System Impact Studies for Near 100% Renewable Energy Systems Dominated by Inverter Based Variable Generation

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***Abstract*—The demand for low carbon energy calls for close to 100% renewable power systems, with decarbonization of other energy sectors adding to the anticipated paradigm shift. Rising levels of variable inverter-based renewable energy sources (VIBRES) are prompting questions about how such systems will be planned and operated when variable renewable generation becomes the dominant technology. Here, we examine the implications of this paradigm shift with respect to planning, operation and system stability, also addressing the need for integration with other energy vectors, including heat, transport and Power-to-X. We highlight the knowledge gaps and provide recommendations for improved methods and models needed as power systems transform towards 100% VIBRES.**

***Index Terms*—Power system operation, variable inverter based renewables, power electronics, energy systems integration.**

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I. Introduction

Ambitious attempts to avoid a rise higher than 1.5 °C in the global average temperature require a rapid reduction in the utilisation of fossil fuels across all energy sectors [1], [2]. The decreasing cost of wind and solar power [3] has made this a more attractive economic prospect. Electrification as a means to decarbonise many services across all energy sectors adds to the need to understand and develop 100% renewable energy systems.

The integration of variable inverter-based renewable energy sources (VIBRES) - mainly wind and solar PV - is especially challenging, mainly due to the variable and uncertain nature of generation and the inverter-based (non-synchronous) interface with the grid [4]. In addition, their near-zero marginal costs and limited power-supply guarantees, challenge designing electricity markets dominated by VIBRES [5].

Some techno-economic studies have examined how hourly energy balances could be maintained in a 100% renewable power system. Some of these studies use unit commitment and economic dispatch to capture wind/solar energy variability/uncertainty, and investigate system and market behavior [6], [7]. A number of studies have coupled other energy sectors, e.g., the heat sector [8], [9]. Often these studies optimize investments in conversion, transmission, and storage of energy, although the operational detail can vary greatly depending on the applied methodology [10]. However, power system stability is often overlooked as part of 100% (energy-balancing) studies, where the main focus is on hourly comsumption-generation matching. No study comprehensively addresses these short term challenges. Exploring possible operational practices with high VIBRES shares, including power system stability, has only started [11].

Concurrently, real-world experience on operating power systems with higher shares of VIBRES is accumulating. Denmark and Portugal are examples of achieving high shares of VIBRES in one part of a large (European) synchronous system. In Portugal the VIBRES share of annual electrical energy is close to 30%, and 100% renewable operation, over several consecutive days, relies on hydro power and exchange with Spain. In Denmark, the VIBRES energy share is approaching 50%, and about 25% of the time renewable generation exceeds the load.

Since 2015 the system sometimes operates for consecutive days without dispatching any of the larger thermal power plants, with system support coming from synchronous compensators and new VSC type HVDC interconnectors [12]. For smaller island power systems the transition to very high or 100% renewables is both studied (Ireland and Hawaii) and implemented in real life (Hawaii, smaller islands in Canada and Caribbean) [13]. Ireland is at 30% VIBRES (mainly wind) by annual energy today, yet it has already reached a ceiling of 65% instantaneous VIBRES share with a target to push that ceiling towards 90% and beyond [14], [15].

Due to the high investment costs and long lifetimes of electric power equipment, the transition to a (near) 100% VIBRES system is expected to happen gradually for most systems. However, already today, a fault may split a large synchronous area, such that one part of the split system must operate at an ultrahigh VIBRES share for an extended period.

Reaching 100% VIBRES implies increasing challenges, but the nature of those challenges depends on what exactly is meant by the term 100% VIBRES:

i) for 100% VIBRES region that is part of a larger non-100% VIBRES synchronous power system the challenges are about balancing, local aspects of stability and efficient sharing of electricity and reserves with neighbouring areas. This highlights importance of how the neighbouring regions are presented in studies.
ii) when a synchronous system gets closer to 100% VIBRES for short periods of time, system-wide stability issues begin to emerge and
iii) for 100% yearly energy from VIBRES a challenge on top of these is the adequacy issue, to meet high demand at low VIBRES contribution.

This article covers all three challenges. A 100% VIBRES power system would differ significantly in both design and operation from traditional practice. There is an urgent need to analyze technical and economic questions related to practical implementation, involving state-of-the-art expertise in power engineering and revisiting tradeoffs between cost efficiency and reliability [16]. Capacity and energy adequacy, operational flexibility as well as stability have to be analysed and resolved, to advise the master problem of planning a future renewable energy system. VIBRES variability and uncertainty brings challenges to current modelling tools, including a need for more detail and integrating planning and operational time scales [16]. The next step is to integrate technical constraints (and solutions) within economic models in a sufficiently proper manner, which requires a detailed review of applied methodologies, as well as practical guidelines. Task 25 of IEA WIND has developed recommendations for wind and solar integration studies [17], complemented by IEA PVPS Task 14, representing solar PV integration within distribution systems. However, these best practices are not sufficient for studying very high shares of VIBRES. This article forms part of ongoing work to fill the gap for such (future) systems.

The transition towards VIBRES dominated systems doesn't occur in isolation, as there will be equal or larger changes in electricity demand as well [16]. Decarbonisation of other sectors, such as transportation, heating and cooling applications, triggers large electrification activities where economically efficient [18]. Energy system coupling, or system integration, brings new demand types that may provide valuable flexibility, for instance on a seasonal basis to the electricity sector [19]. Access to small-scale demand flexibility could be enabled by digital home/building energy management systems, as well as local peer-to-peer markets. Storage, of all types, is developing fast and may provide flexibility and system support services, either together or in competition with new loads [16].

This article predominantly focusses on technical issues, relating to how to model close to 100% renewable power and energy systems, in order to obtain scientific knowledge on the need for, and feasibility of, implementable solutions. Where technical solutions cause additional (investment) costs the issues also become economic, whereby optimization may be required when choosing the "best" mitigation options to achieve costs at an acceptable level. Some of these issues would also need policy input to help solve the problem. The article is structured around the main topics of planning for adequacy (Section II), operational aspects related to balancing and flexibility (Section III) and power system stability (Section IV). Existing practices are summarized, together with noting important gaps in present-day knowledge and study needs for near 100% renewable power and energy systems. Recommendations for how to study a future VIBRES dominated renewable power and energy system are presented.

II. Planning for Adequacy

Planning a future renewable energy system would involve (generation and transmission) capacity and energy adequacy, operational flexibility as well as stability. The current planning tools focus on optimizing generation mix, and assessing capacity adequacy.

A. *Status of Existing Models*

For future studies it is common to use generation capacity expansion models, i.e., investment models which minimize total system cost for given scenarios. This enables optimized generation capacity under different technology cost, performance and policy assumptions, e.g., fuel- and CO_2 prices or phase-out of certain technologies. They can employ a simplified representation of operational details in order to obtain a tractable optimization problem. The planning models do not contain all relevant aspects of operational models and consequently studies that try to demonstrate feasible near 100% renewable energy systems will need to iterate between the planning and other analysis. One aspect that is difficult to capture with investment models is adequacy, since it requires multi-year time series.

Generation capacity adequacy methods are well established [20]. Methods that take into account wind and solar also exist [17], [21]. Generation and transmission adequacy consider the availability of power plants and transmission to serve the demand in all instances. Traditionally this has been particularly for peak demand periods. A common definition is to estimate the loss of load probability (LOLP) or loss of load expectation (LOLE), i.e., probability that consumers are disconnected due to a lack of available generation or transmission capacity. Capacity adequacy calculations focus on capturing rare occasions, tail events, where simultaneous occurrence of high load and failures in generation and/or transmission occur. Multi-area monte carlo techniques are emerging, as well as studies trying to capture energy storage and demand response impacts within generation capacity adequacy [22]–[24].

Analysing energy adequacy has been previously of interest to hydro dominated systems, but for near 100% renewable energy systems this will become more important. Even if enough capacity is installed, the resource may not be there to generate the electricity needed. Energy adequacy can be analysed with scheduling or planning models, but the multi-year time scales makes this challenging. Most methods focus on generation capacity, but transmission and flexibility adequacy is becoming more relevant (Section III).

B. Challenges and Gaps in Knowledge

1) Estimating Future Energy System Portfolios With Capacity Expansion Models: The main gaps in knowledge in planning level analysis is insufficient consideration of the three sub-problems of reliability, flexibility and stability, in addition to the increasing need for energy sector coupling in the planning models. New constraints may be required with existing models [17], or the ability to link such models with more detailed analytical tools [10].

One challenge is to incorporate flexible electricity demand from other sectors, and maximize the total welfare of the entire system. With electrification, surplus electricity can be stored in other energy sectors (thermal storage, hydrogen, synthetic fuels, etc.), which can magnify flexibility in the electricity demand. A further question is how energy sector coupling will be able to provide storage at the seasonal time scale, and thus assist with the energy adequacy challenge [16].

Capacity expansion models have been driven by the need to know which investments should be made – however, the ability to pinpoint that might become more limited when the energy system approaches 100% VIBRES. Investments are driven by expected profits, which are influenced by market prices, bilateral contracts as well as subsidies and taxes. It appears these factors are becoming more difficult to predict when moving towards 100% VIBRES and electrification. When also considering capacity adequacy together with energy adequacy and ramping adequacy, capacity expansion models could benefit from feedback concerning the revenue sufficiency of market participants.

2) Estimating Capacity Adequacy: If capacity adequacy is not sufficient, the standard way to improve is to assume more peak load power plants. However, other options become more relevant with higher VIBRES shares: capacity contributions from neighbouring regions as well as the role of flexible demand and electricity storage. The assessment of capacity adequacy needs to evolve to capture the risks without overestimating the need for back-up capacity with large variable renewable shares.

Larger areas connected by transmission: How to represent the adequacy sharing potential when a larger geographical area is connected by limited capacity transmission?

Flexible demand: Representing the time varying flexibility of demand as a contribution to adequacy will be key, both for new and existing loads that are mainly distribution connected. Loss of load calculations today assume fixed load, thus any loss of load reduces system adequacy. Expected unserved energy (EUE) has a price, but a true model to represent it as a price sensitive demand means that each consumer or type of load needs to be assessed. Cost-reliability interface means getting appropriate reliability taking into account cost efficiency. A least cost perspective would mean disconnecting customers during scarcity hours, e.g., as rolling black-outs (brown-outs).

Storage devices need to be more fully represented, while incorporating state-of-charge limitations during adequacy events. Some demand types, e.g., electric vehicles, space heating and air conditioning, represent untapped resources, where the energy need is relatively constant, but there can be flexibility regarding when to charge/heat/cool.

Wider sector coupling across transport, heating, cooling, gas, H_2, etc. based on power conversion to products such as synfuels and fertilizers make the dimensionality of adequacy calculations even more challenging.

Distribution connected generation, as well as flexibility in loads, can be limited by distribution network bottlenecks.

Weather dependency: Adequacy calculations dependent on many weather linked parameters (temperature, wind speed, irradiation) require extended data in order to reach desired confidence levels.

Energy adequacy: With dominant production from wind, solar and hydro power, there might be very low availability of these sources (even a deficit) for some years, such that the system operates with lower adequacy and flexible demand (i.e., energy rationing) or the system contains sufficient fuel based generation to compenstate for the energy deficit.

C. Recommendations

Capacity expansion:

- Improve representation of demand flexibility, energy storage and sector coupling, to obtain better future price predictions for systems with high VIBRES.
- Include short-term balancing, in order to see the impact of VIBRES forecast uncertainty on the optimal capacity mix.
- Improve representation of grid limitations and expansion costs, since network capacity is very important when determining optimal VIBRES capacity in different areas.
- Improve Generation Expansion Models (GEM) to account for different market aspects, such as price signals for end-users, revenue sufficiency, TSO-DSO interaction and local markets and how these might influence system-level investments.

Adequacy Estimates:

- Develop and test new flexibility metrics. To ensure sufficient flexibility, and include load and storage flexibility, chronological models may be needed for adequacy impacts.

- Update adequacy metrics to reflect the needs of society: which critical loads must be served, and which can be flexible and by what percentage for each type of consumer and area of the network. Use several of the currently available metrics, not just LOLP, which does not indicate how deep (1 or 1000 MW) a problem actually is. Use EUE when the energy deficit volume becomes important. Other recommended metrics are LOLH (Loss-of-load Hours) and LOLE (Expectation). As a first proxy to price responsive demand could be to investigate how much of EUE is acceptable.
- Consider reliability levels: a common LOLP target is 1 event in 10 years, but a lower reliability target such as 2 events per year could be appropriate. Rolling brownouts could be allowed when load (price) responsiveness is insufficient.
- Consider the impact of inter-annual resource variability in the yearly energy reliability.
- Improve data, and sensitivity to capture extreme events. Current models capture correlated events if represented in the data, which means data should be from 10+ years.
- Include neighboring areas, with some recent model developments using Monte Carlo techniques [22].

Some of the measures listed above have already started evolving. This includes economic viability assessment of generation; flow based modeling of the power network and assessing new sources of capacity as required by European law related to adequacy assessment [25] that requests methodology updates in the European resource adequacy assessment [23]. The European Ten-year Network Development Plan includes assessment of the resilience of the system [26].

III. Operations: Flexibility and balancing

Before variability was seen as a major issue, certain modeling simplifications related to how systems are operated were justifiable in order to allow faster and/or more comprehensive models. However, VIBRES dominated systems must be studied with the resulting variability, uncertainty, stability, and sector integration presented in a sufficiently detailed manner in relation to the purpose of the study. For example, moving from hourly resolution models to 5 minute or higher resolution enables greater understanding of short-term balancing issues, while multiple years of weather data will provide additional insights into inter-annual variability.

A. Status of Existing Models

Unit commitment and economic dispatch (UCED) models are widely used to assess the operation of power systems on hourly (or 5–15 min) level. They can assess operational flexibility requirements by allocating operating reserves, and the uncertainty of variable renewables by rolling planning, with updated forecasts in stochastic UCED [27]. The latest developments indicate that it is possible to include stability aspects and be extended to cover sector integration [28].

B. Challenges and Knowledge Gaps

Interaction between neighbouring systems: As with adequacy in Section II.B also for flexibility, access across regions and borders will be more important with high shares of VIBRES. In many regions, there are likely to be complementary sources of flexibility in neighboring regions, and ensuring access to these will improve the overall system balancing.

Capturing more detail in system stability: UCED models should evolve to capture issues such as frequency control, low inertia operation, sufficient voltage control capability, and short-circuit power [29], while recognizing technical limitations. These models need not be complex, but they must address costs and constraints that impact dispatch decisions. Setting up such approximations may require offline studies.

Additional sources of system flexibility could be acquired through new system service requirements like dynamic ramping, fast reserve and congestion products [30], [31]. These could also be supplied by VIBRES, storage and flexible demand from the distribution grid, resulting in a need to improve modeling of distribution limitations in bulk system operational simulation tools.

Representing other energy sectors within UCED models: Decarbonizing all energy sectors will –via electrification - increase the wind and solar energy share in all sectors (gas, transportation, heating, cooling, industry products), offering high flexibility potential to the electricity sector. However, process specific constraints will tend to limit the available flexibility, e.g., space heating seasonality, electric vehicle driving profile, industrial process heat. Additionally, sector coupling requires that not only the ‘production’ side of a generator modeled, but also the fuel storage and consumption side, as the fuel might be delivered by, or have alternative uses in, a different sector [19]. Progress has been made with respect to related methods [32], [33], but much remains to be done [34]. New planning tools are required, while recognizing the need to operate and coordinate across sectors. New flexibility sources may be located anywhere on the electrical network, thus requiring smart grid IT tools to unleash energy system integration’s true flexibility potential.

Changes in dispatch paradigm: (near) 100% renewable scenarios may result in extended periods of very low market prices and some extremely high prices, both framed by high market volatility [35]. Electrification of other energy sectors, an increased volume of price responsive loads, etc. may also happen in parallel, potentially leading to a paradigm shift in how the system is dispatched and balanced. A transition towards flexible, price responsive demand might invert the dispatch operation, i.e., flexible demand is dispatched for the available generation. Despite the uncertainty and complexity, system operation should be prepared for, and robust against, all reasonable outcomes.

Capturing forecast errors As power systems rely more on VIBRES, the impact of forecast errors can become more important, leading to increased reserve procurement/utilization and altering plant commitments, particularly for slow starting units and longer-term storage. Uncertainty also influences when and how VIBRES can provide system services. Improved forecasting of wind/solar variability needs to be captured together with other weather dependent uncertainties. With weather driving the demand, e.g., heating and cooling, the supply side and even the power transmission capacity (dynamic line rating), forecasting should consider all sources of uncertainty together to correctly capture correlation effects. Forecasting of various system characteristics also becomes increasingly valuable, e.g., how much of the demand is flexible, what is the instantaneous synchronous inertia, is there sufficient frequency control capability available, etc. Many of these forecasting methods will need to be probabilistic to adequately capture uncertainty.

Transition to probabilistic models and capturing risk in a decentralized environment: as supply-demand dynamics accelerate, and with growing uncertainty levels, a change from a deterministic risk assessment mindset to something more probabilistic is needed. Many models are capable of probabilistic scheduling, but there has been low industry takeup. Leveraging computational power, better data sets, more user-friendly interfaces and probabilistic tools are an opportunity to reduce flexibility requirements, while increasing availability with cost and reliability benefits.

Capturing grid expansion needs: Increasing VIBRES reliance may cause more bottlenecks at transmission and distribution level. In order to identify potential generation curtailment, improved network modeling and power flow analysis is needed. Using UCED models to analyse alternatives to grid expansion requires the capability to adequately represent those alternatives There are various ways to reduce the (immediate) need for new transmission, including dynamic line rating schemes, greater use of high temperature low sag (HTLS) conductors. FACTS devices, and emerging power flow control technology [36]. Future alternatives might include power to X conversion to different fuels, which might reduce the need to "transport" electricity and thus to build more grid, but instead use existing/new gas/hydrogen/liquid fuel infrastructure. Future alternatives might include power-to-X (P2X) conversion to different fuels, which might reduce the need to "transport" electricity and thus to build more grid, but instead use existing/new gas/hydrogen/liquid fuel infrastructure [37].

Markets: Day(s)-ahead, intraday and short-term markets are typically well captured in modeling tools, and they have been explored for balancing and system services. Changes to market designs arising from increasing VIBRES need to be addressed in future models. The lack of marginal cost energy necessitates a new approach to the governing economics of power systems. Recent years have seen growing interest in different local market designs, and how electricity and flexibility can be traded between different end-users, e.g., peer-to-peer technologies. How local markets will link to each other, and to the markets at system level, is a topic that needs to be studied, especially in areas which expect large growth in distributed energy storage and behind-the-meter PV. It is challenging to develop models for system-level studies which realistically account for resources connected at low voltage grid-levels. Aggregation models are crucial to study the future interplay between large-scale and small-scale VIBRES and flexible technologies.

C. Recommendations

It is not clear-cut how much more detail is sufficient to add to models, and at what VIBRES shares, but at least it is possible to indicate those issues that should be considered:

- *Represent grid and stability constraints in sufficient detail*: grid bottlenecks can cause generation curtailment, so such situations must be located precisely through improved network modeling and power flow analyses. It will be important to consider including new services at the transmission level, such as emerging power flow control technology that aims to eliminate bottlenecks and increase transfer capacity. Stability constraints, e.g., inertia may be represented by system non-synchronous share limits or more directly by inertia or rotational stored energy (MWs) limits; frequency control can be addressed by ensuring sufficient frequency reserves, and voltage stability by confirming the availability of sufficient equipment in relevant locations.
- *Use probabilistic models and risk assessment tools:* apply deterministic and probabilistic assessment approaches for risk-based operation, using new optimization methods and advances in computation, as well as appropriate approximations
- *Enforce high quality information about resources and forecast uncertainty:* Sufficiently high temporal and spatial resolution should be used to ensure that VIBRES output is accurately represented, and with a sufficiently long dataset to cover expected, and extreme, weather patterns. This should be paired with a high quality representation of forecast uncertainty, which integrates weather-dependent parts of the system in multiple decision cycles.
- *Represent other relevant energy sectors:* heating, cooling, transport and P2X will have a large influence on the economics and operations of high VIBRES systems, and they have the potential to be major flexibility sources, so they need to be modeled with sufficient detail and resolution, both for flexibility and process constraints.
- *Represent energy storage and price-responsive loads within system services*: demand response / storage can be cost effective sources of system services, but potentially complex constraints relating to service availability must be modeled. This may require more detailed models of distribution systems or aggregation of distributed resources for bulk systems.
- *Expand market options/products for flexibility trading*: incorporate market options for netting of system/area/nodal/individual imbalances at different time-intervals.

Capturing more detail is emerging, either through adding technical detail and additional constraints to the UCED model [37], or linking the models in order to perform an integrated assessment [39]. However, making available tools or data to cover all of these aspects is on-going work.

IV. Stability, Performance and Technology

Maintaining a (near) constant frequency and voltage is the paramount role of a power system/grid operator. Higher VIBRES shares introduce greater variablity and uncertainty, leading to more frequent and greater voltage fluctuations, and challenges to generation-load balancing. Consequently, the concept of a 'steady state' becomes more 'quasi-steady state'.

A. Status of Existing Models

Power system studies have typically been performed using positive-sequence fundamental frequency tools, with relatively simple models representing physical and control behavior in the cycles-to-seconds timeframe [17]. An aggregated approach has been adopted to approximate grid behavior to assess transient, oscillatory and longer-term dynamic stability, as well as some slower electro-mechanical interactions. Such approaches have served the industry well. For example, low inertia / high rate of change of frequency issues, and available solutions, have been studied and known about for decades [29], [40].

The VIBRES shares seen in some systems today already introduce challenges to voltage and frequency stability, which can, at least to some extent, be addressed using today's models and tools, and mitigated through traditional measures [15]. For example, a range of existing technologies can support voltage stability, including synchronous condensers, STATCOMs, SVCs, fixed/ shunt capacitors, etc., although the drivers and mitigation measures are evolving due to higher VIBRES shares [11]. Similarly, reduced inertia and frequency stability concerns have advanced, but, again, existing measures, such as reducing minimum generation outputs, utilisation of synchronous condensers, etc. can be applied here [40]. In addition, of course, on the VIBRES side, the development of fast frequency support controls to support the system, in the form of variable-speed wind turbines and battery storage is being well documented [29], [40]–[44].

B. Challenges and Knowledge Gaps

VIBRES are different from conventional generation, and their behaviour differs more or less, depending on the implemented controls, and how much they mimic synchronous generators [29]. Major upcoming challenges are depicted in Fig. 1, arranged according to the VIBRES share when concerns become heightened versus the associated difficulty in resolving them. The technological pathway towards close to 100% VIBRES operation remains somewhat uncertain Multiple paradigm shifts will impact on both power system stability and the manner by which it is analysed. These challenges call for more detailed models, more advanced tools for stability assessment, and new ways to control VIBRES to mitigate the challenges [6], [11].

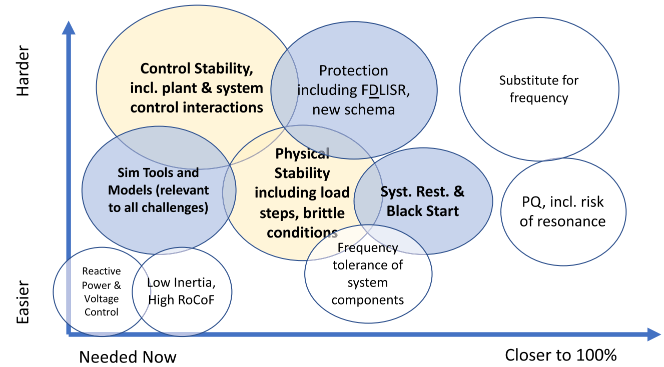

Fig. 1. Summary of challenges and gaps for stability to achieve higher shares of VIBRES versus difficulty to resolve them (FDLISR is fault detection, location, isolation and recover; RoCoF Rate of Change of Frequeny, and PQ Power Quality).

1) Fundamental Questions: Control principles and system stability with a high inverter share are substantially different to that with synchronous machines, and are not fully understood. It is unclear whether system frequency will remain the best parameter to indicate load-generation balance. Fundamental decisions must be made regarding the selection of a suitable indicator, the role of frequency relative to machine speed, and also the frequency sensitivity of active loads.

The proliferation of converter-based generation (and loads) could suggest a transition away from the existing AC-based transmission system to one based on DC, but the sunk investment in network infrastructure and long equipment lifetimes tends to count against such disruptive evolution. However, DC applications are slowly growing in form of HVDC transmission links and local power distribution systems (e.g., in data centres). These DC assets, and possible future extensions of them could be the start of a very slow and non-disruptive conversion towards a DC-based system.

2) Grid Forming Inverter Control: Grid-forming inverters are currently seen as the main innovation on the technological pathway towards close to 100% VIBRES operation. Without synchronous generators, (at least) some inverter-based resources need to participate in creating the grid frequency and voltage, beyond the grid support practices envisioned today. In recent years, efforts have been made to implement grid-forming capability without synchronous generators [45], [46], with the islands of Ta'u [13] and Tokelau [47] as specific examples.

However, analytical studies and field demonstrations are still required to gain experience and to identify necessary enhancements. There is a need to investigate the compatibility of grid-forming inverters with synchronous generators (and other inverter controls). In addition, eventual control mode switching between 100% VIBRES and "synchronous" (less than 100%) operation remains unproven.

3) Upgrading Controls and Control Models: Increasing focus has been placed on improving how VIBRES controls are represented in positive-sequence fundamental frequency models, but the stability of fast inner-loop controls is more challenging, both in reality and to represent within models. Simulation may require faster time steps and more complex structures to represent VIBRES non-linear behavior.

The stability of phase-lock-loop (PLL) controls is highly important for determining if the electrical system will survive a large disturbance. In classical analysis tools, such controls are highly simplified or idealized, which works well for the majority of system conditions seen today. However, with few (or zero) synchronous machines, and low short circuit strength, specific details of PLL controls must be accurately represented, to determine when they may become unstable. To further weaken the value of existing tools, new issues are emerging, such as control interactions due to weak (high impedance) grids or sub-synchronous resonance, and non-fundamental frequency behavior.

Electro-magnetic transients (EMT) tools, with much faster time steps and much more detailed control representations, are required to assess these phenomena. However, EMT tools are not well suited for very large systems with thousands of elements. To bridge this gap, co-simulation, marrying positive sequence and EMT tools, is seen as one solution approach, balancing computational burden against model fidelity.

4) Short Circuit Calculations: Short-circuit current can be seen as a proxy for grid impedance and *network strength*. When the short circuit contribution share from synchronous machines is low at any grid point (high contribution share from VIBRES), the controls of nearby VIBRES (and other power electronics) devices are more likely to interact with each other and to become unstable. Subsequent short-circuit analysis is complicated by the difficulty in estimating the short-circuit impedance of VIBRES inverters [48], [49], due to the their different fault characteristics [50]–[52].

Although some generic dynamic solar PV and wind turbine models have been developed for positive-sequence simulators, most do not include sufficient detail for accurate short-circuit analysis with very high VIBRES shares. This is critical for the assessment of performance under unbalanced faults, and correct operation of control loops (such as the PLL) [52], [53]. In addition, these generic models assume that the inverters operate in a grid-following mode, undermining the validity in an inverter-dominated grid. Consequently, EMT modeling, employing high fidelity control representations, becomes essential for short circuit analysis.

5) Load Modelling: While the main focus has been on converter-interfaced generation, the load-side has to be considered in a similar manner. There is an increasing trend for loads having power electronic interfaces (e.g., light-emitting diodes and electric vehicle chargers). With the converter control being tailored for the needs of the load, the share of constant power loads is increasing, adding negative damping to the power system.

The shift towards power electronics loands also results in more complex load behavior when considering fast time scales. The impacts of control structure and time constans cannot be modelled with simple constant power, current or impedance assumptions. For EMT-simulations, greater emphasis needs to be placed on detailed load modeling.

Another important aspect is the appearance of behind-the-meter generation, altering the "load" behaviour. With increasing amounts of such generation assets, advanced load modelling becomes increasingly important.

6) Protection: The fault-current contribution of VIBRES is usually limited to not more than 120% of the rated value. This might be the most critical aspect of the transition from synchronous machines to power electronics. The fault current of the real machine (unlike other behaviour aspects) cannot be replicated by converter controls (without inaceptable extra costs for overrating the converter). Additionally, the response time depends on the inverter controls [54].

These short-circuit characteristics of VIBRES significantly impact protection coordination. Relays which are designed to distinguish between normal overcurrents and fault currents might operate incorrectly [50]–[52]. The fault current might not contain sufficient negative- and zero-sequence components for proper operation of directional relays [31].

On HV transmission lines, distance or impedance-based protection is common. This relies upon the voltage-behind-reactance principle, whereby the short circuit current is determined by a source voltage and the total driving point impedance feeding the fault. The fault behavior of (grid-following) VIBRES, however, is based upon the injection of a controlled current, which depends on the control design and parameterization as well as the disturbance type, prefault conditions, and even point on wave timing of the disturbance. Consequently, distance protection may false-trip with higher VIBRES shares by confusing the ratio of voltage to current.

Efforts are ongoing to develop current injection models for short circuit and relay coordination simulation tools. Alternatively, communications based distance protection (such as permissive overreaching transfer trip or under-reaching transfer trip schemes or directional blocking schemes), and differential protection may improve selectivity and security, but with added cost and complexity. Protection schemes which recognize emerging technologies, e.g., grid-forming controls, and advanced protection methods for fault detection, location, isolation and recover (FDLISR), is a further step for the future.

7) Black Start: The challenge of black-starting an isolated system in the absence of synchronous generators is closely tied to the ability of VIBRES inverters to create the voltage waveform and provide system "stiffness" (maintain a fixed frequency and voltage). If one or more of these sources can "form the grid", in relative proximity to some load, then they can initiate the restoration procedure. However, a restoration sequence must account for the capabilities and constraints of the relevant generation sources, energy storage technologies, and power electronics interfaces. Key requirements include:

i) Large in-rush currents for electromagnetic grid devices, e.g., transformers and motors, as required for a cold start (cold-load pickup)

ii) Capacitive charging currents for non-energized transmission lines and transformers, while maintaining voltages within acceptable limits

iii) Operation for sufficiently long, such that other resources can come online, and subsequent removal of the black-start resource(s) does not jeopardize system restoration

iv) Ability for the multiple hierarchies of controls to remain stable, with no other synchronous sources, to form the voltage waveform and provide system "stiffness". ´

Detailed studies, or field trials, with full black-start capabilities involving integrated storage and VIBRES are scarce [55], although black-start operation using multiple inverters has been engineered to restore a system from distributed resources with decentralized control [56]. Further R&D is essential to ensure compatibility with present-day systems and maintain system reliability. Finally, it should be noted that the economics of providing such support from the above resources is unclear, while market mechanisms to incentivize investment decisions and commit available capacity need to be developed.

C. Recommendations

The technical analysis methodologies have evolved over time [17], [26] and engagement with industry, market participants, equipment vendors, consultants and research institutes is continuing to further the development of procedures of all of the recommendations below. However, moving towards 100% VIBRES systems implies a fundamental modelling paradigm change for greater detail and higher resolutions than seen today with new stability analysis tools development. Control stability, inertialess power systems and grid-forming inverters, leveraged through VIBRES, must be further developed for high instantaneous power shares. Existing protection systems, designed around synchronous generator characteristics, require modification for large VIBRES shares with different fault characteristics. In addition, technical disparities between inverter technologies and synchronous generators requires the development of novel control schemes for interoperability, new approaches for black-start capability, and distributed control approaches for the larger volume of generating assets, etc. In particular, fundamental changes to maintaining frequency and voltages will impact system operation, as well as underlying analysis tools. However, some clear recommendations for such studies can be made:

- Ensure that the analytical models used are adapted to the characteristics of inverted-based generators and loads. In the latter case, complex, non-linear approaches for various load categories are increasingly required.
- Existing positive-sequence fundamental frequency planning models should be regularly updated to fully reflect the behavior of more advanced functionality, such as fast and primary frequency response. The limiting conditions for these models to predict control stability and fast interactions should be clearly identified, confirming when EMT-based models are necessary for further studies. Particular focus should be placed on accurately representing the PLL control structures.
- Manufacturer-specific EMT models are preferred, as generic EMT model options may not, for example, identify problems or solutions regarding weak grid interconnection or control interactions. Verified generic EMT models are a necessary future development.
- Modern power electronics enable a wide variety of control options to be readily implemented, with the inverters potentially incorporating multiple operating modes depending on local conditions and parameter settings. The variety of control options available should be considered as part of any system study.
- Finally, the inviting potential of advanced non-linear control approaches, such as virtual oscillator controls, should be studied, including the added complexity for controller tuning in such systems, as part of assessing the upper potential for high VIBRES systems.

V. Conclusion

Reaching 100% VIBRES implies vastly different challenges, depending on whether the term refers to (a small) part of a (large) system for part of the time, or representing the yearly average for a (larger) system. For some parts of the world, such as Denmark, the former interpretation is already here. However, reaching the latter interpretation, a full 100% VIBRES system, would mean a radical change, but something that is far away for many, but potentially not all, systems. As VIBRES shares increase in power systems across the world, traditional study methodologies and models require re-examination.

There is need for further development of the models and methods of study, and some key issues and recommendations can be identified across the challenges for planning, operation and system stability:

- *Modelling complexity*: increasing computational burden, as more VIBRES detail needs to be captured – and more data to capture higher resolution and larger areas, with extended time series to capture weather dependent events
- *Larger areas*: the entire synchronous system is relevant for stability studies, and sharing of resources for balancing and adequacy purposes will be more beneficial
- *New technologies*: All tools need to be modified to enable new types of (flexible) demand and storage, while also facilitating further links through energy system coupling
- *Modelling integration*: increased importance of integrated planning and operations methodologies, tools and data. Operational and planning time scales/models need greater overlap. Flexibility needs and plant capabilities must be incorporated within adequacy methods, and stability concerns must be considered for network expansion planning and operating future grids
- *Cost vs. risk*: the reliability interface needs to be revisited, with the evolution of flexibility and price responsive loads to ensure that high cost increases are not imposed when modified reliability targets could yield acceptable results.

As power systems transform towards 100% VIBRES a continuous effort to improve our models and methods is needed to keep up with the pace of change.

The issues identified here are mainly technical, requiring scientific knowledge, but solving them also requires identification of the most economically advantageous solutions, and getting the right policies in place in sufficient time. Economic implications will be seen particularly in planning studies, where determining a cost optimal future generation mix and transmission build out, which is robust to future uncertainties, and which possesses sufficient flexibility in the demand side from sector coupling and storage, will be crucial. Operational issues which are identified will also have economic implications, especially regarding the sharing of system balancing and reaching out to all flexibility sources. Stability issues identified may well result in the largest changes to power system operation and solving them will be mostly technical in nature, but solutions may potentially be implemented through updated grid code requirements (enforcement) and/or through the creation of new system services (incentive), dependent on the severity and timeliness of the identified need, and the ability of existing assets to support the need. A full 100% VIBRES energy system would imply also changes in consumer engagement.

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