

H-D Support Set: Frequency Dynamic Security Analysis through Multidimensional Frequency Parameter Bindings

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Abstract—Existing research on the system frequency response (SFR) and frequency-constrained scheduling studies primarily relies on commonly-used metrics consisting of rate-of-frequency-change, nadir, and quasi-steady-state (QSS). Nevertheless, the complex interdependencies among these parameters have not been fully explored. This letter introduces a new criterion to assess frequency stability by directly considering multidimensional relationships between these frequency parameters. An analytical solution is derived to quantify these interdependencies, and a convex polygon representation is constructed to visualize the feasible operating region defined by these parameters. Using this criterion, the impact of different frequency parameter settings on system stability can be clearly obtained and analyzed. The effectiveness of the proposed approach is demonstrated on a modified IEEE 30-bus test system.

Index Terms—Class, IEEEtran, L^AT_EX, paper, style, template, typesetting.

I. INTRODUCTION

THE low inertia character of electrical power system significantly impact the system frequency security, which implicitly change the scheduling commitment results provided by different generators. In such circumstances, existing studies about power system dynamic response, storage device sizing and control parameter tuning, optimal scheduling operation, and even medium-term & long-term generation planning studies trends to emphasis the consideration of frequency response and frequency stability.

The primary objective of frequency-oriented studies as previously discussed is to ascertain the security of frequency dynamic, while it can be described through the SFR function, typically expressed by multidimensional frequency parameters, including system-level/regional-level *inertia*, *damping*, *droop*, and *reserve*, etc. Conventional methodologies establish dynamic frequency criteria, typically expressed as mathematical inequalities such as RoCoF, nadir and QSS. These criteria define a feasible operating region within which frequency dynamics are deemed secure. System stability is subsequently evaluated by determining if the observed frequency derivation derived from the SFR function remains within this defined region.

Nevertheless, these conventional approaches suffers from an implicitly limitation: it provides only a qualitative assessment of the current frequency parameter configuration's reasonableness. While it can determine if the system operates within

predefined (frequency dynamic) limits, it fails to explicitly delineate the precise safety boundaries of these multidimensional frequency parameters. Consequently, it can neither directly quantify the margins of safety, nor provide actionable insights into how to adjust these parameters to enhance system frequency security.

This letter introduces the new concept of the *H-D* Support Set, which characterizes the feasible boundary of multidimensional frequency parameters. Furthermore, an open-source tool (repo address: <https://github.com/Divas1234/frequencyregions.git>) for *H-D* Support Set simulation is made freely available. Leveraging the SFR theorem, the interaction between these parameters is analyzed, and both the upper and lower bounds of the parameter space are explicitly calculated. In contrast to existing methodologies, the proposed approach provides a well-defined boundary interval for frequency parameters, thereby enabling more effective tuning optimization of frequency control parameters and facilitating comprehensive frequency dynamic analysis.

II. SFR THEOREM IN LOW INERTIA POWER SYSTEMS

Given such a low inertia power systems that considers high penetration of converters, the uniform analytical expression of frequency dynamic processes can be written as,

$$\Delta f(s) = \frac{1 + sT}{2H_{EQU}T_G(s^2 + 2\zeta\omega_n s + \omega_n^2)} \frac{\Delta P_{Step}}{s} \quad (1a)$$

$$\omega_n = \sqrt{\frac{D_{EQU} + R_G}{2H_{EQU}T_G}}, \zeta = \frac{2H_{EQU} + T_G(D_{EQU} + F_G)}{2\sqrt{2H_{EQU}T_G}(D_{EQU} + R_G)} \quad (1b)$$

where $\Delta f(s)$ represents the frequency derivation with a step-type power disturbance ΔP_{Step} , H_{EQU} , D_{DEQ} , respectively, describes the equivalent inertia parameter and damping parameter, T_G is the time constant of conventional generator, R_G denotes the aggregated droop parameter generated by conventional generators, F_G denote the fraction of total power generated by high pressure turbines of conventional generators. In these formulations, the time constants within the transfer function of $\Delta f(s)$ are normalized to unity, and the response times of converters with diverse control schemes are approximated as negligible. A more detailed feasibility analysis is provided in [].

In correlation with (1), the maximum frequency deviation termed as $\max[\Delta f(t)]$ as well as the maximization rate of frequency change termed as $\max[\Delta f'(t)]$ can be derived as below,

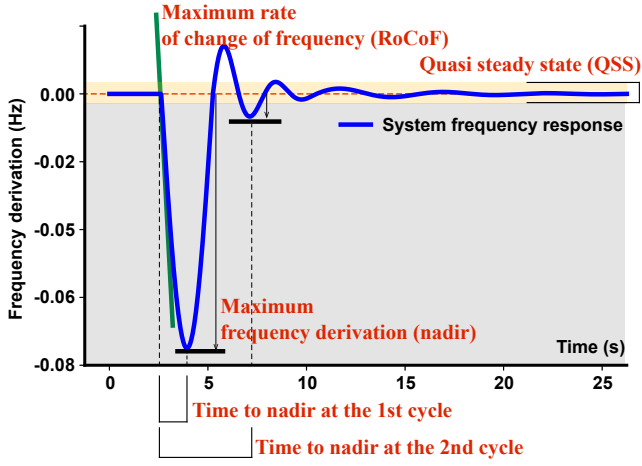


Fig. 1. system frequency response

$$\max[\Delta f(t)]^k = -\frac{\Delta P_{Step}}{D_{EQU} + R_G} \left(1 + \left((-1)^k \sqrt{\frac{T_G(R_G - F_G)}{2H_{EQU}}} e^{-\zeta\omega_n t_{nadir}^k} \right) \right) \quad (2a)$$

$$\max[\Delta f'(t)] = \frac{\Delta P_{STEP}}{2H_{EQU}} \quad (2b)$$

$$t_{nadir}^k = \frac{1}{\omega_d} \arctan \left(\frac{\omega_d}{\zeta\omega_n - T^{-1}} \right) + \frac{k\pi}{\omega_d} \quad (2c)$$

$$\omega_d = \omega_n \sqrt{1 - \zeta^2}, \phi = \sin^{-1} \left(\sqrt{1 - \zeta^2} \right) \quad (2d)$$

where $\max[\Delta f(t)]^k$ enforces the maximum frequency deviation at the k -th cycle, $\max[\Delta f'(t)]$ defines the maximum rate of change of frequency derivation, and t_{nadir}^k denotes the time to the k -th nadir of the frequency deviation.