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Sensitivity Methods of Electric Power Systems

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Abstract—**Reliable operation of large scale electric power networks requires that system voltages and currents stay within design limits. Operation beyond those limits can lead to equipment failures and blackouts. Security margins measure the amount by which system loads or power transfers can change before a security violation, such as an overloaded transmission line, is encountered. This thesis shows how to efficiently compute security margins defined by limiting events and instabilities, and the sensitivity of those margins with respect to assumptions, system parameters, operating policy, and transactions. Security margins to voltage collapse blackouts, oscillatory instability, generator limits, voltage constraints and line overloads are considered. The usefulness of computing the sensitivities of these margins with respect to interarea transfers, loading parameters, generator dispatch, transmission line parameters, and VAR support is established for networks as large as 1500 buses. The sensitivity formulas presented apply to a range of power system models. Conventional sensitivity formulas such as line distribution factors, outage distribution factors, participation factors and penalty factors are shown to be special cases of the general sensitivity formulas derived in this thesis. The sensitivity formulas readily accommodate sparse matrix techniques. Margin sensitivity methods are shown to work effectively for avoiding voltage collapse blackouts caused by either saddle node bifurcation of equilibria or immediate instability due to generator reactive power limits. Extremely fast contingency analysis for voltage collapse can be implemented with margin sensitivity based rankings. Interarea transfer can be limited by voltage limits, line limits, or voltage stability. The sensitivity formulas presented in this thesis apply to security margins defined by any limit criteria. A method to compute transfer margins by directly locating intermediate events reduces the total number of loadflow iterations required by each margin computation and provides sensitivity information at minimal additional cost. Estimates of the effect of simultaneous transfers on the transfer margins agree well with the exact computations for a network model derived from a portion of the U.S grid. The accuracy of the estimates over a useful range of conditions and the ease of obtaining the estimates suggest that the sensitivity computations will be of practical value.**

Keywords- Margins and sensitivity

Introduction (*Heading 1*)

This paper concerns the stability and security of large electric power systems with an emphasis on static or longer term stability. One contribution of this paper is the establishment of a coherent, consistent, and general framework for margin and sensitivity analysis applicable to a variety of security criteria. This paper shows how to efficiently compute the security margins defined by limiting events and instabilities, and the sensitivity of those margins with respect to any model parameter. Part 2 states assumptions defining admissible power system models. Parts 3 and 4 detail computational methods for computing margins and their sensitivities. Parts 5, 6, and 7 describe applications regarding voltage collapse. Part 8 describes applications regarding transfer capability. Part 9 describes applications regarding oscillatory instabilities. Part 10 contains a summary of the thesis and outlines possible avenues for future work. proceedings.

Part

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Many power system phenomena are initiated by the aggregate effect of changing loads. The model should have the ability to partially account for the response of interconnected generators to fluctuating demands. As loads increase the rotational speed and hence frequency of individual generators decreases. A control system using frequency as a feedback increases the mechanical input to the generators which in turn results in increased electrical output and restoration of frequency. Another control system implements a dispatch among generators so that increased output is provided by those generators at which it is most economical to do so and so that interchange agreements for the transfer of power between areas and utilities are maintained. With a cumulative increase in demand, system voltages can decline, initiating several activities. On load tap changing transformers adjust tap positions to maintain load side voltages. Shunt capacitors are switched in to provide reactive power support. Fast starting back-up generation may be brought on-line. The characteristic of changing system equipment and structure as a function of system state is a feature we wish to incorporate in our model. While the demand and then generation increase, so do the flows and losses on the transmission lines, as well as the flows and losses in the circuits and devices that make up each generating unit. When the flows on transmission lines increase, the temperature of the conductors increases resulting in a loss of mechanical strength and increased sag. The increased sag can cause a line to become dangerously close to ground increasing the possibility of flash over and faults. A faulted line can lead to momentary or prolonged outage of the line. Extended operation of a line beyond its thermal rating can permanently reduce the strength of the line. Once lines become overloaded, generation is redispatched torelieve the overloads, and in some cases the lines are interrupted to prevent permanent damage.

Generators can be damaged by overheating and over or under voltage conditions. Protective devices range from controls that remove the generator from the network (severe over or under voltage), to those that limit the output of the generator by controlling its operation. The latter include mechanical limits on the prime mover to fix the maximum power output, and control devices that limit the voltage or current in control circuits or generator windings to prevent overheating, shorting, and unit failure.

The model should account for the operation of protective devices and changes in system operation policy resulting from the condition of the system. Every change in load or generation, switching of a device, or tap change at a transformer is a disturbance to the power system. Disturbances may also be caused by random events like lightning strikes and short circuits. If the system is stable, the controls and dynamics will behave in such a way as to move the system state toward a new equilibrium after the disturbance. As the system becomes less stable, the rate at which the system approaches equilibrium after every disturbance decreases. The duration of time for which the transient effects of a disturbance dominate increases as the stability of the system decreases. Significantly large disturbances can cause the system state to diverge from the equilibrium or for the equilibrium to disappear. When conditions are severe, several generators may reach operational limits and lines may trip due to shorts caused by steady overload, in turn further compromising the system security. The security of a system thus depends upon the accumulated effects of slow events (gradual demand increase and generation response) and discrete events (protective device operation), as well as the immediate effects of transients. When the system is unstable or marginally stable, a small disturbance may propagate and grow, eventually causing cascading operation of protective devices. Even when the system is stable, large random disturbances such as lightning can propagate and trip protective devices. These phenomena, although of importance to power system operation, are not exhibited by our model. We wish to include in our model as many of the operational parameters and characteristics that can reasonably be controlled or forecast, and neglect those that are beyond control or prediction. For instance, we account for the steady state evolution of a power system due to protective device and system operation including generator limits, but we ignore the transient effects caused by operation of the protective devices.We account for the long term effects of generator dispatch and interarea agreements but ignore the short time frame effects initiated by the systems that implement those policies. We do not account for transient behavior, protective device coordination, or instantaneous limits. Hence we do not model power systems during periods when we know that transient effects are dominant. For example, we do not model the large disturbance response of a stable power system, or the dynamic evolution of an unstable power system. For this reason, the type of analysis emphasized in this thesis is classified as “steady-state” or “static” as opposed to “transient” or “dynamic”. The purpose of the next section is to specify the assumptions for a model of a stable power system so that an unstable system can be detected from the model as a condition at which the assumptions are violated or become contradictory.

PART

This section describes methods for computing security margins given a model that satisfies the assumptions stated in Part 2. The problem of computing a security margin to an event involves finding an equilibrium that satisfies a specific condition. For example, the condition can be that the equilibrium have a particular variable at a threshold value, or that the system Jacobian matrix be singular at that equilibrium. The fundamental problem en route to establishing a security margin is the solution for a new equilibrium resulting from a specific change in the parameters. Typically, a forecast of the parameter values at a future time is available without an exact description of how the parameters progressed to those values. Ideally, the solution obtained is an equilibrium corresponding to the forecast parameter values that is connected by a curve of equilibria to the known solution for some reasonable pattern of parameter variation connecting the current and forecast parameter values. The solution must satisfy the equilibrium equations, not violate any limits, and lie on a curve that satisfies the equilibrium and limit conditions for some curve connecting the current and future parameter values. Unfortunately, even given two equilibrium points that satisfy the same limit constraints, it is not possible to verify that they are indeed solutions that satisfy these conditions without very specific restrictions on the equilibrium equations. The situation is complicated even more by the inclusion of limits that can change the form of the equilibrium equations. We instead first address the solution to a simpler problem that ignores any limits.

Problem 1 (Simple)

Given :
$$\begin{pmatrix} (z_0, \lambda_0) \\ F(z_0, \lambda_0) = 0 \\ \lambda_1 \end{pmatrix}$$

Find : z_1 such that
$$\left(F(z_1, \lambda_1) = 0 \right)$$

Method 1 (Newton)

BEGIN: $z^1 \rightarrow z_1$

WHILE: $(|F(z^k, \lambda_1)| >$ TOLERANCE) AND (ITERATIONS $<$ MAX)
DO:

$$\Delta z \rightarrow \quad F_z|_{(z^k,\lambda_1)}\Delta z = -F(z^k, \lambda_1)$$
$$z^{k+1} \rightarrow z^k + \Delta z$$

IF ($|F(z^k, \lambda_1)| <$ TOLERANCE) THEN $z_1 \rightarrow z^k$, ELSE WARNING

Many variants exist. For example, the elements of Fz can be updated only every few iterations (Very Dishonest Newton). In some cases Fz is approximated. There are many ways to solve the linear system in the iterative step [GV], some invented specifically for power systems applications [Sto74], like the popular fast decoupled load flow. In general there is no guarantee that a solution exists or that the initial guess will be sufficiently close to it to get convergence within a reasonable number of iterations. The method may fail for several possible reasons:

1. A solution exists but the initial guess z0 was not close enough to the solution for the method to converge, or converge fast enough.

2. There is no solution of F(z, ¸1) = 0 (previous fold bifurcation for ¸ < ¸1).

3. A solution exists but the method converged to the wrong solution, a solution on another branch of equilibria.

However, if a solution exists and F is continuously differentiable and regular in a neighborhood about the solution, the algorithm is guaranteed to converge to the solution for an initial guess in some neighborhood of that solution.

Thus, it is prudent to modify Method (1) to improve the initial guess. Method 2 (Newton with predictor) This method uses a tangent linear approximation to start the Newton iteration. The initial step is often referred to as the predictor step. Variants exist that use quadratic predictors and predictors that require more than one previous solution.

BEGIN:

$$Z_\lambda \rightarrow \quad F_z|_{(z_0,\lambda_0)}Z_\lambda = -F_\lambda|_{(z_0,\lambda_0)}$$
$$z^1 \rightarrow z_0 + Z_\lambda(\lambda_1 - \lambda_0)$$

WHILE: $(|F(z^k, \lambda_1)| >$ TOLERANCE) AND (ITERATIONS $<$ MAX)
DO:

$$\Delta z \rightarrow \quad F_z|_{(z^k,\lambda_1)}\Delta z = -F(z^k, \lambda_1)$$
$$z^{k+1} \rightarrow z^k + \Delta z$$

IF ($|F(z^k, \lambda_1)| <$ TOLERANCE) THEN $z_1 \rightarrow z^k$, ELSE WARNING

Note that for the case when ¸ appears linearly in F, this method is exactly equivalent to Method (1) except that the first iteration is performed outside of the loop.

As before, convergence is still not guaranteed and Method (2) can fail for all the same reasons as Method (1). If the method fails to converge we may restart it for a different choice of ¸1 closer to ¸0. However, what if the method converged to the wrong solution? Can a wrong solution be detected? In practice, power systems engineers believe that by inspecting the voltage magnitudes they can tell if a solution is reasonable2. This suggests a simple way to improve the method so that convergence to a reasonable solution is more likely.

Instead of solving F(z, ¸1) = 0, we solve an augmented set of equations $\begin{pmatrix} F(z,\lambda) \\ C(z,\lambda) \end{pmatrix} = 0.$

The zero set of the map C specifies a desired characteristic of the solution. For example, if it was expected that the voltage at a particular bus would drop due to increases in loading, C can specify a voltage at that bus lower than its present voltage. Rather than solve for the state corresponding to a specified loading, the loading that corresponds to the specified characteristic of the state is found. Instead of being a fixed parameter of the solution method, ¸ is an unknown and¸1 is an initial guess for. Hence, C(z, ¸) must include enough equations to allow for the solution of ¸. When ¸ is multidimensional, ¸1 can define a direction from ¸0 and the step size in that direction then is an unknown.

PART

This (Boundary Trace) Use the continuation method to find points on a curve situated on the boundary around a nominal boundary point.

Begin: Obtain initial state, parameters, forecast, and control parameter p.
Call continuation method to locate nominal boundary point and condition.
While (step change > min) and (p 6= pmax)
Do:
1. Call predictor-corrector routine (corrector is the event condition at the nominal point), return new equilibrium on boundary.
2. Check limits.
3. If limits, reduce step change, else increase step

The program ends with either the control parameter at its maximum value and the resulting change in the margin, or the maximum control parameter change and margin corresponding to a point on the boundary where the limits in effect change.

The sensitivity of the security margin to changes in many parameters is effectively just an indexing operation once the scaled normal vector is obtained. The normal vector to the event boundary in parameter space defines to first order the proportions by which all the parameters must vary to keep the equilibrium at the security boundary.

The normal vector is useful in determining the relative effectiveness of different parameters on the security margin. Note that if a point on the security boundary is obtained using a direct method that uses the E equations as corrector equations, obtaining the normal vector requires only one additional forward and backward substitution using the previously factored Jacobian matrix. The vector w used to obtain the margin sensitivity formulas is used to define the normal vector to the hypersurface in parameter space that represents the surface on which parameters must vary so that the resulting equilibrium satisfies the event and equilibrium conditions.

Approximate sensitivity methods have found widespread use in power systems for many years. The two most generally accepted methods are termed "Distribution Factors" and "Outage Distribution Factors".

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PART

Sensitivity Methods for Voltage Collapse: Voltage collapse is an instability of heavily loaded electric power systems characterized by monotonically decreasing voltages and blackout. Secure operation of a power system requires appropriate planning and control actions to avoid voltage collapse. This chapter describes and illustrates the use of loading margin sensitivities for the avoidance of voltage collapse. For a particular operating point, the amount of additional load in a specific pattern of load increase that would cause a voltage collapse is called the loading margin. We are interested in how the loading margin of a power system changes as system parameters or controls are altered. This chapter describes how to compute linear and quadratic Taylor series estimates for the variation of the loading margin with respect to any power system parameter or control. The effects on the loading margin of changing the following controls and parameters is estimated:

- Emergency load shedding
- Reactive power support, shunt capacitance
- Variation in the direction of load increase
- Interarea redispatch, wheeling
- Changes to load model and load composition
- Varying line susceptance, FACTS device

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