are the most popular computational-intelligence technique and significant research has been reported in this area [34,46,55,58,60,94,109,114,121,135,143]. Neural networks are frequently used as classifier to perform a filtering screening to possible contingencies and select the ones to be further analyzed. So far, apart from research grade software, no commercial grade applications for on-line TSA using ANN or some other computational intelligence based technique have been reported.

Finally, some attempts have been made for completely different approaches to the issue power system transient stability. References [19] and [33] use catastrophe theory as a means of analysis. However, further work on such techniques has not been reported. References [88,106] investigate TSA on a probabilistic framework.

Almost all the currently existing commercial programs for on-line transient stability assessment use one of the above mentioned methods, or combinations of them. Transient simulation is a common tool and it is the minimum that some on-line TSA software can offer. Most of the programs use some hybrid approach, combining time-domain simulation and energy function methods. Several techniques have been investigated to improve the performance of on-line TSA algorithms. Improved numerical integration algorithms have been investigated to result in more efficient time domain simulation [17,31,35,43,70,75,81,87,96]. Considerable research has also been performed for improving the efficiency and accuracy of TEF methods [15,16,31,44,49].

Also, parallel processing implementations have been proposed and investigated [29,30,40,54,66,108,129,130] that suggest either the use of computers with parallel processor architecture or computer clusters and distributed computing. This approach can prove beneficial to both purely simulation based approaches, by considerably decreasing simulation time, as well as to TEF methods. It has been shown that most of the algorithms used in TSA can be reformulated to take advantage of parallel processor implementations.

Several of the references acquired by the survey describe specific implementations of on-line TSA systems [52,62,76,90,101,118,122,133,134,138] or present guidelines for such implementations and the integration of such modules in an energy management system (EMS) environment [14,68,74,79,91,92,97,99,100]. Such references are very important since they indicate the needs and requirements for implementations, or they indicate the current state of the art in available, working applications.

Appendix B: Quadratic Component Modeling

This Appendix presents a proposed approach for the basic computational engines of transient stability and dynamic security assessment based on a new modeling approach for power systems. The proposed approach holds promise of improved power system transient stability and analysis and DSA.

B.1 Introduction

This section presents some basic ideas on the potential benefits on power system transient stability analysis by the use of quadratized models. The idea of quadratized models is that each component of the system be modeled with a set of differential and algebraic equations of degree no more than two. Thus the system model is made of linear and quadratic equations. The possible advantages of such a representation lie mainly in the following areas: (1) improved efficiency in system time domain simulation, (2) simplification in the application of energy function methods for stability analysis and (3) more detailed, physically-based modeling of power system components without additional complication of the nonlinear set of equations.

A simple procedure has been developed to convert any nonlinear component equations into a set of linear and quadratic equations by the introduction of additional state variables. The procedure is very general and has been successfully applied to any component model used for steady state load flow analysis. As an example, reference [144] describes the methodology as applied to detailed and physically based modeling of electrical machines. This has resulted in the development of the quadratized power flow model (QPF) which demonstrates improved convergence speed in load flow studies, compared to the traditional load flow [145].

It is proposed that the concept is extended and applied to dynamic modeling, as well, for power system transient stability studies. Since in the vast majority of cases, transient stability is studied assuming that the electrical network operates at a sinusoidal quasi steady state, the network model used in transient stability studies is the same as the steady state model. Therefore, the already developed QPF models [145] can be immediately used. In addition to these models quadratized dynamic models for the synchronous generator need to be developed, since the synchronous generator is the main dynamic component of a power system, whose behavior determines the stability of a power system.

To illustrate the concept, we present two simple examples of quadratized generator models: (a) the quadratic classical generator model (commonly used in research on transient stability) and (b) a simplified example of a two-axes transient generator model. Although these models are relatively simple they are quite indicative of the proposed approach. Furthermore, additional equations can be added to construct more detailed generator models, including models for generator control subsystems (governor, exciter, AVR). Most of the additional equations commonly used for these more detailed models are indeed either linear or quadratic (in the d-q axis reference frame) and thus do not introduced additional nonlinearities. Saturation effects and

nonlinearities in the magnetic circuits are not currently discussed. They will be treated separately in future research stages.

B.2 Quadratic Classical Generator Model

The classical representation of a synchronous machine in stability studies represents the electrical part of the machine as a constant voltage behind a transient reactance, as illustrated in Figure B.1.

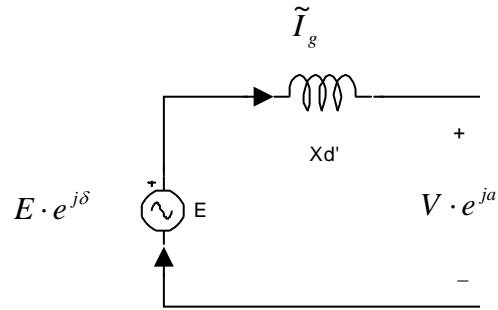


Figure B.1. Simplified Synchronous Machine Model - Constant Voltage behind Transient Reactance

The equation of the electrical circuit is:

$$\tilde{I}_g = \frac{\tilde{E} - \tilde{V}}{jx'_d},$$

$$E = \text{const}$$

The dynamical equations are:

$$\frac{d\delta}{dt} = \omega - \omega_s,$$

$$\frac{2H}{\omega_s} \frac{d\omega}{dt} = T_m - \frac{E \cdot V}{x'_d} \sin(\delta - a) - T_D,$$

where

ω_s is the synchronous speed,

H is the inertia constant of the generator,

T_m is the model input of the mechanical power supplied by a prime-mover (in p.u.),

T_D is the damping torque (p.u.), which can be approximated by $T_D = D \cdot (\omega - \omega_s)$ with D constant,

$\tilde{V} = V e^{ja}$ is the terminal voltage,

$\tilde{E} = E e^{j\delta}$ is the internal voltage, assumed constant in magnitude as specified by an exciter system at steady state conditions.

An additional terminal condition needs to be specified to fully define the generator model. This equation will eliminate the \tilde{I}_g variable.

The trigonometric term is the main nonlinearity of the model. Figure B.2 shows the electrical representation if the quadratized model.

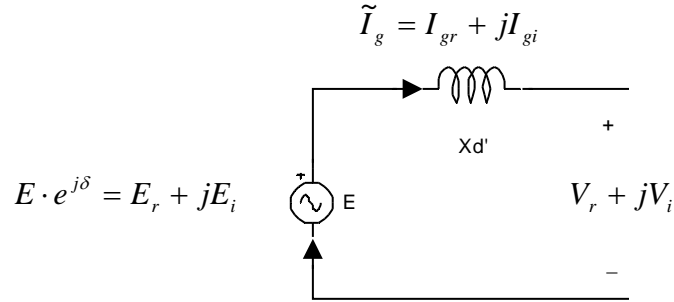


Figure B.2. Simplified Synchronous Machine Quadratized Model - Constant Voltage behind Transient Reactance

The equations for the quadratized model are:

$$I_{gr} = \frac{1}{x'_d} E_i - \frac{1}{x'_d} V_i$$

$$I_{gi} = \frac{1}{x'_d} V_r - \frac{1}{x'_d} E_r$$

$$0 = E_r^2 + E_i^2 - E_{spec.}$$

$$0 = E_r s(t) - E_i c(t)$$

The dynamic equations are:

$$\frac{d\delta(t)}{dt} = \omega(t) - \omega_s$$

$$\frac{2H}{\omega_s} \frac{d\omega(t)}{dt} = T_m - \frac{1}{x'_d} (E_i V_r - E_r V_i) - T_D$$

$$\frac{ds(t)}{dt} = c(t) \cdot (\omega(t) - \omega_0)$$

$$\frac{dc(t)}{dt} = -s(t) \cdot (\omega(t) - \omega_0)$$

The state vector is

$$\begin{bmatrix} x^T(t) & y^T \end{bmatrix} = \begin{bmatrix} \delta(t) & \omega(t) & s(t) & c(t) & V_r & V_i & E_r & E_i \end{bmatrix}^T.$$

It is noted that the states of this component have been separated into “dynamic” states, i.e. states that obey differential equations, and “static” states that obey algebraic equations. It is to be noted that the number of equations is consistent with the number of states. The generator currents will be eliminated by the terminal conditions imposed by the connectivity constraints, when the generator is connected to a network.

Finally it is to be noted that the trigonometric function have been eliminated by the introduction of the variables $s(t)$ and $c(t)$, without any approximations. The model is quadratic.

B.3 Quadratic Two-Axes Transient Generator Model

The model in phasor diagram is illustrated in Figure B.3. Since the notation in Figure B.3 is standard, no extensive explanatory remarks are given.

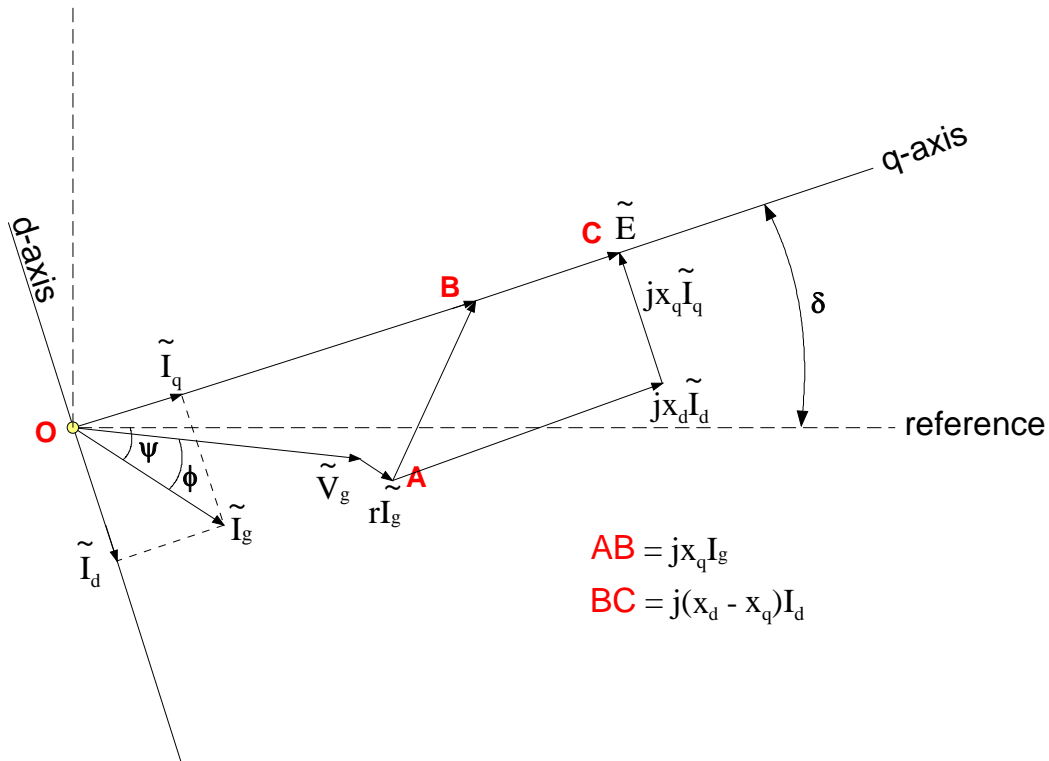


Figure B.3. Two-Axis Synchronous Machine Phasor Diagram

The quadratized equations are derived as follows. Consider the angle of rotor position (d-axis) $\theta(t)$ and the rotor angular velocity $\omega(t)$:

$$\delta(t) = \theta(t) - \omega_0 t - \frac{\pi}{2},$$

where $\delta(t) + \frac{\pi}{2}$ is the angle difference between the rotor (d-axis), rotating at speed $\omega(t)$, and a synchronously rotating reference frame at speed ω_0 .

$$\frac{d\delta(t)}{dt} = \frac{d\theta(t)}{dt} - \omega_0 = \omega(t) - \omega_0,$$

and

$$\frac{d^2\delta(t)}{dt^2} = \frac{d^2\theta(t)}{dt^2} = \frac{d\omega(t)}{dt}.$$

\tilde{I}_g : armature current (positive direction is into the generator)

r : armature resistance

x_d : direct-axis synchronous reactance

x_q : quadrature-axis synchronous reactance

\tilde{V}_g : terminal voltage

The state vector is defined with:

$$\begin{aligned} X^T &= [y^T \quad x^T] \\ y^T &= [V_{gr} \quad V_{gi} \quad E_r \quad E_i \quad I_{dr} \quad I_{di} \quad I_{qr} \quad I_{qi} \quad z_1 \quad z_2] \\ x^T &= [\delta(t) \quad \omega(t) \quad s(t) \quad c(t)] \end{aligned}$$

The model equations in quadratic form are:

$$\begin{aligned} I_{gr} &= I_{dr} + I_{qr} \\ I_{gi} &= I_{di} + I_{qi} \\ 0 &= E_r - V_{gr} + rI_{dr} + rI_{qr} - x_d I_{di} - x_q I_{qi} \\ 0 &= E_i - V_{gi} + rI_{di} + rI_{qi} + x_d I_{dr} + x_q I_{qr} \\ 0 &= E_r s(t) - E_i c(t) \\ 0 &= E_r I_{dr} + E_i I_{di} \\ 0 &= E_i I_{qr} - E_r I_{qi} \\ 0 &= z_1 \omega(t) - E_r \\ 0 &= z_2 \omega(t) - E_i \\ 0 &= E_r^2 + E_i^2 - E_{spec}. \end{aligned}$$

$$\frac{d\delta(t)}{dt} = \omega(t) - \omega_0$$

$$J \frac{d\omega(t)}{dt} = T_m(t) - 3 \cdot [z_1(I_{dr} + I_{qr}) + z_2(I_{di} + I_{qi})] - T_D$$

$$\frac{ds(t)}{dt} = c(t) \cdot (\omega(t) - \omega_0)$$

$$\frac{dc(t)}{dt} = -s(t) \cdot (\omega(t) - \omega_0)$$

It is noted again that the states have been separated into “dynamic” states, i.e. states that obey differential equations, and “static” states that obey algebraic equations. It is also to be noted that the number of equations is consistent with the number of states.

The above model can be easily augmented with additional equations to model the subsystems that specify the constant quantities that are left as constant inputs (governor, prime-mover, excitation system, etc.)

B.4 Solution Methodology

The proposed modeling methodology results in the following general quadratic state-space component model:

$$\frac{dx(t)}{dt} = A_1 x(t) + A_2 y + \text{diag}(x(t), y) B \begin{bmatrix} x(t) \\ y \end{bmatrix}$$

$$\begin{bmatrix} w \\ 0 \end{bmatrix} = C_1 x(t) + C_2 y + \text{diag}(x(t), y) D \begin{bmatrix} x(t) \\ y \end{bmatrix}$$

where $x(t)$ are the “dynamic” states of the component, y are algebraic states of the component and A_1, A_2, B, C_1, C_2 and D are matrices of appropriate dimensions.

By application of the connectivity constraints on the component model equations, the “through” variables (terminal currents) are eliminated and the following state space equations are obtained for the entire network:

$$\frac{dx_N(t)}{dt} = A_{1N} x_N(t) + A_{2N} y_N + \text{diag}(x_N(t), y_N) B_N \begin{bmatrix} x_N(t) \\ y_N \end{bmatrix}$$

$$0 = C_{1N} x_N(t) + C_{2N} y_N + \text{diag}(x_N(t), y_N) D_N \begin{bmatrix} x_N(t) \\ y_N \end{bmatrix}$$

The subscript N indicates state vectors and matrices for the entire network. Note that the resulting state space network equations are quadratic. The network matrices are sparse. Note that

the network model preserves the structure of the network, i.e. state variables of the network are explicitly represented.

The proposed modeling methodology has the following advantage: **a complex nonlinear system is represented with a set of state space equations of highest degree two. The dimensionality of the model has increased, but the nonlinearities of higher degree than two have been removed. The quadratic state space model is completely equivalent to the initial nonlinear complex system.** It is proposed to exploit the quadratic state space model for the purpose of developing advanced transient stability methodologies.

B.5 Application in System Stability Studies

Stability analysis and system stabilization is a difficult problem for the complex and large scale electric power system. Stability of electric power system is typically studied by extensive and exhaustive dynamic simulations and appropriate energy function methods. By far, energy function based methods are superior providing stability regions. These methods are basically Lyapunov methods. The success of these methods, in terms of providing realistic stability regions, is dependent upon the selected energy function. The complexity and nonlinearities of the traditional electric power model make the application of these methods quite complex and computationally demanding.

The proposed approach is to take advantage of the quadratic integrated model for the purpose of studying large signal stability. There is a plethora of work on stability of quadratic systems. The proposed approach, since it is based on an equivalent quadratic model, can take advantage of prior theoretical work on quadratic system stability. As an example, the proposed approach has the potential of (a) providing an efficient methodology to determine post disturbance equilibria points, (b) providing a simple method to select energy functions (Lyapunov functions) and (c) providing an efficient computational approach to determine the stability region. The basic approach is briefly described as follows.

Post disturbance equilibria points are determined by the quadratized model of the network by simply setting the time derivatives to zero. This procedure results in the quadratized power flow model which has been shown to be very efficient [145]. Specifically, the solution of the quadratized power flow equations with a Newton's type method provides fast convergence and a reduced overall execution time [145]. The computation of the post disturbance equilibria points is one of the major computational procedures in energy function approaches.

The proposed quadratized model also simplifies the construction of the energy function. The energy function may have a form of the type:

$$V(x_N(t)) = x_N^T(t)Px_N(t)$$

where P is a positive definite matrix, thus making the energy function positive definite. The time derivative of the energy function is computed to be:

$$\frac{dV(x_N(t))}{dt} = 2x_N^T(t)PA_{1N}x_N(t) + 2x_N^T(t)PA_{2N}y_N + 2x_N^T(t)Pdiag(x_N(t), y_N)B_N \begin{bmatrix} x_N(t) \\ y_N \end{bmatrix}$$

The states are also obeying the algebraic equations:

$$0 = C_{1N}x_N(t) + C_{2N}y_N + diag(x_N, y_N)D_N \begin{bmatrix} x_N(t) \\ y_N \end{bmatrix}$$

The stability region is computed as the region where the above derivative of the energy function $V(x)$ is negative semi-definite. The stability region can be evaluated by numerically eliminating the variables y_N . Since the equations are quadratic, the computational problem is expected to be much simpler than the traditional energy function methods. Note that this approach can be characterized as a structure preserving energy function method.

Similar simplifications are also expected in small signal stability studies. Since the state space equations for the entire system are either linear or quadratic linearization techniques can result in much simpler expressions and in improved computational efficiency.

B.6 Time Domain Simulation

Time domain simulation has an important role in transient stability assessment, even in an on-line application environment. It provides accurate stability analysis of specific pre-defined conditions and disturbances. The speed of numerical integration is a key feature of the simulation, if it is to be used for on-line stability assessment. It is important to recognize that state of the art DSA method utilize a hybrid approach combining time domain simulation methods and energy function type methods.

Implicit numerical integration methods are usually preferable for power system simulation, because of they superior numerical stability properties, compared to explicit methods. However, implicit methods perform considerable slower, compared to explicit ones, since a system of nonlinear algebraic equations is iteratively solved at each integration step, by a method like Newton's method. This becomes a serious disadvantage for on-line applications.

The use of quadratic component models may prove useful in such situations, by alleviating the computational burden to some extend. More specifically, the quadratized models of all components of the system are numerically integrated to yield a set of algebraic (quadratic) set of equations. Application of connectivity constraints yields a set of algebraic (quadratic) equations for the entire system. These equations are solved via Newton's method. However, Newton's method is best suited for quadratic problems, that is, it demonstrates better convergence behavior when the equations that are solved are quadratic, compared to equations with more complex nonlinearities. Therefore, the use of quadratic models may prove to be a considerable advantage. As a matter of fact, some initial results on use of quadratic models result in a more accurate and

efficient time domain method. Reference [146] presents some preliminary but very promising results on these methods.

Appendix C: References

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