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Closest security boundary for improving oscillation damping through generation redispatch using eigenvalue sensitivities

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ABSTRACT

This paper proposes an algorithm for determining a minimum generation redispatch capable of moving specific oscillation modes to the closest small-signal security boundary that guarantees them a desired damping factor. The algorithm combines nonlinear optimization techniques with numerical eigenvalue sensitivities obtained from multiple runs of a load flow solver and partial eigensolutions. The algorithm, namely Closest Security Boundary for Generation Redispatch using Eigenvalue Sensitivities (CSBGRES) relies on sparse matrices and is applicable to large-scale power systems. The work presents results on the Brazilian Interconnected Power System (BIPS) and the Nordic 44 Test System (N44S).

1. Introduction

Bifurcation theory [1] applied to power system voltage stability problems had a large momentum in early 90s [2,3], particularly with saddle-node bifurcation analysis in load flow equations. In sequence, investigations considering the Hopf bifurcation analysis in differential-algebraic equations (DAE) [4–7] were performed under the voltage stability phenomenon.

The Hopf bifurcation theory was also applied to small-signal stability and control system evaluations [8–14]. The early works on Hopf bifurcation in small-signal stability have been concentrated on the analysis of eigenvalues with focus on controller parameters, such as power oscillation dampers (POD) and power system stabilizers (PSS). Some other works on Hopf bifurcations were related to subsynchronous stability analysis [15–18].

Some attempts to study Hopf bifurcation with respect to generation or demand parameters were made in [19–23], but the analytical determination of eigenvalue sensitivities with respect to the load flow parameters is complex and necessary to solve large scale problems [24].

This paper uses a numerical computation of eigenvalue sensitivities with respect to generation dispatch, obtained through multiple runs of a load flow solver combined with partial eigensolutions, namely Generation Sensitivities (GenSens). These numerically-computed sensitivities become the basis of the algorithm used to calculate a minimum redispatch for power systems, considering a damping factor criterion for oscillation modes, which is being proposed in this paper. Some previous works deal with this kind of sensitivities [14,24,25], but this is the first work where these sensitivities are used to solve the Hopf bifurcation problem considering minimum redispatch.

Using nonlinear programming, this algorithm determines the minimum generation redispatch of a selected number of power plants capable of moving a specific oscillation mode to the closest small-signal security boundary, defined by a desired damping ratio locus in the s-plane.

Moreover, if the system is unstable and a null damping ratio locus is chosen, corresponding to the geometric locus in the s-plane of Hopf bifurcations, the algorithm will find the minimum redispatch to stabilize the system. The algorithm can also be used, in the other way around, to calculate the small-signal security or stability margins with respect to generation redispatch.

The proposed algorithm, namely Closest Security Boundary for Generation Redispatch using Eigenvalue Sensitivities (CSBGRES), uses complete models of system components, numerical

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generation sensitivity calculation and optimization techniques, considering a damping factor criterion for system oscillation modes.

The CSBGRES method relies on sparse matrices and is applicable to large-scale power systems, as it was done in [8,13], where only controller parameter variations were considered, but, in the case of this paper, dispatch variations can also be considered. This work presents simulation results on the Brazilian Interconnected Power System (BIPS) and the Nordic 44 Test System (N44S). The proposed method is the first one to solve this kind of problem for large scale power system.

The remainder of the paper is organized as follows: Section 2 reviews the small-signal stability concept and its relation to the problem being solved; Section 3 presents the numerical eigenvalue sensitivity computation with respect to active power to be used in the development of the proposed algorithm, which is described in Section 4; Sections 5 and 6 present simulation results for the BIPS and the N44S, respectively; and Section 7 presents the conclusions of this paper.

2. Small-signal stability review

The small-signal stability and modal analysis are very important to understand the power system dynamic behavior, which can be evaluated through calculating system eigenvalues or oscillation modes. The main concepts related to these subjects are the basis of the CSBGRES method definition, therefore, they will be reviewed in this section.

The set of nonlinear differential and algebraic equations that describes electric power systems for electromechanical transient analysis can be represented through (1) and (2), according to [8,13]:

$$\boldsymbol{T}\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{p}, u) \quad (1)$$

$$y = \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{p}, u) \quad (2)$$

where $\boldsymbol{x}$ is the vector of state and algebraic variables, $\boldsymbol{u}$ and y are, respectively, input and output variables of the system, $\boldsymbol{p}$ is a vector of a system parameter set and $\boldsymbol{T}$ is a diagonal matrix with ones and zeros, identifying the algebraic and differential equations of the system.

The differential and algebraic equations are initialized through using the results of a power flow solution, considering that the system is operating in a steady-state condition. The correct initialization guarantees that the relation between the differential equations in steady-state, the power flow equations and the other algebraic equations are consistent.

Small-signal assessment is obtained through the linearization of (1) and (2) around the steady-state condition, yielding (3) and (4):

$$\boldsymbol{T}\Delta\dot{\boldsymbol{x}} = \boldsymbol{J}(\boldsymbol{x}_0, \boldsymbol{p}_0)\Delta\boldsymbol{x} + \boldsymbol{b}(\boldsymbol{x}_0, \boldsymbol{p}_0)\Delta u \quad (3)$$

$$\Delta y = \boldsymbol{c}(\boldsymbol{x}_0, \boldsymbol{p}_0)\Delta\boldsymbol{x} + d(\boldsymbol{x}_0, \boldsymbol{p}_0)\Delta u \quad (4)$$

where $\boldsymbol{J}$ is the augmented Jacobian matrix, $\boldsymbol{b}$ and $\boldsymbol{c}$ are, respectively, the input and output matrices, d is the direct transmission term and the subscript "**0**" in $\boldsymbol{x}_0$ and $\boldsymbol{p}_0$ means the corresponding initial condition of vectors $\boldsymbol{x}$ and $\boldsymbol{p}$.

The generalized system eigenvalues, which describe the frequency and damping factor of natural oscillations of the system, can be computed for the linear matrix pencil ($\boldsymbol{J}$,$\boldsymbol{T}$), commonly performed in small-signal stability solvers [8,13]. These eigenvalues are the poles of the system.

The problem being solved in this paper consists in obtaining the vector $\boldsymbol{p}$, displaced from $\boldsymbol{p}_0$, according to a minimum norm, that moves a critical oscillation mode to lie on a specified security boundary locus in the s-plane (which is a constant damping ratio line). The solution of this problem was proposed in [8,13], where parameters in $\boldsymbol{p}$ were PSS or POD gains.

Some mathematical difficulty arises when elements of $\boldsymbol{p}$ are related to power flow parameters, such as generation or demand. In this case, using the same approach of [8,13], the whole set of power flow and initialization equations must be included in the equationing, which brings a large complexity to the proposed optimization problem and its modeling.

The main contribution of this paper lies on solving the aforementioned problem in a different way, using eigenvalue sensitivities obtained by a numerical differentiation procedure. This methodology effectively solves this problem considering an alternating solution, involving data communication between a small-signal stability solver and a power flow solver.

In this work, the small-signal stability software PacDyn [26] was used for the computational implementation of the proposed algorithm and the software ANAREDE [27] was used for the power flow computations. The communications between them were performed in memory, using a Windows Dynamic Link Library version of ANAREDE inside PacDyn's programming code.

3. Generation sensitivity calculation

This section presents the procedure to calculate eigenvalue sensitivities with respect to the active power dispatched by plants in power systems, namely generation sensitivities. The GenSens can be mathematically defined as the derivative of an eigenvalue λ related to the active power P dispatched by a power plant specified in the power flow data.

These sensitivities could be analytically computed through building a complete Jacobian matrix, which includes the linearization of power flow equations, dynamic modeling equations and pole definition. However, it yields a very complex mathematical expression.

Additionally, some power flow controls (such as transformer tap changes, switching devices or intertie power flow controls), which are usually implemented as an alternating procedure in power flow solvers, should be fixed or described by approximate equations.

Due to the aforementioned difficulties, in this work, a numerical procedure was adopted to calculate the eigenvalue sensitivities with respect to each power plant dispatch. This numerical method is based on the central difference procedure.

In this procedure, a small positive variation ($P+\Delta P$) and a small negative variation ($P-\Delta P$) are applied in the active power dispatched by a given power plant and the corresponding oscillation modes are obtained for both situations ($\lambda_{+\Delta P}$ and $\lambda_{-\Delta P}$), through running the power flow solver, initializing the system dynamic model and using the DPSE method [28], where a transfer function with high residues for the mode under analysis should be used.

Note that, this GenSens calculation may consider any power flow controls of the system, since the power flow computation is solved stand-alone. Both power flow solution and model initialization are performed prior to the eigenvalue calculations, as commonly done in a conventional small-signal stability software, in an alternating procedure. Therefore, there is no need of simultaneous solution for determining these eigenvalue sensitivities.

After the calculation of these new oscillation modes, obtained for the mentioned conditions, the generation sensitivities of an oscillation mode λ, computed in the original steady-state condition of the power system, with respect to the dispatch P of a specific power plant can be approximately determined through (5) and (6):

$$\frac{\partial\lambda}{\partial P} \approx \frac{\Delta\lambda}{2\Delta P}, \quad \Delta P \to 0 \quad (5)$$

$$\frac{\partial\lambda}{\partial P} \approx \frac{\lambda_{+\Delta P} - \lambda_{-\Delta P}}{2\,\Delta P}, \quad \Delta P \to 0 \quad (6)$$