Doctoral Program in Electrical, Electronics and Communications Engineering
(33rd Cycle)

Summary

**Methodologies for Frequency Stability Assessment in Low Inertia Power Systems**

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The energy transition is a needed and undeferrable pathway for a sustainable future towards the transformation of the global energy sector from an extensive use of fossil fuels to a massive implementation of zero-carbon assets. Renewable energy sources (RESs) exploitation is crucial in this framework, to decarbonise the energy sector and reduce $CO_2$ emissions to limit the climate change.

The electrical sector is playing an important role in the energy transition, being subjected to major changes in its historical paradigms. Nevertheless, the shift from conventional generators, synchronous and centralized, to non-conventional RESs, non-synchronous and decentralised, is challenging the way Transmission System Operators (TSOs) manage and plan their networks.

RESs have different features which affect the security of traditional power systems, designed to work with conventional generation. First, they are dispersed, mostly connected to the lower voltage systems, and variable, with uncertainty in different time scales, rising needs for new sources of flexibility to maintain constantly the balance between generation and demand and to ensure an efficient electricity system. Furthermore, RESs are mainly connected through power electronics devices, which provide lower short-circuit levels, imply reduced control capabilities, reduced inertia, and reduced system strength, impacting the system security and stability.

This thesis has the primary objective to contribute and provide a methodological framework to assess the frequency stability of modern power systems by exploring, applying, adapting, and combining the main methods, tools, and solutions in low inertia contexts.

A review of the scientific literature is performed to identify limitations and weaknesses of different approaches, particularly when dealing with real case studies and practical applications of system operators. The technical organization of the existing frequency control structure in Continental Europe is investigated in deep and the state-of-the-art in technologies, control schemes and services that can support frequency stability is presented and analysed, highlighting benefits

and drawbacks of each solution. The main examined technologies are Battery Energy Storage Systems (BESSs), High Voltage Direct Current (HVDC) and Synchronous Compensators (SyCs). A set of tools to estimate and calculate the inertia and parameters to quantify the frequency performance in both current and future power systems is defined and implemented, together with possible trajectories to investigate the distributional impact of inertia.

A dynamic aggregate model is developed and validated using MATLAB/Simulink to study the frequency performance of real power systems in case of contingencies and during normal operation. The aggregate model is demonstrated to be reliable and fast enough for security contingency studies and to carry out extensive parametric analysis in the planning phase when the primary objective is the overall frequency stability. The model can be used also to estimate the generation-load imbalance which determine a specific frequency deviation during normal operation. The explored contingencies are the reference incident and system separations, presenting novel approaches to identify and quantify the consequences of large power system splits in subsystems. The impact of SyCs, HVDC and BESSs during contingencies shows their capabilities to improve the frequency response. Emphasis is placed on assessing the BESSs contribution in primary and inertial control and ensuring its accurate dimensioning, imitating the behaviour of synchronous generators using an Equivalent Saturation Logic. It is shown that only the implementation of inertial control is not enough, and a primary response is needed to balance the system. At the same time, inertial and primary controls are not able to significantly improve frequency deviations in normal operations, where the slow dynamics make the secondary control apparently more valuable. Frequency stability and inertia constraints are investigated and evaluated in the power plant unit commitment in a technical economic view, analyzing costs and dynamic performance. A Multiple-Criteria Decision Analysis is outlined to select the best compromise solution and it can be easily managed by a decision maker to create a preliminary background and to deliver technical, financial, and environmental insights for the definition of energy plans.

The proposed methodological framework is applied to several real case studies, from smaller (Sardinia) to larger power systems (Continental Europe), from current to future cases taken by the most relevant scenarios developed by the European system operators. All the case studies provide numerical evidence to results and offers a background to assist system operators, researchers, and decision-makers in managing and planning future power systems.