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2016 CIGRÉ USNC International Colloquium

Future System Challenges in Europe - Contributions to Solutions from Connection Network Codes

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SUMMARY

The European Energy Supply for Electricity is undergoing fundamental changes. This includes strong moves away from heavy reliance on fossil fuels as the primary energy source mainly provided by large synchronous generators connected to the transmission systems, towards a decarbonised future supply relying increasingly on variable renewable energy sources (RES) using non synchronous generation predominantly connected to the network via power electronics and extensively connected deeply embedded in the Distribution Networks. Some countries in Europe have already experienced times in which in some periods the national demand for electricity has been exceeded by the RES production alone. As this phenomenon continue to extend, the development of Europe wide markets and system operation will facilitate greater sharing of resources.

This new and varied generation mix changes power system characteristics leading to major system technical challenges in normal operation as well as during disturbed or even emergency operation. Maintaining stable operation becomes a challenge in the face of an increasingly varied array of both conventional and emerging power system stability aspects. A major new challenge is coping with extremely weak power systems for some hours (during high RES production) followed a few hours later (during low RES production) with operation of a strong power system again supported by large centrally connected synchronous generators.

This paper initially identifies the main system technical operability challenges now and as expected in 2030 and even further towards 2050. It then focuses on new capabilities needed to deliver mitigating actions [1] including replacing from RES previously relied upon services from synchronous generators as far as practical and economic. It also touches on work in early stages to make the networks capable of coping with less, e.g. with very limited system strength. It identifies capabilities already included in new Connection Network Codes (CNCs) [2] at European level, as well as some further optional capabilities that may be introduced later or initially in parts of the system only, such as in those countries with the strongest early move towards RES reliance.

KEYWORDS

Integration of Renewable Energies, Integration of HVDC systems, Extreme Penetration Level of Non Synchronous Generation, Low System Strength, System Stability, Inertia, High Frequency Instability, Protection Non Operation, Quality of Supply, Harmonics, Unbalance, Capabilities of Power Electronics, Connection Network Codes, Grid Connection Requirements.

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1. THE CHANGING ENERGY MIX NOW AND UNDER FUTURE SCENARIOS

European Network of Transmission System Operators for Electricity (ENTSO-E) expects renewable energy sources will have a dominant role in new generation capacity over the next 10-20 years. Installed wind and solar capacities are forecast to increase by 80% and 60%, respectively [3]. All the 2030 Visions in TYNDP (Ten Year Network development plan) are expected to be in line with the recent 2030 targets set for renewables. The percentage of the annual demand covered by RES spreads from 44 % in Vision 1 to close to 60 % for Visions 3 and 4 [4].

Required future (2050) transmission system structures that are capable of coping with the ambitious European climate targets in five scenarios have been identified in the e-HIGHWAY 2050 project. Two of five scenarios focus on the deployment of RES technologies while one scenario is 100% based on renewable energy [5] where both large scale and small scale RES options are used.

Installations connected in the distribution systems means that exporting grid supply points become more common. In addition, resource location of RES (offshore wind parks in the North and high imports of solar from the South) leads to large and varies power transfers across Europe.

Indices such as the RES Energy Penetration Index (REPI) have been defined. REPI means the share of annual energy demand covered by RES. REPIs of overall ENTSO-E countries are expected to grow and reach 16 % by 2025. RES Load Penetration Index (RLPI) or percent of Non Synchronous Generation (%NSG) [6] have been defined, as the maximum hourly variable RES (and HVDC import) coverage of load (and HVDC export). Figure 1 illustrates RLPI per countries for 2025. In total 22 countries are expected to have a RLPI level higher than 50% and 8 countries (DE, DK, GB, GR, IE, NI, NL and PT) will reach full hourly load penetration level without energy export.

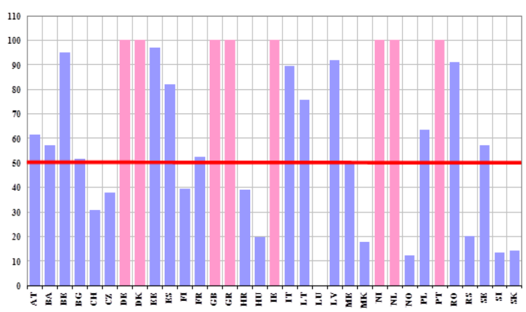

Fig. 1. RLPI by countries for 2025 [3]

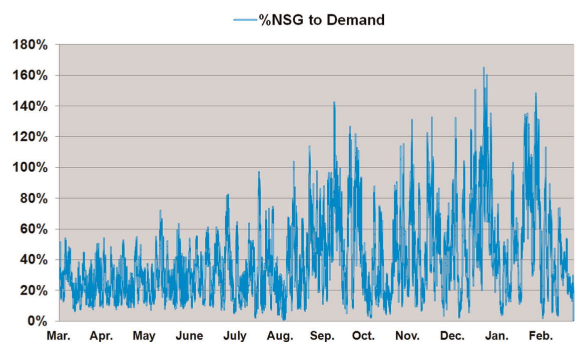

Fig. 2. GB hourly (%NSG) for year 2030 [6]

Great Britain hourly NSG unconstrained production as % of demand for year 2030 with "Gone Green" scenario is presented in Figure 2 [6]. It shows the %NSG varies greatly, with the highest unconstrained value reaching 160 % of the total GB demand in the Christmas period. The extreme variations illustrate the challenge of selecting appropriate measures to ensure the required system technical capabilities to secure stable operation of the power systems under all credible conditions.

2. IMPACT ON SYSTEM CHARACTERISTICS OVERVIEW & NEED FOR ANCILLARY SERVICES

The large and rapid variation in output from RES will result in similar but opposite availability of conventional synchronous generation capacity connected directly to the transmission system. These have traditionally provided most of the flexibility to ensure MW balancing for frequency management as well as varying their reactive power to manage EHV system voltage. In the developing low carbon future, these services will still have to be delivered under all operating conditions. Additional capacities to provide equivalent services are being required in new Connection Network Codes, NC RfG for new generators including Power Park Modules (PPMs),which covers wind & solar PV, as well as NC DCC covering Distribution Systems and Demand Side Response and NC HVDC covering support between synchronous areas as well as from large scale offshore wind power connected via HVDC.

The transmission system strength, sometimes expressed in terms of local fault level (FL), is greatly affected by the developments described in section 1. The same applies to total system inertia (TSI) for a synchronous area (SA) or a country's contribution within a SA.

Analysis indicated in [6] and [8] can be applied to evaluate FL and TSI under a variety of conditions. Services need to be secured (mainly from Users and defined typically 10 years in advance) to allow such operation covering the most onerous production operating conditions, including a variety of system stability aspects.

NSG do not naturally provide support in form of contribution to FL and TSI unlike SG, which provide these inherently. For NSG some limited such capabilities can be considered and may be economic to deliver. However, they have to be explicitly required and detailed in codes, in Europe via CNCs. The 3 CNC, which were all 3 voted for unanimously by each of 28 EU member States, being NC RfG the first one published by EU [8], contain outlines of such capabilities, but their requirements are not exhaustively defined. Instead, they are defined as "non-exhaustive", meaning they are not fully detailed in terms of parameters. Making them exhaustive at a national level is a process under way and is expected to reflect varied needs, e.g. from differences in expected instantaneous penetration level (IPL) and level of connections which are embedded in distribution.

The weak power systems of the future, as indicated by varied and at times extremely low FL and TSI, are detailed in the following chapters focused both on the need cases and on the ability of new technologies to deliver mitigating capabilities covering:

- low total system inertia – impact on frequency management
- conventional keeping in synchronism & new high frequency stability challenge
- lack of fault level for converter stable operation
- lack of fault current for transmission system protections
- lack of system strength for voltage quality of supply

3. LOW TOTAL SYSTEM INERTIA (TSI) & IMPACT ON FREQUENCY MANAGEMENT

In order to support the daily management of the interconnected power system, ENTSO-E has proposed that all TSOs regularly calculate their TSI in operational time scales. TSOs of two of the 5 European SAs already have, from time to time, to take constraining actions in relation to having too low TSI in context of the rate of change of frequency (RoCoF) arising from their largest infeed loss.

In future, this situation is likely to become more severe and spread to more SAs. Forward calculation of TSI (e.g. for the next 20 years under different energy scenarios) are emerging, [8]. Such analysis provides information for the need case for mitigating measures, such as:

- synthetic inertia provision by some of the new generation sources, PPMs
- inertia contribution shared between SAs using HVDC
- use of synchronous compensators (SCs), even decoupling generators to become SCs under changing operating conditions in real time from generators such as GTs and CCGTs or permanently from decommissioned nuclear (Germany)..
- contributions from demand, e.g. very fast DSR

In this area the major challenges relates to appropriate measurements of df/dt and also the impact on need for headroom or alternatively risk of deferred later loss of power (hopefully not before adequate slower frequency response is available). ENTSO-E endeavours to guide its members on these aspects ahead of the national implementation processes.

The other end of mitigating actions relate to greater robustness for high df/dt of the total system including all connected users to withstand without disconnection. In this context the NC HVDC sets the expected highest standard by requiring capability of 2.5Hz/s for new HVDC installations, ensuring the main infrastructures remain connected.

4. CONVENTIONAL SYNCHRONISM & NEW STABILITY CHALLENGE

Conventional dynamic simulation studies need to be performed to validate that, as SGs are replaced by NSGs, the first swing stability of the remainder SGs on the system is retained. This should confirm that the control strategy and parameters selected for the NSGs are positively contributing to the overall stability. NSGs with reactive controls selected for voltage control mode with order of same speed of response as AVRs for SGs should improve transient stability. Other reactive controls with slower speed of response may be less helpful.

Recent work [6, 9] has demonstrated that very high % of NSGs (e.g. 70%) can result in loss of stability at higher frequencies, such as 150-250Hz. This type of instability differs from the traditionally found when dealing with power systems with high penetration of SGs. This initially led to a suspicion of numerical instability. Increasingly evidence [9] has shown that the instability is more than a feature of the study platform.

To enable Voltage Source Converter (VSC) to improve synchronising torque, a VSC can be designed to behave as a SG or at least possess some features of a SG (e.g. inertial response, frequency response and voltage regulation). However, as demonstrated in [6] the exact choice of control strategy is critical to avoid the problem of high frequency instability, because common control strategies to deal with lack of inertia contribution has been shown to make high frequency instability worse [9].

Conventional converter models for wind turbines and Voltage Source HVDC links, as submitted to System Operators for running system stability studies, typically use dq-axis controllers with current injection (DQCI). In these converters, active and reactive power set points are translated to dq-axis current references in the rotating reference frame. For DQCI converter-interfaced sources it has been proven [9] that there are overall penetration limits, i.e. ‘tipping points’, beyond which the system will become unstable, unless alternative converter controller techniques are used. Conventional controllers are based on Phase Locked Loops (PLL), which are effectively followers of existing system voltage. As a fundamental component in a DQCI converter control system model, the PLL synchronises the dq axes of the converter with the network at the connection point, and allows the frequency to be measured. However, it has been shown that using a PLL to measure frequency is not always effective or accurate [9]. When %NSG is very high there is a need for a proportion of leaders operating on principles different from the PLL controllers.
The TSOs now need to define in a high level functional manner, i.e. through CNCs implementation, what control strategy mix should be provided by converters in HVDC, wind and PV.

5. LACK OF FAULT LEVEL FOR CONVERTER STABLE OPERATION

HVDC and NSG, interfaced via Power Electronics (PE), such as wind or PV plants increasingly replacing conventional synchronous generation show behaviour dominated by choices made in Network Codes (minimum performance requirements) and implemented by the converter designers. One main difference to SG is the lack of fault current of NSG, which is constrained by very small thermal capacity of PE and thus smaller overload capability.

Converters behaviour during faults was initially focused primarily on avoiding damage to the electronics from high currents and fast transients. In the last 10 years, this was supplemented by the TSOs need for the NSG to ride through faults and remain connected. Lately, as %NSG increases, the focus is further set on the next phase, making PE positively contribute to the power system strength during transmission system faults. The paper [10] divides this task into 3 distinct time periods A, B and C. Periods A (the first 30-40ms) and B divides the fault duration into two parts and period C covers the immediate post fault period. It is important to stress that the system needs vary between these 3 periods:

- Period A: delivery of a fault current within 20 ms to recognize, locate and initiate clearance of the fault by electrical protection systems;
- Period B, Delivery of (additional) reactive current supporting voltage retention. Magnitude of current prevails over control accuracy.
- Period C: Delivery of a reactive current to restore voltage and restoration of active power to remove power imbalances and corresponding frequency deviations. Control accuracy is crucial to avoid overvoltages.

The vast majority of today's NSG are based on self-commutation, with the relevant exception of conventional HVDC converters, based on line-commutated converters (LCC) devices, which still have the advantages of low losses and higher withstand voltage and larger ampacity. Their major drawbacks are high (but predictable): current harmonics, natural reactive power demand and the fact that their control does not allow for reactive power or voltage control. Nevertheless, LCC HVDC may still be chosen for large power transfers (multi-GW applications) with high DC voltages. Since LCC devices use the grid voltage for commutation the quality of this voltage is important and distortion of the voltage sinusoidal shape and voltage dips may lead to converter blocking.

Regarding weak networks the current harmonics of the LCC will have a larger impact on the voltage quality and commutation notches will additionally distort the voltage. Stable operation requires a minimum ratio between FL and rated power. Improvements are made to allow for a stable operation for a lower ratio than the traditional value of 3, but with further NSG even these improvement may not be sufficient under all operating conditions. The PE sources may therefore in the future be required to contribute more to the fault level and improvement of the local voltage quality.

Self-commutated converter devices are today mainly based on IGBT technology and the DC link is designed as voltage source. For this reason they are usually called and are designed as VSC. This is the case of the majority of wind and photovoltaic and the VSC HVDC.

LCC have made already progress to lower the required a minimum ratio between FL and rated power . Further efforts have to be taken to contribute to voltage quality to ensure stable operation. VSC systems have to be enhanced from current controlled mode to voltage controlled mode. This will support both stability and improve local voltage quality. In recent years renewable power plants were often built using default parameters and parameters were not adapted to new network situations (connect and forget). In the future plant configurations should be revised regularly and PE control has to the designed as configurable after commissioning (future-proof).

6. LACK OF FAULT CURRENT FOR TRANSMISSION SYSTEM PROTECTIONS

NSG, i.e. Type 3 (DFIG) and Type 4 (Full converter) wind turbines, PV systems or HVDC links, are expected to have a strong impact on the behaviour of the protection systems of the power system and on the need for mitigation measures. To date, NSGs have made little or no contribution in absence of network code requirements. However, most of these sources have considerable potential capabilities:

- fault current that could reach (2-4pu) for a very limited time, typically less than a full cycle or a few cycle [11], but this facility has so far largely remained unexploited.
- fault current after that period would typically be limited within several cycles to a value of 1.0-1.2 pu
- in case of unbalanced faults, a fault current contribution depends on the control approach of the converter. Only positive-sequence current are typically supplied in order to comply with now outdated requirements. This needs to change and consideration is also needed to the step-up transformer connection. [11, 12].

In meshed transmission systems with developing large penetration level of converter-based sources, to date provided with large fault current contribution from synchronous generation, future absence of significant fault currents and of negative and zero sequence currents for unbalanced faults is a concern for the protection engineers[8]. National Grid UK has already raised publicly these concerns for its future power system [13]. Tripping delays, loss of discriminations, even total inability to detect unbalanced faults has been reported by several authors [14], [15] and [16]. Different mitigation measures needs to be taken in order to efficiently secure the power system performance. In the mid-term and long-term, transmission system protection schemes are expected to see an evolution of the relay algorithms and a shift towards more differential protections [16, 11] and an enhancement of the models used for protection coordination studies [12]. In the short term, the evolution of the expected fault current contribution of converter-based sources is an effective mitigation measure which is supported by the CNCs RfG and HVDC. These CNCs are requiring PPMs and HVDC systems to have the capability of providing a fast fault current contribution. The magnitude, the time period for providing 90% of the required fast fault current contribution and the interdependency between fast fault reactive current injection requirements and active power recovery as well as the contribution in case of asymmetrical fault must be specified by the relevant TSO.

7. LACK OF SYSTEM STRENGTH FOR VOLTAGE QUALITY OF SUPPLY

Voltage quality of supply is dependent on the level of system strength, which in turn is dependent on the number, size and location of synchronous units in the system. To date a major focus of the RES industry (wind and solar power plants) as well as HVDC has been on minimising and eliminating harmonic and imbalance current contributions from the PE converters to limit their potential negative influence on voltage quality.

Changes in the generation mix have influenced the level of voltage quality in the system. A critical consideration is the level of voltage harmonics in the system. Lowering the system fault level increases the level of voltage harmonics proportionally. As a rough estimate the level of voltage distortion will double if the fault level is halved. This has to be considered during system design and when operating the system. Synchronous units inherently behave as a sink for low-order harmonics. Without them the levels of low-order harmonics will increase. Because traditionally NSG connected to power system are at least in some extent responsible for emitting harmonics and measures, e.g. filters, control, etc., have been used to limit them. For mitigating voltage quality issues the future converters connected to the system could do more and actively participate to deliver better voltage quality. To achieve this changes are needed in codes and in converter designs to encourage both harmonic currents and imbalance currents contributions from inverters to counter existing system voltage imperfections. This is going to be challenging, but some lessons already learnt by small independent power systems may prove applicable [2]. These advanced approaches may in the future be considered as possible types of auxiliary services, although the complexities would be considerable.

Experience of system operation as described above is limited for large power systems. Offshore wind power plant offshore AC collection network can be considered as good examples of future converter based grid. In [17], discussion and examples on harmonic resonance and converter control issues are provided. As a conclusion it should be emphasized that in future power systems coordinated converter control is relevant and absolutely needed for stable system operation.

With respect to voltage quality, the CNCs define the criteria needed to ensure voltage quality in steady-state and transient conditions. The focus to date on converters not introducing harmonics that would breach voltage quality compliance and affect the optimum operability of the TSOs needs in future to be complimented by converters contributing a clean-up service for the system voltage.

8. DISCUSSION ABOUT HOW TO DELIVER MITIGATING SOLUTIONS

ENTSO-E has gathered national experts and established working groups on the subject for drafting Network Codes in a collaborative way. In order to ensure the support of all branches of the electricity sector, ENTSO-E has worked in close cooperation with stakeholders and has applied a set of principles in the development of on-going and future codes of transparency, open engagement, explanation and consistency. Further collaborative work is needed across the industry and academia to find the most optimal approach and technical solutions for securing future power system operation. Currently there are various EU supported R&D projects, whose purpose is to gain knowledge on future system characteristics and control applications.
In many cases, the specifications in CNCs or in national grid codes have triggered development of new technical solutions from manufacturers. Another option is to enable market to deliver those new solutions. This relies on a large expansion in the % of the total energy costs focused on Ancillary Services as anticipated in Ireland [18].

9. CONCLUSIONS

The European Energy Supply for Electricity is undergoing fundamental changes. This triggers the need for fundamental evolutions in the field of system control, stability, protection, voltage quality, frequency control, etc. A major new challenge is coping with extremely weak power systems and enabling capability of stable operation of RES dominated systems with or without synchronous generation. For this, it is essential for all parties to enhance their understanding of the different phenomena at stake and exploit optimally the current and future technological possibilities in manufacturing. More specifically, mitigating capabilities of the generating units and HVDC systems will be needed to solve low total system inertia, inadequate fault levels for converters, inadequate fault currents for protection, and inadequate contributions to voltage quality.

Further collaborative work is needed across the industry, combining efforts from TSOs, power system analysis tool providers, university researchers and converter manufacturers. Only with this type of collaboration is it possible to find the most optimal approach and technical solutions for securing future power system operation. Currently there are various EU supported projects, which purpose is to gain knowledge on future system characteristics and control applications and to enable markets to deliver new solutions.

Technical requirements for connecting plants are usually described in national Grid Codes. With respect to future system challenges implementation of the pan European Connection Network Codes should be based on a balanced approach. On the one hand they should be barrier to equipment which is clearly not suitable for application today or in the near future. On the other hand they should drive technology by setting up and defining new requirements. The requirements have to be well-considered as they could block technologies which cannot yet be replaced.

The way forward in Europe is to combine the knowledge obtained from studies, experiences and collaboration between different parties into Connection Network Codes and nationally in Grid Codes. These codes should set the path to the future for integrating large amount of RES as part of the low carbon future and therefore enable secure system operation in spite of future system challenges. In order to be effective the new requirements may need to be in the codes 10-15 years before the system need for them arises.

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