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Effects of Increasing Power Electronics on System Stability: Results from MIGRATE Questionnaire

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***Abstract*—Power systems throughout the world are experiencing increasing levels of power electronics interfaced generation in their generation portfolio. As these devices have a significantly different dynamic behavior than conventional synchronous generators, it is expected that this trend will pose power system stability related challenges. This paper presents the results of a questionnaire conducted within the MIGRATE project. The aim of this questionnaire, to which more than 20 European transmission system operators (TSOs) responded, was to identify and prioritize these challenges. The TSOs identified challenges related to rotor angle stability (two), frequency stability (three), voltage stability (five), and power electronics interactions and resonances (two). In a follow-up survey, the TSOs were asked to rank the challenges based on their severity, probability of occurrence, and time of manifestation. The decrease of inertia was ranked the highest among the 11 issues. Additionally, the TSOs gave insight into current practices with regards to system monitoring and analysis. Based on the ranking, mitigation measures are currently being designed in order to facilitate an even higher amount of power electronics interfaced renewable energy sources in the power system.**

***Index Terms*— MIGRATE, Power Electronics, Power System Stability, RES**

I. INTRODUCTION

MIGRATE stands for Massive InteGRATion of power Electronic devices and is an European Union (EU)-funded project under the framework of Horizon 2020 research and innovation programme. The overarching goal of the project is to develop and validate innovative, technology-based solutions in view of managing the pan-European electricity system, which is experiencing a proliferation of power electronics interfaced devices (PEIDs), i.e. power electronics interfaced generation (PEIG), power electronics interfaced load (PEIL), and HVDC.

In the short to medium term, incremental technology-based solutions are needed to operate the existing high voltage AC system. In the long term, breakthrough technology-based solutions are required to manage a power system in which all load and generation are connected through power electronics (PE). The combination of the goals in these two timeframes is illustrated in Figure 1 [1].

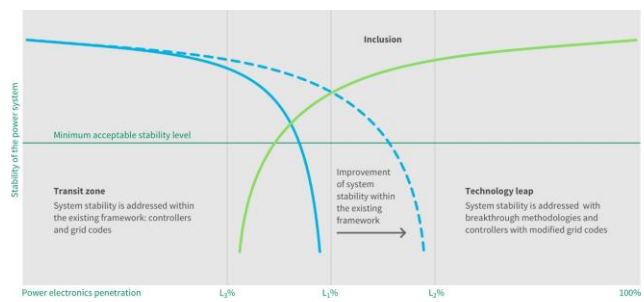

Figure 1. Main concept of MIGRATE [1] .

It conceptually shows the level of stability that could be achieved by transmission system operators (TSOs) when operating the system at different levels of PE penetration. The short to medium term goal is represented by the blue curve on the left hand side: the observed trend means that, as the PE penetration increases, TSOs will face stringent stability issues when operating the system. The "L1" asymptote merely means that there exists a maximum level of PE penetration where the existing power system can be operated. A first challenge to be addressed by the MIGRATE consortium is to come up with new tools and methodologies to appraise this limit value for a given control zone. The accurate computation of this limit would also allow TSOs to plan their network developments in order to implement in time the necessary modifications so as to remain within acceptable stability ranges. As a consequence, a second challenge of the project is to investigate if this stability limit can be further increased with novel methods and tools within the existing framework, i.e. with the existing grid codes and the existing controllers (this new stability limit is the "L2" asymptote in Figure 1, i.e. the dashed blue curve representing the new achievable stability levels with novel methods and tools). If proven to be possible, this limit would represent the highest achievable PE penetration with today's technologies and system operation rules.

The MIGRATE project is governed around five technical work packages (WP). A short description of the WPs is given below (elaborated descriptions in [1]).

WP1 aims at identifying and prioritizing power system stability issues faced by TSOs taking into account a variety of network topologies, geographical locations and levels of PE penetration. This identification and prioritization was achieved through a questionnaire to which more than 20 European TSOs responded. Another goal of WP1 is to analyze and deeply understand the causality of these issues in order to develop new methods for analyzing and mitigating the impacts of increasing levels of PE penetration on system stability.

WP2 develops new indices (e.g. Area Inertia) as well as methodologies for its real time monitoring using phasor measurement units (PMUs). A real time wide area control algorithm is being developed and tested on the Icelandic network [2].

The research carried out in WP3 is focused around the development of new controls for a transmission grid in which 100% converter-based devices are connected. One criterium for these new controls is that they should remain effective when the PE penetration is slightly lower than 100% [3].

WP4 will provide detailed insights into the ability of actual protection practices to properly operate under system disturbances with high levels of PE penetration. It will evaluate and test emerging technologies and develop new protection strategies in order to overcome the identified threats when operating at 100% PE penetration.

WP5 deals with power quality (PQ) issues in transmission systems with high PE penetration. It will identify critical PQ disturbances in order to numerically study their propagation through the transmission system, analyze the impacts of these PQ disturbances on the performance of PEIDs, and examine to which extend PMUs can assist in mapping of PQ issues [4], [5].

The goal of this paper is to present the results from the questionnaire that was conducted in WP1. This questionnaire aimed at identifying and prioritizing power system stability issues that could be expected with increasing levels of PE penetration.

The results are presented in two parts. Section II contains the results on the identification and prioritization. Section III provides additional valuable insights into TSOs' practices with regards to real time simulations, modeling, and real time monitoring of system stability.

This paper is a summary of MIGRATE's Deliverable D1.1. For more elaborated results, the reader is encouraged to read the full report [6].

II. Questionnaire Results Part I: Stability Issues

This first part of the questionnaire results presents the 11 identified and prioritized power system stability challenges that TSOs already observe or expect to observe in the future. These identified challenges, illustrated in **Error! Reference source not found.**, are categorized in four classes, i.e. rotor angle stability, frequency stability, voltage stability, and an undefined class 'others'. A short technical description of each of the challenges is given below.

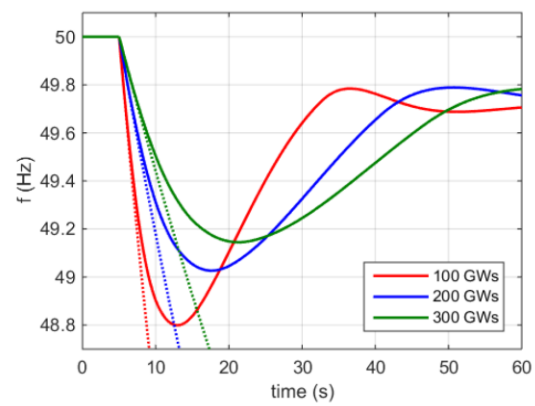

Figure 2. The effect of the amount of inertia on the behavior of frequency after the loss of generation with (solid) and without (dotted) FCR [13].

Issue 1: Reduced Damping & New Power Oscilliations

In a power system, multiple local or global power oscillations can exist between synchronous machines. These oscillations can happen at different frequencies, each with their own level of damping. Insufficient damping can lead to (cascaded) generator or line tripping, which eventually could result in severe stability issues [7]. The modes and damping of each oscillation depends on the system configuration as well as the type and location of power plants. PE penetration can affect the modes and damping by several means[8], [9]:

- Replacement of synchronous machines by PEIG (and usually loss of associated power systems stabilizers)
- Changes in the synchronizing forces by impacting the major power flows as a result of HVDC transmission
- Interactions between PE controls and the damping torque of large synchronous generators, which could also result in new oscillation modes.

Issue 2: Reduction of Transient Stability Margins

Transient stability is concerned with the ability of synchronous machines to maintain synchronism after a severe disturbance [10]. Increasing PE penetration affects transient stability in various, interdepending ways, and whether the absolute impact is negative or positive depends on the superposition and interaction of these influencing factors. However, even at a more detailed level, the effect can either be positive or negative. In [11], a detailed differentiation with respect to the dimensions of impact of PEIG on transient stability is given:

Technology-dependent impact: there is a positive effect on transient stability, if modern generation devices are able to ride through faults and provide fast voltage support.

Penetration level-dependent impact: while a moderate penetration level of PEIG can improve transient stability due to decreased loading of (still grid-connected) conventional synchronous generators, decreased loading of transmission lines and additional voltage support by PEIG, a higher penetration can reverse this impact.

Pre-fault operating point-dependent impact: the pre-fault loading of synchronous generators and transmission lines affects transient stability margins (cf. penetration level-dependent impact). Likewise, the loading of PEIG is relevant. Their voltage support contribution, which has a positive effect on transient stability, cannot exceed the rated current of the converter, and therefore, a lower loading enables better voltage support by injecting higher fault currents without reducing the active power output.

Location-dependent impact: PEIG installed electrically close to synchronous generators can increase transient stability by voltage support in case of faults. The further the PEIG is installed, the lower its voltage support and hence the short-circuit power at the synchronous generator's connection point.

Control system-dependent impact: as mentioned above, voltage support provided by PEIG in fault situations can improve transient stability. The higher the terminal voltage of synchronous generators during and after faults, the higher the electrical torque which leads to a lower acceleration during faults and a higher deceleration afterwards. A reduced active power infeed during and after faults can further improve transient stability, as it can increase the synchronous generators' electric torque by a shifting of load supply from the devices with reduced active power infeed to the synchronous generators.

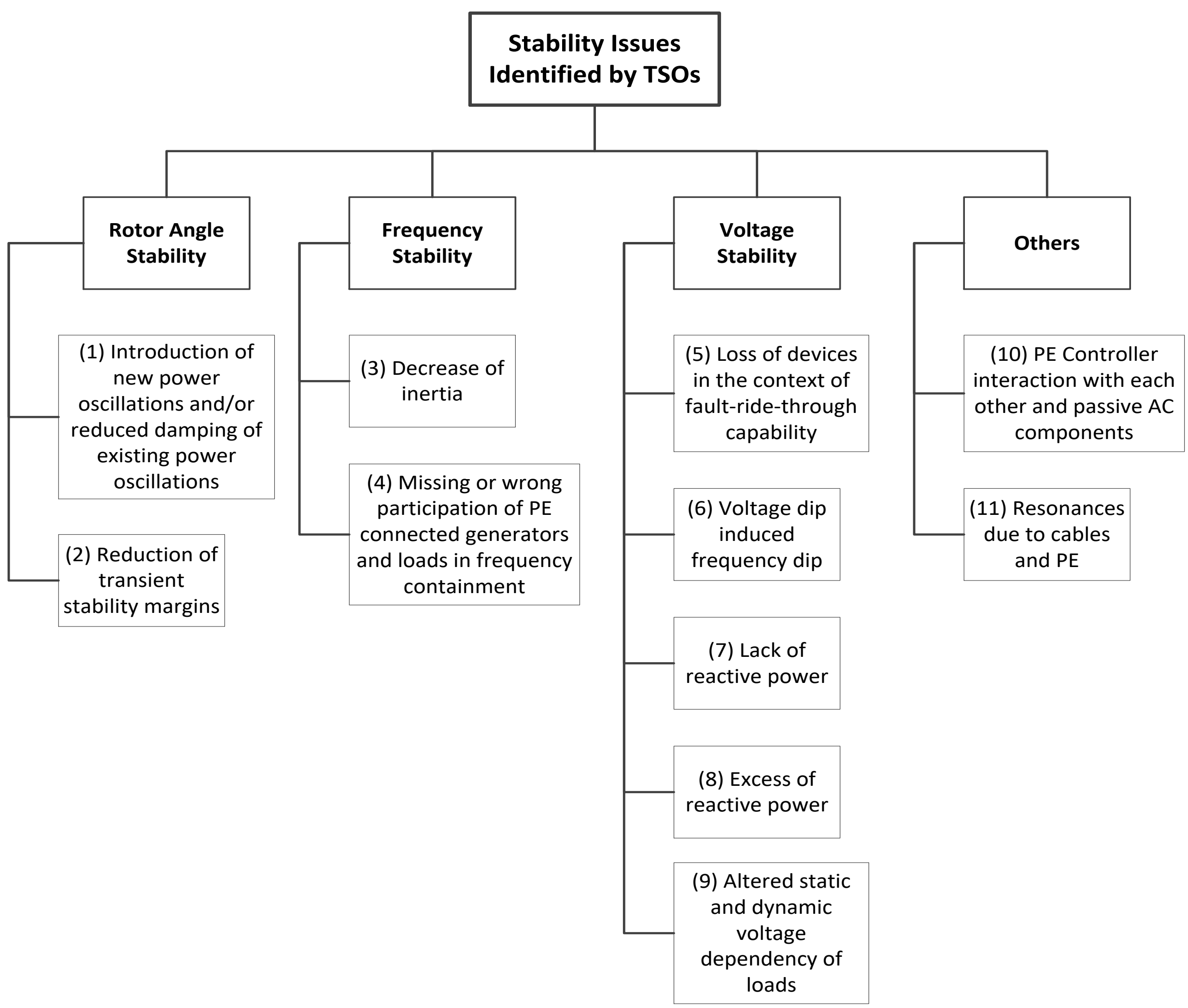

Figure 3. Power System Stability Issues as identified by TSOs.

C. Issue 3: Decrease of Inertia

The inertia within today's power systems is largely provided by synchronous generators and the mechanically coupled turbines of conventional power plants. Conventional power plants are increasingly being replaced by PEIG. As long as there is no supplementary control, the PE decouples the electrical and the mechanical (or in case of PV the photoelectric) part of the generating device, which results in a lack of inertial response to changes in the grid frequency. Additionally, directly grid-connected motor load is also increasingly being interfaced with converters. Both aspects lead to a significantly reduced remaining inertia of the power system [12]–[14]. While the power system's inertia decreases, the potential power imbalance incidents, which is the other main factor influencing the rate of change of frequency (ROCOF) and the frequency nadir, remains constant or even increases. Both effects combined lead to higher ROCOFs and dynamic frequency nadirs or peaks. As an example, **Error! Reference source not found.** shows the frequency versus time for the same incident with three different amounts of inertia expressed as the energy stored in the rotating masses in GWs. The dotted lines exclude frequency containment reserves (FCR) and load reaction and therefore show a frequency decrease with the initial ROCOF. The solid lines include FCR.

D. Issue 4: Missing or Wrong Participation of PEID in Frequency Containment

For an effective operation of the frequency containment plans, no load or generation should trip unintentionally as long as frequency remains within a predefined band, as this might increase the imbalance between load and generation even further. On the contrary, a participation in frequency containment by providing frequency containment reserves is beneficial. Some loads, such as electrical pumps, traditionally participate in frequency containment by a positive dependence between frequency and power consumption (self-regulation effect). Especially when distributed generation expansion began, network codes requirements for distributed PEIG concerning under- or over-frequency tripping and subsequent reconnection as well as participation in frequency containment were less strict than for conventional transmission-connected generation. However, with their rapid increase, the absolute rated power of distributed generation became relevant for transmission system operation. Besides, a planned participation in over-frequency containment was planned at fixed thresholds instead of requesting a proportional reduction of power with increasing frequency. This leads to the risk of simultaneous generation tripping, which could significantly exceed the reference incident [15].

E. Issue 5: Loss of Devices in the Context of FRT Capabilities

Fault-ride-through (FRT) capability is defined by a voltage-against-time profile for the time during and after the fault. During a short-circuit event on transmission level, the voltages near or at the fault location are zero. Starting from the fault location, this voltage dip propagates through the system. Due to the voltage drop caused by the short-circuit currents and the impedances of the transmission lines, the voltage increases with increasing electrical distance to the fault location. As the extent of the voltage gradient during a short-circuit event and therefore the number of devices potentially affected by undervoltage is inversely proportional to the amount of short-circuit power at the fault location, the influence of increasing PE penetration on the short-circuit power is also relevant. Although a one-by-one replacement of a synchronous generator by a PEIG with the same maximum capacity would significantly reduce the short-circuit power at the respective busbar, the overall effect of increasing PE penetration on the short-circuit power remains unclear and is, amongst others, dependent on PE technology, penetration level, pre-fault operating point, location, protection settings and controls.

F. Issue 6: Voltage Dip Induced Frequency Dip

This issue refers to the recovery phase of the active power after short-circuit events [12]. The active power recovery of transient stable synchronous generators follows the recovering voltage and is therefore very quick. The active power recovery of wind turbine generators may be slower in order to keep mechanical stress on the structure at acceptable levels. Figure 4 shows active power recovery characteristics of a conventional and a wind power generator. The impact of this issue is strongly dependent on the size of the synchronous area together with its inertia and the wind power penetration. The issue is aggravated by decreasing inertia (issue 3) and a broader propagation of voltage dips (issue 5).

G. Issue 7: Lack of Reactive Power

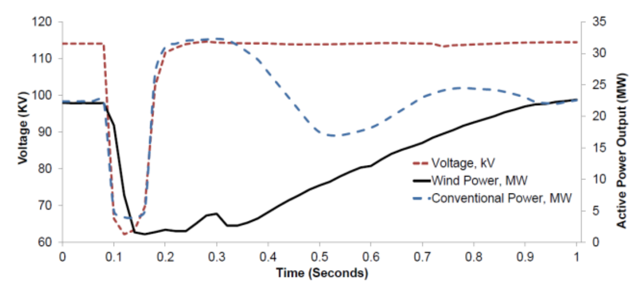

Figure 4. Active power recovery characteristics of conventional and wind generators [12].

Increasing PEIG replaces synchronous generators, if a certain penetration level is reached. This reduces the voltage control capabilities within the transmission grid if the PEIG does not provide the same capabilities. Additionally, depending on the location of the PEIG and the replaced synchronous generators, the system's loading might increase due to increased distances between generation and load centers. Finally, PEIG is often installed at distribution level, so that voltage support for the transmission system is impeded due to one or more transformer impedances [12].

H. Issue 8: Excess of Reactive Power

The reactive power demand of transmission system elements like overhead lines, cables and transformers is highly dependable on their loading. Overhead lines require reactive power (inductor behavior) in case they are highly loaded and provide reactive power (capacitor behavior) for low loading. Transformers always require, and cables always provide reactive power, but in either case the amount depends on the current and therefore on the loading. Most of the load supplied by transmission systems is connected to the distribution systems. Hence, apart from reactive power demand of transmission system elements, the demand at the grid supply points (interface between transmission and distribution grid) mainly determines the reactive power that has to be balanced by generators or compensation devices.

In case the reactive power demand of distribution systems at the grid supply points reduces or even gets negative during times of low load, the surplus of reactive power has to be consumed by generators or compensation devices. Because this capability is limited, the voltage could rise above the permissible voltage band in case of excess reactive power. As increasing PEIG penetration can reduce the voltage control capabilities of transmission grids (cf. issue 7), this might worsen the issue, especially because the relative share of PEIG (in particular wind generation) can get higher in times of low load. Figure 5 illustrates the change in National Grid's power system with regards to the reactive power demand [16].

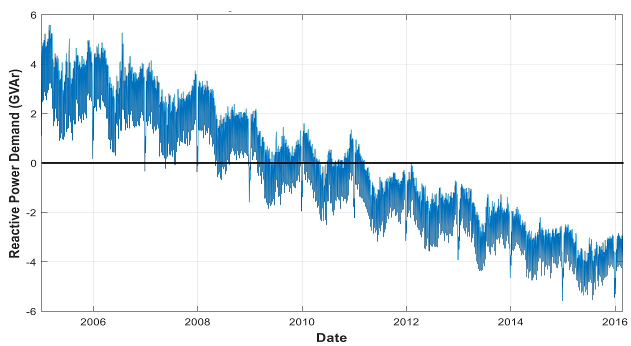

Figure 5. Daily Reactive Power Demand UK [16].

I. Issue 9: Altered Voltage Dependence of Loads

Typically, dynamic loads restore power consumption completely or to a certain extent following a voltage variation. Classic examples for dynamic loads are induction motors, loads connected to on-load tap-changing transformers and thermostat-controlled loads. As load behavior is a main factor influencing voltage stability, alterations in both static and dynamic voltage dependence have an effect. Due to the complexity of current power systems with its numerous highly nonlinear relations, the effects depend on several factors (e.g., composition and location of load, location and type of devices with voltage regulation) and can only be evaluated in detail by studies on the concrete system, e.g. by time-domain simulations with detailed modeling of load dynamics and voltage regulation.

Besides voltage stability, frequency stability is also affected by the voltage dependence of load. As the loss of generation or an importing HVDC link is often accompanied by voltage drops, voltage dependence of load has a stabilizing effect on frequency, because the loads affected by declining voltages reduce power consumption. Depending on the power system, its specific configuration and also type and location of a fault, the positive effect of voltage dependence of load can largely exceed the effect of frequency dependence [14].

J. Issue 10: PE Controller Interactions

Different modules of the PE control structure, i.e. the current-control loop, power-control loop or the phase-locked loop (PLL), can cause poorly damped oscillations in the current or power output. These oscillations can have frequencies in the sub synchronous as well as super synchronous frequency range.

K. Issue 11: Resonances due to Cables and PE

In addition to cable resonances, an increase of harmonic currents due to the combination of additional HVAC underground cables and the harmonic voltages emitted by PEs were indicated by the TSOs and in literature.

L. Prioritization of Identified Issues

In a follow-up questionnaire, TSOs were asked to rank all these challenges on their severity, probability, and timeframe (i.e. in how many years from date is the issue expected to manifest) based on the scoring system given in Figure 6 [6]. The results of the ranking are given in Figure 7.

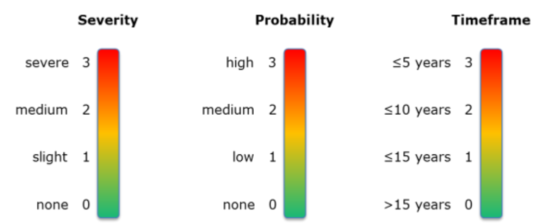

Figure 6. Scoring.

The final rank of each issue, as given in Table I, is determined by multiplying its scores on severity, probability, and timeframe and can be interpreted as a timeframe weighted risk.

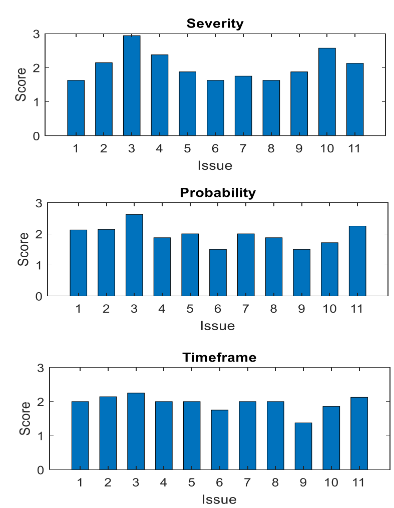

Figure 7. Ranking Results.

TABLE I. FINAL RANKING

Rank	Stability category	Issue
1	Frequency stability	Issue 3: Decrease of inertia
2	Others	Issue 11: Resonances due to cables and PE
3	Rotor angle stability	Issue 2: Reduction of transient stability margins
4	Frequency stability	Issue 4: Missing or wrong participation of PE-connected generators and loads in frequency containment
5	Others	Issue 10: PE controller interaction with each other and passive AC components
6	Voltage stability	Issue 5: Loss of devices in the context of fault-ride-through capability
7	Voltage stability	Issue 7: Lack of reactive power
8	Rotor angle stability	Issue 1: Introduction of new power oscillations and/or reduced damping of existing power oscillations
9	Voltage stability	Issue 8: Excess of reactive power
10	Voltage stability	Issue 6: Voltage-dip-induced frequency dip
11	Voltage stability	Issue 9: Altered static and dynamic voltage dependence of loads

III. QUESTIONNAIRE PART II: OTHER QUESTIONS

This second part of the questionnaire provides insights into the practices at ENTSO-E TSOs in terms of dynamic studies, monitoring of power system stability, and use of real time simulations (incl. hardware in the loop) as well as their future perspectives on these topics. These results are presented as generalized, anonymized answers to the questions asked in the survey. The questions aimed at getting insights into the current as well as future practice on aforementioned topics.

A. Dynamic Studies

How are dynamic studies currently performed: RMS or EMT? What is the frequency (times per year) for performing these studies? What stability aspects are being studied? What is the geographical size of the grid model you use for the different stability aspects? Which utilities are modeled in which detail? Which control systems are modeled in which detail?

Dynamic studies are basically performed in RMS. Dynamic analysis is often performed regularly as part of (long-term) transmission system planning, but also when required by specific projects and developments. One TSO mentions that it performs RMS dynamic studies in real time. For local analysis, the national extra high voltage (EHV) and high voltage (HV) grid is normally considered, while for wider area analysis, either the grids of the surrounding countries are (partly) included or the complete ENTSO-E dynamic model is used. Distribution grids are normally represented as equivalents. Usually, all large generators (at EHV/HV level) are modeled in detail with their controllers (turbine/exciter regulators, automatic voltage regulator, PSS, governor, under-excitation limiter). Models of national generators are often tuned, while large generators abroad are modeled by standard models and parameters. Normally, generic models and manufacturer models are used for HVDC connections and wind farms.

Some TSOs perform EMT studies for the analysis of specific situations. The size of the considered grid and the level of detail strongly depend on the studied situation and the goal of the study. EMT studies are mostly local studies and are performed for new developments like the integration of large PE devices, HVDC connections, flexible AC transmission system (FACTS) devices, large offshore wind farms, mutual coupling of transmission lines, and underground 380 kV cables. The level of detail also depends on the data available from manufacturers and power plant owners. EMT studies are used to perform insulation coordination as well as to study harmonics, saturation and other high-speed phenomena. In EMT studies, control systems of specific projects (wind farm converters, HVDC links, multi-terminal HVDC) can be modeled in detail.

Most TSOs expect that the frequency at which they perform stability studies will not change significantly in the coming years. Stability analysis will be performed regularly and whenever required by new developments. The size and level of detail will depend on the kind of study. The stability studies will basically be performed using RMS models, while the application of EMT analysis is expected to increase in the future. Some TSOs mention that they expect to perform real-time stability analysis in the near future.

B. Load Modeling

How is the load currently being modeled for your dynamic studies? Do you have generic models? If so, how is the parameterization being done? Do you have user defined load models? If so, how is the parameterization being done?

Normally, the load is modeled as static load, with a typical breakdown into constant admittance, constant current and constant power components (alternatively: ZIP-loads). This includes some voltage dependency of the loads. User defined load models are possible, but normally not used, except in specific situations for some large industrial load.

Most TSOs do not expect to change the way of load modeling. Some TSOs expect to use more detailed load modeling, which depends on the availability of data and the development of load characteristics in the future. Dynamic load modeling is mentioned as possibility as well and will be considered in future research. One TSO mentions that load modeling might change when demand side response will be applied more regularly. However, more generally speaking, most TSOs agree that at least the parameter sets of the current load models need to be updated. While research on load modeling was not in the focus of the last years, some TSOs deem new research activities to be necessary due to the trend of an increased share of PEIL.

C. Load Composition

What is the level of motor load in your grid? What is the level of PE load in your grid?

For most TSOs, this is not known at the moment. Estimations are sometimes made by expert judgement, where in general the level of PE is expected to increase significantly in the future. One TSO mentions its level of motor load is about 50% (compared to the peak load) The installed capacities of photovoltaics (PV), wind and HVDC connections are 30%, 13% and 3% respectively (compared to the peak load). Another TSO estimates 5% of (mainly PE connected) wind capacity and 5 HVDC connections. A third TSO has about 65% of industrial load with PE rectifiers, while the motor load is assumed to be so low that modeling would not have any impact. A fourth TSO mentions about 10% wind capacity and a few percent motor load. A fifth TSO says that its level of PE load is essentially 0, while the level of motor load is not known. Although this information is thus not known for most TSOs, these five examples show that the level of motor and PE loads differs much between TSOs.

For future prospects, it is generally expected that the amount of motor load will decrease while the amount of PE load will increase. Some TSOs do not expect any significant change in the levels of motor load and PE load. The TSO with already a large industrial PE-load, expects that its level of PE load stays the same, 70% of the total system load.

D. Monitoring of System Stability

Which Key Performance Indicators (KPIs) do you use for monitoring the stability in your grid? How do you define an acceptable level of stability? What is your current experience with KPIs for stability: do you observe any missed detection, false alarm, etc.?

The TSOs mention several KPIs and criteria to monitor the stability, mostly used in offline dynamic studies. Most of the KPIs and criteria are defined in the network codes.

- Critical Clearing Time (CCT): the fault clearing time of the protection system must be shorter than the CCT (with a certain margin).
- Poor damping: where electromechanical oscillations of generating units are such that the resultant peak deviations in machine rotor angle and/or speed at the end of a 20 seconds period remain in excess of 15% of the peak deviations at the outset (i.e. the time constant of the slowest mode of oscillation exceeds 12 seconds).
- Pole slipping: where one or more transmission system connected synchronous generating units lose synchronism with the remainder of the system to which they are connected.
- The voltages and currents are within predefined limits (critical voltage/current).
- A minimum level of short-circuit power at connection points is available.
- Voltage recovery after a fault clearance is within limits (FRT curve).
- There is no risk of cascading failures noted in simulations.

In real time, the stability of the grid is often monitored indirectly by monitoring the power flows, loads, voltages and frequency, and comparing these to the results of offline studies. The TSO that performs online dynamic analysis uses the following criteria:

- Voltage stability: all transmission system bus voltages are within the security limits, and there is no voltage collapse following any N-1 and some pre-defined N-2 contingencies.
- Transient stability: there is no pole slip of any conventional generator and all renewable generation rides through the three-phase transmission system faults cleared by emulated protection actions.
- Frequency stability: following the sudden trip of a generating unit or interconnector, or a three-phase fault in the transmission system, frequency deviates within acceptable limits and returns to normal.

One TSO mentioned the application of PMUs to measure the synchro-phasors. If there is a large angle difference, the system is studied in offline stability analysis. Another TSO mentions that it uses PMUs at selected substations in combination with WAMS to monitor the system stability in normal operation, during faults and during restoration. These results are then used to calibrate the system simulator.

It is not exactly known yet how stability will be monitored (i.e. which KPIs will be used) in the future. Research is currently performed to define KPIs for the visualization of stability. Some TSOs mention that they will use similar stability criteria as they are using now. It is suggested that future KPIs will probably be frequency-related, related to damping of (inter-area) oscillations, and related to the short-circuit level. Other TSOs mention graphical colored diagrams, synchro-phasor angle (voltage value, angle and trend) or a minimum inertia criterion as indicator. It is also mentioned that the number of stability studies should be increased to obtain more insight into the stability behavior and its relation to KPIs.

E. Modeling of Power Electronics

How are PE (load and generation) currently modeled in your grid: user defined models, black-box models, generic models, static loads? What are the experiences with the current choice of modeling?

For most TSOs, the PE load is not modeled as its presence is insignificant. One TSO with PE load uses generic models for the loads. Another TSO mentions that generic library models are preferred in RMS studies because of easier maintenance of models and data exchange with other TSOs. A third TSO mentions that it uses black-box models as provided by vendors. In EMT studies, black-box and manufacturer models are often preferred because generic models do not provide the level of detail required for the specific EMT study. For PE at generation and transmission level (SVC, HVDC, PV, wind), various models are applied: generic, manufacturer, user defined/developed, black-box, open models. This differs per TSO.

Some TSOs mention that while there are good standardized models for conventional generation, standardized models do not exist for PE devices because of the many different vendors that have their own approaches in control design and philosophy. Dialogue and collaboration with manufacturers and standardization is mentioned to be very important. Open models are preferred instead of black-box models provided by manufacturers. These models should cover transient stability, short-circuit and steady-state behavior, and also cover all the technical capabilities that may be required in the new network codes.

F. Hardware in the Loop Testing

What experience do you have with hardware-in-the-loop (HIL) testing using real time simulations?

Some TSOs do not have any experience with HIL testing. For HIL testing in RTDS, TSOs mention the following applications:

- Protection relay testing
- Controller testing
- HVDC (including protection and control systems)
- PMU simulation
- SVC simulation
- Training of system operators and maintenance personnel
- Testing of altered sets of control parameters

Some TSOs do not consider HIL testing as a necessity, while other TSOs consider HIL testing as a useful approach to obtain more insight. According to TSOs, the following components are used for HIL testing:

- Replica HVDC controllers
- PV inverter
- AC/DC/AC converter for wind generation
- Battery Energy Storage Systems
- Compliance of PE setting with respect to control behavior and disconnection protection
- SVC with Power Oscillations Damping
- Wind Power Plant control systems
- Short circuit protection
- Special protection schemes

Furthermore, HIL testing could be used for the demonstration of harmonic emission.

G. Data Management for RMS/EMT analysis

What gap do you experience for collection and management of data between RMS and EMT models?

There is a large gap between RMS and EMT regarding data collection and management. Generic RMS models are widely available, while EMT models of specific components need to be developed. The data collection for RMS models and EMT models is performed separately because of the different needs of each model. The high level of detail of EMT models seems to be the most challenging. Some TSOs mention that conversion software (e.g. E-TRAN) can convert RMS models into EMT models with an acceptable mismatch. Some typical missing data are related to grounding, inductive coupling between lines, transformer types, and zero-sequence data.

The data exchange with manufacturers for both (black-box) RMS and EMT models, the development of realistic generic models and the construction of a database for all model information are mentioned as the most desired improvements.

H. Network Codes

What is the current experience with the PE-based requirements as stated in the network codes? Are the requirements sufficient?

Most TSOs regard the current network codes as sufficient for the present situation. The current network codes provide a good starting point by specifying general and specific requirements for PE. The harmonization of network codes in Europe and the implementation of European network codes (e.g. NC RfG) into national network codes are currently running. For the future, the definition of network codes for specific PEID, especially for PEIL is seen as the main challenge. It is mentioned that in general there is a time delay between system needs and the development of new network codes.

The TSOs mention that the following topics are currently not covered (enough) in the network codes:

- Voltage distortion
- Harmonic stability issues
- Frequency response of PE
- Control philosophy of PE (from current controlling to voltage controlling)
- Ability of operating in island systems
- Robustness to system splits
- Reactive power requirements
- System inertia
- Minimum short-circuit power
- Negative-sequence injection
- PLL stability

Some of these topics (e.g. voltage distortion and harmonic stability issues) might not be covered intentionally in the network codes, as these are very network specific. Other topics (e.g. frequency response of PE, reactive power requirements, synthetic inertia, negative sequence injection) are to a certain extent covered in the current network codes.

Furthermore, standardized calculation methodologies for frequency, rate of change of frequency, voltage and voltage angles are mentioned as important topics. It is also mentioned that network codes describe requirements for data from new generation modules for stability assessment, while guidelines for collecting data from existing generators are not provided.

IV. Conclusions

Increasing levels of power electronics are expected to pose new power system stability related challenges. To tackle these, the Horizon 2020 project MIGRATE was initiated in 2016. The aim of this project is to develop and validate innovative, technology-based solutions in view of managing a power system which is experiencing a proliferation of power electronics interfaced devices.

One of the first steps within the project was to identify expected stability challenges and then to prioritize these with regard to their severity, probability and timeframe. Based on a questionnaire, to which more than 20 European TSOs responded, 11 issues were identified: two issues relate to rotor angle stability, three issues to frequency stability, five issues to voltage stability, and two issues to power electronics interaction and resonances. Decrease of inertia was ranked as the most important issue, whereas altered static and dynamic voltage dependence of loads was ranked last.

It must be mentioned that the identified issues are not completely independent from each other. The voltage dip induced frequency dip (issue 6), for example, is due to collateral effects of control reactions, combined with decreasing system strength. The resonances in issue 11 are not only due to power electronics, but also due to necessary HVAC underground cables, as it is practically impossible to build new HVAC overhead lines in densely populated areas.

Based on this ranking, some of these challenges are currently being investigated in different work packages across the MIGRATE project. The goal is to define mitigation solutions for these challenges, with the ultimate aim of facilitating more and more renewable energy sources in the power system.

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