FUTURE SYSTEM NEEDS AND THE ROLE OF GRID-FORMING CONVERTERS

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EXECUTIVE SUMMARY

INTRODUCTION

Since the early development of wind power, wind have been allowed (accepted) to be asynchronous generators connecting to the power systems. HVDC and PV technologies have always been converter-based technologies, adding to the group of asynchronous technologies for the last 70 years. Some TSOs have identified future challenges to the operability of their systems in cases where synchronous generators are largely displaced by inverter based generators. Consequently, they are currently studying remedies including changes to the controls of power-electronics-based assets, which can be summarized under the term Virtual Synchronous Machine (VSM). As the name implies, the controls aim to replicate some of the behaviours of synchronous machines valued by TSOs. In some sense, a VSM control strategy aims to change the paradigm for power-electronics-based assets from being asynchronous to being synchronous to the main power system. It may make sense to change the technical characteristics of both wind power, hydro, PV and HVDC, but it is not something which can be easily done within a few years with e.g. minor control modifications. It is much more profound - it will take a very long time and need to be based upon a reasonable solid industry consensus regarding the technical direction. It should also be kept in mind that the inherent technical characteristics for wind power, PV and HVDC are quite different by nature.

Such change to the technical characteristics comes with the following implications for manufacturers:

1) Power electronic hardware design and rating- How much energy storage is needed. How much oversized for fast current injection, etc.
2) Control software development: harmonics, Fault-ride-through (FRT), normal operation, stability, etc.
3) Energy yield, blades, mechanical drivetrain, tower structure and foundation design are intimately interconnected and would all need reconsideration (are some of the advantages of variable speed wind turbine operation negated?)
4) Implications for reliability
5) Implications for product cost (CAPEX), wear and tear and service cost (OPEX)
6) Testing and validation: A clear roadmap (time horizon) to develop and master the technology if the “go” is given

For TSOs it is also very important that a large amount of future assets don’t enter the grid with unintended or unpredicted characteristics which could be very costly to alter (e.g. 50.2 Hz case in Germany). For TSOs the challenges can be presented as follows:

1) What is the achievable level of system support from a converter based unit and what is the price tag?
2) What are the limits to stable operation of existing and new converter based generators?
3) A power converter controlled with grid-forming control cannot be equated with a synchronous generator
4) The behaviour of new converter technologies needs to be learned, understood and undesired characteristics removed. Thus, demonstrators of increasing complexity should be initiated to start

acquiring operational experience with the technology before considering rolling it out on a large scale.

It is at this stage difficult to judge what the most cost-effective solution is to the challenges reported by the TSOs (for which VSM control is one of several potential solutions). The wind industry must engage with TSOs to make sure that challenges are correctly identified and acknowledged, potential solutions are evaluated and the most economic action plans are executed. Excluding the wind industry from this process could lead to an underestimation of cost, effort, and time to develop and mature the technology. At the same time, the wind industry would not like to see that new wind projects are restricted due to system operational issues.

Past discussions clearly show that there is misinformation about what is possible with the existing hardware (electrical and mechanical) within the wind turbines. This is an area where WindEurope and the wind industry can work together with TSOs ensuring that the proper assumptions on capability and cost scaling are used when different technologies are compared.

The goal of this paper is to explain the above stated situation in more detail.

KEY MESSAGES

- The power system is undergoing a radical transformation driven by both advanced system operational practices, as well as new generation technologies (including a significant increase of converter-based generation technologies) and new type of loads.
- WindEurope recognize the tremendous effort of TSOs and utilities worldwide in providing power transmission services, system integration and a market place to facilitate integration of renewables
- The wind industry recognises its role and responsibility in enabling the operation of a power system with higher share of renewables. Ensuring stable operation with high penetration of converter interfaced generation is a common challenge to all participants in the power industry. New technical solutions and operational/market regimes are likely to be needed to address that challenge.
- To master the rising technical challenges a few TSOs have proposed a specific solution: the so called Virtual Synchronous Machine (VSM) control of converters.
- Before specifying detailed solutions, Wind Europe encourages TSOs to **specify and quantify the desired performance (need) –what assumptions and criteria** the need is based upon.
- Presently, there is a lot of uncertainty about the direction and size of the challenge. Equally, it is uncertain to what extend the different technologies are equipped and suitable for a higher degree of system support and interaction. Today there is no real technical consensus but there is a strong need to find answers to those questions; those answers need to be found in collaboration within the power industry.
- Solutions based on new technical developments involving hardware upgrades (of all wind turbine components, not only power converters) lead to increased costs (including R&D) and are time consuming, thus governments and regulators will want robust justifications and the wind industry will need clear specifications and a long-term investment framework.
- Realistically, new solutions (from wind farms) to tackle the changing system requirements are not ready today and require typically 5 years development and testing before introduction.

- Various alternatives exist today and could be used to tackle upcoming issues in the short term (e.g. the deployment of synchronous condensers in the DK transmission system has helped to put an end to the TSO's dependence on must-run thermal generators).
- Cost Benefit Analyses are essential for evaluating the use of existing solutions vs. possible new technology developments for each particular defined system need.
- New VSM-type functionalities will lead to higher CAPEX and OPEX. It is important for the industry to receive the right market signals (market or regulated remuneration) in order to optimise the solution and reduce its cost.
- The wind industry recognises its role and responsibility in the transformation of the energy system and will remain active and engaged in discussions to solve future challenges in the best possible way.

1. SYSTEMS WITH HIGH SHARES OF RENEWABLES

Terminology

SG: Synchronous generation (power plant synchronous generators or synchronous compensators)

NSG: Non-synchronous generators (current technology – wind power, PV and HVDC)

ASG: Asynchronous generation – another typical word used to characterise NSG above

VSM: Virtual synchronous machine – A special control algorithm that mimics parts of synchronous machines characteristics. Sometimes also called 'grid-forming.'

Handling high instantaneous penetration levels

Many countries or regions in the world are aiming to supply 100 % of their energy needs from renewable sources. This type of goal is mainly related to annual energy consumption (electricity without transportation), and electricity consumption is expected to increase thanks to the decarbonisation of transport and heating. The share of converter-connected generation and loads is increasing. Already today we are observing operation scenarios of 100% instantaneous non-synchronous generation (instantaneous power generation) in countries like Denmark and Germany, which have many interconnections with the power systems of neighbouring countries. This is also sometimes called "converter-dominated grids" or "pure converter grids."

There are a few examples worldwide of isolated synchronous zones with increasing shares of non-synchronous generation (NSG), operated satisfactorily with today´s known technology.

- **Texas** is an isolated interconnected system and is operated with high penetration of wind and PV[1], reaching up to 54% of instantaneous NSG.
- **In South Australia**, the dependence on spinning reserve is significantly reduced through much higher requirements for faster frequency response[2].
- **The Iberian Peninsula** has very limited interconnection capacity, with the continental synchronous system (2.9 GW maximum) and traditional grid code requirements not as stringent as those enforced through the national implementation of Reg. 631/2014. However, for several years now the Spanish TSO has been handling high instantaneous NSG rates (in the range of 50 to 70%[3]).

[1] J. Matevosyan, C. Anderson: "Potential for Provision of Ancillary Services from Wind Generation Resources in ERCOT", Proc. 2018 Wind Integration Workshop, Stockholm, Oct. 2018.

[2] New wind and PV projects in South Australia are already obliged to provide synchronous inertia (or a disproportionately larger amount fast frequency response energy). Developers are installing synchronous condensers or BESS. See e.g.

- Lessons Learned from the Recent Blackout, ESIG October 2018 Link
- Generator Development Approval Procedure, South Australia Government, July 2017 Link
- Web update by Electranet, March 2019 link
- Inertia Requirements & Shortfalls, AEMO July 2018 link

[3] Press releases of Red Eléctrica de España. Examples from 21st November 2015 (Link) and 23rd January 2019 (Link).

- **In Ireland**[4], limits towards higher system non-synchronous penetration (SNSP) are realised and already operate in a satisfactory way with today´s known technology[5].
- Going forward, National Grid in **Great Britain** has stated an ambition[6] to run the system with 100% zero-carbon generation by 2025.

There are concerns about the (stability) impacts of high levels of NSG penetration on the classic operation of power systems. However, there is a great deal of uncertainty about the precise mechanisms of instability. Currently, there is limited understanding both of stability limits and the anatomy of the precise sequence of events which may make power systems unstable in the above context. Due to this uncertainty, it is difficult to assess the viability of mitigating the largest instability risks with existing technology.

Main challenges and changes for the system

There is currently a lot focus and **concern on loss of system inertia.** TSOs are monitoring this more and more because they are concerned that this will increase the challenge and cost of controlling system frequency. But system inertia is just one of the several physical aspects that are concerning system operators. These include:

- **The reduction of short circuit current in future systems**. A lack of short circuit current could negatively affect the coordination of protection systems (these recognise system faults by quick injections of current);
- **Reduction in damping torque** for stabilisation of remaining synchronous generators;
- **Increase in network impedance** leading to instability of Phase-locked Loop (PLL)-based generator inverter controls;
- **Frequency control from wind and solar generators** (including maintaining reliable quantities of reserve);
- **Long-distance transmission** of power from new resource areas to existing load areas; and
- **Lack of visibility**/control of large numbers of small generators and demand units (e.g. smart charging EV).

The holistic approach

From a broader perspective, loss of system inertia may result in other challenges. That is why the reengineering of power systems (in part or as a whole) requires a so-called ‘holistic approach’ – one which is supported by the wind industry. While the industry recognises the holistic approach, for obtaining good R&D progress the wind industry needs the TSOs to define the most essential services needed, instead of

[4] M. Gilsenan, D. McMullin, S. Engelken: “System Services by Wind Power Plants Supporting 75% Wind Penetration in Ireland”, Proc. 2018 Wind Integration Workshop, Stockholm, Oct. 2018.
[5] The Irish TSOs (Eirgrid and SONI) use the ratio SNSP (Synchronous / Non-Synchronous Penetration). They can handle 65% SNSP routinely (tends to occur at night) and are aiming for 75% http://www.eirgridgroup.com/newsroom/record-renewable-energy-o/

[6] National grid ESO, April 2019 Link

working on all potential aspects which may become relevant in the future. Trying to address all system challenges simultaneously when defining the technical requirement for specific generators (non-synchronous) might also result in the wind and solar PV industry bearing the full cost of dealing with the system transformation challenges. Such a scenario would discriminate some market players and could have unnecessary cost implications for consumers.

However, if TSOs create marketplaces for specific services to satisfy their system need (services that still need to be valued, defined and which methods for measuring must be developed), that would allow developers and OEMs to optimise, respectively, their sites and products; making it a commercial rather than a grid code legal question of what type of converter control that is deployed to different converter interfaced equipment. Something similar is being proposed by National Grid in their "Zero Carbon Operation 2025[7]".

2. THE NEED-CASE

From system design rule to connection requirements

The `holistic approach` is basically about the ability of a power system to withstand a palette of relevant **system event/system stability performance cases**. Acceptable system performance is often specified in terms of a set of system design events and performance which shall fulfil certain stability criteria (grid design rules).

For a system in a certain stage of evolution, the expected future boundary conditions (e.g. generation mix) are typically defined. For a set of representative base balances (different initial conditions: generation mix, load, ramps) the future system is now tested against a set of system events expected to fulfil a set of already defined system stability criteria. Such studies will normally derive the needed performance for generation assets (point of common connection) and other assets across the system which are needed to maintain the future system security.

In challenging situations, relevant aspects will often be evaluated for adjustments, e.g.:

- Can the boundary conditions (generation mix, level of interconnectors, peak load, etc.) be adjusted?
- Can the grid expansion plans be changed or accelerated?
- Can the events be adjusted?
- Can the stability criteria be adjusted?
- Can the characteristics of existing or future assets be changed?

Understanding the future system needs

There are a number of ongoing research programs and projects involving TSOs aiming to better understand future system needs and the effects of VSM. In the UK, a consortium[8] is looking into the issues

[7] See footnote 6
[8] "Transient voltage stability of inverter dominated grids and options to improve stability",2018-2019, the project is led by NationalgridESO, link

of transient voltage stability of inverter-dominated grids. The Migrate EU-project continues to evaluate system future needs and new options in system operations[9] .

However, progress in understanding the effects of grid-forming converter control is low. It seems to be a major current challenge for the power industry to **specify and quantify** the desired performance (the need) – and explain the **assumptions and stability criteria** that this need is based upon. In our view, the situation is as follows:

- The technical stability studies are either extremely limited or it is not possible for the wind industry to access/discuss them;
- There seems to be no thorough understanding of very high penetration stability mechanisms (i.e. large systems where several mechanisms are often present at the same time);
- There is a lack of understanding, discussion and consensus regarding the sequence of events that make the system unstable; and
- Small study systems are generic but not representative, while big systems often get too complicated to draw meaningful conclusions.

More transparency regarding these events and the associated technology costs will help policymakers take the right decisions (e.g. value of lost load and possible cost of a system split/blackout).

3. COST-BENEFIT ANALYSIS (CBA)

The principle strategy should be to aim at the technology that is able to solve most of the needs in both the short and long term (including lifetime aspects of the solution). It is likely that not only one solution will prevail but rather a small palette of solutions.

The optimal solution may consist of generating plants doing part of the work and, for example, system-level central solutions doing a similar or another part of the work. The optimal share between “generating plants only” – or “generating plants + system level” solutions is currently unknown.

To define and derive these optimums, TSOs need to perform CBAs. Currently no CBAs of this type exist or have been published.

4. REMUNERATION

Power plants incorporating the “new functionalities specified by TSOs” (e.g. VSM control type) will have both life-cycle costs (currently unknown) and increased capabilities (with associated higher investment costs, e.g. use of storage).

An additional CAPEX and unknown OPEX lead to important financing risks that will translate into higher costs for developers and eventually for electricity consumers. Such risks would impose a significant

[9] New Options in System Operation, Migrate EU Project, January 2019 link

burden on the wind industry. To minimise this, a premium on top of the inherent additional plant CAPEX/OPEX should be envisaged.

Such remuneration scheme could follow those used for other ancillary services such as black start, reactive power (e.g. in the UK) and Frequency containment reserve (FCR, in Central-Western Europe)[10]. It is not the purpose of this paper to define the preferred method (whether it is based on cost-recovery basis or as part of a market scheme based on marginal price). But it is important to acknowledge the importance of that market signal (premium) to support the development of the technology in a cost-effective way.

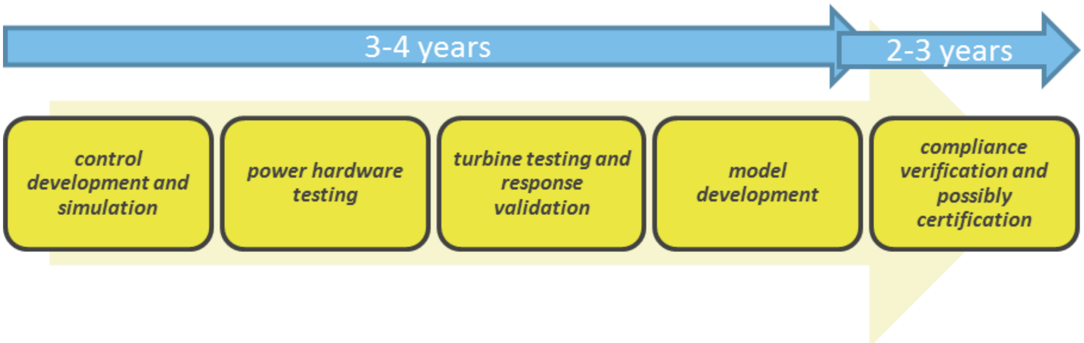
In either case (fixed remuneration, market-based), geographical considerations are important as solutions might only be needed in certain control zones and/or grids.

5. TIME TO ROLL OUT NEW TECHNOLOGY

Development of new features and functions (e.g. a VSM-like control to a level where it could be commercial deployed) needs to go through a high number of R&D steps before it can face full commercialisation and implementation.

The time to roll out a new technology is considerable and should not be underestimated. The following chart presents the needed steps and timeline. The wind industry believes that **at least 3 to 4 years** are needed for manufacturers to bring new control concepts to prototype. **An additional 2 to 3 years** will be needed for grid tests, validation, and full compliance.

On a commercial basis, the type of **new VSM technology would need at least 5 years to be developed from the moment manufacturers have very clear specifications**. If we had clear specifications today (which is currently not the case), we could expect the technology to be ready by 2025.



6. CONCLUSION

The wind industry sees the potential future need for VSM type technology as follows:

- The technical challenge in mastering the grid is increasing;
- It is important to keep in mind that far from all these challenges are due to penetration of renewables;

[10] It is also important to note that other TSOs impose certain services without remuneration (e.g. reactive power in Germany, Primary response for synchronous generation in Spain)

- In the future the grid may need new functionalities, e.g. some type of VSM technology;
- One major challenge is for TSOs to **specify** and **quantify** the wanted performance (need) – **why** it is needed (motivation) and what **assumptions** and **criteria** that need is based upon;
- Most aspects relevant to the **need cases and specification are currently very immature**;
- Today a number of technical solutions exists to substitute some of the functionalities inherent to synchronous generators. These alternative solutions should not be neglected;
- The industry will face high R&D costs – and will need a rather long transition period. So long-term certainty is crucial and market signal (market or regulated remuneration) are needed;
- The situation in 2019 can be characterised as a very **"early phase of pioneering";**
- Realistically the type of new technology should not be expected before **at least 2025**. Meeting this timeline would require having very clear specifications today; which is currently not the case; and
- The industry will remain active and engaged in discussions to solve future challenges in the best possible fashion.

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