

What Experts Say about Using Load-Flows to Assess Stability

Preliminary -- February 19, 2007

White Paper prepared by
Savu C. Savulescu



Summary

- According to a relatively widespread belief in the utility industry, it would be possible to assess voltage stability by running load-flows (until they diverge) or continuation load-flows (bifurcation analysis)
 - since the internal reactances of the machines are not included in the load-flow model, this sounds like attempting to perform stability analysis without representing the generators
- However, well known stability experts have shown that:
 - computational models that do not represent the generators are, at best, optimistic
 - the stability of the steady-state equilibrium point should be determined by evaluating the dynamic state Jacobian, rather than the load-flow Jacobian
- The following slides summarize a White Paper that aims at clarifying this issue

It all started in 1975 when ...

- V. A. Venikov et al. proposed that **under "certain conditions"** the singularity of the standard load-flow Jacobian indicates steady-state instability

- Venikov, V. A., Stroyev, V. A., Idelchick, V. I. and Tarasov, V. I., 1975, "Estimation of electrical power system steady-state stability", *IEEE Transactions on Power Apparatus and Systems*, PAS-94, 3, May/June 1975, pp. 1034-1040

- ↳ these "special conditions" imply neglecting the generator reactances and assuming constant terminal voltages

- Venikov, V. A., 1977, *Transient Processes in Electrical Power Systems*, Edited by V. A. Stroyev, English Translation, MIR Publishers, Moscow

In principal, the forced-action AER can provide almost constant voltage across the generator terminals (or, if necessary, at the sending end of the line) under all operating conditions including that of maximum power transfer. Based on this factor, a synchronous machine with a forced-action AER is usually represented in the equivalent circuit by $x_g = 0$, $V_g = \text{const}$. Synchronous machines with proportional-action AER's are generally represented by $x_g = x'_d$, $E'_q = \text{const}$. Such equivalent circuits of controlled synchronous machines are used when assessing the steady-state stability neglecting the self-oscillation, when plotting the power-angle characteristics, calculating the power transfer capacity of transmission lines at the design stage or during their operation provided that no self-oscillation may occur in the system.



But later on, in 1990 ... 2006 ...

- P. Sauer and M. A. Pai clarified that the "special conditions" mentioned by Venikov lead to results that should be considered optimistic ...

- Sauer, P. W. and Pai, M.A., 1990, "Power system steady-state stability and the load-flow Jacobian", *IEEE Transactions on Power Systems*, 5, 4, November 1990, pp. 1374-1383

In 1975, V. A. Venikov et al published a paper which proposed that under certain conditions, there is a direct relationship between the singularity of the standard load-flow Jacobian and the singularity of the system dynamic state Jacobian [11]. This paper has been cited as the primary justification for studying the load-flow Jacobian matrix to determine critical load levels. In this paper, we clarify this result in the context of a fairly general dynamic model and show that the result should be considered optimistic for any type of steady-state stability analysis.

... and demonstrated that there are two cases, "**not necessarily realistic**", where the standard load-flow Jacobian can be related to the system dynamic state Jacobian:

But later on, in 1990 ... 2006 ... (cont'd)

There are two very special cases when the determinant of the standard load-flow Jacobian implies something about the steady-state stability of a dynamic model. Both of these cases involve very drastic assumptions about the synchronous machines and their control systems. The load level which produces a singular load-flow Jacobian should be considered an optimistic upper bound on maximum loadability. The actual upper bound would be either the same or lower since it requires both the existence of a solution and stable dynamics.

Case A assumptions:

- ▶ stator resistance is negligible
- ▶ transient reactances of every machine are negligible
- ▶ field and damper winding time constants infinitely large
- ▶ constant mechanical torque to the shaft of each generator
- ▶ swing bus machine has infinite inertia, which makes $V_{\text{swing}} = \text{const}$ and $\delta_{\text{swing}} = \text{const}$ (infinite bus)
- ▶ all loads are constant power



But later on, in 1990 ... 2006 ... (cont'd)

Case B assumptions:

- stator resistance is negligible
 - no damper windings or speed damping
 - high gain and fast excitation systems so that all generator terminal voltages are constant
 - constant mechanical torque to the shaft of each generator
 - all loads are constant power
- This is how Sauer and Pai conclude their paper:

For voltage collapse and voltage instability analysis, any conclusions based on the singularity of the standard load-flow Jacobian would apply only to the phenomena of voltage behavior near maximum power transfer. Such analysis would not detect any voltage instabilities associated with synchronous machine characteristics or their controls.

Further Reasons to Represent the Generators

- Here's what Barbier and Barret had to say in their seminal paper that practically started the research in the field of voltage stability -->

- Barbier, C. and Barret, J.P., 1980, "An analysis of phenomena of voltage collapse on a transmission system", *Revue Générale de l'Electricité*, 89, 7, pp. 3-21

2.2. Non constant voltage source.

When the source substation can no longer hold its voltage constant, because it has reached its limit (rotor or stator current of a generating unit for example) there are two possibilities :

- either a further constant voltage point is found (such as e.m.f. behind the synchronous reactance of an alternator for operation of the latter at constant excitation, another source further along the system). We are then brought back to the case of para. 2.1, but with a higher value for impedance Z_L of the two-terminal system, or a lengthening of the route over which must be effected the summation $\sum P/U$;
- or there is no point of constant voltage and the risks of voltage collapse are considerable. This would be the case, for example, of a system in which all the generating units are at the limit of armature current and in which the latter is maintained constant (at its maximum value) during taking over of load. This would lead to a collapse of voltage and instability of the transformer tap-changers.

We may consider, as an example, the case of the two-terminal system of Figure 1. Increased load demand corresponds to reduction of impedance Z and



Further Reasons to Represent the Generators (cont'd)

- The first bullet in the caption on the previous page is actually an indirect injunction to represent the machines
- The second bullet tells us that, in addition to including the generators in the model, we must also detect whether they are simultaneously at Q_{\max} and P_{\max} because this condition may trigger instability
- On the other hand, if:
 - ☞ *load-flow calculations were used to evaluate stability, none of these provisions could be implemented*
 - ☞ *nevertheless, we would attempt to include generator reactances in the load-flow model, then the:*
 - ☞ *generator terminals would be replaced with their internal nodes*
 - ☞ *generator bus voltages would actually become the internal e.m.f.*
 - ☞ *Newton-Raphson load-flow calculations would diverge because e.m.f. are typically much higher than 1.0 p.u.*



In a Nutshell ...

- **Steady-state instability** is identified by the singularity of the dynamic state Jacobian
 - the singularity of any of its submatrices results in steady-state instability, in other words:
 - *steady-state instability can be detected by identifying the state where any of the $dP/d\delta$, dP/dV or dQ/dV submatrices becomes singular*
 - on this basis, three "practical" stability criteria are defined:
 - voltage stability criterion dP/dV
 - steady-state stability criterion dQ/dV *← used in QuickStab*
 - angle stability criterion $dP/d\delta$
- **Steady-State Stability Limit (SSSL)**
 - total MW (internal generation + imports) such that the system is stable in the presence of small load changes



In a Nutshell ... (cont'd)

- **Stability Reserve = "distance" from the current system state to the SSSL**
 - **Safe Operating Margin**
 - system MW loading where there is no risk of transient instability
 - implies no risk of aperiodic steady-state instability
 - always much smaller than SSSL
 - changes in the same direction with SSSL
 - conceptually similar to TTC as defined by NERC
- ☞ *"any network that meets the steady-state stability conditions can withstand dynamic perturbations and end in a stable operating state"***
- (Magnien, M., "Rapport Spécial du Groupe 32 Conception et Fonctionnement des Réseaux", Conférence Internationale des Grands Réseaux Electriques à Haute Tension, CIGRE Session 1964)***