# Real-Time Stability Monitoring at Transelectrica

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***Abstract* -- This paper describes the approach taken by Transelectrica S.A. to real-time stability assessment. Seamlessly integrated with the Real-Time Network Analysis sequence is a fast voltage and steady-state stability application that runs automatically after each successful state estimate. The calculations are performed both for the entire interconnected system of Romania and for the areas connected via "stability constrained links". The "stability constrained links" are transmission paths where the stability limits are more restrictive than the thermal limits. They are identified via off-line studies and are dynamically reconfigurable. The key results are posted on intuitive diagrams, including a real-time stability trending chart, which allow the operator to continuously monitor the distance to instability both on a system level and across critical area interfaces. This is a first, and very efficient, line of defense against blackouts. The next step consists of periodically evaluating what-if scenarios with comprehensive off-line stability tools.**

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

## I. Introduction

IN the context of electricity market operations, a primary concern is the ability to transfer power across large interconnected networks while meeting a broad range of operating reliability constraints. A common scenario consists of compensating load increases and/or generation outages in a system area by raising the generation elsewhere. These energy transactions typically encompass vast multi-area systems and may cause parallel flows, excessive network loadings and low bus voltages. Under certain conditions, such degraded states may lead to blackouts.

The analysis of recent blackouts due to instability revealed that most of them follow a similar pattern:

- Large MW blocks get transferred from areas with inexpensively priced energy toward areas where the load demand has increased due to an actual increase in load, or perhaps because one or several local generating units are scheduled for maintenance, or simply because the local generation is too expensive
- As a result, certain transmission paths get loaded closer and closer to their stability limits whereas their stability reserves get smaller and smaller
- At this moment, a generation or transmission outage takes place. Typically, such incidents evolve into cascading outages
- Since the transmission path was already operating within a shrinking stability reserve, the wide-spread disturbance becomes unavoidable.

In order to find out whether the grid is getting too close to its stability limits, one should evaluate *both* the system-wide risk of steady-state instability and voltage collapse *and* the maximum transfer capability across stability constrained transmission paths -- and to do it as often as possible. Ideally, this assessment should be performed on a continuous basis, thus obviously leading to the need to monitor the stability limits in real-time.

The subsequent sections describe the state-of-the-art solution implemented by AREVA T&D (AREVA) on the SCADA/EMS of Transelectrica S. A. (Transelectrica) for the monitoring of the distance to instability in real-time, and to provide the results quickly and in a user-friendly format as required for fast and reliable on-line decision-making.

## II. Monitoring the Distance to Instability: Concepts and Approach

### A. Background

The evaluation of the operating reliability of transmission networks in normal or emergency operating conditions is a complex undertaking. As a minimum, the analyst should take 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.

Traditionally, the operating reliability studies encompass:

- Load-flow and contingency evaluation
- Stability assessment.

An important goal of stability assessment is to determine whether the system can withstand a set of large, yet credible, contingencies. This is the realm of transient stability analysis.

An equally important objective is to evaluate the risk of instability approaching in small steps, e.g., via small load changes accompanied by slow bus voltage changes that may trigger a voltage collapse, or by gradual load changes that may

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eventually cause one or several generators to get out of synchronism. Traditionally, this topic has been addressed by steady-state stability analysis. At the present time, the industry refers to it as "voltage stability", but this terminology is neither uniformly understood nor universally accepted. In order to avoid confusion, throughout this paper we will say *voltage and steady-state stability analysis*.

There is no way to handle all the aspects of stability at once. Each one 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 and the stability calculations are performed in real-time, or, as a minimum, off-line with real-time data, the end-users may have neither the time nor the background needed assess the results. This opens the door for fast methods that not only are based on sound modeling assumptions but also produce the output in formats that are easy to interpret and 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" [13], [27]. These techniques provide for a comprehensive analysis but are hampered by computational burden and non-convergence of load-flow calculations near instability. Voltage stability analysis tools, on the other hand, are quite popular but have their own limitations. To begin with, the results are affected by the assumptions made about the load. Ionescu and Ungureanu [11] demonstrated that if the loads were modeled as constant impedances, successive load increases would first cause the generated MW to increase until the point of maximum power transfer -- and then, beyond that point, the total generated power would get smaller and *dual power states* (same power at different voltages) would be obtained, which is the reason for the "nose" shape of the PV curves. But dual states *cannot* happen in real life, and more realistic load models lead to P-V graphs that stop at the point of instability. Also questionable is the practice of "assessing" voltage stability by running load-flows at successively increased load levels and stopping when the load-flow diverged [17], [23, pp. 1380].

As shown in the following, however, a fast and reasonably accurate solution to the problem of *quantifying* the distance to instability and performing the calculations in real-time comes from the realm of steady-state stability.

### B. Steady-State Stability Revisited

#### 1) General Concepts

The Steady-State Stability Limit (SSSL) of a power system is "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" [28]. An earlier definition refers to this concept as the "stability of the system under conditions of gradual or relatively slow changes in load" [6].

But these definitions neither provide the support needed to classify the power system *events* that may impact the stability nor identify the causes of instability. Other aspects must also be considered, such as the:

- Physical nature of instability
- Most relevant system parameter where the instability can be observed
- Severity of the disturbance considered in the simulation
- Most adequate method for computing and predicting stability
- Equipments, processes and scenarios that must be taken into account in order to achieve stability.

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.

#### 2) Conventional Approach

The conventional method of the small oscillations for estimating the steady-state stability [6], [12], [21] 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 [21]. 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 (characteristics) 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 [21] refers to these relations as "steady-state stability criteria" and classifies them into *algebraic* (Routh-Hurwitz), *frequency-domain* (Nyquist) and *practical*.

A necessary 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 instability. The instability in the form of self-oscillations, however, remains unrevealed by this method.

If the generators are radially connected to a nodal point, which is always the case if the short-circuit currents transformation is applied, and if, based on practical considerations, it may be assumed that some operating variables are constant, the condition **D** = 0 leads to "practical criteria" that are valid within certain limits. For example the *synchronizing* *power criterion* $dP/d\delta > 0$, which assumes constant frequency and constant voltage at the nodal point, and the *reactive power voltage and steady-state stability criterion* $dQ/dV < 0$ or, rather, $d\Delta Q/dV < 0$ which assumes that the frequency is constant and the power balance is maintained at the nodal point [21]. The practical stability criteria have been instrumental in the development of techniques aimed at quickly evaluating the degree of operating stability of a power system.

Since steady-state instability occurs when a change of the state variables causes the dynamic Jacobian to become singular, one might think that instability happens in only one way regardless of *how* the system conditions were stressed, or "worsened", in order to reach the limit. Published references, however, suggest that the network characteristics that generate the *most probable system stressing patterns* should be taken into account when selecting the procedures and indicators used for steady-state stability analysis.

In this context, for vast interconnected systems it is essential to assess stability when large blocks of power are transferred across the network. This, in turn, requires evaluating the maximum transfer capability across "links", i.e., between the areas that get involved in the transactions, when a reduction in generation in one area is compensated by raising the generation elsewhere.

#### 3) *Stability Constrained Links*

A "link" identifies a group of transmission lines that form a topological cut-set, i.e., their removal splits the network in two areas, one on each side of the link. The maximum power that can be transferred across a link is limited by thermal and stability constraints. The stability limit of a link can be quantified by the *further loading* of the link, i.e., the *additional* amount of power that can be sent from one side of the link to the other side, without causing instability. This indicator, which is referred to as the *stability reserve* of the link, can be expressed either in MW or in percentage from the maximum link loading.

In a sense, the concept of *stability constrained link* is similar to the concept of "congestion path", with the difference that the former is concerned with stability, rather than thermal, violations. Stability constrained links may appear in any multi-area power system where large MW blocks are transferred between weakly interconnected areas. This is often the case in longitudinal transmission networks that span distinct system areas with significant load-generation unbalances.

Potentially, there are many links in the network -- some with adequate margins to further increase the MW transfer without risk of instability, but some others where a further loading of the link might cause steady-state instability. Needless to say, the early identification of such *stability constrained* links is imperative for the operating reliability of the transmission system.

### *C. Fast Voltage and Steady-State Stability Assessment*

Approaching the search for a stability limit from the steady-state stability perspective brings promising results.

First, the SSSL can be defined both system-wide and for individual buses. Then, the system-wide SSSL can be quantified as the maximum MW system loading, including both internal generation and tie-line imports, right before instability, thus making it possible to *measure how far from SSSL* is a given operating state. Known as *steady-state stability reserve*, this metric, expressed as a percentage of SSSL, has been used in Europe since 1950s [7], [8], [9], [18]. Most importantly, it is also possible to quantify a "safe" amount of stability reserve, referred to as *security margin*, such that, for any system state with a steady-state stability reserve smaller than the security margin, no contingency, no matter how severe, would cause instability.

Each system has its own security margin. For example, Paul Dimo [9] was recommending a 20% security margin for the Romanian power system as it was in the 1970s. Reference [22] 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 fast and versatile technique predicated on this background was developed by Paul Dimo [7], [8], [9] and was demonstrated to be usefulness for real-time applications in the EPRI Research Project RP2473-43 [25] and various US and international publications [10], [18], [19]. Dimo's method uses the:

- Short-circuit currents transformation to convert the meshed network to a radial scheme of short-circuit admittances
- Bruk-Markovic reactive power stability criterion, also known as dQ/dV, or dΔQ/dV, to evaluate stability
- Classic representation of generators through a constant e.m.f. behind the transient reactance $x'_d$
- Zero Power Balance Network to aggregate the system loads into a single load-center
- Case worsening procedure, instead of a succession of load-flow computations, to stress the system until it becomes unstable.

The following sections will focus upon the approach taken by Transelectrica and AREVA to effectively implement this technique in real-time and to use it to continuously monitor the distance to instability of the power system -- by using real-time data, performing split second computations and providing the results on user-friendly charts and diagrams.

## III. Transelectrica's Approach to Real-Time Monitoring of the Distance to Instability

### *A. Overview of Transelectrica's Network Analysis Applications Environment*

#### 1) *The Overall Picture*

The dispatching of the electric power system and the operation of the electricity market in Romania are supported by an integrated information system that creates and maintains an extensive raw data and processed information reservoir available, based on appropriate access jurisdiction, to all the electricity market agents in Romania. This information architecture encompasses a Hierarchical SCADA/EMS and a Balancing Market System. Both systems are operated by Transelectrica and are located at National Dispatch Center (DEN).

*2) System Dispatching Support Applications*

Transelectrica's SCADA/EMS applications encompass:

- SCADA, including: analog, status & accumulator data processing; limit checking; value replacement; calculations; historical data recording; intersite data processing; tagging; controls; and load shedding
- Generation Control and Scheduling, including: AGC; reserve monitoring; AGC performance monitoring; historical loss model update; transaction scheduling; transaction evaluation; load forecasting; market interface
- Network Analysis, including: topology processing; state estimation; real-time stability monitoring (QuickStab, [28]); monitored element processing, bus load model update; loss sensitivities; contingency analysis; security enhancement; power flow; optimal power flow / Voltage VAr Dispatch; off-line short-circuit analysis; and off-line stability analysis (Eurostag).

### *B. Real-Time Stability Monitoring at Transelectrica*

*1) Need for Fast Stability Assessment*

The Romanian transmission system is in the center of the Southeastern European interconnection and sustains MW transfers between parties situated beyond its geographical borders. A further complication comes from the fact that the network consists of electrical areas interconnected through stability constrained transmission paths. The system operation is quite complex and the dispatchers must meet conflicting requirements in order to maximize the use of the transmission system while avoiding the risk of blackout.

Therefore, in addition to conventional security monitoring based on classic network analysis applications, there is also a need to perform *split-second stability checks* and to *monitor continuously* the:

- Distance to the voltage and steady-state stability limit and the safe operating margin of the system as a whole
- Stability reserve across the interfaces between system areas separated by stability constrained links.

*2) Stability Constrained Links in Romania*

The populated areas and the industrial zones of Romania are aggregated in concentric areas divided by the Carpathian mountain chain. The center area is surrounded by mountains and encompasses a dense 110 kV network sustained by a 220 - 400 kV backbone. Around it there is an outer ring of major power plants that inject power into a strong 220 - 400 - 750 kV transmission system. The power flows between the center area and the outer ring. The power is transferred primarily from south-southwest towards the center, from south-southeast towards the northeastern part of the outer ring, and from the northern part of the central area towards the northeastern part of the outer ring. The existence of stability constrained links is a direct consequence of this particular pattern of the MW transfers across the network.

DEN has identified 5 stability constrained links. The system sub-areas interconnected through stability constrained links are not necessarily disjoint. Some of them overlap. They are not fixed, either, and change depending upon the pattern of load, generating reserves, transmission outages, line flows, voltage levels and reactive resources.

The configuration of stability constrained links is periodically re-assessed off-line with an application developed by Dr. Marius Pomarleanu [15], [16], which, for a given load-flow solution, identifies all the links and computes the stability reserve for each link. Weak, i.e., security constrained, links are detected and ranked in the descending order of their stability reserve, and then the most critical five are selected. This procedure is executed off-line twice a year. In real life, however, the *actual* stability limits across the weak links may differ substantially from those computed off-line and need to be reassessed continuously based on the system conditions determined by the state estimator. The problem is now solved in real-time by QuickStab which computes the stability reserves both for the entire system and for the areas separated by the most critical stability constrained links.

*3) Implementation Overview [2], [22]*

Figure 1 illustrates the seamless integration of stability assessment module with the real-time network analysis sequence of Transelectrica's SCADA/EMS. After a successful state estimation run, a snapshot file in a standard format (PSS/E) is created and, together with a dynamic generator data file, is used as input by QuickStab. The application predicts the maximum power transfer (or MW loadability) of the transmission network and computes the distance to the critical state where steady-state instability occurs. The distances to the stability margin state (user specified margin) and the optimal state (re-dispatching of generation to maximize the distance to critical state) are also evaluated.

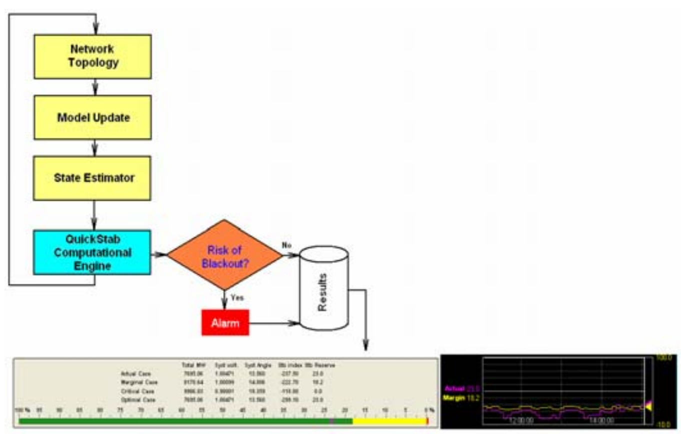


Figure 1. Integration of a fast steady-state stability module in the real-time network analysis sequence

The relevant information for the EMS operator is summarized in a results table display and in a bar chart providing a graphical indication of the current stability reserve as displayed. Furthermore, after each analysis an alarm is sounded if the stability reserve percentage is below a user-specified danger level. A trend of the stability indices over several hours is also displayed and provides very useful information about the stability evolution over time, as shown in Figure 2. This allows operators to anticipate critical system conditions that may lead to instability.

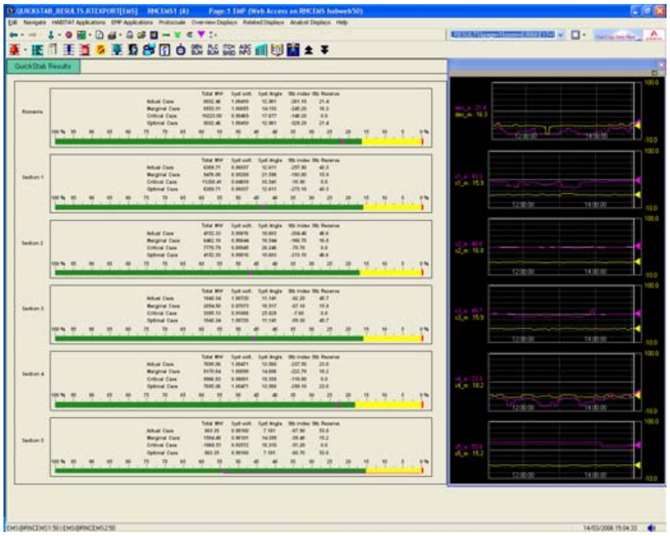

Figure 2. Real-time stability monitoring display (left) and trending chart (right) at Transelectrica.

## IV. Off-Line Stability Assessment at Transelectrica

In addition to the real-time stability monitoring implemented via QuickStab [26], Transelectrica also performs off-line stability assessment by using load-flow and state estimation cases from the real-time system. The off-line stability assessment capabilities are supported by Eurostag, from Tractebel, and SAMI, which is an in-house developed stability application based on the technique described in [5]. The data interfaces between the real-time system and Eurostag and, respectively, SAMI are shown in Figure 3.

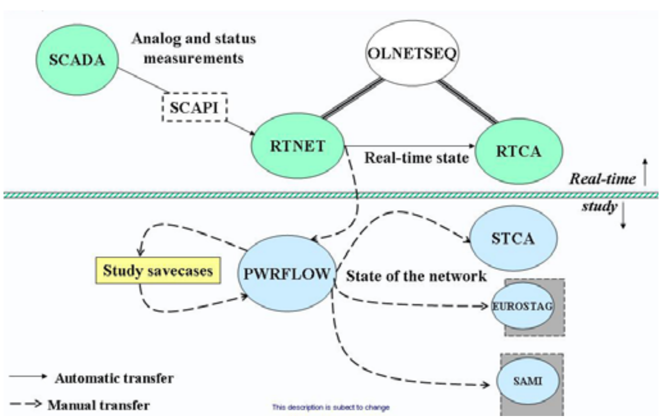


Figure 3. Off-line integration of Eurostag and SAMI with the real-time system at Transelectrica

## V. Other On-Line Stability Assessment Tools Supported by AREVA

In the frame of its other SCADA/EMS projects, AREVA has implemented real-time and study interfaces between its Energy Management System (*e-terraplatform*®) and the following Dynamic Stability Assessment (DSA) packages: Voltage Stability Assessment Tool (VSAT) and Transient Stability Assessment Tool (TSAT) from PowerTech Labs; and Eurostag and Syscan from Tractebel. The interface between SCADA/EMS and DSA packages is provided through the following components:

- Stability scenarios definition and validation on the EMS platform using the Dynamic Case Preparation (DCP) application
- Data exchange between the EMS and the VSAT/TSAT server
- Stability analysis output results and visualization on the EMS platform

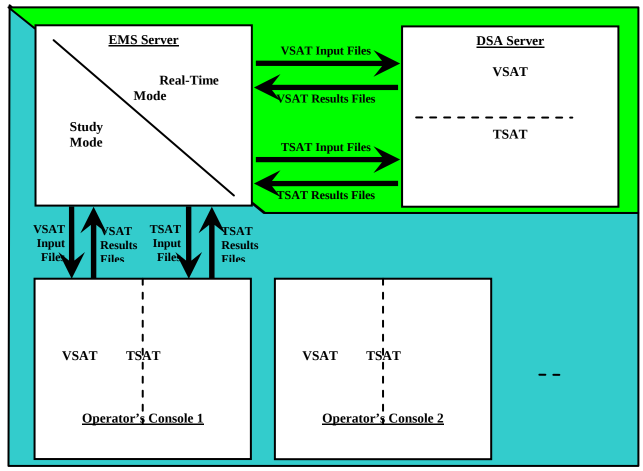


Figure 4. DSA integration with **e-terra***Platform* ®

## VI. Conclusions

This paper described the architecture and functionality of the real-time and off-line stability assessment tools implemented by AREVA T&D on Transelectrica's SCADA/EMS. The real-time voltage and steady-state stability application is seamlessly integrated with the Real-Time Network Analysis system and runs automatically after each successful state estimate. The calculations are performed both for the entire interconnected system of Romania and for each of the areas separated by the most severe stability constrained links. The stability constrained links are identified via off-line studies and are dynamically reconfigurable. The key results are posted on intuitive displays, including industry-unique real-time stability trending charts. This approach to visualizing the computational results in a user-friendly manner allows the operator to continuously monitor the evolution of the stability reserve of the interconnected system as well as across critical network interfaces.

The experimental results obtained to date have been very good. The real-time and off-line stability assessment tools described in this paper have been adopted for daily use both in system dispatching and for short-term operations scheduling. Plans are also under way to enhance the balancing market system with a fast steady-state and voltage stability assessment capability that would quickly identify market clearing MW schedules that may pose a risk of blackout due to instability.

## VII. Acknowledgement

Portions of section II.A and the entire section II.B have been reprinted, with permission, from reference [20].

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