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Damped Nyquist Plot for a pole placement design of power system stabilizers

S. Gomes Jr[a,b,*], C.H.C. Guimarães[b], N. Martins[a], G.N. Taranto[c]

[a] CEPEL – Electrical Energy Research Center, Av. Horácio Macedo, 354, Rio de Janeiro, RJ 21941-911, Brazil
[b] UFF – Fluminense Federal University, Rua Passo da Pátria, 156, Niterói, RJ, Brazil
[c] COPPE/UFRJ – Universidade Federal do Rio de Janeiro, Cidade Universitária, Centro de Tecnologia, Bloco H, Rio de Janeiro, RJ 21941-972, Brazil

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ABSTRACT

This paper proposes a new frequency domain control design method through the use of a modified Nyquist diagram with an embedded partial pole-placement capability. The proposed Damped Nyquist Plot (DNP) method evaluates the open loop transfer function (OLTF) along a line of constant damping ratio to provide a graphical tool to design power system stabilizers (PSS). The graphical tool shows how the closed loop poles move around this damping ratio line for different choices of PSS parameters, all of them placing a selected pair of complex-conjugate poles at the same desired point in the complex plane. New formulas are developed to determine the exact PSS parameters that promote the several possibilities of partial pole placement considering the parameter ranges used in tuning practice. These formulas can also be used for phase compensation of conventional methods of PSS design, such as GEP or Residue Angle Compensation. Multiple PSSs can be tuned using the DNP method sequentially. The proposed method is applied to two stabilization examples, the first of tutorial nature and the second is the large actual Brazilian Interconnected Power System.

1. Introduction

The small-signal stability analysis of power systems is carried out through linear techniques [1,2] and the damping control of power system oscillations is its most important objective. Such damping may be effectively improved using PSSs [3,4] designed by linear control system techniques. The final design considers the analysis of numerous operating points and the verification through non-linear time-domain simulations and field tests. Modal analysis tools were developed from many sources to determine the best points in the system for the installation of stabilizers [5,6] and also to help designing them [1,2,7–17]. A good overview on the industry practice is given in [18]. Pole placement techniques have been proposed in the literature [19–23], but none of them are based on a graphical analysis of the closed loop poles for selection of PSS parameters, such as the proposed method.

This paper describes a new stabilizer tuning technique based on the use of a modified Nyquist diagram, called here Damped Nyquist Plot (DNP). The stabilizer parameters are calculated using the new formulas developed in this paper, which can also be used for phase compensation of conventional methods, such as GEP and Residue Angle Compensation [2], or any other method that requires calculation of parameters for phase compensation blocks. GEP is an acronym for "**G**enerator-**E**xciter-**P**ower system" because it is applied to a transfer function that involves these elements [1,2]. The proposed DNP method, which is not limited to power system applications, allows the placement of a complex-conjugate pair of poles at a desired location of the left-half of the complex plane (s-plane). The method also provides graphical information on the movements of the other poles that are affected by the PSS being designed that helps selecting the best PSS parameters.

The proposed DNP method presents some advantages compared to other methods from literature. For example, the classical GEP (ideal phase curve method) or synchronizing and damping torque methods [2,4,7,10] are based on adjusting the phase compensation for having a pure damping behavior of the PSS. However, this phase compensation usually reduces the closed loop pole frequency, even when it is exactly compensated at the open-loop pole frequency. Other negative characteristics of these methods are that they focus on the local mode, several dominant poles are not well tuned, the gains required for a suitable damping in the frequency range is not known and the control modes are not even treated.

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* Corresponding author at: CEPEL – Electrical Energy Research Center, Av. Horácio Macedo, 354, Rio de Janeiro, RJ 21941-911, Brazil.

E-mail addresses: sgomes@cepel.br, sergiogomes@id.uff.br (S. Gomes Jr).

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In the same way, for the Residue Angle Compensation method [2,6], which can also be called Departure Angle Compensation, because it is based on the compensation of the initial phase of the branch of root locus [6], the compensation is usually excessive too and the required gain for stabilization is also unknown.

Note that the previous methods indirectly pursue the final objective of shifting the poles to the left in an almost horizontal way on the *s*-plane. The proposed DNP is the only one that does it directly. It performs a precise pole placement and provides a graphical method to have a good overview of the impact of each PSS design on the whole set of dominant poles, including electromechanical and control modes that move around the desired damping ratio line.

Multiple stabilizers can be tuned by the sequential application of the DNP design method where the PSS dynamic interactions can be verified. Such procedure is useful when implementing the retuning in the field. During the field implementation, the stabilizing loop parameters can be updated to solve or mitigate problems such as adverse transients, excessive control noise and higher frequency instabilities, which cannot be fully anticipated from the computational simulations due to modeling errors and unmodeled dynamics. This sequential procedure allows validating the impact of each PSS retuning in field that can always be reviewed and updated if necessary at each step. This is an advantage of the proposed DNP method compared to methods of simultaneous coordinated design [11,13,15–17]. Any required changes in tuning would modify completely the simultaneous PSS designs and the new set of designs may present the same problems in field.

The proposed DNP method allows the analysis of multiple scenarios as in Refs. [12,15,16] using other design methods. Such as any other PSS design based on modal analysis, or even for the PSS design in field, the PSS parameters are tuned for some operating condition and, after that, the PSS performance is verified for many other conditions. If an inadequate behavior is found, the tuning is reviewed to attend the performance requirements for the operating point with the problem. Even when the whole set of scenarios are simultaneously considered, the most critical one that will end up defining the final tuning.

Therefore, the proposed DNP method can be applied to some expected critical operating point, such as peak load scenario, to obtain a first attempt of PSS design. Several other expected scenarios can then be evaluated with different loadings, dispatches, network topologies and contingencies. This retuning can be based on the first design, increasing for example the gain value or changing time constants from compensation block, based on the graphical inspection of the DNP, or a new design can be made, based on the critical operating point, where the whole set of parameters can change. This procedure may be repeated until the oscillation damping is adequate for all the scenarios.

The verification of the PSS performance can be done closing the PSS loop and calculating the resulting closed loop poles or, even before closing the PSS loop, using multiple compensated DNPs, one for each scenario, all of them with the same PSS in analysis. When using multiple compensated DNPs, the PSS design can be reviewed based on the graphical visualization. Results on the use of multiple compensated DNPs are presented.

Besides the advantages of the proposed method compared to other approaches, the DNP method is a novel alternative where the main characteristic is to leave to the analyst the final decision on the selection of the multiple PSS parameters, providing graphical information for helping in this task and leaving the burden of the PSS parameter calculation to the computational program when different parameter combinations are evaluated.

The DNP method has been implemented in the small signal stability software PacDyn used by the Brazilian utilities, operator and planning agencies [24], which was used to produce all the results of this paper. The remainder of the paper is organized as follows. Section 2 reviews the small-signal stability analysis; Section 3 revisits the conventional Nyquist criterion applied to the design of feedback controllers; Section 4 introduces the DNP design method with the embedded pole placement capability; Section 5 develops analytical formulas for phase compensation; Section 6 lists guidelines for the productive use of the DNP; Section 7 presents results on the application of the DNP to two test systems, while the main conclusions are summarized in Section 8.

2. Small-signal stability analysis

The small signal stability model obtained by the linearization of the power system dynamic equations around an operating point has the form of Differential and Algebraic Equations (DAE) [1,25]:

$$\begin{aligned} \boldsymbol{T}\Delta\dot{\mathrm{x}} &= \boldsymbol{J}\Delta\boldsymbol{x} + \boldsymbol{b}\Delta u \\ \Delta y &= \mathbf{c}\Delta\boldsymbol{x} + d\Delta u \end{aligned} \tag{1}$$

where the symbol Δ denotes incremental variable changes around their initial values for a given operating point, **x** is the vector of system variables, *u* is the input variable and *y* is the output variable, which are defined respectively by vectors **b** and **c**. **J** is the Jacobian matrix and *d* is the direct term. **T** is usually a diagonal matrix whose elements are either ones or zeros that are used to distinguish the differential from the algebraic equations. The small-signal stability analysis is based on the calculation of the generalized eigenvalues of the pencil (**J**,**T**), which are the poles of the system [1,25]. The damping ratio ξ of a pole $\sigma_c + j\omega_c$ is defined in (2), being a damping measure of the modal component associated to that pole [26–28]. For positive frequencies, (2) defines in the *s*-plane a straight line of constant damping ratio starting at the origin, named ξ-line. For a given ξ, from 10% to 15%, the pole is well-damped when on the left of the ξ-line and poorly damped, when it is quite on the right.

$$\xi = \frac{-\sigma_c}{\sqrt{{\sigma_c}^2 + {\omega_c}^2}}, \quad \sigma_c = k|\omega_c|, \text{ where } k = \frac{-\xi}{\sqrt{1-\xi^2}} \tag{2}$$

Classical methods of control theory are based on transfer functions [26–28]. The transfer function *G*(*s*) is given in (3), obtained by applying the Laplace transform to the DAE (1).

$$G(s) = \frac{\Delta Y}{\Delta U} = \mathbf{c}(s\mathbf{T} - \boldsymbol{J})^{-1}\boldsymbol{b} + d \tag{3}$$

where ΔU and ΔY are the Laplace transforms of Δu and Δy.

A system showing unstable or poorly damped oscillations may be damped through the feedback of a stabilizer *H*(*s*) at a control loop described by the transfer function *G*(*s*), as shown in Fig. 1. An example of a power system stabilizer (PSS) derived from generator rotor speed ω_{ger} is also presented in Fig. 1. This PSS is usually applied to the voltage regulator with positive sign at the summation block of the voltage reference V_{ref} [1,2], therefore *G*(*s*) is equal to $-\omega_{ger}/V_{ref}$ to consider this positive feedback.

The open loop transfer function (OLTF) *F*(*s*) and the closed loop transfer function (CLTF) *T*(*s*) are defined in (4) [26–28].

$$F(s) = G(s)H(s), \quad T(s) = \frac{G(s)}{1 + G(s)H(s)} \tag{4}$$

3. Conventional Nyquist design

The proposed method is an extension and improvement of the conventional Nyquist design which is reviewed in this section. The design based on the conventional Nyquist Plot (NP) is well-known and used in different areas of control engineering [26–28]. Its main objective is to assess the stability of a system with feedback based on the open loop frequency response. The NP for a transfer function *G*(*s*) is the plotting of *G*(*jω*) in the complex plane (*G*(*s*)-plane) while