

QuickStab[®] Validation Testing Results

José Santos Vergara P. and Savu C. Savulescu

Abstract – This paper presents the results of a study conducted by the National Dispatch Center of Empresa de Transmisión Eléctrica S.A. (ETESA), Panama aimed at validating the accuracy of QuickStab[®] calculations. The load-flow model used in the study encompassed the Central American interconnected system. The stability calculations focused on the actual network of ETESA. The study scenarios included peak, medium-high and medium-low load level conditions. A major line contingency was also evaluated. The tools used for comparison included Siemens PTI's PSS/E load-flow and transient stability programs.

QuickStab[®] correctly predicted the stability limit in all the study scenarios, regardless of how near or how far was the load-flow case from the critical state. The transient stability simulations resulted in instability in all the cases where the system MW load was higher than the security margin computed by QuickStab[®]. All the security margin cases were found to be stable.

The voltage stability conditions at each major load bus in the system were also evaluated. All the buses identified as critical by QuickStab[®] were validated as such by the practical experience of the operating personnel. The study confirmed the already demonstrated speed and precision of QuickStab[®] and pointed at an invaluable tool for daily use in system operations.

I. BACKGROUND

The National Dispatch Center (CND) of Empresa de Transmisión Eléctrica S.A. (ETESA), Panama has been using QuickStab[®] in real-time and off-line since 2001 to monitor the risk of blackout caused by instability.

Although the operating reliability measures adopted at CND have prevented major disturbances so far, nearly critical situations have occurred, as it was the case on August 22, 2002 when the system experienced low voltage conditions. The situation was quickly identified and successfully acted upon by the system operator and security engineers. As shown in [6], QuickStab[®] was used to assess the incident and correctly determined that the system was indeed approaching conditions that could have caused a blackout.

With the advent of the coordinated operation in Central America, it is now felt that the impact of the MW transfers in the region will have to be continuously monitored in order to detect and prevent the risk of blackouts. Since operators and security engineers must rely on the predicted distance to instability, CND considered important to validate the accuracy of QuickStab[®] computations by comparing them with results from simulations performed with PSS/E load-flow and transient stability programs.

The computations were conducted at CND [16]. The load-

flow model covered the entire interconnected system in Central America, but the stability calculations focused only on the actual transmission network of ETESA. The study assumptions were based on the actual operating guidelines adopted at CND. The load modeling options of QuickStab[®] were set to replicate the way PSS/E represents the load in load-flow calculations. These and other methodology aspects along with the detailed description and analysis of the simulation results are presented in the following.

II. METHODOLOGY

A. Theoretical Background

It is well known that near the stability limit of a power system, voltages are low and load-flows may diverge [13]. But a non-convergent load-flow does not necessarily mean that the system is unstable. It was shown in [9] and [14] that the system load where the load-flow diverges is just an *upper bound*, for it is possible that one or several units get out of synchronism before that point. Also, “for voltage collapse and voltage instability analysis, any conclusions based on the singularity of the load-flow Jacobian would apply only to the voltage behavior near the state of maximum power transfer. Such analysis would not detect any voltage instabilities associated with synchronous machines characteristics and their controls” [9, pp. 1380].

However, running load-flows at increasingly high load levels until they diverge is the only way to obtain a base case near the limit of stability -- then, starting from this base case, voltage and steady-state stability tools can be used to perform the assessment.

B. Approach

QuickStab[®] performs fast voltage and steady-state stability calculations that are predicated on theoretically sound simplifying assumptions [11]. Given a state estimate or a solved load-flow, the program computes, in addition to several other indicators, the total system loading and the MW generation schedules for the:

- *Critical state* where voltages collapse and units may get out of synchronism
- *Security Margin state* that corresponds to a user-defined security margin, typically 15% below the critical state.

1) Accuracy Testing of the Critical State Predictions

If a load-flow calculation was executed with the MW generation schedules computed for the critical state, one of the following mutually exclusive outcomes must be expected:

- (a) The load-flow solution was found *critically stable*, i.e., by further increasing the load, the system would become unstable
- (b) The load-flow solution was found *unstable* by QuickStab[®]

José Santos Vergara P. is an Operating Security Engineer, ETESA, Panamá, e-mail jvergara@etesa.pa.com

Savu C. Savulescu is with Energy Consulting International, Inc., New York, New York, e-mail scs@eciqs.com, <http://www.eciqs.com>

(c) The *load-flow diverged*, in which case the generation MW schedules have to be reduced until a solution is obtained.

The critical MW loading is not a fixed constant. It changes depending upon the topology, reactive compensation and voltage schedules in the base case. The critical MW is higher if the base case entails high bus voltages and large amounts of reactive sources, and is lower when voltages are lower and reactive sources are fewer in the base case.

Therefore, the idea was to compare the stability limits predicted from the base case with those computed for a load-flow solution near instability -- and to repeat the procedure for different system MW and voltage levels.

The first step of the procedure entailed solving a base case load-flow, called Case 1, for peak-load level conditions. The second step consisted of running QuickStab[®] to compute the:

- MW output of the generators for the critical state
- MW output of the generators for the security margin state corresponding to a steady-state stability reserve of 15%.

The third step consisted of executing a load-flow calculation with the generators' MW computed by QuickStab[®] for the critical state in Case 1. If the load-flow would converge, then:

- Run QuickStab[®] with the results of this "critical state load-flow" -- it was expected that QuickStab[®] would find this new case either unstable or critically stable
- Calculate new load-flows by maintaining the critical state MW schedules and increasing the slack-bus generation in small steps until the load-flow program diverges
- Run again QuickStab[®] for the last load-flow that converged -- this case should be found unstable by QuickStab[®].

If the "critical state load-flow" would diverge, reduce the slack-bus generation in small increments until convergence has been reached, then:

- Run QuickStab[®] again -- this case should be found either unstable or critically-stable by QuickStab[®]
- Reduce by 1% the total generation and run a new load-flow, then execute QuickStab[®] -- this case should be found either critically stable or stable but close to the stability limit.

Repeat Steps 1 through 3 for scenarios with lower MW load and different levels of reactive compensation, e.g., medium-high and, respectively, medium-low load levels, then:

- Calculate "security margin load-flows" by using the generators' MW schedules determined by QuickStab[®] for the security margin state in the peak, medium-high and medium-low load cases
- Run QuickStab[®] for the "security margin load-flows" and compare the results.

2) Testing of the Security Margin Predictions

The security margin state corresponds to a "safe" MW system loading, referred to as security margin, such that, for any system state with a stability reserve smaller than this value, no contingency, no matter how severe, would cause transient instability [7], [4]. Just like the critical MW loading, the security margin, which is expressed as a percentage below the critical MW loading, is not a universal constant. It depends upon the

specific combination of topology, loads, generators and reactive compensation, and must be determined and periodically reassessed for each particular transmission system through extensive transient stability simulations. The expected outcomes of such transient stability calculations are as follows:

(d) For load-flow cases with MW loadings *higher than the security margin*, at least one fault or contingency should result in transient instability

(e) For load-flow cases at the *critical MW* level, all the faults and contingencies cases should be unstable

(f) For load-flow cases where the system MW load is *equal to, or below the security margin*, all the fault and contingency cases should be stable.

Since transient stability calculations are time consuming and require significant person power to prepare the data and set-up the study cases, and, also, in order to keep the QuickStab[®] accuracy testing effort to a reasonable level, the following procedure was followed:

- Identify a small number of faults and contingencies known a priori to correspond to the worst case scenarios
- Perform transient stability calculations for the base case and security margin state load-flow solutions for peak-load level conditions -- skip the critical state because, most probably, all the faults and contingencies would result in transient instability
- Repeat the procedure for the medium-high and medium-low load level scenarios and, for these cases, run transient stability simulations also for the critical state.

3) Accuracy Testing for Line Contingency Cases

The theory predicts that during line contingencies the system gets closer to its stability limit -- when lines trip, the overall system reactance increases and, accordingly, the steady-state stability reserve decreases.

If the procedure for testing the accuracy of the critical state predictions were repeated for a contingency case, one should expect that the critical MW in the contingency case would be lower than the critical MW in the base case, i.e., the contingency case would have a smaller steady-state stability reserve -- and the same is true for the security margin, too.

In order to verify the accuracy of QuickStab[®] predictions for a contingency case, the complete validation suite was executed by starting from a load-flow base case that simulated a major line contingency at the medium-high load level scenario.

III. LOAD-LEVEL SCENARIOS

The validation suite that was used to compare QuickStab[®] calculation results with PSS/E load-flow computations included the following load-level scenarios:

- *Maximum Expected Demand* -- in this scenario, all the shunt capacitors are on-line, the shunt reactors are disconnected, and a small unit that normally is not needed to generate MW is brought on-line to generate MVARs. These reactive compensation sources ensure that the highest possible MW load can be met without risk of voltage collapse

□ *Medium-High Demand* – in this scenario, several steps are taken to reduce the reactive compensation: 15 MVAr in capacitor banks are taken off-line; 40 MVAr in shunt reactors are reconnected; and the machine used to generate MVAr is not activated. These provisions in the load-flow set-up emulate the operating procedures at lower MW levels where the amount of reactive compensation is reduced to ensure that the system voltages would not violate the higher limits

□ *Medium-Low Demand* – this scenario is similar to the Medium-High scenario, but at a further reduced MW load level and 15 MVAr less in capacitor banks.

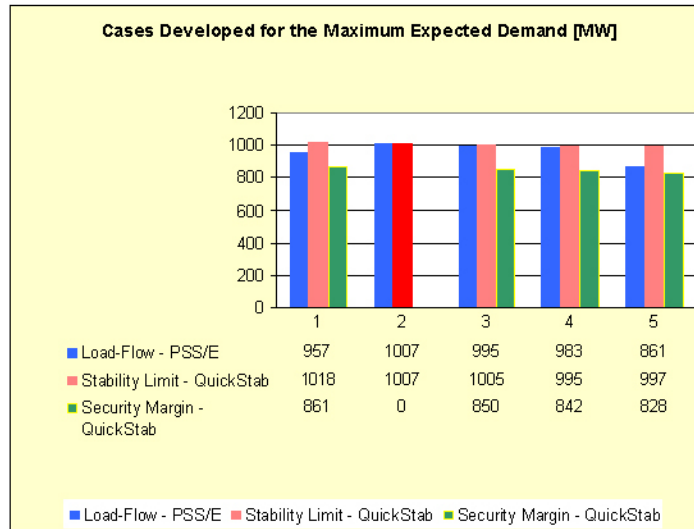


Figure 1 Expected Maximum Demand

IV. RESULTS

A. Maximum Expected Demand Scenarios

Figure 1 depicts the results of the simulations performed for the Maximum Expected Demand scenario.

Five cases were developed and analyzed as follows:

□ Case 1 – 957 MW base case calculated with PSS/E (shown in blue in Figure 1). QuickStab[®] predicted that instability, i.e., the critical state, occurs at 1018 MW (pink in Figure 1), with a security margin of 15% at 861 MW, and calculated critical MW schedules for the critical state and security margin MW schedules for the security margin state

□ Case 2 – PSS/E diverged with the critical MW schedules from Case 1. The slack bus generation was then slowly decreased, while maintaining all the other MW generation schedules unchanged, until convergence was obtained at 1007 MW (shown in blue in Figure 1). QuickStab[®] evaluated this case as unstable (red in Figure 1). The concept of security margin does not apply when the state is unstable, and, therefore, it was not calculated

□ Case 3 – A new PSS/E load-flow was run by reducing the slack-bus generation by approximately 10 MW. The case converged at 995 MW (shown in blue in Figure 1). For this case, QuickStab[®] determined that the system is stable with a stability reserve of 1% -- the new limit of stability calculated at 1005 MW (pink in Figure 1). The security margin for Case 3 was evaluated at 850 MW

□ Case 4 – The MW generation in Case 4 was further reduced to 983 MW (shown in blue in Figure 1). QuickStab[®] determined that the system is stable with a 2% stability reserve and predicted instability to occur at 995

MW (pink in Figure 1). The security margin for Case 4 was evaluated at 842 MW

□ Case 5 -- The MW generation in Case 5 was set at 861 MW, which corresponds to the 15% security margin predicted for the Case 1. The steady-state stability limit computed by QuickStab[®] was 997 MW (shown in pink in Figure 1).

B. Medium-High Demand Scenario

Figure 2 illustrates the simulation results for the Medium-High Demand scenario. Three cases were analyzed as follows:

□ Case 1 – 798 MW base case load-flow calculated with PSS/E (shown in blue in Figure 2). QuickStab[®] predicts that instability occurs at 909 MW (pink in Figure 2), with 15% security margin at 766 MW, and calculates the MW generation schedules for both the critical and the security margin states

□ Case 2 – The PSS/E load-flow was executed with the critical MW schedules predicted by QuickStab[®] in Case 2 and converged at 906 MW (shown in blue in Figure 2). QuickStab[®] evaluated this case as critically stable (red with a salt-and-pepper pattern in Figure 2). The security margin of Case 2 was evaluated at 765 MW

□ Case 3 – A new PSS/E load-flow was executed by increasing the generation in small steps at the slack bus, while maintaining all the other MW schedules unchanged, up to the point where the load-flow would diverge. The last converged load-flow was obtained at 931 MW (shown in blue in Figure 2) and evaluated by QuickStab[®] as unstable (red in Figure 2). The security margin does not apply when the state is unstable and was not calculated

□ Case 4 -- A special case was derived from the Case 1 by including a small machine that did not generate any MW in the base case but was allowed to pick-up some load during the case worsening calculations performed by QuickStab[®] in the search of the steady-state stability limit. The idea was to simulate the real operating conditions where, in order to operate the system at higher load levels, the actual practice is to bring this small generating unit on-line to generate the MVAr needed for reactive compensation. As shown in Figure 2, starting from a 798 MW case, QuickStab[®] correctly predicted a higher stability limit, i.e., 937 MW vs. the 909 MW in Case 1.

C. Medium-Low Demand Scenario

The Medium-Low Demand scenario calculation results are shown in Figure 3. The following four cases were analyzed:

- Case 1 – 742 MW base case load-flow calculated with PSS/E (shown in blue in Figure 3). QuickStab® predicts that instability (critical state) occurs at 881 MW (pink in Figure 2), with a security margin of 15% at 742 MW, and calculates the MW generation schedules both for the critical state and for the security margin state

- Case 2 – The PSS/E load-flow was run with the critical MW schedules predicted by QuickStab® in Case 1 and converged at 881 MW (shown in blue in Figure 3). QuickStab® evaluated it as critically stable (red with a salt-and-pepper pattern in Figure 3). The security margin was computed at 737 MW

- Case 3 – A new PSS/E load-flow was solved by increasing the slack-bus generation in small steps until the load-flow calculations diverged. The last converged solution was at 913 MW (shown in blue in Figure 3) and was evaluated as unstable by QuickStab® (red in Figure 3). The security margin does not apply when the state is unstable and was not calculated

- Case 4 -- This case was supposed to be created with the MW schedules computed for the security margin in Case 1, but since the security margin in Case 1 was already 15%, Case 4 is identical to Case 1 and is shown in Figure 3 for reference only.

D. Major Line Contingency Case

Figure 4 illustrates the calculation results for a major line contingency case simulated for the Medium-High Demand scenario. Three cases were analyzed as follows:

- Case 1 – 799 MW base case load-flow calculated with PSS/E (shown in blue in Figure 4). QuickStab® predicts that instability occurs at 885 MW (pink in Figure

4), with 15% security margin at 738 MW, and calculates the MW generation schedules for both the critical and the security margin states

- Case 2 – The PSS/E load-flow was executed with the critical MW schedules predicted by QuickStab® in Case 2 and converged at 890 MW (shown in blue in Figure 4). QuickStab® evaluated this case as critically stable (red with a salt-and-pepper pattern in Figure 4). The security margin of Case 4 was evaluated at 751 MW

- Case 3 – A new PSS/E load-flow was run by increasing the generation in small steps at the slack bus, while maintaining all the other MW schedules unchanged, up to the point where the load-flow would diverge. The last converged load-flow was obtained at 902 MW (shown in blue in Figure 4) and evaluated by QuickStab® as unstable (red in Figure 4). The security margin was not calculated

- Case 4 -- This case was built with the MW schedules computed for the security margin in Case 1. The stability limit computed by QuickStab® was 895 MW (shown in pink in Figure 4), with a 15% security margin of 739 MW (green in Figure 4) which was identical to the load-flow case loading (blue in Figure 4).

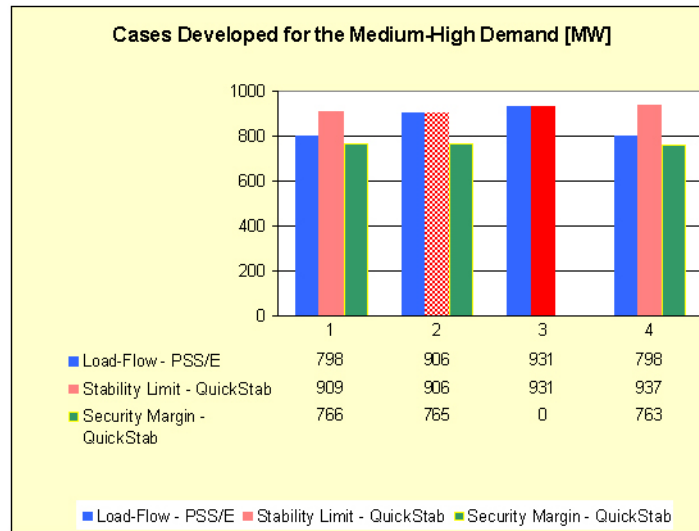


Figure 2 Medium-High Demand

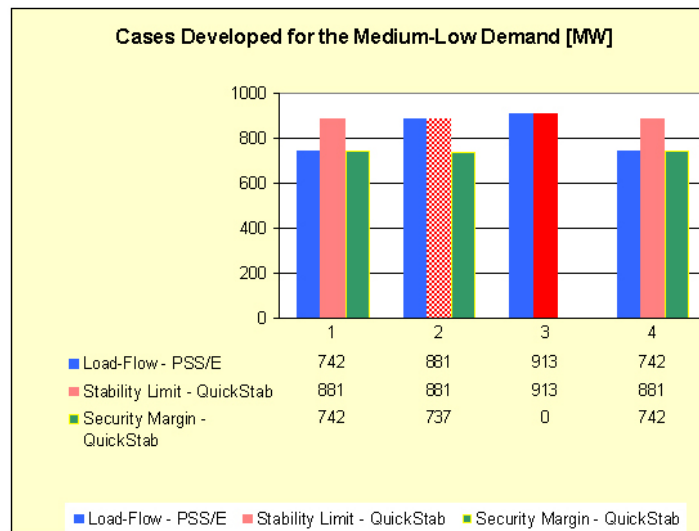


Figure 3 Medium-Low Demand

E. Transient Stability

Simulations

The following transient stability calculation scenarios were evaluated for the Expected Maximum Demand, Medium-High Demand and Line Contingency Case:

1. Major generating unit trip in the Western area
2. Major generating unit trip near the major load centers
3. All units of a mid-sized power plant out of service
4. Major transmission line trip

The results were similar in all the cases and are synthesized as follows:

- *Actual State* (Base Case), corresponding to the “Case 1” conditions described in the previous sections -- the system withstood the fault scenarios 1 and 2, but become unstable for the faults scenarios 3 and 4

- *Security Margin State*, i.e., MW loading 15% lower than the critical MW in the corresponding base cases -- the system withstood all the fault scenarios

- *Critical State*, corresponding to the critical MW in the corresponding base cases -- all the transient stability simulations resulted in instability.

V. ANALYSIS

The results of the simulations were fully consistent with earlier testing of [5], [15] and many years of practical experience with Paul Dimo’s approach to voltage and steady-state stability assessment [2], [3], [4], [11].

In all the scenarios, QuickStab[®] accurately determined the stability limit, regardless of how near or how far was the base case from the critical state.

As predicted by theory, the stability limits computed for the peak load conditions were higher than those at medium-high and medium-low load levels. Indeed, in system states with less reactive compensation, we expect that the voltage would collapse at MW levels smaller than the maximum MW loadability of the same network where significant amounts of reactive compensation were added.

In all the cases evaluated, the input load-flow model represented the entire Central American interconnected system but the stability calculations were performed only on the area corresponding to the transmission network of ETESA. Accordingly, QuickStab[®] computed MW schedules only for the generators situated in the ETESA area. These MW values were then used in PSS/E to create new load-flow cases, but all the other load-flow data remained the same. The accuracy of the calculations therefore confirms the validity of the multi-area approach used by QuickStab[®] to assess local stability aspects within large interconnections.

The outcome the transient stability simulations confirmed the usefulness of the concept of *security margin*. In all the cases evaluated, the system was stable when the transient stability simulations were run at the security margin MW loading, but became unstable in various fault scenarios when the MW loading was higher than the security margin MW. Furthermore, all the transient stability calculations performed at critical MW loadings resulted in instability.

Another series of calculations consisted in evaluating and ranking the major load buses in the order of their stability indices. This was done by using the bus-level voltage stability analysis feature of QuickStab[®].

This evaluation, however, was qualitative, rather than quantitative, because CND doesn’t use conventional voltage stability analysis software, so there were no tools available that could be used for comparison.

The results of the bus-level stability analysis were found consistent with the current observations of operations personnel -- all the load buses identified as critical by QuickStab[®] were already known, from experience, to be critical.

The ranking of generators as “seen” from the load buses being analyzed was also consistent with what operators and engineers knew from practical experience.

Finally, a note about the computational speed. For practical purposes, all the simulations performed with QuickStab[®] converged instantly, which was expected both because the program is intrinsically fast and because the network area evaluated for stability encompassed only about 200 buses, out of approximately 1000 buses in the load-flow model of the Central American interconnected power system.

In order to evaluate the performance of both system-wide and bus-level voltage and steady-state stability calculations for a large network, a 3289 bus power transmission system was modeled and analyzed. The system-wide calculations completed in 1 second, and the bus-level calculations converged at the rate of approximately 1 second per bus, on a PC equipped with Intel Pentium 4 running at 2.8 GHz.

VI. CONCLUSIONS

The study fully confirmed the already demonstrated speed and precision of QuickStab[®]. The excellent results obtained during the simulations point to a fast and reliable tool for real-time and off-line voltage and steady-state stability analysis.

VII. REFERENCES

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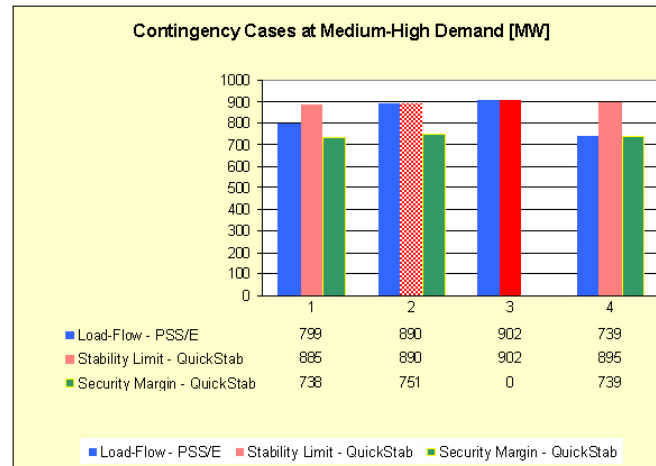


Figure 4 Major Line Contingency Case

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