

# A Metric for Quantifying the Risk of Blackout

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**Abstract** -- This paper addresses the problem of quantifying the risk of blackout and the need to do it fast, in real-time and for multiple off-line simulations. Is there a metric that can tell how far is a given power system state from its stability limit? But then, what is *stability limit*? How to quantitatively describe such limit, or perhaps, *limits*, if more than one, and how to quickly determine how far is the transmission network from a state where a blackout might occur? The concept of *steady-state stability reserve*, introduced half a century ago to quantify the distance to instability, is also reviewed. Space and presentation time do not allow a detailed analysis, but an extensive list of references is provided to help promote further research. The main theme of this paper is particularly relevant in the aftermath of the wave of blackouts that affected utilities in US, UK and mainland Europe in 2003. The approach presented herein can help system dispatchers and reliability engineers foresee whether the transmission loading progresses, or is projected to progress, beyond the operating reliability limit.

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

## I. INTRODUCTION

MODERN utilities are discovering the side effects of the open access paradigm the hard way. Today, the transmission networks must sustain MW transfers that can be quite different from those for which they had been planned. This is because 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 – but how to measure the risk of blackout? And how to quickly evaluate it in real-time or for fast and multiple off-line simulations?

The first question points to a "metric" to assess the risk of blackout. An example of such "metric" is the *steady-state stability reserve*, which has been around for a long time and quantifies the *distance* to the state of maximum power transfer, or steady-state instability.

The second question identifies the need to perform fast stability calculations with minimum amount of data and within continuously running sequences, e.g., the EMS real-time network analysis, and to provide the results quickly and in a user-friendly format as required for fast and reliable on-line decision-making.

## II. NEED TO LOOK AT THE RISK OF BLACKOUT FROM A DIFFERENT ANGLE

Until now, the industry has taken for granted concepts such as the Available Transfer Capability (ATC), Total Transfer Capability (TTC), Transmission Reliability Margin (TRM) and Capacity Benefit Margin (CBM), but stopped short from performing stability computations in real-time dispatch, routinely triggering maximum transfer capability calculations after each and every load-flow, and validating market transactions with fast stability checks.

According to NERC [22], the TTC is given by:

$$\text{TTC} = \text{Min} \{ \text{Thermal Limit, Voltage Limit, Stability Limit} \}$$

The thermal limits reflect the equipment's characteristics and are relatively constant. The voltage limits are also well known and understood. Both the thermal and the voltage limits are predictable and can even be violated for short periods of time. But how about "stability limits"? How many "stability limits" are there in the first place, and how to define and quantify them? Can they be "violated"? And, if they can, by how much and for how long?

Conceptually, the "stability limit" is a local property of the system state vector: 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. It is precisely this changing nature of the "stability limits" that makes it necessary to recompute them as often as possible.

On the other hand, instability develops instantly and leaves no time to react. Therefore, in addition to a *metric* that would quantify the stability limits, there is also a need to rapidly reevaluate such limits for each new system state, after each state estimate, and after each load-flow.

In fact, NERC's Policy 9 [26] requires Reliability Coordinators to compute the "stability limits" for the current and next-day operations processes to foresee whether the transmission loading progresses or is projected to progress beyond the operating reliability limit. Is this being done?

The wide and fast spreading August 14 2003 blackout suggests that this may not be the case – perhaps because detecting thermal and voltage violations is straightforward and can be executed on-line, whereas performing stability assessment is a difficult proposition. But operating a power system without knowing its actual stability limit is like walking on thin ice -- and since conventional stability methods cannot be used in real-time, a new way to define and solve the problem must be identified.

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### III. IN SEARCH OF THE STABILITY LIMIT

#### A. Transient and Voltage Stability Limits

Sophisticated stability assessment tools are currently available to determine “whether a given condition is stable or unstable, but have not been efficient in quickly and automatically determining the stability limits, that is, how much a system, or part of a system, can be loaded before instability occurs” [10]. Two tracks have been investigated in the industry during the last two decades: transient stability and, respectively, voltage stability.

On the *transient stability* venue, much work was done to develop “transient stability indices” that would provide the “degree of stability” [10]. Regardless of the specific details, these methods follow similar scenarios:

- Start with a base case and a postulated major contingency
- Derive a “severity index” for this contingency
- Compute new power flows
- Repeat the process until an unstable case has been obtained [24]

Their limitations are similar, too:

- Computational burden, which some authors alleviate via simplifications such as merging all the machines into an equivalent generator, or using the infinite bus assumption, i.e., implying that voltages are constant although, in real life, the voltages drop during the worsening of the system state
- Non-convergence of Newton-Raphson load-flow calculations near instability
- The “stability limit” thus identified qualifies as a limit only for the particular disturbance that was evaluated -- but since many disturbances are possible, a true “system-wide transient stability limit” for a given state vector would require that a huge set of possible disturbances be examined.

*Voltage stability* tools, on the other hand, determine the point of voltage collapse at individual buses by making certain assumptions about the nature of the load. The process needs to be repeated to evaluate all the load buses or, at least, a minimum set of load buses known *a priori* to be critical.

The accuracy of voltage stability simulations depends upon how the loads and the generating units are represented. Although voltage stability is actually load stability [18], the synchronous machines must be included in the model [2], [11], therefore significantly increasing the complexity of the solution technique, especially if detailed machine models are to be used [21].

As far as the loads are concerned, their representation impacts the P-V relationship. Reference [3] demonstrated that if the real and reactive part of the loads are modeled as constant impedances, successive load increases cause the generated MW to increase until the point of maximum power transfer, whereas beyond that point, the total generated power gets smaller and *dual power states* (same power at different voltages) are obtained. This is exactly the pattern displayed by the P-V characteristics commonly known as “PV-Nose curves”. But dual states *cannot* happen in real life. If the P and

Q characteristics of the loads, which in reality are non-linear, were represented as such, dual states would not happen and the P-V graph would stop at the point of instability.

Let’s mention *en passant* the practice of “assessing” voltage stability by running load-flows at successively increased load levels and stopping when the load-flow diverged. While it is true that Newton-Raphson load-flows diverge near instability, the state of maximum power transfer has probably been reached before this point.

According to Sauer and Pai, “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” [5, pp. 1380].

#### B. The Steady-State Stability Connection

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 lose stability” [25].

Approaching the search for a “stability limit” from this perspective brings promising results. First and foremost, the SSSL is mathematically definable and *does* represent an operating limit, albeit one that is:

- Local, i.e., it depends both upon the current state vector and the assumptions made to “worsen” the case, and
- Unsafe, in the sense that operating states immediately below this limit may quickly, or even instantly, become unstable.

Then, the SSSL can be quantified, i.e., can be expressed in terms of the total MW loading of the transmission system, including both internal generation and tie-line imports, under a given scenario of voltage conditions. Incidentally, this limit is also connected to the state where voltage instability might occur [11], [12], [18].

On this basis, a metric can be defined to quantify “how far from SSSL” is a given operating state. Known as *steady-state stability reserve*, this measure was used in Europe since 1950s [4], [5], [6], [16] and, as we will show in the following, is at the core of the *stability envelope* concept.

#### C. TSL, TTC and the Stability Envelope

So far we know that a Transient Stability Limit (TSL) *does* exist even if: (a) it’s local, i.e., applies to a given system state vector; and (b) cannot be found easily. Intuition also suggests that, for a given state vector, the SSSL and TSL are interrelated:

- They change in the same direction: if SSSL is high, TSL is also high, and vice-versa
- For a given set of relay settings, both TSL and SSSL depend upon topology, voltage levels and system loading.

We do not know whether a mathematical formula relating the TSL and SSSL can be found, but we believe that the *TSL/SSSL*

ratio can be approximated empirically. In other words, it is possible to find a “safe” MW system loading, referred to as *security margin*, such that, for any system state with a steady-state stability reserve smaller than this value, no contingency, no matter how severe, would cause transient instability.

Such a security margin can be expressed as a percentage of the SSSL. Paul Dimo [4] [6] used to recommend, for the power system of Romania in the 1960s and 1970s, a 20% security margin, thus implying that for system loadings below 80% from the SSSL there was no risk of transient instability.

We are not aware of an explicit formula for computing the security margin, but a possible heuristic might be as follows:

1. Start with a base case load-flow at a medium load level.
2. Run an extensive suite of transient stability simulations. If no instability has been detected, calculate the SSSL and the steady-state stability reserve for this case.
3. Get a new base case for an increased load level and repeat all the transient stability checks. If no instability has been detected, recalculate the SSSL and the steady-state stability reserve for this new case.
4. Repeat step 3 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.

Assuming there are no thermal violations, i.e., the TSL is actually the same as NERC’s TTC, the security margin represents a “safe system MW loading limit” that can be interpreted as a *stability envelope* (Figure 1) and, conceptually, corresponds to NERC’s definition of TRM.

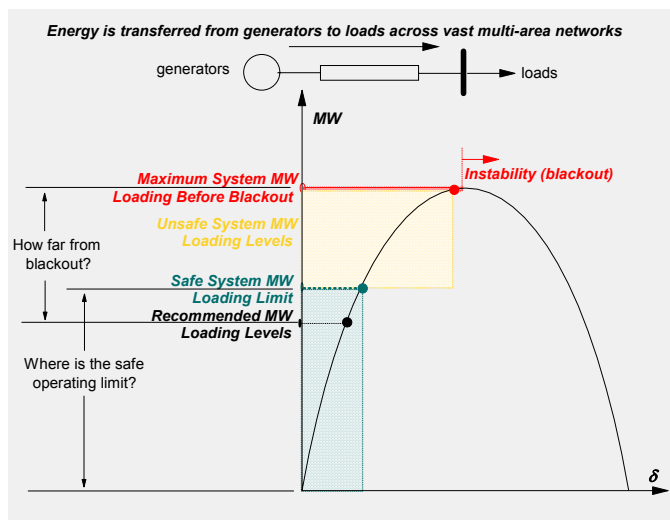


Figure 1. The “stability envelope”

#### IV. QUANTIFYING THE STABILITY ENVELOPE

Operating states near the SSSL are not safe and the TSL (TTC) is an elusive target. This is the bad news. The good news is that we can replace an otherwise unsolvable problem with the computation of a *stability envelope* 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 given x% value of the security margin, determine the corresponding safe system MW loading below the SSSL.

This can be accomplished both by detailed analysis, which is well suited for off-line studies but not (or ... not yet) applicable if the computations must complete within split seconds, and by fast approximate methods, the latter approach being appropriate for real-time and quick off-line decision making. Such a technique was developed by Paul Dimo [4], [5], [6] in Europe. Its validity and usefulness for real-time applications were demonstrated in the EPRI Research Project RP2473-43 [20] and presented in various US and international publications [8], [14], [15].

##### A. Paul Dimo’s Simplified Steady-State Stability Approach in a Nutshell

Dimo’s method, first published in France in 1961 [4] then used in production-grade studies in Europe and awarded the Prix Montefiore in Belgium in 1981, is predicated on the:

- Short-circuit currents / short-circuit admittances network transformation
- Reactive power voltage stability criterion (Bruk-Markovic)
- Simplified representation of generators, modeled by constant e.m.f. behind the transient reactance  $x'_d$
- Fictitious load-center obtained by aggregating the loads via a Zero Power Balance Network
- Case worsening procedure used instead of a succession of load-flow computations.

Further details, including the mathematical formulation of Dimo’s approach, can be found in many publications, e.g., [4], [5], [6], [8], [14], [15], [16], [20].

##### B. A Two-Step Stability Limit Evaluation Paradigm

The steady-state stability reserve concept in conjunction with a fast solution technique, e.g., Dimo’s algorithm, can generate a two-step approach as follows.

The first step would consist of a *quick check* aimed at:

- Determining “how far from instability” is the current system state
- Identifying the “stability envelope” based on a user-defined “x% security margin”

The second step would encompass a *full analysis* to be performed with more powerful tools, e.g., the ones described in [11], [13], [27], and would be executed only if needed, i.e., if the case under evaluation is situated outside the stability envelope.

##### C. Practical Implementation

The metric to assess the risk of blackout described in this paper was implemented in several off-line and real-time installations. Figure 2 illustrates how a fast computational engine that determines the steady-state stability reserve was seamlessly integrated in the real-time network analysis

sequence of an actual EMS. Further implementation details can be found in reference [27].

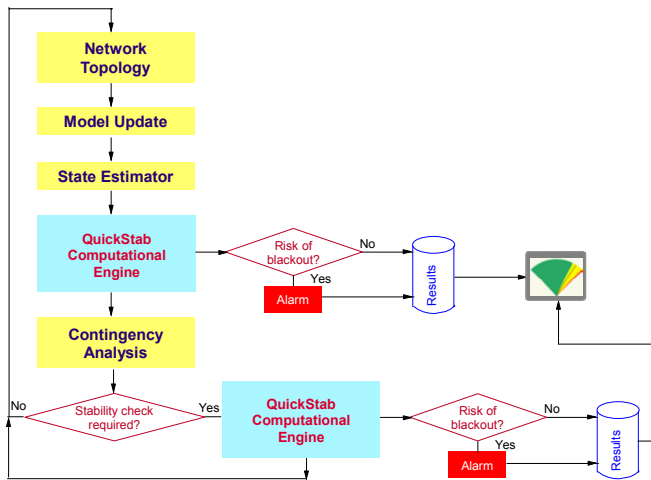


Figure 2. Integration of a fast steady-state stability module in the real-time network analysis sequence

## V. CONCLUSIONS

This paper discussed several aspects of the important need to assess the risk of blackout -- and to do it quickly, in real-time and for fast off-line simulations. It was shown that a simple metric suitable to achieve this goal is the distance to steady-state instability, also known as steady-state stability reserve, and can be computed quickly by using suitable simplifying assumptions. Practical results obtained with this technique point to a viable tool for real-time and off-line studies.

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