Dynamics and Stability of Power Systems With High Shares of Grid-following Inverter-based Resources

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Abstract— **This paper provides a tutorial on the dynamics and stability of power systems with high shares of grid-following inverter-based resources (IBRs). The integration of renewable energy sources, particularly grid-following IBRs, is reshaping the dynamics and stability of power systems. The paper addresses the stability and reliability challenges pertinent to the integration of grid-following IBRs, emphasizing their impact on system stability and reliability. The paper offers valuable insights into the interrelated dynamics of electric angle, frequency, and voltage, as well as the implications of system inertia on system stability. Through industry-grade electromagnetic transient simulations, the paper elucidates the complex interactions between synchronous generators and grid-following IBRs.**

Keywords—grid-following, inverter, inverter-based resources, power system dynamics, renewable energy systems (**key words**)

I. Introduction

The global electric power grid is undergoing a significant transformation with the increasing integration of renewable energy sources, such as solar photovoltaic and wind power plants. This transition from traditional synchronous generators to power electronics-backed generation technologies, particularly grid-following inverter-based resources (IBRs), presents new challenges and opportunities for the stability and reliability of power systems. Understanding the dynamics and impacts of high shares of grid-following IBRs on power grid operations is crucial for ensuring system resilience and efficiency. This paper explores the complexities of integrating grid-following IBRs into power systems, shedding light on the evolving landscape of renewable energy integration and its implications for the energy sector.

II. Methodology

The research design and methods employed in the paper involve a comprehensive review and analysis of the dynamics and stability of power systems with a focus on the integration of grid-following inverter-based resources (IBRs). The authors leverage industry-grade electromagnetic transient simulations in Power Systems Computer-Aided Design (PSCAD) to demonstrate the concepts presented in the paper **[20].** Additionally, the paper utilizes open-source models, which are made available to the public, to facilitate transparency and accessibility in the exploration of power system dynamics with high shares of grid-following IBRs **[5].** The research design encompasses both small-signal and large-signal stability problems, aiming to provide a holistic understanding of the interrelated dynamics of electric angle, frequency, and voltage, as well as the impacts of system inertia on system stability **[12].** This approach enables the authors to offer valuable insights into the industry's current state of integrating renewable energy sources and the underlying phenomena that could challenge power grid reliability and stability, setting a basis for further exploration of power system dynamics with high shares of grid-following IBRs **[20].**

III. Mathemetical Expression

i. Synchronization speed equation in a power system with n-generators: $\dot{\delta}_1 = \dot{\delta}_2 = \dot{\delta}_3 = \dot{\delta}_n = \omega_s$ where $\dot{\delta}_i$ represents the electric angle of the i^{th} generator **[3].**

ii. System dynamic equation for an SG during an electrical fault: $\ddot{\delta}_i = \frac{1}{M_i}\left(p_{m_i} - p_{e_i}\right)$ where P_{mi} is the mechanical output power, Pei is the electric output power, and Mi is the inertia coefficient of the i^{th} generator **[5].**

iii. Equation for electric power output of a generator in steady state: $p_e = EVx \sin\delta$ where E and V are voltage parameters, X is the reactance, and δ is the electric angle **[3].**

iv. Equation for the system trajectory on the P-f plane for a change of loading condition of a GFL interfaced generator: $\frac{\delta P_e}{\delta f} = \frac{1}{x}\sqrt{\frac{E^2}{v^2} - \left(\frac{px}{v}\right)^2}$ where E and V are voltage parameters, X is the reactance, P is the active power, and Q is the reactive power **[6].**

These equations play a crucial role in understanding the dynamics and stability of power systems with high shares of grid-following inverter-based resources.

IV. RESULTS

The tutorial "Dynamics and Stability of Power Systems with High Shares of Grid-Following Inverter-Based Resources" presents the following key findings:

1. **Operational Scenarios:** Various scenarios were considered to investigate the effects of replacing synchronous generators (SGs) with grid-following inverter-based resources (IBRs) in power systems. Several cases, including GFL1, GFL2, GFL3, GFL12, GFL13, and GFL23, were investigated to determine the impact of this transition **[10].**
2. **System Trajectories:** The trajectories on the P-δ and P-f planes were illustrated to demonstrate the behavior of the system under different loading conditions of SGs and GFL interfaced generators. These trajectories provide information about the generators' dynamic responses, such as electric angles, speeds, power generation, and voltage profiles **[10],[6],[5].**
3. **Small-Signal Stability:** The study emphasized the significance of small-signal stability in power systems incorporating SGs. The equations that describe the dynamics of SGs, including mechanical power generation, frequency regulation, and inertia coefficients, were analyzed to assess system stability **[4].**
4. **Active Power Response:** A summary of the generators' active power response after a three-phase short-circuit electrical fault on bus 1 was provided. Peak-to-peak transient power values were recorded during the post-fault period to evaluate the system's response to such disruptions **[16].**

V. CONCLUSION

The research in "Dynamics and Stability of Power Systems with High Shares of Grid-Following Inverter-Based Resources" is crucial in understanding the challenges of integrating renewable energy sources like grid-following inverters. It emphasizes small-signal stability, the impact of IBR replacements on system reliability, and the need for advanced control strategies.

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