Real-Time Calculation of Power System Loadability Limits

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Abstract -- **Determination of loadability limits in real-time is essential for the effective and efficient utilization of the power system network particularly in an open access environment. However, determining these limits in real-time in an Energy Management System (EMS) has been extremely difficult and off-line studies, time consuming simulations, and the operator's knowledge and experience, have been the basis for determining the limits especially when taking into account stability consideration.**

Therefore, accurate and reliable estimates of the limits in real-time based on the current system state are highly desirable. In this paper, we describe the theoretical basis for an approach that has been successfully installed and proven in several EMS systems. The approach relies on several distinct theoretical concepts: criterion for assessing the steady-state stability limit, the development of a radial equivalent network to which the steady-state stability limit criterion can be applied, a procedure for determining the "distance" of the current operating state from the stability limit (hence finding the available margin of loading), evaluating the effect of contingencies, and determining the "weak" flow gates (links) in the network. Field experience in NOS BiH (ISO Bosnia and Herzegovina) is also presented.

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

I. INTRODUCTION

Modern transmission grids must sustain MW transfers that can be quite different from those for which the networks were planned. Therefore, it is necessary to determine continuously whether the grid is getting too close to a state where a system collapse may occur. Ideally, one should evaluate the "distance" of the current operating state from the appropriate limit (hence finding the available margin of loading). The theoretical and practical difficulties entailed in this quest are significant especially when the appropriate limit is based on considerations of system stability.

In this paper we deal primarily with the steady-state stability limits. Currently, steady-state stability analysis techniques verify whether a given operating state is stable or unstable but do not say "how far" is the hypothetical state where voltages may collapse and/or units may lose synchronism. Therefore, the evaluation of such operating point stability must be followed by increasing the system loading, or "case worsening" procedures whereby various system parameters are changed in a direction that is unfavorable to stability. Thus one can determine the margin of stability. A series of degraded states is thus obtained, and the total 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 system's loadability limit. Then, once the loadability limit has been determined for the base case, the calculations must be repeated for contingency cases.

Since the "stability limit" depends both upon the system state vector associated with the current operating point and the system stressing procedure used to reach the limit, for each new system state, there is a new stability limit.

It is this continuously changing nature of the stability limits that makes it important to repeatedly execute the entire suite of computations as the system evolves, This can be done after each state estimate (or after each load-flow), so that adequate corrective actions could be quickly enacted if and when needed. The ability to complete this computation in near real time is a key feature of the proposed approach.

II. COMPUTING AND MONITORING THE DISTANCE TO INSTABILITY: CONCEPTS AND APPROACH

A. Background

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 and is not the principal focus here although a technique for determining a margin of safety for accounting for transient stability is presented later.

An equally important goal is to evaluate the risk of instability when the system is approaching a dangerous state gradually, in small steps. This risk is determined by steady-state stability analysis, which aims at assessing the "stability of the system under conditions of gradual or relatively small, slow changes in load" [4] and, also, allows quantifying the loadability limits.

The Steady-State Stability Limit (SSSL) 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" [26]. 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 – MWcurrent)/SSSL]x100.

In addition to the steady-state stability reserve, for any given system state a "security margin" should also be computed which would allow qualifying the current state as "safe" or "unsafe".

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The SSSL, “steady-state stability reserve” and “security margin” concepts (see Appendix A) have been developed in Europe in the late 1950s and early 1960s [5], [6], [7], [13].

B. Steady-State Stability Revisited

The conventional method of small oscillations for estimating the steady-state stability [1], [4], [19] consists of examining the eigenvalues of the characteristic equation associated with the linearized system of differential equations. Alternately, the Routh-Hurwitz criteria can be used. A condition for steady-state stability is obtained by evaluating the sign of the last term of the characteristic equation, which is the determinant of the Jacobian.

A significant hurdle for these approaches 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, then it becomes possible to develop methodologies that are fast and can be applied in real-time.

One way to simplify the calculations is to assume that the generators’ terminal voltages are constant; neglect the internal reactances; and use load-flow or continuation load-flow algorithms to push the system as close as possible to the point of voltage collapse. The negative consequences of making these assumptions are briefly discussed in Appendix B.

A more accurate approach consists of representing the machines via constant e.m.f. behind the transient reactance in conjunction with a modeling technique that allows applying “practical stability criteria”.

The *practical* stability criteria were developed in Russia [19]. They handle aperiodic instability, i.e., are not intended to detect instability due to self-sustained oscillations; are derived from the condition that the dynamic Jacobian is singular, i.e. **D** = 0; and are valid if:

- The generators are radially connected to a nodal point -- this is not 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 network using short-circuit admittances
- 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, more accurately , $d\Delta Q/dV < 0$.

The *reactive power criterion* is at the core of the fast and relatively accurate technique developed by Paul Dimo [5], [6], [7]. This method has been successfully implemented and is currently used in several SCADA/EMS installations to compute the system loadability limits in real-time and to continuously monitor the distance to instability [10], [17], [18], [21], [25].

C. The Approach to Steady-State Stability Assessment

The approach using Dimo’s method 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, known as REI Net, which is connected radially to a nodal point. The REI Net is illustrated in Figure 1

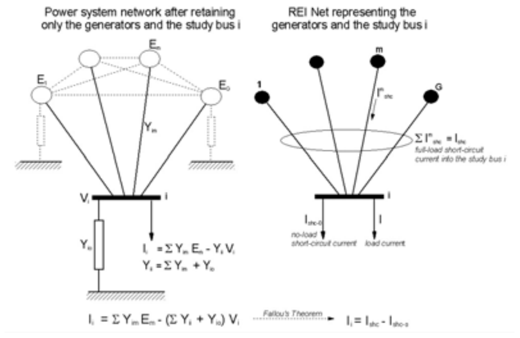


Figure 1. The REI Net

- *Reactive power stability criterion dQ/dV or more accurately dΔQ/dV* -- 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 implies that the generators are equipped with “proportional action voltage controllers” [19]. If the machine has reached both its P_{max} and Q_{max} limits during the case worsening algorithm, x'_d is replaced with the synchronous reactance x_d, which is consistent with [2, pp. 681] and [9], among other references
- *Zero Power Balance Network* to aggregate the bus loads into a single load-center -- this method, known in the industry as “REI equivalencing”, 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 identity of individual generators is maintained (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 is illustrated in Figure 2

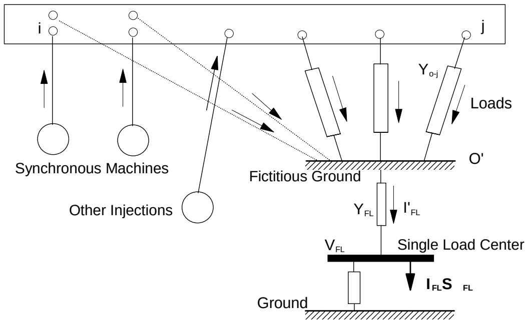


Figure 2. The Zero Power Balance Network

- *Case Worsening (increasing system loading)* procedure, which is used, instead of a succession of load-flow computations, to stress the system until it becomes unstable.

The following procedure is 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: (a) light load conditions, replacing the transient reactance with the synchronous reactance will cause the steady-state stability to decrease but not to be destroyed; (b) 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. The SSSL thus calculated tends to be conservative at low system loadings, but the prediction of the distance to instability becomes more and more accurate when the total MW system loading increases and additional reactive compensation resources get committed.

This apparent paradox can be explained if we note that operating policies typically call for raising TCUL taps, removing shunt reactors, adding shunt capacitors and bringing on-line synchronous condensers when the system is approaching peak-load conditions. At medium and light load levels, capacitors are removed, shunt reactors are reconnected and synchronous condensers and/or units that were running essentially for generating MVArs are taken off-line. Such operating procedures push the network's maximum loadability at values much higher than those at medium and light load levels. A fine example that illustrates this situation is described in the reference [21].

III. Independent System Operator in Bosnia and Herzegovina Approach to Real-Time Stability Assessment

A. *The Implementation Overview*

One of the most critical responsibilities of the Independent System Operator (NOS) of Bosnia and Herzegovina (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.

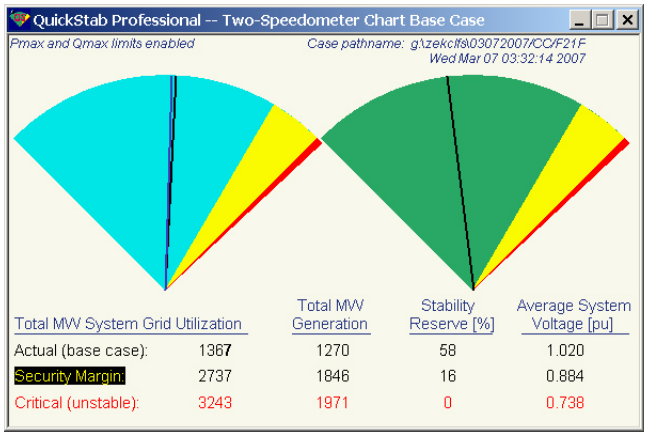
In order to fulfill its operational mission from an early stage, NOS BiH implemented an interim SCADA system in 2001 and, in 2005, it expanded it with a fast steady-state stability application (QuickStab) that uses the technology described in this paper. Initially, the program was loosely integrated with the state estimator that runs on the interim SCADA system.

The second and last phase has already been completed. The SCADA/EMS vendor (Siemens) 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 interim system and the main features of the upgraded solution are briefly discussed in the next section. Further details are provided in reference [22].

B. *Implementation and Practical Experience*

In the current interim implementation, the fast stability application is used in study-mode and in real-time. In study-mode, it is executed on off-line PCs with off-line load-flow and generator data in PSS/E format prepared on the PSS/E platform. In real-time, it runs 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 user definable time intervals, e.g., 5, 10, etc. minutes and: retrieves the most recent state estimate file from the SCADA/EMS server via FTP; copies it on the PC; triggers the QuickStab computational engine; saves both the computational results and the input data in a special directory for archival purposes; and, then triggers the QuickStab display engine to update and present the results on a clear graphical interface on a Windows operator console.

One of the key displays uses the "meter" paradigm where the dial is divided into three regions – a safe operating state, a marginal state and an unsafe (blackout state). The meter needle is positioned to show the location of the current state (Figure 3).



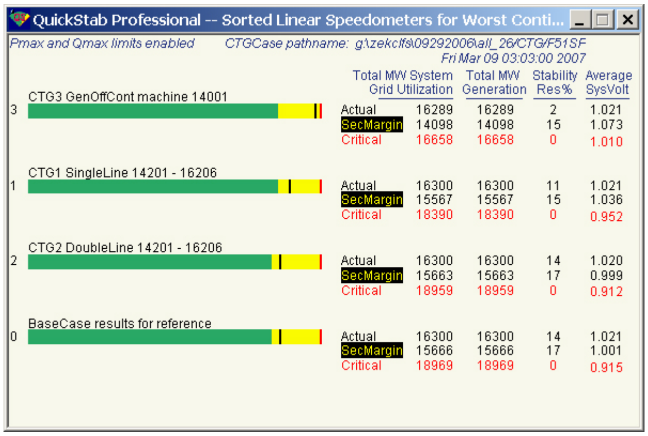
Pmax and Qmax limits enabled

Case pathname: g:\zekclfs\03072007/CC/F21F
Wed Mar 07 03:32:14 2007

Total MW System Grid Utilization		Total MW Generation	Stability Reserve [%]	Average System Voltage [pu]
Actual (base case):	1367	1270	58	1.020
Security Margin:	2737	1846	16	0.884
Critical (unstable):	3243	1971	0	0.738

Figure 3. Two-Speedometer Chart for the base case

The effect of contingencies is evaluated by, first, using a full Newton-Raphson load-flow calculation to determine the post contingency initial system state, and, then, determining the loadability limit with this contingency. The entire process is repeated for every contingency in the pre-specified list. The results from the base and contingency cases are displayed on linear speedometers, either sorted (Figure 4) or unsorted. Two-speedometer charts are used to show the most severe contingency case and to present side-by-side the most severe contingency and the base case for comparison. These graphical interfaces are actually being used in several EMS systems [3], [21], [22], [28].



Pmax and Qmax limits enabled CTGCase pathname: g:\zekclfs\09292006\all_26/CTG/F51SF
Fri Mar 09 03:03:00 2007

			Total MW System Grid Utilization	Total MW Generation	Stability Res%	Average SysVolt
3	CTG3 GenOffCont machine 14001	Actual	16289	16289	2	1.021
		SecMargin	14098	14098	15	1.073
		Critical	16658	16658	0	1.010
1	CTG1 SingleLine 14201 - 16206	Actual	16300	16300	11	1.021
		SecMargin	15567	15567	15	1.036
		Critical	18390	18390	0	0.952
2	CTG2 DoubleLine 14201 - 16206	Actual	16300	16300	14	1.020
		SecMargin	15663	15663	17	0.999
		Critical	18959	18959	0	0.912
0	BaseCase results for reference	Actual	16300	16300	14	1.021
		SecMargin	15666	15666	17	1.001
		Critical	18969	18969	0	0.915

Figure 4. Sorted Linear Speedometers for the worst contingency cases

Based on the experience gathered with QuickStab on the interim system, NOS BiH considered that it was a useful application and decided to require its seamless integration in the SCADA/EMS environment. The main benefits of the seamlessly integrated approach are:

- Immediate update of the "distance" of the operating state from the stability limit both periodically and after each significant system change – as opposed to periodical updates only
- Presentation of the key results directly in the native SCADA/EMS user interface – as opposed to a separate user interface
- The steady-state stability reserve computed after each state estimate is stored in the real-time database as a calculated point and tracked on a standard SCADA trending chart
- Ability to detect instability for postulated scenarios by means of the SCADA/EMS study case management and as easily as in real-time – as opposed to using a separate offline study environment.

IV. CONCLUSIONS

This paper has discussed several useful and valuable theoretical and modeling issues that help address the very difficult issue of steady-state and voltage stability in determining loadability limits in real-time. This approach has been successfully installed and proven in several EMS systems and is currently being used at the Independent System Operator in Bosnia and Herzegovina (NOS BiH).

The program is integrated with the Real-Time Network Analysis system and runs automatically after each successful state estimate. 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 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.

V. APPENDIX A: 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 burden involved for detecting transient instability, TSL is not quantifiable through a specific formula. 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 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 intractable. However, intuitively one can assume 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, so is TSL and vice-versa.

In the past, empirical values approximating the *TSL/SSSL ratio* were used to compute a "safe" amount of stability reserve, referred to as *security margin*, such that, for any system state with a stability reserve higher than this value, no contingency, no matter how severe, would cause instability [13], [14]. Accordingly, the security margin can be regarded as a stability envelope (Figure 5) such that all 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.

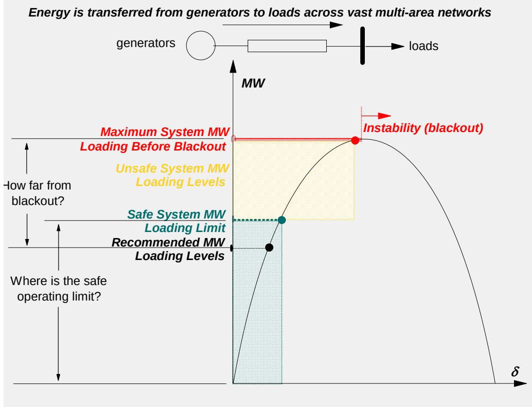


Figure 5. The "stability envelope"

The security margin depends upon the specific combination of topology, loads, generators and reactive compensation, and must be determined, and periodically reassessed, for each 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 σ is known, the system loading at TSL can be approximated by first computing SSSL and then identifying the safe total MW loading corresponding to σ x SSSL.

We are neither aware of a mathematical formula relating TSL and SSSL, nor whether such a relationship can be developed, but the empirical approach described in [21] can be expanded to build the following heuristic approach:

- Step 1: start with a peak load base case load-flow and compute the SSSL and related security margin.
- Step 2: 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.
- Step 3: use the security margin MW generation schedules from Step 1 to calculate a new base case load-flow.
- Step 4: for the load-flow computed in Step 3, run an extensive suite of transient stability simulations.
- Step 5: if no instability has been detected, repeat Step 4 for successively increased MW levels until at least one contingency causes transient instability. The SSSL for the immediately precedent state is the security margin.

If the stability calculations in Step 4 detected at least one contingency that causes 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 (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 valuable hints. For example, reference [8] recommended a 20% security margin for the Romanian power system as it was in the 1970s. Reference [21] identified a 15% security margin for the transmission grid of ETESA, Panama. A 15 % value of σ is also used in the NOS BiH system.

VI. APPENDIX B: NOTE ABOUT HANDLING GENERATORS IN CONVENTIONAL VOLTAGE SECURITY ASSESSMENT

In the realm of voltage stability, or "voltage security" assessment, tools based on load-flows and continuation load-flows are quite popular. The idea to use load-flow calculations to detect instability was first proposed by V. A. Venikov et al [20] who proposed that under "certain conditions" the singularity of the standard load-flow Jacobian indicates steady-state instability. This of course appeared attractive because evaluating the singularity of the load-flow Jacobian, which also forms the basis of continuation load-flow techniques, is much easier than evaluating the singularity of the dynamic Jacobian.

However, according to Sauer and Pai [15], [16] *"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 maximum power transfer. Such analysis would not detect any voltage instabilities associated with synchronous machines characteristics and their controls"* [15, pp. 1380].

The assumptions under which the standard load-flow Jacobian can be related to the system dynamic Jacobian:

- Stator resistance of every machine is negligible
- Transient reactances of every machine are negligible
- High gain and fast excitation systems so that all generator terminal voltages are constant.
- Swing generator has infinite inertia, which together with the previous assumptions makes it an infinite bus.

In reality, this is the load-flow model, where the internal reactances of the generators are *not* represented, and the voltages are maintained constant on the machine terminals or on the high-voltage side of the step-up transformers. Let us note *en passant* that if the generator reactances were to be included in the load-flow model, the PV buses would "move" to the internal generator nodes where the e.m.f. are applied, and since the e.m.f. are higher, or much higher, than 1.0 p.u., the Newton-Raphson calculations would likely diverge.

VII. APPENDIX C: STABILITY CONSTRAINED LINKS

The analysis of recent system collapse 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.

For vast interconnected systems it is thus 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" or flow gates, 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.

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. The further loading capability, i.e., the stability reserve of the link, can be expressed either in MW or in percentage of the maximum link loading. A detailed description of this technique is provided in [11] and [12].

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 may 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.

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