Real-Time System Stability Monitoring in the Transmission Network of Bosnia and Herzegovina

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Dusko Vickovic[1], Roland Eichler[2], Savu C. Savulescu[3]

Abstract *- This paper describes the implementation of, and experience with, real-time stability monitoring at the Independent System Operator in Bosnia and Herzegovina (NOS-BiH). It identifies key methodology features that make it possible to rapidly quantify the risk of blackout, track the distance to instability in real-time, and present the results in meaningful and user-friendly formats. Related topics include: which stability aspects are amenable to real-time monitoring; how stability monitoring can help avoid blackouts; and how to overcome traditionally difficult issues such as extensive computation time, extensive modeling, and complex presentation of the computational results. Also addressed are the requirements from the control room user's point of view, e.g., automatic activation, single and consistent user interface, and the ability to use the standard SCADA trending capability to monitor the distance to instability in real-time. Finally, the paper describes the seamless integration of the fast stability assessment tool (QuickStab) with the SCADA/EMS, illustrates the main benefits derived from real-time stability monitoring with actual examples that depict the QuickStab results displayed directly on the SCADA/EMS (SINAUT Spectrum) user interface, and shows how the NOS-BiH system operators use this information to maintain and enhance the operating reliability of the transmission grid.*

Index Terms *-- open access transmission, maximum loadability, energy management systems, independent system operators.*

1 Introduction

Modern transmission grids must sustain MW transfers that can be quite different from those for which the networks were planned. This is because energy transactions across multi-area systems of continental or sub-continual size may cause parallel flows, significant network loadings and low bus voltages. Such system states may further deteriorate and become unstable, for once the system got in the neighborhood of the mathematical condition that characterizes the state where voltages may collapse and units may loose synchronism, instability develops instantly and leaves no time to react. But in order to be *prevented*, the risk of blackout due to instability must first be *predicted*, so that adequate corrective actions could be quickly enacted if and when needed.

The ability to predict the risk of blackout rests on the capability to quantify and compute the *distance* to the stability limit that corresponds to the current operating state. Each operating point is characterized by a different stability limit. Therefore, the distance between the current conditions and the state where voltages may collapse and units may loose synchronism must be reevaluated after each state estimate and after each load-flow.

In other words, the detection of the risk of instability must be envisioned as a continuous process, i.e., the distance to instability must be *monitored*. "Monitoring" is a real-time process and points to the need to perform stability calculations: in a SCADA/EMS environment; with minimum

[1] Independent System Operator of Bosnia and Herzegovina, Sarajevo, Bosnia and Herzegovina, d.vickovic@nosbih.ba
[2] Siemens Power Transmission and Distribution, Energy Automation, Nuremberg, Germany, roland.eichler@siemens.com
[3] Energy Consulting International (ECI), Inc., New York, USA, scs@eciqs.com, http://www.eciqs.com

amount of data; within continuously running real-time network analysis sequences; and quickly enough so that the results would be available immediately after the execution of the state estimator, thus allowing the user to examine them before the next real-time network sequence run. To further increase the complexity of such an already difficult proposition, the results must be presented in a user-friendly format as required for fast and reliable on-line decision-making.

This problem was solved effectively and efficiently by the Independent System Operator in Bosnia and Herzegovina (NOS-BiH) by blending a very fast, reasonably accurate and field-proven stability tool with the versatile computing facilities provided by its new SCADA/EMS.

The subsequent sections briefly describe the methodology, shade light on the innovative approach used to implement the stability tool in real-time, and provide further insight into the most significant practical aspects of this implementation.

2 Theoretical Background

2.1 Applied concept of stability analysis and stability limits

The evaluation of the operating reliability of transmission networks in normal or emergency operating conditions is a complex undertaking. Depending upon the scope of analysis, the methods are referred to as static and, respectively, dynamic security assessment.

An important objective of dynamic security assessment is to determine whether the system can withstand a set of large, yet credible, contingencies. This is the field of transient stability analysis. As a minimum, the analyst takes into account: the system conditions prior to a disturbance, actual or postulated; the location, duration and size of the disturbance; and the system's trajectory from the initial state to the critical state, i.e., the scenario envisioned for stressing, or worsening, the system conditions.

An equally important goal is to evaluate the risk of instability when the system is approaching a dangerous state slowly, in small steps, as a result of: small topology and/or load changes accompanied by slow bus voltage changes that may trigger a voltage collapse; and/or gradual load increases that may eventually cause one or several generators to loose synchronism. Both voltage collapse and units loosing synchronism can be detected by steady-state stability analysis, which aims at the “stability of the system under conditions of gradual or relatively slow changes in load” [2]. A related, and quite important, concept is the Steady-State Stability Limit (SSSL) that identifies “a steady-state operating condition for which the power system is steady-state stable but for which an arbitrarily small change in any of the operating quantities in an unfavorable direction causes the power system to loose stability” [26].

There are other types of instability, e.g., units loosing synchronism due to self-oscillations. But regardless of how instability happens, the bottom line is that there is no way to handle all the aspects of stability at once. Each form of instability requires detailed models and adequate tools tailored to the physical phenomena under evaluation. The problem becomes even more complex when the target is a vast interconnected system. The sheer amount of data, the large computing times, and the technical skills needed to interpret the results render the analysis difficult.

The latter point is not academic. Even if computational speed is achieved by using fast computers in multi-processor configurations, thus enabling the stability calculations to be performed more or less "on-line", i.e., with real-time data and response times that may or may not qualify for "real-time", the end-users may have neither the time nor the background needed to assess the results. This opens the door for *intrinsically* fast methods that entail sound modeling assumptions and produce the output in formats which are easy to interpret and to understand.

On the transient stability venue, much work was done to develop "transient stability indices" and other tools that would determine the "degree of stability" [10], [25]. These techniques, when not based on heuristics, provide for a comprehensive analysis but are hampered by:

- Computational burden and non-convergence of load-flow calculations near instability
- Inherent limitation to handle the concept of "stability limit".

How many "stability limits" are there in the first place? Are they computable? Can they be quantified? Conceptually, the "stability limit" depends upon the system state vector associated with the current operating point: for each new system state, there is a new stability limit. Simply stated, "stability limits" exist, are not fixed, and change with the system's loading, voltages and topology. But in order to compute the stability "limit", or "limits", we first need to define a *metric* that would enable us to quantify such limits. This goal can be met only if we approach the search for stability limits from the steady-state stability perspective.

The steady-state stability analysis provides the mathematical framework where stability limits can be computed both system-wide and for individual buses. But since the steady-state stability criteria only verify whether a given state is stable or unstable without saying "how far" is the hypothetical state where voltages may collapse and/or units may loose synchronism, the steady-state stability checks must be alternated with a "system stressing", or "case worsening", procedure whereby various system parameters are changed in a direction that is unfavorable to stability. A series of successively degraded states is thus obtained, and the value of the maximum MW system loading, i.e., the total MW network utilization including both internal generation and tie-line imports immediately before instability can be used to quantify the SSSL.

On this basis, given a MW system loading and a case worsening strategy, once the SSSL has been found, the distance to instability can be measured by the percent value of the *steady-state stability reserve* which is equal to [(SSSL – MW)/SSSL]x100.

An equally important goal is the ability to quickly assess whether the current system state is "safe" in the sense that none of the most sever contingencies that can reasonably be envisioned would cause transient instability. In other words, for any given system state, in addition to SSSL and the steady-state stability reserve, a "security margin" should also be computed which would allow qualifying the current state as "safe" or "unsafe".

The SSSL, "steady-state stability reserve" and "security margin" have been developed in Europe in the late 1950s and early 1960s [3], [4], and [5]. For example, the 1964 Special Report of the Group 32 of CIGRE explicitly stated that *"any network that meets the steady-state stability conditions can withstand dynamic perturbations and end in a stable operating state"* [11]. A more detailed discussion of these concepts is provided in Appendix 1.

2.2 Steady-State Stability Revisited

The phenomena encompassed by steady-state stability are extremely complex. Accordingly, specialized tools have been tailored to address natural stability vs. stability maintained by fast voltage controllers, local stability vs. global stability, and the stability of power transfers across paths between system areas vs. voltage stability.

The conventional method of the small oscillations for estimating the steady-state stability [2], [3], [19] consists of examining the eigenvalues of the characteristic equation associated with the system of differential equations that describe the free transient processes after a small disturbance takes place in an automatically controlled power system. The necessary and sufficient condition for steady-state stability is that all the real parts of the eigenvalues be negative [19]. The analysis encompasses the following steps:

- Describe the transient processes in the form of a system of nonlinear differential equations
- Linearize the equations around the solution point by expanding them into a Taylor series and retaining only the linear (first order) terms
- Calculate the main determinant and its minors and develop the characteristic equation
- Determine the sign of the real roots and the sign of the real part of the complex roots of the characteristic equation.

The approach is laborious and is replaced by determining relationships between the roots and the coefficients of the characteristic equation. Venikov [19] refers to these relations as "steady-state stability criteria" and classifies them into *algebraic* (Routh-Hurwitz) and *practical*. A necessary, but not sufficient, condition for steady-state stability is derived from the Hurwitz criterion by evaluating the sign of the last term of the characteristic equation, which is the Jacobian determinant **D**. A change of sign from positive to negative (all Hurwitz determinants are positive) with further loading of the system indicates *aperiodic*, or monotonic, instability. The instability in the form of self-oscillations, however, remains unrevealed by this method.

Perhaps the most significant hurdle is the representation of the generators. Detailed analysis methods entail modeling the machines via transfer functions. The data requirements, the complexity of the ensuing algorithms, and the heavy computational burden render such techniques impractical for real-time implementation. But if the generator modeling is simplified without introducing unacceptable inaccuracies, then it becomes possible to develop methodologies that are fast and reasonably accurate, thus suitable for real-time implementation. Historically, two approaches that meet these requirements have emerged as follows:

- Represent the generators via constant e.m.f. behind the transient reactance in conjunction with a modeling framework that makes it possible to apply the so-called "practical stability criteria" – this technology has been known and used in the industry for quite some time, forms the basis of the real-time stability monitoring at NOS BiH's, and is further described in section 2.3
- Assume that the generators' terminal voltages are constant, i.e., the internal reactances of the machines are negligible, and apply continuation load-flow techniques to push the system conditions all the way through the point of voltage collapse – this technology has also been available for a long time and is briefly described in Appendix 2.

Both approaches have their fields of applicability. While the first method yields more accurate results around the linearization point, the latter allows the proper consideration of power system changes, e.g. due to automatic transformer tapping, on the way to the point of voltage collapse.

The *practical stability* criteria were developed by the Russian school of stability [19]. In a nutshell, these criteria: refer to aperiodic instability, i.e., are not intended to detect instability due to self-sustained oscillations; are derived from the condition **D** = 0; and are valid if:

- The generators are radially connected to a nodal point -- this may or may not be true in real-life, but, as we will show in the next section, *is always the case* if the short-circuit currents transformation is applied to convert the power system network to a scheme of short-circuit admittances connected radially to a nodal point
- The system frequency is constant during the short period of time associated with the transient process and, furthermore:
  - Either the voltage is constant at the nodal point, which leads to the *synchronizing power criterion* $dP/d\delta > 0$
  - Or the power balance is maintained at the nodal point, which leads to the *reactive power voltage and steady-state stability criterion* $dQ/dV < 0$ or, rather, $d\Delta Q/dV < 0$.

The reactive power voltage and steady-state stability criterion was used by Dimo [3], [4] in conjunction with the REI Net, Nodal Image, Zero Power Balance Network and the Case Worsening algorithm to develop a fast and reasonably accurate technique for voltage and steady-sate stability assessment. These concepts are briefly addressed in the following.

2.3 Dimo's Technique for Steady-State Stability Assessment

The technique developed by Dimo in Europe [3], [4] and demonstrated to be useful for real-time applications in the EPRI Research Project RP2473-43 [25] and various US and international publications [8], [16], [17] is predicated on the:

- *Short-circuit currents transformation* to convert the power system network, which is highly meshed, to a scheme of short-circuit admittances connected radially to a nodal point known as the REI Net -- this network transformation is error-free and forms the basis to build the Nodal Image which is subsequently used in the Case Worsening algorithm
- *Reactive power stability criterion dQ/dV, or dΔQ/dV*, developed by Bruk-Markovic and fully documented in [3], [4], [14], [18] -- the radial nature of the REI Net makes it possible to apply this practical stability criterion without introducing any error
- *Classic representation of generators* via a constant e.m.f. behind the transient reactance x'_d -- this is an industry accepted modeling approximation which actually implies that the generators are equipped with "proportional action voltage controllers" [19]. This modeling approach was enhanced in [17], [27] by replacing x'_d with the synchronous reactance x_d if the machine has reached both its P_{max} and Q_{max} limits during the Case Worsening algorithm. This approach is consistent with the findings documented in [1, pp 681] and [6], among other references
- *Zero Power Balance Network* to aggregate the bus loads into a system-wide single load-center -- this method, known in the industry as the "REI equivalencing technique", has been demonstrated to be accurate if the individual bus loads vary conformingly with the total system load [24]. It must be emphasized that in the context of evaluating stability, the

generators are represented with their actual identities (as opposed to REI network equivalents where the generators are equivalized as well), and the Zero Power Balance Network is used only for the purpose of creating an equivalent load center. This in turn makes it possible to develop the system-wide stability index referred to as steady-state stability reserve

- *Case Worsening* procedure, which is used, instead of a succession of load-flow computations, to stress the system until it becomes unstable. The following provisions are implemented to stress the network conditions *without* having to recalculate the base case load-flow:
  - Increase the total system generation to meet successively higher load levels by raising *coherently* the MW produced by each generator while observing the maximum MW limit of the machine
  - Represent the real part of the loads as MW, rather than as impedances, and model the reactive part of the load as a susceptance that either has a fixed value, derived from the base case, or varies proportionally with the power factor in the base case
  - Model the sudden change of the operating conditions of generators that have reached the reactive power limits. If this happens under:
    - ✓ Light load conditions, replacing the transient reactance with the synchronous reactance will cause the steady-state stability to decrease but not to be destroyed
    - ✓ High loadings, the same machine model change may destabilize the system and precipitate a voltage collapse.

Throughout the case worsening process the system model remains constant. If major topology or other changes need to be simulated, e.g. line and generator contingencies, a new load-flow solution is required. Once the base case has been recalculated, the REI Net and the Nodal Image are updated, the case worsening procedure is performed, and the SSSL, steady-state stability reserve and security margin for the new system state are obtained – but since the algorithm is fast, the evaluation of contingencies has little impact on the overall solution time.

The inability of the case worsening procedure to handle topology changes has an interesting implication: when the current system state is far away from its stability limit, the SSSL value computed with Dimo's algorithm tends to be too conservative – but when the total MW system loading increases and additional reactive compensation resources get committed, the prediction of the distance to instability becomes more and more accurate.

In order to explain this apparent paradox, let's note that operating policies typically call for raising the TCUL taps, removing shunt reactors, adding shunt capacitors and bringing on-line synchronous condensers when the system is approaching peak-load conditions. When the same power system operates at medium and light load levels, the reactive compensation goes the other way -- capacitors are removed, shunt reactors are reconnected, synchronous condensers and/or units that were running essentially for generating MVArs are taken off-line, and major high voltage transmission lines are disconnected.

Such operating procedures push the network's maximum loadability at values much higher than those at medium and light load levels – and since the corresponding network changes cannot be simulated in one single case worsening run, the steady-state stability calculations must be restarted from different base cases, each one reflecting the structurally different operating scenarios. A fine example that illustrates this situation is described in the reference [21].

The following sections will focus upon the approach taken by NOS-BiH and the SCADA/EMS vendor to effectively implement this technique in real-time and to deploy it to continuously monitor the distance to instability of the power system -- by using real-time data, performing fast stability computations, and providing the results on user-friendly charts and diagrams.

3 The Current Implementation of Real-Time Stability Assessment at NOS BiH - Application Experience

3.1 NOS BiH Transmission System in the Regional Context

The Independent System Operator (NOS) of Bosnia and Herzegovina (BiH) has full dispatch responsibility and authority for the operation of the BiH power system and electricity market, which comprises the electrical generation and transmission facilities in the entire country and is operated as a UCTE Single Control Area within the UCTE Control Block encompassing Bosnia and Herzegovina, Croatia and Slovenia. In order to support its operational mission, NOS BiH has undertaken the implementation of state-of-the-art control, information and communications facilities. This complex SCADA/EMS, Communications and RTU/ISAS project, contracted with Siemens, is currently in its final stages and the new system is expected to become fully operational in the middle of the year 2008.

One of the most critical responsibilities of the NOS BiH consists of maintaining the uninterrupted supply of electricity within BiH and allowing significant power transfers across the BiH transmission network caused by energy exchanges in Southeastern Europe while protecting the BiH customers against blackouts and unwanted disturbances. Due to its location at the center of significant MW transfers between the market participants in the region, which may significantly affect the operating reliability of the transmission system, NOS BiH developed an interim solution aimed at providing at an early stage the key tools needed to maintain and enhance the operating reliability of the grid.

First, it acquired off-line network analysis software, consisting of Power Technologies Inc. PSS/E load-flow and transient stability programs. Then, in 2001, it implemented an interim SCADA system predicated on Siemens SINAUT Spectrum® technology -- and, in 2005, it expanded the interim SCADA system with a state estimator, also on SINAUT Spectrum technology, and the QuickStab® fast steady-state stability program that is used both on-line, to perform maximum loadability analysis with real-time data, and off-line, in conjunction with study cases developed with the PSS/E software. These tools make it possible to assess, on a continuous basis, the actual utilization of the BiH network, support on-line decision making, and help maintain and enhance the operating reliability of the grid.

The fast steady-state stability application uses the technology described in the section 2.3 of this paper. Initially, the program was loosely integrated with the state estimator that runs on the interim SCADA system. The implementation approach, practical experience and lessons learned from the interim solution are discussed in sections 3.2 and 3.3.

The second and ultimate phase has already been completed. The SCADA/EMS vendor has seamlessly integrated QuickStab with the new SCADA/EMS and, in addition, has provided the capability to display the key stability calculation results and to monitor the distance to instability in real-time, directly in the native SCADA/EMS user-interface. The upgraded solution is documented in Section 4.

3.2 Current Implementation of Real-Time Stability Assessment at NOS BiH

NOS BiH implemented the fast steady-state stability assessment technique described in section 2.3 in two computing environments: off-line, to support the short- and mid-term operations scheduling process; and in real-time, where it is used in system dispatching. In study-mode, the fast stability application runs on off-line PCs and uses off-line load-flow and generator data in PSS/E format prepared on the PSS/E platform. In real-time, the steady-state stability assessment program has been loosely integrated with the interim SCADA system as follows.

The stability assessment software is installed on a separate PC connected to the SCADA/EMS LAN. On the SCADA/EMS side, after each successful execution of the State Estimator, the output is saved in PSS/E format on the data administration server. On the PC side, a control program developed specifically for this purpose runs at fixed time intervals that are user definable, e.g., 5, 10, 15, etc. minutes. The control program retrieves the most recent state estimate file from the SCADA/EMS server via FTP, copies it on the PC, and then automatically triggers the QuickStab computational engine.

Upon completion of the stability calculations, the control program triggers the display engine of QuickStab to present the results on the PC. In addition, both the computational results and the input data are copied in a special directory for archival purposes. The archived input data and computational results can subsequently be exported to an external data storage device. This process is schematically depicted in Figure 1.

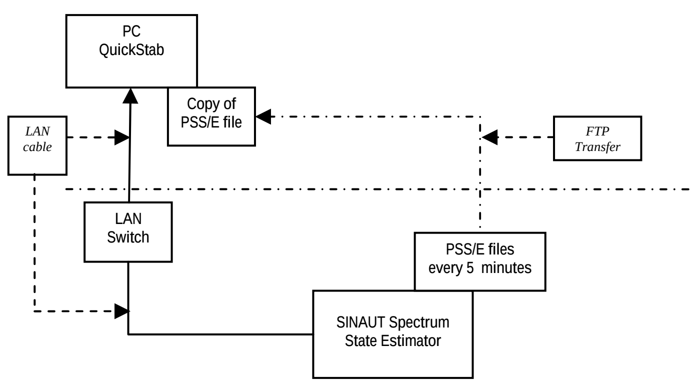

Figure 1: *Schematic description of the interim implementation of real-time stability assessment at NOS BiH*

3.3 Experience

The ability to compute the steady-state stability reserve of the BiH power system in real-time and to display the results in a graphical format that can be easily interpreted and understood by the system dispatcher has proven useful, and the experience acquired to date has been positive.

One of the key displays that are continuously updated on a Windows operator console is the so-called Two-Speedometer Chart for the base case, i.e., the current system state as computed during the most recent successful run of the state estimator (Figure 2).

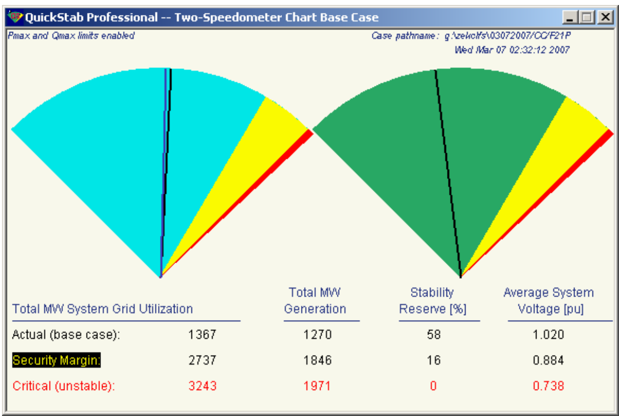

Figure 2: *Two-Speedometer Chart depicting the distance to instability (red) and to the security margin (yellow)*

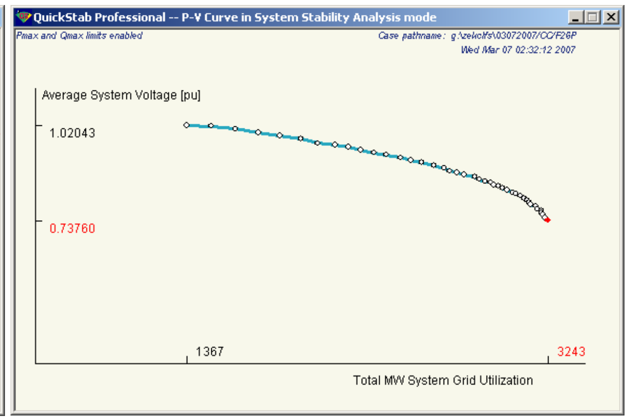

Figure 3: *P-V curve depicting the case worsening process -- the average system voltage decays while the total MW system grid utilization increases up to the point of voltage collapse*

The right hand speedometer displays the distance to instability on a linear MW scale. The needle corresponds to the total MW system grid utilization in the base (current) state. The left edge of the read sector depicts the SSSL. The distance between the black needle (base case) and the red area (critical state) is quantified by the stability reserve in [%] below the SSSL. The width of the yellow sector is proportional with the percent value of the security margin. This representation can be related with the "stability envelope" concept illustrated in Figure 7, where the "safe" operating region is shown in green and corresponds to total system MW loadings smaller than the MW security margin.

The left hand speedometer shows the distance to instability on a non-linear scale where the values of the dQ/dV reactive power practical steady-state stability criterion are mapped for: the base case (black needle); and for a hypothetical state (blue needle) where the generators and the virtual units representing the tie-line injections would have been redispatched to maximize the distance to instability. In the case illustrated in Figure 2, the blue and the black needles are very close to each other, thus suggesting that even if the units were redispatched to achieve maximum stability, the gain would be minimal. Incidentally, since the stability reserve is already very large, an attempt to maximize stability would not be necessary.

Let us also note that the distance between the black needle and the red sector on the blue speedometer is smaller than the distance between the black needle and the red sector on the green speedometer. This suggests that during the case worsening process, the system approaches "slowly" the critical state, i.e., many small MW increases are needed for the dQ/dV derivative to increase from its initial negative value up to the point where it changes sign from minus to plus. This information is corroborated by the P-V curve shown in Figure 3 which shows many successively degraded states from the base cases through the state of instability.

Another important output of the stability tool is the bar chart that ranks the units, generators and tie-line injections, in the decreasing order of their impact on the system's stability (Figure 4).

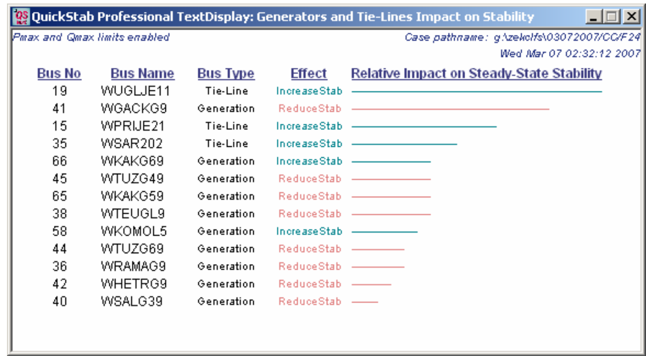

Figure 4: *Unit ranking bar chart depicting the impact of generators and tie-line injections on stability*

A relatively small increase in the MW output of the units shown in green causes the stability conditions to improve, whereas the machines represented in red need to reduce their output in order to improve the stability conditions. Let us also note that the lengths of the bar charts in Figure 4 are proportional with the moduli of the generators' short-circuit currents divided by the internal angles of the machines. A detailed discussion of this concept goes beyond the scope of the paper. The interested reader is directed to the reference [16] where all the mathematical aspects are presented in detail.

To summarize, the computational speed of the steady-state stability tool and the user-friendly format of the displays used to present the results are significant benefits and fully justify its real-time implementation. But the interim solution also revealed some areas where further improvement is needed.

In terms of functionality, the software version that was available at the time when the interim solution was devised did not have a stand-alone contingency evaluation capability -- and since neither contingency analysis nor dispatcher's power flow functions were available on the interim SCADA, the only way to evaluate contingencies for stability violations would have been to run QuickStab in conjunction with PSS/E and to use the real-time case. In reality, this is not possible because of the different bus naming and bus numbering conventions of the real-time and, respectively, the off-line databases. In the mean time, QuickStab has been upgraded with a contingency analysis feature that scans the list of contingencies, and then, for each contingency, performs a full Newton-Raphson AC load-flow followed by the complete suite of stability calculations. This new functionality will be supported by the new SCADA/EMS, in addition to a more complex contingency evaluation process as described in Section 5.

Another limitation of the current solution stems from the fact that QuickStab uses a Windows PC user-interface which is very different from the SCADA/EMS User Interface. This forces the operators to navigate between two display environments, one on the SCADA/EMS console and the other one on a Windows PC, which is neither easy nor comfortable.

Also missing in the loosely integrated implementation is the ability to monitor in real-time the distance to instability. Although the data needed to implement stability monitoring are calculated by QuickStab, they do not get transferred to the real-time database. A significant benefit of the seamlessly integrated approach is that after each calculation cycle, the steady-state stability reserve is written in the real-time database and then it can be trended by using the standard trending facilities of the new SCADA/EMS. This, in turn, will allow the operator to see the evolution of the distance to instability over a user-selectable period of time. Furthermore, the new implementation would allow the activation of QuickStab after State Estimator solutions outside the fixed time grid chosen at the PC, e.g. after switching event triggered activations.

4 The Real-Time Implementation of System Stability Monitoring

The standard Siemens SINAUT Spectrum SCADA/EMS already includes a VSA application (see Appendix 2) as part of its Transmission Network Analysis (TNA) package. However, software like QuickStab following the approach described in chapter 2.3 was deemed a valuable alternative for stability evaluation to the SCADA/EMS user.

When designing the integration of QuickStab in SINAUT Spectrum emphasis was put on the ability to easily integrate QuickStab also to existing users of the TNA package. Further considerations governing the real-time implementation of QuickStab into the SCADA/EMS were derived from the major drawbacks experienced from the interim solution, as outlined in the previous section. Hence major goals were

- immediate update of the operator on the distance from instability periodically as well as after each significant system change – as opposed to periodical updates only
- display of the decisive results in the user interface of the SCADA/EMS – as opposed to a separate and unfamiliar user interface
- capability to evaluate system instability for perceived situations by means of the familiar SCADA/EMS study case management and in the same convenient way as in real-time – as opposed to using a separate and unfamiliar offline study environment

A design as shown in Figure 5 was chosen. It should be noted that the SCADA/EMS is Unix-based while the PC runs under Windows operating system:

- As opposed to the interim implementation as outlined in chapter 3.2 the initiation of QuickStab calculations is with the SCADA/EMS rather than the PC. For that purpose the **N**etwork **A**nalysis **S**equence **C**ontrol program (NASC) of the SCADA/EMS is extended in a way that after producing a PSS/E data file by means of the existing **N**etwork **A**nalysis Data E**x**port program (NAX) a dedicated script named NA_QuickStab is activated.
- This activation happens after <u>each</u> run of the State Estimator (SE) in real-time mode as well as after <u>each</u> run of the Dispatcher Power Flow (DPF) in study mode. In order to separate SE-based activations from (several) simultaneously running DPF-based activations their respective working directories are named ‘Realtime’ vs. ‘Study Case ALPHA’, ‘Study Case BETA’, etc.
- The script NA_QuickStab uses ‘secure shell commands’ as well ‘secure copy commands’ to create directories on the PC in parallel to those created on the SCADA/EMS and to fill them with the respective PSS/E file

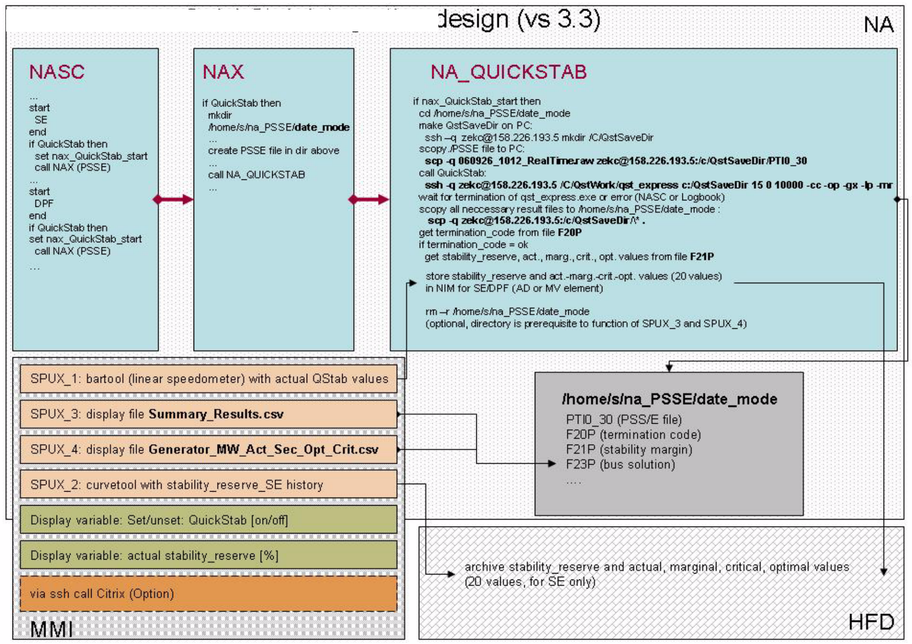

Figure 5: *Schematic description of the final implementation of real-time stability assessment at NOS BiH*

- QuickStab is called by the script to be executed on the PC using the respective working directory; after termination the results are stored in the respective working directory on the PC. Here they reside until they are deleted. This means that at any time the PC user can access the complete input and output data of any calculation done with data received from the SCADA/EMS by means of the QuickStab detailed visualization tools – or use the data for performing more detailed QuickStab analysis offline.
- The script NA_QuickStab waits for the termination code, then it copies selected results from the PC into the respective working directory on the SCADA/EMS
- The current stability reserve values are written into the database of the SCADA/EMS (real-time area or study case areas, as appropriate)
- The script NA_QuickStab terminates.

At this point the regular SCADA/EMS features for alarming and displaying take over. As the most prominent result, the current stability reserve value is displayed in the execution control display of SE or DPF, respectively (please refer to Figure 6, lower right corner). The figure is spontaneously updated as soon as new calculation result is written by NA_QuickStab into the real-time database. If limits are violated, an alarm is raised in the SCADA/EMS in the same way as for another analog value.

By means of buttons 'QstDisplay 1' and 'QstDisplay 2' on the execution control display of the SE or DPF application, the user can call tabular displays providing more detailed results out of the SCADA/EMS real-time database. Figure 6 shows the Critical Bus Data Table as an example (middle area on left side). Last but not least, since the current stability reserve values are treated by the SCADA/EMS like regular analogs, they can be archived and displayed in trend curves (see Figure 6, lower left area). This allows the operator to see the evolution of the distance to instability over a user-selectable period of time.

In case the operator is actually interested to see more results of the most recent QuickStab calculation he/she can press a button on the execution control display of the SE or DPF application that – by the means of VNC Viewer - opens a window on the Unix-based console of the SCADA/EMS actually displaying the desktop of the PC running QuickStab. By these means the operator can use all displaying facilities of the genuine QuickStab program without actually moving to another monitor.

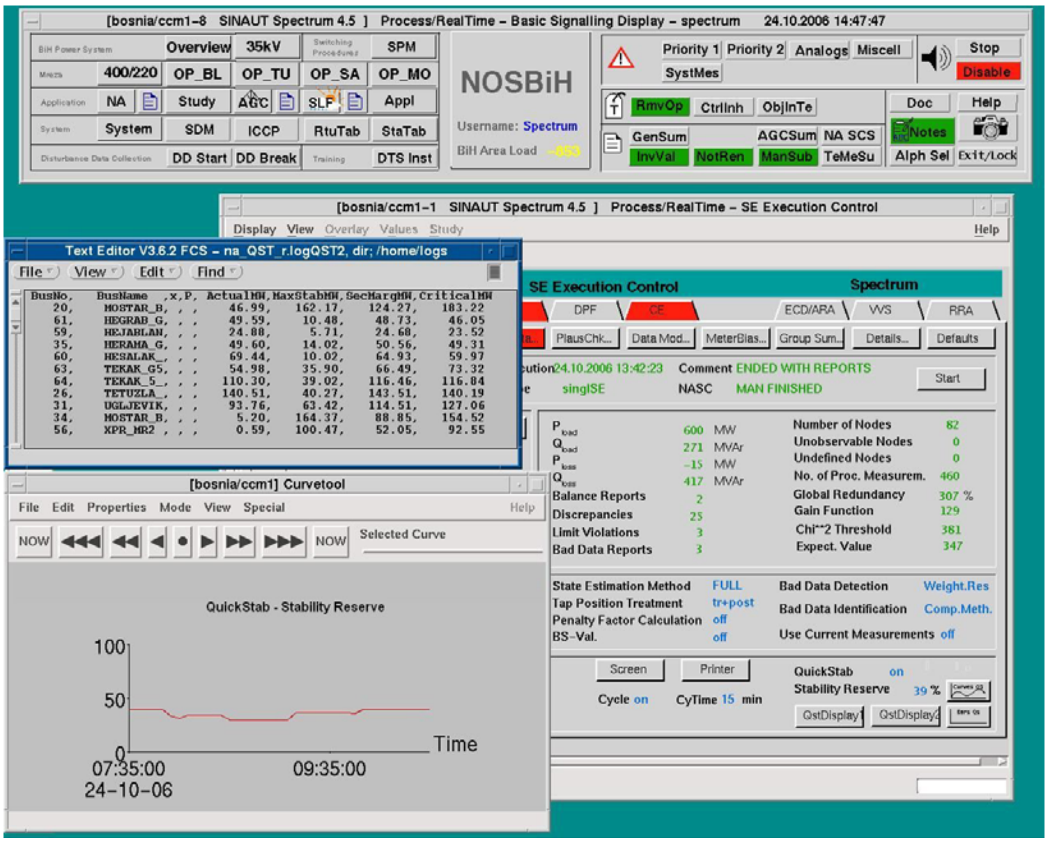

Figure 6: *Visualization of real-time stability analysis results in the SCADA/EMS user interface*

5 Conclusions and Outlook

The power system stability analysis during system operation is very important and especially over the last years even more transmission system operators realized the strong need for such analysis after energy markets have been opened and large cross-border energy trades started to impact the stability of power systems. Proper stability analysis requires continuous application to track the continuous changes of the power system loading and to assess the impact of discontinuous events such as switching state changes. Such real-time monitoring of system stability, however, is hampered by the computational burden imposed. Therefore, in order to be applicable, the solution approach needs to be based on acceptable approximations. The Independent System Operator of Bosnia and Herzegovina has elected to implement a technology based on Dimo's steady-state stability analysis method. Using this technique allows extremely fast calculation of the stability reserve of the power system whilst an accurate generator model is retained, thus yielding results with excellent accuracy around the operating point.

It is important for the results produced by sophisticated tools such as real-time stability analysis to be presented to the operator in a way that makes it easy and convenient to use them. Therefore the integration of such a tool in the real-time mode of the SCADA/EMS of the Independent System Operator in Bosnia and Herzegovina was done in a way that there is immediate update on system stability reserves not only after a cycle time such as 5 minutes has elapsed, but also after each significant system change. It was particularly important to meet the operators' requirement for displaying the key results of the stability analysis directly in the user interface of the SCADA/EMS and to provide the capability to evaluate system stability reserves for perceived situations by means of the familiar SCADA/EMS study case management (study-mode). Thus the need to get into a user interface environment other than SCADA/EMS was entirely abolished.

The thorough evaluation of the power system stability conditions requires the consideration not only of the base case but also of contingency cases. With the approach of system stability analysis integration in SCADA/EMS as described in the paper it is possible to perform such contingency case studies using the separate QuickStab environment on a separate PC – whose user interface, however, is fully accessible from the operators' well-known Unix user interface of the SCADA/EMS. The next step of integration will enable contingency case stability analysis based on the contingency lists of the SCADA/EMS entirely in the user environment of the latter.

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APPENDICES

Appendix 1: TSL, TTC and the Stability Envelope

Just like for each system state there is a SSSL, a Transient Stability Limit (TSL) can also be thought to exist. However, as opposed to SSSL, and because of the computational procedures used to detect transient instability, TSL it is not quantifiable through a specific formula. In order to further clarify this point, let us assume that at the TSL there are no thermal and voltage problems and therefore, according to the definition of the North American Electric Reliability Corporation (NERC), this limit would be the Total Transfer Capability (TTC) [29]. Should thermal and/or voltage violations be detected, than the total system loading would have to be decreased until the violations have cleared and a new state that would qualify for TTC has been found. *This state would obviously correspond to the ideal safe operating limit* but, in practical terms, a computational process to identify it can not be implemented. This is because in order to find the TSL, transient stability simulations would have to be performed for each potential disturbance starting with a base case scenario and continuing with a sequence of successively degraded operating states until the first unstable state has been identified. The intrinsic technical complexity and the large number of credible contingencies render such a problem practically unsolvable.

However, intuition suggests that:

- For a given set of relay settings, TSL depends, just like the SSSL, upon topology, voltage levels and system loading
- For any system state, SSSL and TSL are interrelated and move in the same direction: if SSSL is high, TSL is also high, and vice-versa.

In the past, empirical values approximating the *TSL/SSSL ratio* have been used to compute a "safe" system loading, expressed as a percentage of the SSSL and referred to as *security margin*, such that, for any system state with a steady-state stability reserve higher than this value, no contingency, no matter how severe, would cause transient instability [12]. Accordingly, the security margin can be regarded as a stability envelope: all the states with a total MW loading smaller than the MW value of the security margin are safe, even if a "safe" system state with higher MW loading might possibly be found. This concept is illustrated in Figure 7.

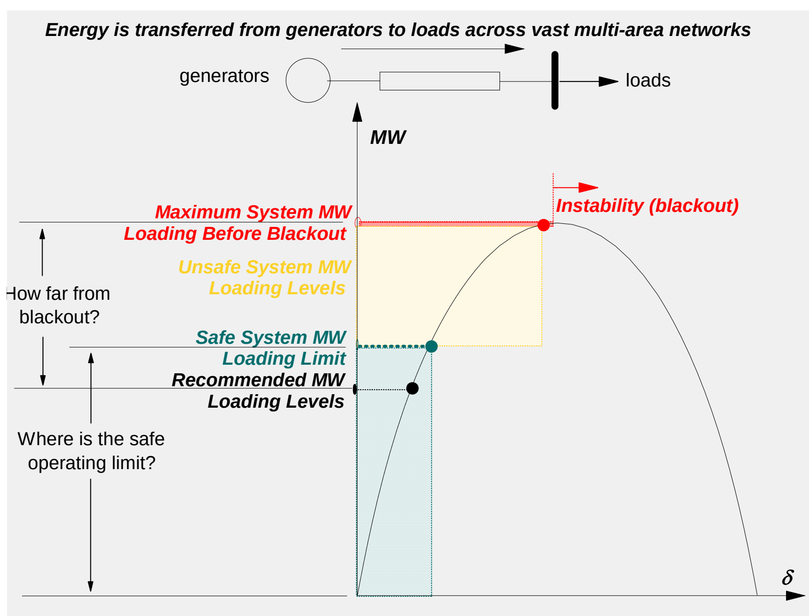

Figure 7: *Stability envelope concept*

The security margin depends upon the specific combination of topology, loads, generators and reactive compensation, and must be determined, and periodically reassessed, for each particular transmission system. For strong and highly meshed networks where the post-disturbance configuration is relatively close to the pre-disturbance state, the ratio σ = TSL/SSSL can be assumed to be approximately constant.

If this ratio σ is known, the system loading at TSL can be determined by first computing SSSL and then identifying a new system state with total MW loading equal to σ x SSSL. We are not aware of a mathematical formula relating TSL and SSSL, nor do we know whether such a relationship can be developed analytically, but the empirical approach described in [21] can be expanded to build the following heuristic:

- Start with a base case load-flow for peak load conditions and compute the SSSL and related security margin.
- Run an extensive suite of transient stability simulations. If no instability has been detected, go to Step 5. If at least one contingency (fault) case was found to be unstable, go to Step 3.
- Use the security margin MW generation schedules from Step 1 to calculate a new base case load-flow.
- For the load-flow computed in Step 3, run an extensive suite of transient stability simulations.
- If no instability has been detected, repeat Step 4 for successively increased MW levels until at least one contingency causes transient instability. The steady-state stability reserve for the immediately precedent state is the security margin of the system under evaluation.
- If the stability calculations in Step 4 detected at least one contingency (fault) that would cause instability, build a new load-flow case for a slightly reduced load level and repeat the transient stability checks. If no instability has been detected, recalculate the SSSL and the steady-state stability reserve, which is the security margin of the system under evaluation.

Once a percent value of the security margin is known, the stability envelope associated with a given system state is obtained as follows:

- *First*: starting from a state estimate or solved load-flow, determine the steady-state stability reserve, i.e., the distance to SSSL
- *Then*: for a postulated x% value of the security margin, determine the corresponding safe system MW loading below the SSSL.

Each system has its own stability envelope. As we already pointed out, it may be difficult, or even impossible, to reach the exact value of σ, but operating experience provides invaluable hints. For example, reference [5] recommended a 20% security margin for the Romanian power system as it was in the 1970s. Reference [21] describes the procedure used by ETESA, Panama, to validate the value of the security margin (15%) that is currently used in conjunction with its real-time stability assessment application. A 15 % value of σ is used in the NOS BiH system, too.

Appendix 2: The Continuation Power Flow Approach

Security margins to the point of voltage instability are defined as the difference between the initial MW load and the collapse point MW load minus a MW back-off value equivalent to the security margin. One way of obtaining those margins is running Continuation Power Flow (CPF) as the system is stressed by increasing the load in a sink area and generation in the source area. CPF traces PV-curves at the monitored buses and determines the critical equilibrium point on this curve, and thus computes the stability margins.

CPF is a power flow program enhanced with continuation methods. Its input consists of the state of the power system as determined by a state estimator or conventional power flow solution typically stored in the real-time database of the SCADA/EMS. In the CPF method, the power system approaching voltage instability is calculated as a series of solutions to power flow equations that have been extended by a parameter λ used to represent the change in demand at all buses of the power system as compared to the operating point. For slow changes of λ, these solutions mean computing the equilibrium points defined by the well-known steady-state power flow equations given as:

$$f(x,\lambda) = 0 \qquad (1)$$

where x is the n-vector of state variables (voltage magnitudes and angles at all the buses). The above equation may be written as:

$$\begin{aligned} P_{Gi}(\lambda) - P_{Li}(\lambda) &= \sum_{j \in i} V_i * V_j * (G_{ij} * \cos\theta_{ij} + B_{ij} * \sin\theta_{ij}) \\ Q_{Gi}(\lambda) - Q_{Li}(\lambda) &= \sum_{j \in i} V_i * V_j * (G_{ij} * \sin\theta_{ij} - B_{ij} * \cos\theta_{ij}) \end{aligned} \qquad (2)$$

Where

$$\begin{aligned} P_{Gi}(\lambda) &= P_{Gi0} * (1 + \lambda * K_{Gi}) \\ P_{Li}(\lambda) &= P_{Li0} * (1 + \lambda * K_{Li}) \\ Q_{Li}(\lambda) &= Q_{Li0} * (1 + \lambda * K_{Li}) \end{aligned} \qquad (3)$$

P_{Li0}, Q_{Li0} are the active and reactive load at bus i, and P_{Gi0} is the active generation at bus i at the operating point (base case).

The above power flow equations may be more compactly written as

$$f(x,\lambda) = F(x) + \lambda * b = 0 \qquad (4)$$

The direction vector b represents the changes in real and reactive power demand and the changes in real power generation.

Solutions of this set of equations are used to trace both the stable and unstable branches of the voltage versus power (or λ) curve for any particular bus voltage magnitude in the power system. Any power flow method can potentially, be used to solve for the state variables in the above equations given a particular load change. To trace the complete branches of the V-versus- λ. -curve, however, the use of a continuation method is required. A continuation based method consists of two steps: a predictor step, which produces an approximate solution to be used as initial condition to the second step, the corrector step. Figure 8 shows these steps. Differences between continuation methods are usually due to how these steps are implemented.

For the purposes of this paper it is sufficient to know that by the successive application of these steps it is possible to trace the stable branch of the V-versus-P (or λ) curve to obtain point C in Figure 8. Given C the distance to collapse is then obtained as the difference in the power at C and the power at the initial point S.

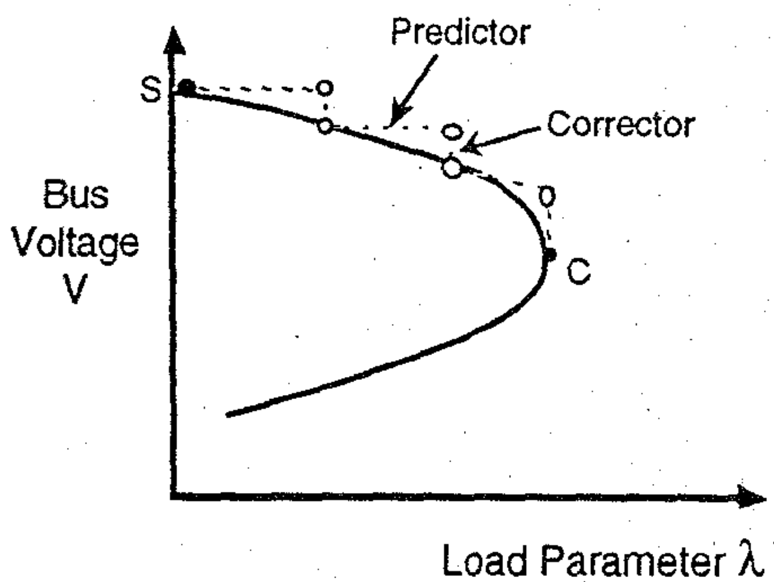

Figure 8: Steps of the Continuation Power Flow method

Often CPF is applied as part of a Voltage Stability Analysis (VSA) package. VSA is used in a SCADA/EMS in conjunction with static voltage or thermal security analysis to provide a more complete picture of system security by determining how close the system is to voltage collapse. The objective is to determine, from a large set of potential contingencies, those that may lead to voltage stability problems. A contingency is defined by the user in terms of the critical buses (points) where analysis is applied, together with the zones or areas where load changes are expected, plus the definition of applicable equipment outages. Typical output results of VSA comprise, for each combination of source and sink:

- The most limiting contingency
- Collapse MW level
- The most limiting contingency collapse MW level
- Critical voltage at monitored buses
- Transfer flows on critical transmission lines, between areas, and between zones

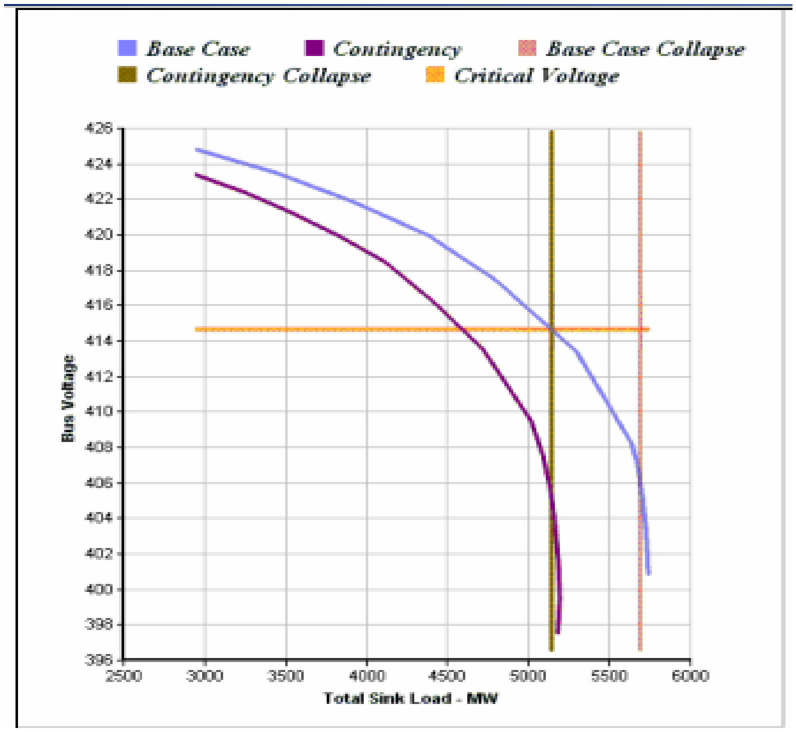

Figure 9: Typical result of VSA

Base case and the limiting contingency case are shown in Figure 9 with their associated MW back-off value (indicated by the two vertical lines). The critical voltage for the monitored bus is determined by projecting the contingency case collapse point onto the base case P-V curve.

In practice, the VSA algorithm consists of various steps:

Step 1: Operating point stability assessment

Step 2: Contingency selection

Step 3: Contingency screening and ranking

Step 4: Contingency evaluation

For Step 3 fast, approximate methods other than the full CPF can be applied in order to decrease the computation time [7].