Stability Assessment Requires Much More Than Just Load-Flow Calculations[1]

White Paper (preliminary draft)

Summary. *According to a relatively widespread belief in the utility industry, it would be possible to assess "voltage stability" with load-flows, continuation load-flows and other tools that allow drawing "P-V" and "Q-V" curves* <u>*without*</u> *representing the internal reactances of the generators. As shown in the following, nothing is further from truth. Well known stability experts suggest that stability calculation models that do not represent the generators are, at best, optimistic -- and that, if we're serious about performing fast and reliable voltage and steady-state stability assessment, we need a tool like QuickStab® and cannot, and should not, restrict our bag of tools to just load-flows, bifurcation analysis and assorted gimmicks aimed at drawing P-V and Q-V curves.*

Background

In the realm of voltage stability, or "voltage security" assessment, tools based on load-flow and continuation load-flow quickly became popular and did not receive the critical scrutiny they might have deserved. In 1975, V. A. Venikov et al. [19] proposed that under "*certain conditions*" the singularity of the standard load-flow Jacobian indicates steady-state instability. These "*certain conditions*" were shown by Venikov [18] to imply: neglecting the generators' internal reactances; and assuming that the generators are equipped with forced-action voltage controllers which can keep constant the voltage at the machine terminals regardless of anything else.

Actually, this is precisely the load-flow model. In load-flow computations, 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 this helps transcend an otherwise insurmountable difficulty in the load-flow paradigm. If the generator reactances were to be included in the load-flow model, the P-V buses would "move" to the internal generator nodes where the emf are applied, and since the emf are higher, or much higher, than 1.0 p.u., the Newton-Raphson calculations would diverge.

> state stability [1-10]. While load-flow has been the primary method used to compute steady-state conditions, its role in evaluating stability has not been fully clarified. 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. The paper includes a tutorial on the role of load-flow in dynamic analysis.

Reference [19] has been cited as the primary justification for studying the load-flow Jacobian matrix to determine critical load levels. However, while it is true that Newton-Raphson load-flow calculations diverge near instability, the divergence may be due to other reasons as well and should not be used as a stability criterion [16]. 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"* [11, pp. 1380].

In subsequent publications, P. Sauer, M. A. Pai and C. Vournas [13], [22], have:

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

  a. Stator resistance of every machine is negligible $\left(R_{si}=0,\ \ i=1,\ldots,m\right)$

  b. Transient reactances of every machine are negligible $\left(X'_{di}=0,\ X'_{qi}=0,\ i=1,\ldots,m\right)$.

  c. Field and damper winding time constants for every machine are infinitely large $\left(E'_{qi}=\text{constant},\ E'_{di}=\text{constant},\ \ i=1,\ldots,m\right)$.

  d. Constant mechanical torque to the shaft of each generator $\left(T_{Mi}=\text{constant},\ \ i=1,\ldots,m\right)$.

  e. Generator number one has infinite inertia. This together with (a1) – (a3) makes $V_1=\text{constant},\ \theta_1=\text{constant}$ (infinite bus)

  f. All loads are constant power $\left(P_{Li}(V_i)=\text{constant},\ Q_{Li}\left(V_i\right)=\text{constant},\ \ i=1,\ldots,n\right)$.

- Further clarified the “special conditions” mentioned by Venikov and demonstrated that they actually imply the following:

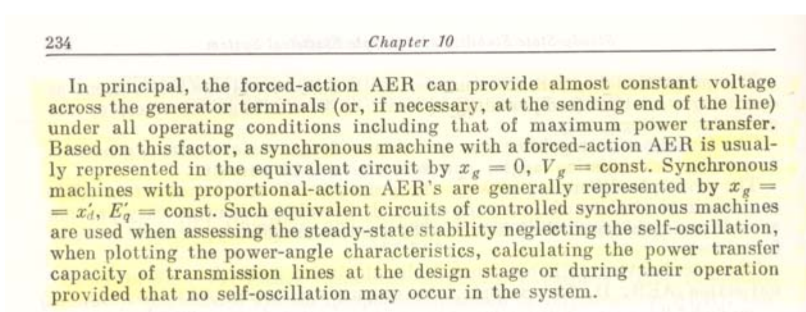
  a. Stator resistance is negligible $\left(R_{si}=0,\ \ i=1,\ldots,m\right)$

  b. No damper windings or speed damping $\left(T'_{qoi}=0,\ \ D_i=0,\ \ i=1,\ldots,m\right)$

  c. High gain and fast excitation systems so that all generator terminal voltages are constant $\left(V_i=\text{constant},\ \ \ i=1,\ldots,m\right)$

  d. Constant mechanical torque to the shaft of each generator $\left(T_{Mi}=\text{constant},\ \ \ i=1,\ldots,m\right)$

  e. All loads are constant power $\left(P_{Li}(V_i)=\text{constant},\ Q_{Li}\left(V_i\right)=\text{constant}, i=1,\ldots,n\right)$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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 = const. Synchronous machines with proportional-action AER's are generally represented by $x_g = x'_d$, E'_q = 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.

In all fairness to Venikov, it must be noted that his text book [5] clearly states that neglecting the internal reactance of the generators in stability calculations would correspond to machines equipped with forced-action voltage controllers which, in turn, implies that the generators can keep constant the voltage on the machine terminals no matter what – but this assumption is not correct and, as it is well know in the industry, e.g., [] [], generators that reached both their P_{max} and Q_{max} limits can cause instability.

On the same venue, but in a different context, C. Barbier and J. P. Barret published in 1980 a seminal paper [1] that promoted the use of the maximum power transfer theorem to identify the point of voltage collapse at any given load bus. Whereas Barbier's and Barret's P-V curves ignited a new area of research and became common place in the industry, followed very quickly by the so-called Q-V curves, their injunction to model the generators via a constant emf behind an internal reactance went unnoticed -- which perhaps explains why so many subsequent papers spread the idea that voltage collapse could be detected without representing the machines!

To set the record straight, this is what Barbier and Barret wrote [1, pp 681]: "*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 emf behind the synchronous reactance of an alternator for operation of the latter at constant excitation …; or there is no constant voltage and the risk of voltage collapse is 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*".

2.2. Source à tension non tenue.

Lorsque le poste source ne peut plus maintenir la tension, parce qu'une limitation de la source est atteinte (courant rotor ou courant stator d'un groupe par exemple), il y a deux situations possibles :

• ou bien l'on retrouve plus loin un point à tension tenue (force électromotrice derrière la réactance synchrone d'un alternateur pour un fonctionnement de celui-ci à excitation constante, autre source plus éloignée sur le réseau). On est alors ramené au cas du § 2.1, mais avec une valeur de l'impédance du dipôle Z_L plus élevée, ou un allongement du trajet sur lequel doit s'effectuer la sommation *X P/U* ;

• ou bien il n'y a aucun point à tension tenue et les risques d'écroulement de tension sont importants. Ce serait le cas, par exemple, d'un réseau où tous les groupes seraient en limite de courant stator et où celui-ci serait maintenu constant (à sa valeur maximale) au cours de la prise de charge. Ceci conduit à un écroulement de la tension et une instabilité du réglage des transformateurs.

En effet, considérons, par exemple, le cas du dipôle de la figure 1. Une demande supplémentaire des charges correspond à une diminution de l'impédance Z

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 X 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

Another problem with the potentially misconstrued application of the maximum power transfer theorem is the very shape of the P-V curves. Ionescu and Ungureanu [8] demonstrated that when the loads are modeled as constant impedances, which is how they are represented in Barbier's and Barret's equations, successive load increases cause the generated MW to increase until the point of maximum power transfer. Then, beyond that point, the total generated power starts getting smaller and *dual power states* (same power at different voltages) are obtained, hence the "nose" shape of the P-V curves. But dual states *cannot* happen in real life, and more realistic load models are needed so that the P-V graphs would stop at the point of instability.

Is the "continuation load-flow" any better? According to Canizares and Alvarado, the basic assumption of the continuation load-flow is that "*voltage collapse points … are detectable by looking only for the singularities of the steady-state power flow Jacobian*". That's right. C. A.

Canizares and F. Alvarado [2] clearly tell us that the continuation load-flow does not represent the machines. So, once again, we have to rely on some mythical “special conditions” that might help assess stability by running load-flows.

The way out of this impasse is to recognize that what we really have to address is the very concept of “stability limit”.

> During the last few years several methodologies for detecting saddle-node bifurcations in dynamic systems using steady state analysis techniques [1], have been tailored and applied to the determination of loadability limits of power systems. In this paper dynamic saddle-node bifurcations, or voltage collapse points, will be considered to be detectable by looking only for singularities of the steady state power flow Jacobian, since, under certain assumptions, saddle-node bifurcations of ac/dc dynamic systems with algebraic constraints can be shown to occur when the corresponding power flow Jacobian becomes singular [6, 7].
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> One simple alternative to find loadability limits is to use an ordinary power flow and to gradually increase loads un-

Stability Limits. What they are and How to Quantify Them

How many “stability limits” are there in the first place? Are they definable? Can they be quantified? 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. But in order to compute the stability “limit”, or “limits”, we first need a *metric* that would enable us to define and quantify such limits.

As we will show in the subsequent sections, most of the aforementioned limitations and difficulties are resolved and eliminated if we revert to the classical framework of steady-state stability.

-- To be completed soon --

The DΔQ/dV Avenue

-- To be completed soon --

How to Detect the Risk of Voltage Collapse Quickly and Accurately to Support On-Line Decision Making

-- To be completed soon --

Further Reading

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