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Review of Stability Analysis in Power Systems with High Penetration of Non-synchronous Generation

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Abstract. Sustainability goals basically change the power generation portfolio, as the renewable energy resources developing rapidly. This means system integration challenges for system operators, as these new resources have different attributes. Most of the emerging generation technologies connect to the grid via power electronic converters, therefore does not contribute inherently to the system's rotational inertia. However, advanced control methods became a progressive research area, where many practical pilots deliver valuable results and discussions nowadays. These stability enhancement techniques have great potential to enhance security of supply with synthetic inertia services.

This paper aims to review generation-driven stability analysis techniques based on the modelling methods used for the non-synchronous generators. Based on the stability phenomena (angle, frequency), system size, generation portfolio, computational time the adequate methods could be quite different. The proposed extension of the stability classification convers the need of different approaches with the integration of non-synchronous generation.

Based on the review presented in this paper, the stability assessment needs for a specific system operator can be identified to choose the appropriate modelling assumptions. This can help system operators in long-term planning (stability adequacy) and in the dynamic security assessment tasks as well, both on the identification of possible issues and evaluate the countermeasures.

Key words. Power system stability; Non-synchronous generation; Power system inertia, Transient stability

1. Introduction

The generation portfolio of power systems is changing due to sustainability goals. Energy policies usually define targets for the share of renewable energy generation, such as the so-called "Fit for 55" [1] guidelines of the European Union. The vast majority of new capacities are based on renewable energy, such as wind and solar generators. However, the attributes of these generation technologies are quite different from those of traditional synchronous generators. In addition to distributed connections, lower unit power, fault behaviour (and therefore, electrical protection scheme principles) and balancing aspects, generator-driven stability (angle and frequency stability) are particularly important [2].

In the case of traditional synchronous generators, each unit was considered as an electromechanical element. For these, the swing equation describes the dynamic state, as the kinetic energy of the rotating mass provides a buffer to absorb power inequalities, while the connection between mechanical rotation and electrical frequency provides an opportunity to build up the system level active power – frequency control. The synchronous inertia of the system is associated with the instantaneous physical response of conventional generators. Electrical frequency follows the rotational speed changes proportionally, indicating the need for additional control adjustments.

Non-synchronous generators are connected to the grid via power electronic converters, which means that the generation technology is practically decoupled from the power system. These technologies are associated with non-synchronous generators, which do not contribute inherently to power system inertia. The field of traditional, generator-driven stability assessment methods has been researched for over 70 years, and considered solely synchronous machines in dynamic modelling, as practically the whole portfolio consisted of such units. In contrast, nowadays even whole countries might run on 100% of non-synchronous generation in some cases, and even large interconnected systems have a significant share of those in the portfolio. This leads to the need of the extension of the generator-driven stability concept. Modelling of the elements and simulation scenarios must consider the generation portfolio adequately to have reliable results.

Beside the transformation in the generation portfolio, the flexible alternating current transmission system devices and high voltage direct current lines also contribute to the structural change of power systems. Also, the structure of the system load is changing as the share of frequency dependent consumer parts are receding. All in all, the reduction of the power system inertia is an ongoing process which must be taken into account when defining the stability concepts.

This paper proposes an extension of the generation-driven stability classification to consider the generation portfolio transformation. This approach considers both system and unit level attributes while discusses results that confirm the differences between the calculations. The quantification of non-synchronous generation's stability enhancement, the effects of the reducing rotating mass on individual synchronous generators and trends in microgrids all play key roles in the stability of sustainable power systems.

2. Extension of the stability definitions

Power system stability is defined as "the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact" [3-4]. The clarification and classification have been addressed by several expert groups, including an IEEE/CIGRÉ Task Force [4], which established a clear view on the terminology. There are two main categories of power system stability at a high level in the classic definition: (i) generator-driven stability (exclusively on synchronous generators), which covers the single machine's interaction with the whole system (angle stability) and the system level (frequency stability), and load driven (voltage) stability. The classification focuses on the following considerations [4]:

- The main system variable from which the instability can be observed.
- The size of the disturbance, which determines the calculation methods.
- The considered elements and timespan.

Figure 1 depicts the stability categories proposed by the Task Force [4]. This paper focuses on the changes in the generation mix; therefore, it only considers the generator-driven stability categories, and it does not discuss voltage stability in detail. Since the publication of the Joint Task Force [4], several research projects and working groups proposed an extension that considers changes in the system perspectives. The IEEE Power and Energy Society members published a study that concentrates on the special attributes of microgrids [5], while another working group [6] considered converters as a new type of generation and extended the stability categories under the generator-driven part. The H2020 MIGRATE project [7] conducted a survey with TSOs, identified and evaluated the issues that experts see. This included a new group besides the rotor angle, frequency and voltage stability which covered the interaction between power electronics and other elements.

A. Changes in the physical attributes considered

The MIGRATE project [7] collected and prioritized the most important changes due to the inclusion of non-synchronous generation. Regarding rotor angle stability, the reduction of transient stability margins is expected. The definition of rotor angle stability – the ability of the interconnected synchronous machines in a power system to remain in synchronism under normal operating conditions and to regain the synchronism after being subjected to a disturbance – remains the same with the introduction of further non-synchronous generation. Transmission system operators already observed the effects of the non-synchronous generators on the critical clearing time. Studies concluded that low share of distributed, non-synchronous generators might improve the critical clearing time but after a threshold the limit will decrease rapidly. In this process other system parameters also play an important role beside the generation portfolio change. Also, the substitution of synchronous generators in the system could lead to new type of oscillations and lack of damping capability for the existing oscillation. As the controllers of converter-faced generators are different compared to conventional generators (also the timescales are different due to the usually missing slower thermodynamic processes), the settings of these controllers define the physical interactions between the elements. Regarding frequency stability, the key question is the inertia reduction. Synchronous generators inherently contribute to synchronous system inertia, as the mechanical rotation and the electrical frequency is directly connected. In steady state, if ne neglect the loss of the conversion, the mechanical power of the governing turbine equals to the electrical power of the generator, which covers the sum of the load and the losses. This state is also called static equilibrium from the system dynamics perspective. In that case, the mechanical and electrical torques are equal for the machine, which results in a steady rotation and constant frequency. Any changes in the power system (short circuit, loss of a generator or import/export line, sudden load changes) results in the misalignment of this torque equilibrium. If the electrical torque is higher, the machines decelerate and provides surplus active power from the kinetic energy of the rotation (frequency also decreases). If the mechanical torque is higher, the machine accelerates and stores the excessive power in the form of kinetic energy. This stored energy provides resistance against frequency changes and limits the frequency gradient (rate of change of frequency). System operators try to limit the frequency gradients as severe transient may harm equipment or lead to protection tripping. There is lack of experience with the non-synchronous generator's participation in the reserve provision as well. The adequate planning of the frequency containment, restoration and replacement reserves is essential in keeping the frequency stability. Also, the frequency-dependent tripping of generators must be planned adequately to avoid massive disconnections at specific frequency values. The complexity of reserve products might increase with the integration of intermittent renewable generation in the reserve markets Regarding the voltage stability part, the fault ride through capability, lack of reactive power, power quality issues and voltage dependency changes were identified as the most important processes. The MIGRATE project also suggested "other" issues (which could not be included in the classical stability definitions) such as the power electronic controller interactions and resonance occurrences between cables and power electronics (mostly at offshore wind turbines). System operators identified the reducing inertia and angle stability margins as the top priority issues along with the power electronics and cable resonances.

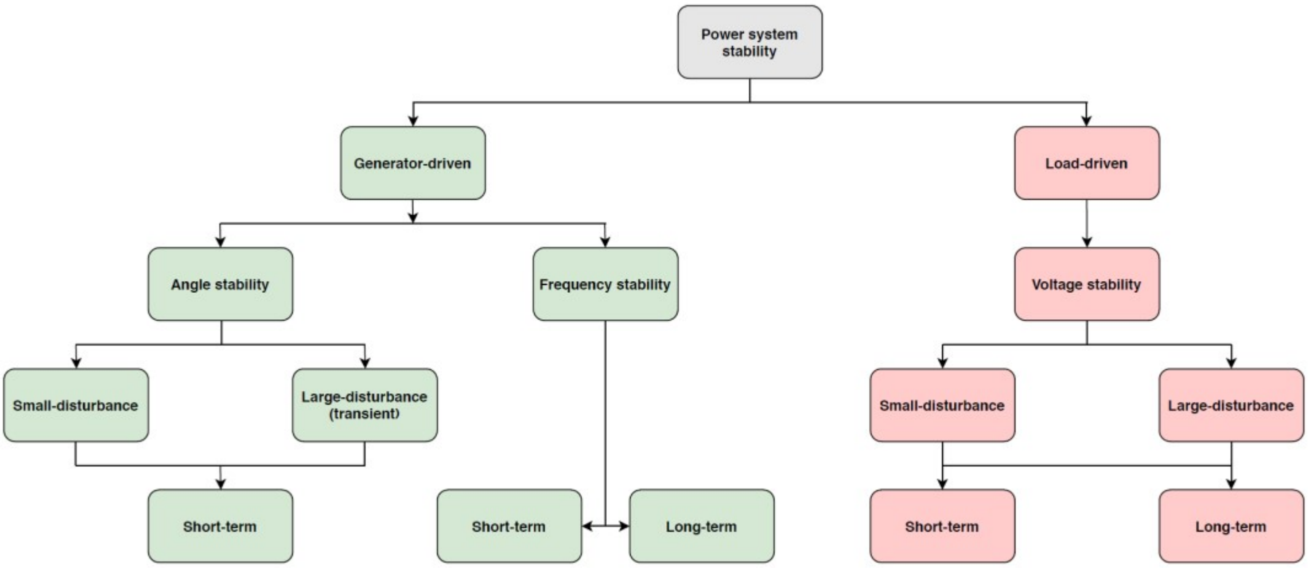

Fig. 1. Classification of power system stability [4]

B. *Extending the physical processes considered*

Hatziargyriou et al. [6] proposed new categories, converter-driven stability and resonance stability. As more and more non-synchronous generators are integrated into the system, the timespan where power system stability is considered also expand. Power electronic converters bring time constants in the range of electromagnetic transients.

Resonance occurs when energy exchange takes place periodically, through oscillations in the system. If there is insufficient dissipation energy in the flow path, electrical attribute magnitudes might grow (voltage, current, torque), and when these magnitudes exceed a defined limit, resonance instability happen. Sub-synchronous resonances, such as resonance between a series compensation and mechanical torsional frequencies of the turbine-generator unit, or series compensation and electrical characteristics of the generator.

Non-synchronous generators usually operate as voltage source converters, rely on control loops and have faster response time than the conventional synchronous generators. Converter-driven stability covers the wide frequency range of the interaction between any power system element (including other converters) and the converter itself. Fast transients occur between converters and stator dynamics of synchronous generators or other converters. The slow interactions include system-wide instabilities between power electronic devices and slower components, like conventional synchronous generators. Low frequency oscillations (range around 20-40 Hz) in systems with low short circuit ratios might result in instability. Weak system stability (phase locked loop synchronization may be problematic) and issues related to the power transfer limits (the current limit of the converter is reached) also considered as part of the converter driven stability issues. This classification extension was focused on the intrinsic system dynamics, extended the stability categories in the timespan to include electromagnetic stability processes as well. However, these categories do not expand based on the analysis tools or system parameters.

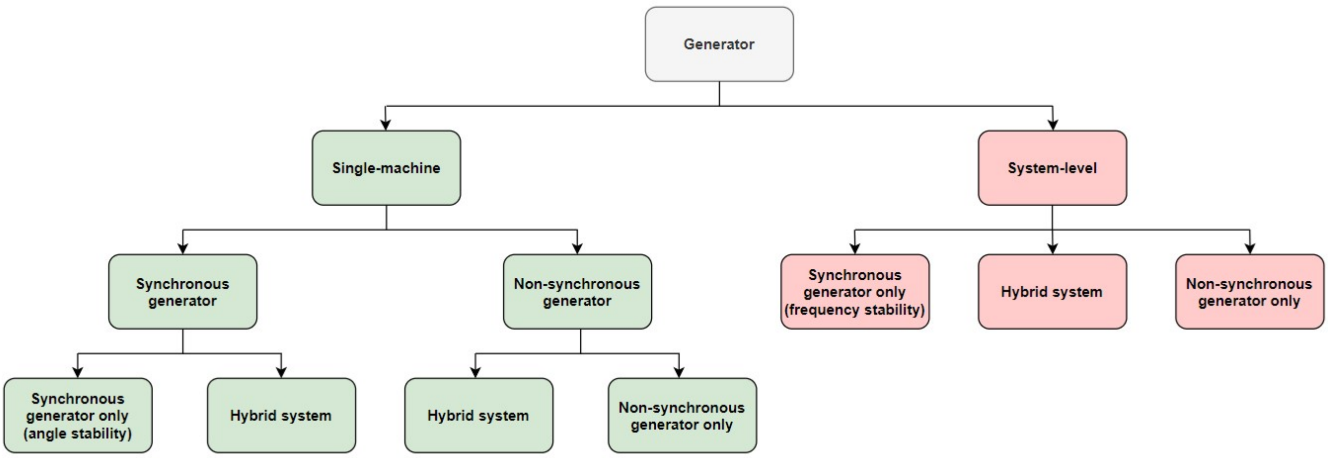

Fig. 2. Proposed extension for the classification of power system stability based on the generation mix

C. Proposed classification

Present paper divides the generator-driven stability categories based on the generation portfolio (Figure 2). If the generation portfolio is still dominated by synchronous generators, and the effects of non-synchronous generation can be neglected, the categories cover the already existing parts of Figure 1. Electromechanical transient simulations in the time-domain can give accurate results, while the already existing direct methods, such as the equal area criterion or energy-function based approaches can indicate the system states which need further analysis even in the real time period of the dynamic security assessment.

If the share of non-synchronous generation reaches a threshold where the effects cannot be neglected (from the simulation point of view: the classic electromechanical transient simulation or direct methods will not be accurate, models must be developed for the converter-based generation as well), the system has a hybrid generation portfolio. In that case, the system level frequency stability must consider the twofold characteristics of generation (synchronous and non-synchronous), while the unit-level assessment is different, based on the technology category (conventional angle stability and converter stability).

Meanwhile, in the case of a fully non-synchronous system (no synchronous inertia present), the electromechanical simulation is meaningless, the stability definitions are only based on converter characteristics. This case is only present at the microgrid level nowadays; however, e.g., the MIGRATE project [7] aimed to consider large-scale non-synchronous systems, which can be a scenario in the future.

In addition to the generation portfolio, the size of the system is also of utmost importance [5]. Mehigan et al. collected and evaluated comprehensive data on the synchronous zones of Europe [8]. As the synchronous inertia lowers in different systems, larger, well-interconnected systems such as the Continental Europe or Nordic System still have enough rotating mass to cope with frequency stability issues. Meanwhile, smaller island systems (such as Great-Britain or Ireland) could face difficulties in some system states if no countermeasures are taken. According to the categories introduces by the present study, the synchronous zones of Europe belong to hybrid systems., in which the electromechanical equivalent description might not be accurate enough. Microgrids of even smaller systems have special attributes, as the topology and locality become a decisive factor in stability phenomena [5]. Completely non-synchronous systems appear on the microgrid size scale.

3. Examples for stability assessment methods in power system with hybrid generation portfolio

Regarding hybrid systems, both conventional generators and converter-based generation are present with a significant share in them. Either group needs an assessment for the individual units. System level (frequency stability) must be calculated, and the countereffects (e.g. resonances between controllers) could also lead to stability issues. Current research showed that proper assumptions for the non-synchronous generation share mark operation boundaries more accurately. As an example, the MIGRATE project [7] developed a load model to substitute conventional load models. The proposed solution considered simplified dynamics and proved to be accurate in the transient stability index (TSI) calculations. TSIs – e.g. proposed by Ribbens-Pavela [9] – are useful for dynamic security assessment, as the simplifications in the system description lead to low computational efforts. These indexes are usually used to cluster the system states and identify the groups which need further analysis.

The first versions of the TSI considered angular accelerations or rotor angle differences, while extensions that cover transient or potential energy followed as alternatives [10]. Improvements to the TSI were proposed [11], as the consideration of the connecting elements through the grid reduction with Ward-equivalents indicated that non-synchronous generation could lower the angle stability boundary of the remaining synchronous generators after a determinable threshold. The proposed method was analysed on an IEEE test system and a real-life example of the Hungarian power system, where the critical clearing time changes were observed. This depends on many system attributes, and in some cases, the non-synchronous generation can even extend the stability boundary; so exact assessment is always needed [12]. Such methods can help in the identification of angle stability issues in power systems with a hybrid generation portfolio. Since the operation principles of the synchronous generators remain the same, the critical clearing time for those machines remains a viable option to measure angle stability.

Frequency stability evaluation is becoming a complex task due to the growing share of non-synchronous generation. Electromechanical transient simulations determine the rate of change of frequency (RoCoF) (gradient) and the frequency extremes (frequency nadir for loss of generation), which are the key parameters. Transmission system operators have to ensure stability during severe events, and in most of the cases, the largest single fault (loss of load/generation/interconnector) is considered. If the system is in a steady state before the event, the largest RoCoF and expected frequency extremes can be calculated. The RoCoF is important due to the operation of synchronous machines (mechanical stress) and protection devices (RoCoF relays, islanding), while the frequency nadir could lead to inadequate control actions (frequency containment and restoration) which results in automatic load shedding or system split.

The growing share of non-synchronous generation reduces the available synchronous inertia; therefore, higher RoCoF and larger frequency deviations are expected. However, converters that are capable of providing frequency stability enhancement services such as synthetic inertia can contribute to avoiding instability. This usually needs a power source (energy storage capability) and advanced control to mitigate power imbalances between the generation setpoint and active power needs (substituting the kinetic energy storage capability of synchronous rotating masses in

conventional turbine-generator units). Synthetic inertia provision with converter-interfaced non-synchronous generators is capable of limiting the RoCoF and increasing the frequency nadir [13]. Some synchronous zone transmission system operators are currently testing the synthetic inertia provision as a service to maintain stability during severe events.
Microgrids represent a unique challenge regarding power system stability. The intrinsic performance differences compared to bulk power systems (system size, connections, share of non-synchronous generation and low synchronous inertia, impedance characteristics, short circuit power and share of unbalanced elements). The control system stability of such systems depends on the type of generation, while the balance and power supply stability cover voltage and frequency stability in the IEEE PES approach [5]. These small-scale systems have higher uncertainty factors than interconnected large power systems. Purely non-synchronous systems appear in this system scale nowadays.

4. Conclusion

Changes in the power generation mix have a direct effect on generator-driven power system stability assessment. This paper summarized the background of power system stability classification and described an extension of the classification which considers the generation portfolio attribute as well. Current research showed that novel methods, which address the different attributes of synchronous and non-synchronous generation, provide a possibility for more accurate estimation. While stability remains an area where a limited number of system states are important, the need for direct methods which can quickly indicate the need for accurate calculations as the part of the dynamic security assessment is clear from the practical point of view.
The modelling assumptions for converter-based generation is still a developing research area. Accurate models would need much computational capacity. Approaches like synthetic inertia control can be traced back to traditional approaches, as converter-based generation mimics the synchronous machine attributes. The examples indicated that the class of hybrid system is needed, as the reviewed methods showed quantifiable accuracy enhancement. However, in the case of a fully non-synchronous system, the system-level control could be quite different from the principles of the synchronous operation, as converters also offer advanced controlling capabilities. As power systems evolve to reach sustainability goals, stable operation requires proper calculation methods for each of the proposed extensive classes regarding power system stability.
Current research results show that the proper consideration of the generation portfolio can help to identify the operation boundaries more accurately. This can also help to integrate further non-synchronous renewables into the power system securely.

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