

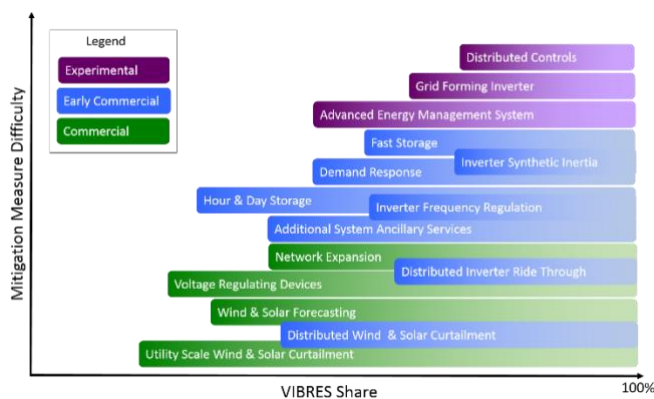
# Addressing Technical Challenges in 100% Variable Inverter-Based Renewable Energy Power Systems

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## Abstract

Rapidly increasing levels of variable inverter-based renewable energy sources (are quickly changing electric power systems and prompting questions about how the systems will be operated when renewable generation become the dominant technologies. In this article, we review the status of this shifting paradigm in power systems throughout the world. We then review the implications of this shift, focusing on the rising challenges, and we provide an overview and technology-readiness classifications of some proposed mitigation strategies. Finally, we highlight outstanding questions that will require solutions to reach these ultrahigh shares of variable inverter-based renewable energy sources.

## Graphical/Visual Abstract and Caption



shows mitigation measures classified (color scale) by technology-readiness stage. Short descriptions of the three mitigation measures follows.

## 1. INTRODUCTION

Variable renewable energy generation capacity, such as wind and solar photovoltaic (PV) power, has increased dramatically worldwide during the past decade and now fulfills more than 7% of electricity demand (BP p.l.c., 2019; *GWEC Wind Report 2017*, 2017; REN21. 2018, 2018). Because of the decreasing costs of these generation technologies (Lazard, 2017; Schmidt et al., 2017; Vartiainen et al., 2019), and because of global carbon-dioxide reduction goals, continued growth in wind and solar generation shares is expected during the coming decades. Against this background, in some power system balancing authority areas, at times the share of variable inverter-based renewable energy sources (VIBRES)—i.e., wind and solar PV—has exceeded 50%. Examples include 50% wind in the Colorado portion of the Western Electricity Coordinating Council (*Texas, Colorado set model for increased renewables integration under Clean Power Plan*, 2015) and more than 100% in Denmark and Portugal (Holttinen et al., 2019). Note, however, that these balancing authority areas are part of

larger, synchronous interconnected power systems. Perhaps more interestingly is the high instantaneous shares achieved in isolated, or non-synchronously connected power systems, such as the island of Tokelau at 100% (Meneguzzo et al., 2015; Rocky Mountain Institute, 2013), Hawaiian island of Maui at 76% (Cochran et al., 2015), the island of Ireland at 65% (Holttinen et al., 2019), and the Electric Reliability Council of Texas (ERCOT) at 54% (Electric Reliability Council of Texas (ERCOT), 2018).

These contemporary experiences, and the continued expansion of renewable generation, raise many questions about how to securely and robustly plan and operate a power system when the generation is frequently dominated by VIBRES. A distinction is made here between synchronous connected renewable sources—such as hydropower, solar thermal technologies, and geothermal power—and those that are connected via inverters and are therefore asynchronous. A second distinction is made regarding subsystems, or regions, that are part of a larger synchronous power system and could experience ultrahigh renewable shares while relying on the remainder of the larger system for stability. Regions of a large synchronous system can be operated somewhat independently, but the underlying physics of AC power flow dictate that there will be important (and generally beneficial) interactions with the rest of the interconnected system. Note that DC-only links between systems serve to decouple two synchronous systems—e.g., ERCOT and the Western Interconnection of the United States are DC-linked, but they are two separate synchronous systems.

In this article, we focus on the dynamic challenges that VIBRES introduce to a power system—for instance, the influence on rotor, frequency, and voltage stability, as shown in the three right-side panels of Fig. 1. These are often overlooked as part of (energy-balancing) work on 100% renewable power systems, where hourly load and generation matching is the primary focus; these are also shown in Fig. 1. There has been considerable work on 100% renewable energy systems (Hansen et al., 2019), but in this work we limit ourselves to 100% renewable power systems and focus primarily on the shorter timeframe (microseconds to few minutes) operational, reliability, stability challenges of these systems, as opposed to the longer timeframe energy balancing issues (several minutes to hours or longer). Low annual energy shares do not indicate low instantaneous shares; indeed, Ireland is at 29% VIBRES (predominantly wind) by annual energy, yet it has already reached an engineering-imposed ceiling of 65% instantaneous VIBRES share (Milano et al., 2018; Sustainable Energy Authority of Ireland, 2018). Additionally, while the associated costs and complexity of solutions to these discussed dynamic challenges are of great interest, they are not yet well defined in the research. When available, information is provided regarding the cost of these solutions, however, we do not speculate in the article if the costs are not yet well understood.

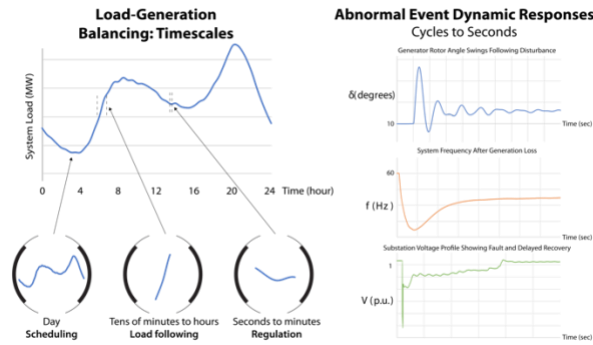


Fig. 1: The timescales of energy balancing as well as the timescales and state variables under disturbances considered in the three power system stability fields.

A 100% VIBRES (synchronous AC transmission) power system would differ significantly in both design and operation from a traditional power system, and the unique technical and economic considerations necessary for such a system are highlighted. Because of the high investment costs and long lifetimes of electric power equipment, for most systems the transition to a (nearly) 100% annual VIBRES system is expected to happen gradually during the next couple of decades. A system split as a result of some disturbance, however, could result in a large region of an existing system potentially operating with an ultrahigh VIBRES share for an extended period of time (hours) today. Further, even at today's modest annual energy shares of VIBRES, the variable nature of renewable sources requires periods of high VIBRES power shares to achieve renewable energy goals. This article delves into the challenges and potential solutions of 100% instantaneous VIBRES AC transmission systems using examples from real power systems or power system studies. An idea that is not considered in this article is switching from an AC-based transmission system to a DC-based one, in part because such an enormous infrastructure transition is unlikely to be widely accepted in the time frames considered.

The remainder of this article is structured as follows:

- Section II provides some examples of current power systems with high shares of VIBRES.
- Section III discusses some of the major challenges associated with designing and operating a 100% VIBRES synchronous AC power system.
- Section IV discusses technical measures that can be adopted to mitigate these challenges as well future research that will be required to realize the integration goals described in this introduction.
- Section V concludes.

## 2. CURRENT STATUS OF HIGH VIBRES SYSTEMS

To delineate the scope of this article, a few examples from real systems are described in Fig. 2 and as follows. Fig. 2 shows examples of synchronous AC power systems with the annual penetration level of VIBRES provided both in terms of maximum instantaneous power share and annual energy share. These are listed by power rating in gigawatts across the x-axis and percentage of VIBRES (maximum instantaneous share in the square, annual share in circles) on the y-axis. The island of Ta'u in the southern Pacific Ocean (an island of American Samoa) is an interesting example of a 100% renewable electric grid: it consists of 1,410 kW of PV generation and 12,600 kWh of batteries. Although this system conceivably fits all the criteria that might be specified for a 100% VIBRES synchronous AC

power system, its limited size—with a peak load of less than 200 kW—and the fact that it includes only one generation technology and storage makes it difficult to extrapolate lessons for larger systems. Iceland is also a 100% renewable power system, but it is dominated by synchronous generators—i.e., hydroelectric and geothermal, which are essentially conventional generation technologies compared to wind and solar. Thus, Iceland’s system is neither planned nor operated much differently from traditional systems. In contrast, Ireland has a synchronous AC power system with a sufficiently high share of wind (29% by energy in 2017 (O’Sullivan, 2018)) that also experiences high instantaneous shares, allowing significant lessons to be learned. Denmark has an even higher share of variable RES: 46% in 2017 [5]; however, one part is synchronously connected to the neighboring Nordic system, and the other part is synchronously connected to the continental European power system, therefore, electrically speaking, Denmark is only a small part of two much larger synchronous systems, and still operates many type-1 wind turbines, i.e. a squirrel-cage induction generator connected directly to the step-up transformer.

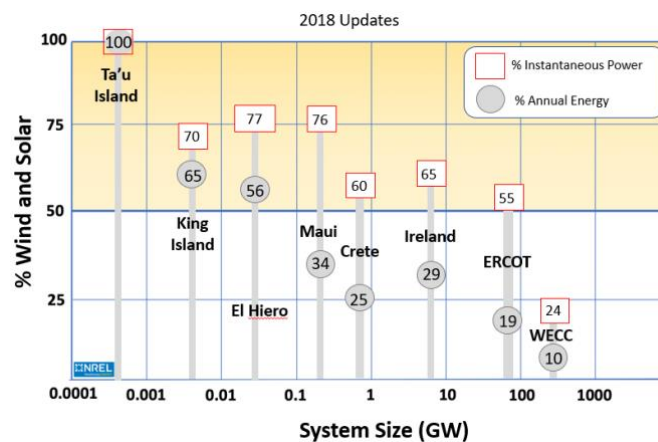


Fig. 2: VIBRES instantaneous and annual shares as a function of power system size. Please note that Ta’u is an island that is part of American Samoa, while ERCOT (Electric Reliability Council of Texas) and WECC (Western Electricity Coordinating Council) are interconnections in the United States.

Current implementations of 100% VIBRES synchronous AC power systems are quite limited (in terms of physical size and power ratings), and, as such, approaches for their design are not yet well defined. Thus, major challenges need to be identified to determine how to design and operate such systems so that future work determine and implement solutions to these challenges. Fig. 3 shows how the present grid, on the left-hand side, is based on large synchronous generators and only a small number of inverters. Synchronous generators provide inertia in power systems as a physical characteristic of their rotating mass. Inertia decelerates initial frequency disturbances, which provide the time buffer necessary for generator governors to respond to load-generation imbalances. The right-hand side of Fig. 3 shows a future grid with more inverter-based technologies deployed and fewer synchronous generators. This type of system would have much less physical inertia on the grid. Grids with high amounts of physical inertia and the capability to source large quantities of short-circuit current are often referred to as strong or stiff, whereas grids with small amounts of inertia are often called weak grids.

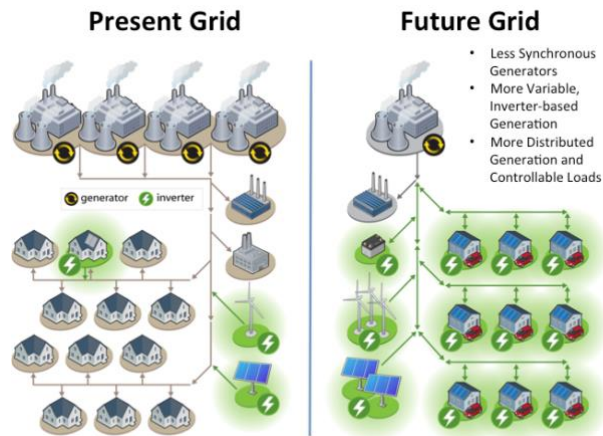


Fig. 3: The existing power system (left) is dominated by synchronous generators having large rotational inertia with a relatively small number of VIBRES. The future grid (right) will be realized as VIBRES shares increase and conventional synchronous machines are gradually replaced with power electronics-based generation, storage, and loads.

### 3. MAJOR CHALLENGES RELATING TO DESIGNING AND OPERATING 100% VIBRES POWER SYSTEMS

The integration of VIBRES is mostly challenging because of their:

- i) Variable and uncertain nature of generation
- ii) Inverter-based (i.e. asynchronous) interface with the grid

Moreover, because these resources have zero, or close to zero, marginal costs, there is also an unresolved challenge of how power markets should be adapted or redesigned to facilitate trading energy and ancillary services in power systems dominated by VIBRES. The following discussion focuses on these challenges for wind and solar because these are expected to be the dominant VIBRES technologies in the time frames considered in this article; however, the discussion should be applicable to other VIBRES technologies that share these two key characteristics.

#### 3.1 Wind and Solar Resource

##### 3.1.1 VIBRES resource variability

Wind and solar power represent sources of variability in power systems that—similar to electricity load—have certain patterns over multiple timescales. Both resources have seasonal patterns that depend on location, but to a large extent they can also vary during a short period of time, such as tens of minutes, at individual locations because of localized conditions. These short-term variations are partially smoothed as the geographic area under consideration grows. Moreover, the solar resource has a diurnal pattern that is mostly a function of geographic location and therefore cannot produce electricity at night, although a coupled electricity or heat storage technology can introduce this capability. This issue is currently being partially mitigated through the large decreases in storage technology costs, which have incentivized the increasing development of combined PV-storage plants which are gaining increasing prominence. However, these hybrid plants tend to have energy storage capacities which are insufficient to completely eliminate the diurnal power profile issue.

The challenges related to wind and solar variability can be very different depending on the duration of the time period considered—e.g., an instantaneous share or annual average share. For an in-depth

discussion on this topic the interested reader is referred to (Graabak & Korpås, 2016; Perez et al., 2018)

### 3.1.2 VIBRES resource uncertainty

Wind and solar power cannot be perfectly forecasted at any time horizon; however, the same is true for electricity load, and thus existing power systems are already designed and operated to cope with uncertainty. With high shares of VIBRES, additional uncertainty will be introduced, and this can affect the reliable operation of the power system. For example, large differences between forecasted and actual production from VIBRES can result in a rapid decline in grid frequency in low-inertia grids. Section IV discusses several mitigation measures to reduce or eliminate the impact of VIBRES resource uncertainty.

## 3.2 VIBRES Grid Interface Characteristics

Although fossil-fired, hydro, and nuclear power stations are based on synchronous generators—which are electromagnetically coupled to the frequency of the power system—the majority of modern-day wind turbines are connected to the grid with either doubly-fed induction generators and partial power-rated converters or variable-speed generators decoupled with full power-rated converters, which essentially decouple these rotating masses from the power system frequency. There are four types of wind turbines (Muljadi & Gevorgian, 2012). Type 1 wind turbines are squirrel cage induction generators with capacitor compensation linked directly to the AC mains with a step-up transformer. These turbines operate over a very narrow slip range and therefore are also referred to as fixed-speed wind turbines. Type 2 wind turbines expand on Type 1 wind turbines by incorporating external resistors in the rotor circuit to control the rotor slip. Type 3 wind turbines use a concept known as slip recovery to allow a far greater range of rotational speeds. These are also referred to as doubly fed induction generators or DFIGs. Up to one-third of the power is passed through a power electronics converter in Type 3 wind turbines. Finally, in Type 4 wind turbines all the output power is passed directly through a power electronics converter. Types 2-4 wind turbines are also known as variable speed wind turbines. PV power plants also employ fully rated inverters but with no rotational aspects whatsoever. The synchronous generator's electromagnetic coupling to the grid—which injects the physics of rotating bodies into power system stability—has been a historical anchor for the secure and robust operation of power systems. Additionally, the rotational aspects associated with synchronous machines have been heavily leveraged in modern control schemes. Thus, the gradual displacement of synchronous generators by VIBRES raises fundamental questions about how future power systems will operate and be controlled.

Fig. 4: Type 3 and Type 4 wind turbines, showing the coupling of these rotating masses with power electronics and thus the decoupling of inertia in a synchronous sense.

### 3.2.1 Maintaining constant steady-state voltages and frequency

In the current paradigm of interconnecting wind and solar PV power plants to the grid, it is assumed that the grid acts as a stiff source of frequency and, locally, also of voltage. Conventional inverters use a technique called a phase-locked loop (PLL) to synchronize wind and solar generators to the existing grid frequency (Dong et al., 2015) and then inject current corresponding to specified real and reactive power set points. Because the inverters are controlled to behave as a current source following the grid—i.e., adjusting their three-phase sinusoidal output to the grid frequency—inverter controls are commonly known as grid following. In this case, the steady-state grid voltage and system frequency are maintained by the synchronous generators, the dominant sources in the legacy system, which the

VIBRES plants follow to inject their power contribution into the grid. Expressed simply, the grid characteristics that grid-following VIBRES track are maintained by synchronous generators.

As the increasing share of VIBRES transforms a conventional synchronous AC power system into an inverter-dominated system, the grid-following control assumption of a stiff grid (i.e., an infinite voltage source) begins to lose credibility. Because grid-following VIBRES require synchronous generators to maintain the stiff grid necessary for control, it follows naturally that removing most, or all, synchronous generators nullifies this control mechanism. In future systems, at least some inverter-based resources will need to participate in maintaining the grid frequency and voltage, beyond the grid support practices envisioned as of today. It is possible to continue to use the legacy method of grid stabilization without fundamental changes with sources that provide sufficient spinning inertia, e.g., synchronous condensers. Although simple to implement, the cost impacts of expanded deployment of such devices operating in the system must be considered.

In addition to grid-forming characteristics, inverters will need to use power-sharing control methods. A widely accepted control strategy for synchronous generators that can be applied to inverters in the bulk power system is droop control (Brabandere et al., 2007), which applies linear relationships between frequency and active power output and voltage and reactive power output, respectively. VIBRES programmed with droop control can thus share power output in ways similar to generators. More innovative methods based on virtual oscillator control have also been proposed (see Section IV) to improve system dynamic performance and contribute to system resilience (B. B. Johnson et al., 2016; Seo et al., 2018), but system-level verification is ongoing, and further advancements are necessary for industry adoption.

Note also that the terms grid-following and grid-forming are not yet particularly well defined, so the term grid-supporting, also introduced here, lies somewhere between the two, implying an ability to support the grid in terms of voltage and frequency control but not able to form the grid voltage and frequency. It is also important to note that the same services could be provided by other non-VIBRES grid assets which are inverter-based, such as battery storage systems and potentially new loads.

### *3.2.2 Inertia – maintaining grid stability through physical response*

Synchronous generators driven by hydro, gas, steam, diesel, or biofuel are typically directly connected to the grid and produce an AC waveform at a specified frequency, coupled directly to the rotational speed of their shafts. When a disturbance creates a load-generation imbalance, the (generally large) rotating mass (of the synchronous generator and associated hydro/steam turbines, compressors, etc.) will oppose the resulting change in rotor speed and thus slow the frequency decline. This classic process of stabilizing AC power systems is normally denoted as the inertial response, which provides time for primary frequency control to adjust the prime mover power output and arrest the change in frequency of the system. Fig. 5 shows the inertia response following a large generation loss. This rate of decline is known as the rate of change of frequency (ROCOF), which is inversely proportional to the total system inertia. Hence, less inertia results in a larger ROCOF. Secondary frequency control follows the primary recovery and brings the frequency back to its nominal value.

Although wind turbines also have rotating masses—in the form of rotating blades—these masses are decoupled from the AC power system through a rectifying and inversion process, as shown in Fig. 4. Additionally, the turbines are typically controlled to maximize the extraction of power from the incoming wind, and when they are in that control mode, they will not provide fast frequency support to the grid unless specifically controlled to do so (Estanqueiro, 2012; Muljadi & Gevorgian, 2012).

Fast frequency support controls (often called synthetic inertia or emulated inertia) have begun to be included in variable-speed wind turbines, and their ability to support the system has also been documented (Ela et al., 2014; Fairley, 2016a; Muljadi & Gevorgian, 2012). Note that fast frequency support responds to the  $df/dt$  quantity shown in Fig. 5. But these controls rely on providing a very fast

response, instead of a direct physical response, which requires the system operators to gain considerable experience with the technology before it can be fully accepted, and the response obtained from an inverter should not be treated the same as that obtained from a synchronous generator. In this same vein, similar fast frequency response (or even grid-forming services) can be provided by other grid assets, whether storage or new demands, however, the most cost effective provision of this service remains an open question.

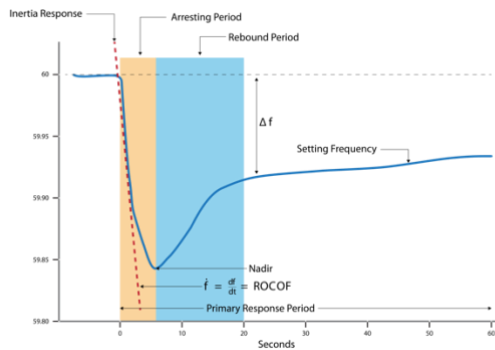


Fig. 5: A generic frequency response trace for a power system following a significant loss in generation.

As the level of synchronous inertial response declines because of the displacement of conventional generators by an increasing share of VIBRES, the initial ROCOF following load/generation imbalances becomes larger (assuming that the dimensioning contingency does not reduce in size). Further, using the stored rotational energy from wind turbine rotating blades means that re-acceleration of the wind turbine will be required after some seconds, and this could hinder system frequency restoration (Eriksson et al., 2018).

As briefly mentioned earlier, there is potential for a portion of an existing system to operate at ultrahigh VIBRES shares following a system split as a result of some disturbance. In particular, this might occur during periods of large export of VIBRES sourced power from one region to another. Therefore, even in a system operating at lower penetrations, care must be exercised to ensure that the ability to operate any potential islands at higher VIBRES penetrations exists.

For most VIBRES types, it is possible to operate them at a suboptimal operating point with respect to the available wind or solar resources. This is subject to lost energy revenue but can provide headroom for fast up-regulation and fast frequency response. Frequency support control has also been actively engineered for PV inverters (Dreidy et al., 2017; Nanou et al., 2015; Pierre et al., 2018). Exploiting the superior dynamic performance of the power electronics-based generation, fast frequency support for a frequency increase can be straightforwardly implemented—i.e., limiting the PV power output in response to a frequency event by operating at an off-maximum power point (MPP). On the other hand, support for a frequency drop would be less straightforward and potentially have a revenue impact by operating the PV inverters at a derated power output, which allows them to retain reserve power capability to support some degree of fast response. The adverse impact on energy yield resulting from off-MPP operation, however, must be compared to the system-wide benefits, and as such changes will be required to existing grid codes to require such a response or markets to incentivize its provision.

### 3.2.3 Black-start: restoring power after outages

The problem of restoring a power system after a partial or system-wide outage is not new, and much work has been completed on developing black-start plans for bulk power systems dominated by synchronous generators (Adibi et al., 1987; Lindenmeyer et al., 2000). For example, the North American Electric Reliability Corporation has standards (e.g., EOP-005-2) that require transmission system operators, generator operators, transmission owners, and distribution providers to develop black-start plans (North American Electric Reliability Corporation (NERC), 2018).

The challenge of black-starting an isolated power system in the absence of synchronous generators is closely tied to the ability of wind and solar PV inverters to maintain a fixed frequency and voltage (also referred to as forming the grid). If one or more of these sources can form the grid, in relative proximity to some load, then they can be used to start the restoration procedure; however, a restoration sequence must account for the capabilities and constraints of these generation sources, the energy storage technologies, and the power electronics interfaces (Lopes et al., 2005). Key requirements for a black-start with VIBRES will include:

- The ability to provide large in-rush currents that electromagnetic grid components, such as transformers and motors, need for a cold start (known as cold-load pickup)
- The ability to provide capacitive charging currents of unenergized transmission lines and maintain voltages within acceptable limits
- The ability to provide black-start support for a sufficient period of time such that sufficient resources are online and the removal of the black-start resource(s) does not jeopardize system restoration

Using wind and solar to provide black-start services has not been actively pursued but will need to be studied to achieve systems with ultrahigh shares of VIBRES.

### *3.2.4 Short-circuit analysis and protection coordination*

Short-circuit analysis in the absence of conventional synchronous generators, or when the grid is weak (i.e., small load changes can change the grid voltage substantially), is complicated by the difficulty in estimating the short-circuit impedance of VIBRES inverters (Burman et al., 2011; Keller & Kroposki, 2010; Muljadi et al., 2010b; Plet & Green, 2014). This is because the fault characteristics of inverters are significantly different from those of synchronous generators (Kroposki et al., 2017; Muljadi et al., 2010a; Winternheimer et al., 2015). Moreover, although some generic dynamic models of solar PV and wind turbines have been developed for use with positive-sequence simulators, these do not include sufficient details for accurate short-circuit analysis with very high shares of VIBRES, such as performance under unbalanced faults, and the correct operation of control loops such as the PLL (IEEE/NERC Task Force on Short-Circuit and System Performance Impact of Inverter Based Generation, 2018; WECC Renewable Energy Modeling Task Force, 2014a, 2014b). Further, the generic models assume that the renewable generation resources operate in a grid-following mode, as outlined in Section II.B.1. In an almost 100% inverter-based grid, these models are insufficient because (at least) some power plants must operate in a grid-forming mode to maintain steady voltage and frequency. Therefore, existing short-circuit analysis approaches do not accurately determine short-circuit current levels in an inverter-dominated grid.

The short-circuit characteristics of VIBRES impact protection coordination under very high shares (or even 100%) of inverters, given that they provide much less fault current and their response time depends on how the inverter controller is programmed (Keller & Kroposki, 2010). Because the fault-current contribution is usually limited to 120% of their rated currents, relays that distinguish between normal overcurrents and faults based on the short-circuit current levels might operate incorrectly [31], [34]. In addition, the fault current contribution from inverter-based resources might not contain sufficient negative- and zero-sequence currents for the proper operation of directional relays (IEEE/NERC Task Force on Short-Circuit and System Performance Impact of Inverter Based Generation, 2018).

## **4. MITIGATION MEASURES AND AREAS FOR FUTURE RESEARCH**

Different mitigation measures can help overcome the challenges discussed in Section III. Fig. 6 shows the need for different mitigation measures as a function of the maximum instantaneous share of VIBRES. Fig. 6 does not specify precise VIBRES shares (in percentages) and/or power system size (peak load in megawatts) because the relationships among these different mitigation measures—as a function of system size and/or renewable share—are system-specific. The most appropriate mitigation measures for a particular power system can be obtained only after a detailed analysis of the system.

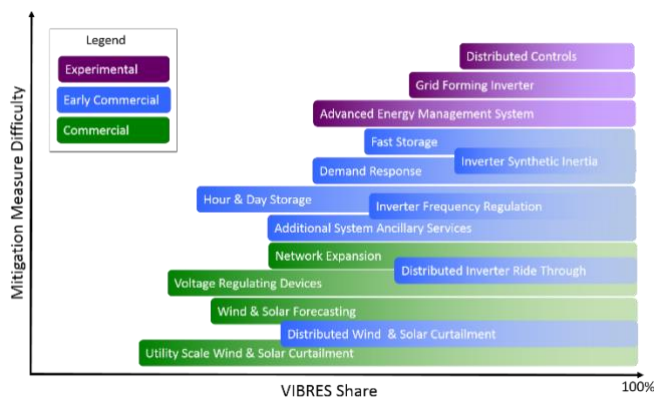


Fig. 6: Mitigation measures in power systems as a function of the maximum instantaneous share of variable renewable energy for the reliable operation of a power system

Fig. 6 shows mitigation measures classified (color scale) by technology-readiness stage. Short descriptions of the three mitigation measures follows.

#### 4.1 Experimental

##### 4.1.1 Distributed and autonomous control

With most, or all, generation being distributed and inverter-connected, existing communications networks (to/from power plants) for control and operation might not be universal. In such cases, distributed and autonomous control is needed to ensure reliable system operation. Virtual oscillator control is a newly proposed technology that allows distributed inverters to be autonomous and ensures their controllability as well as overall system operability.

Virtual oscillator control is inspired by the Kuramoto model (Bonnell, 2011), which describes synchronization between weakly coupled oscillators and assumes that the interactions between them depend sinusoidally on the difference between their phase angles. For control purposes, the behavior of an oscillator (a nonlinear dead-zone oscillator) is emulated in all voltage source inverters that are coupled by the underlying electric network (B. B. Johnson et al., 2014), (Kroposki, 2016), thereby leading the system similar to the Kuramoto model. It has been shown that with certain design parameters, virtual oscillator-controlled inverters mimic the behavior of droop control when the system is in a quasi-stationary steady state (Sinha et al., 2017) and show superior dynamic load-sharing and synchronization performance to conventional droop control (B. Johnson et al., 2017). Additional research and development is required for real-world applications, however, such as compatibility with synchronous generators and other inverter controls as well as fault/protection operations.

##### 4.1.2 Grid-forming inverters

In recent years, efforts have been made to introduce grid-forming capability in island power systems without using synchronous generators (B. B. Johnson et al., 2014; SMA Solar Technology, 2011; Mueller-Stoffels et al., 2013). The islands of Ta'u (Glenwright et al., 2016) and Tokelau (*Tokelau Renewable Energy Project Case Study*, 2013) are examples of actual implementations of grid-forming inverters that can function in the absence of synchronous generators. Small off-grid hybrid power systems that use a diesel generator, energy storage, and VIBRES typically employ an inverter that can produce an AC grid when the diesel generator is turned off. Recently proposed grid-forming inverter-based solar PV systems can act as voltage sources, emulating the real and reactive power behavior of synchronous machines and providing fast frequency support to the grid (Huang, 2017). Studies and field demonstrations of the parallel operation of grid-forming inverters of large VIBRES plants are essential to gain experience with and identify the enhancements required in the ability of grid-forming inverters to set and maintain grid voltage and frequency under very high VIBRES-based grids. Understanding the role of grid-forming distributed VIBRES in maintaining grid voltage and frequency, and their interactions with large grid-forming VIBRES, also needs more research and development to derive standards and regulations suitable for inverter-dominant power systems.

## 4.2 Early Commercial

### 4.2.1 Fast frequency response

In a synchronous AC power system with a very high share of inverter-based renewable generation, VIBRES might need to provide fast frequency support to prevent unacceptable frequency levels that could trigger underfrequency load shedding. Much work has been performed in recent years to evaluate the ability of VIBRES and battery storage to provide fast frequency support (EIRGRID & SONI, 2016; Everoze, 2017; Fairley, 2016b; Muljadi et al., 2012; Rahmann & Castillo, 2014; Spahic et al., 2016; Zarina et al., 2012). Studies of high VIBRES shares in Ireland's system show the need for carefully coordinating the timescales of fast frequency response to properly reduce the ROCOF during a contingency event (EIRGRID & SONI, 2016). It was further observed that if the inertial response is modified to include a droop-based response during the frequency recovery, then the overfrequency problem can be avoided.

The advantages of combining fast frequency and primary frequency response in quickly reducing the ROCOF and increasing the frequency nadir have also been highlighted in (Lidström & Wall, 2016; Muljadi et al., 2012; Pierre et al., 2018; Singhvi et al., 2013; Spahic et al., 2016; Zhang et al., 2013). The controller speed of response can be a concern in small systems with very low synchronous inertia because unlike synchronous generators that respond naturally to changes in rotor speed, a frequency disturbance must first be detected before the grid-following inverter controls can respond (Everoze, 2017). Synchronous condensers can also be used to complement the response from wind, solar, and battery storage plants while providing reactive power support, much like synchronous generators. These types of services have seen limited direct utility thus far, although some interconnections with high shares of VIBRES, such as ERCOT, have begun requiring droop-characterized frequency responses from these resources (Lidström & Wall, 2016). Additionally, in December 2015, fast frequency controls on wind turbines were said to have prevented a frequency drop by 0.1–0.2 Hz in Hydro Quebec (Fairley, 2016a).

### 4.2.2 Demand response

If demand flexibility is an available option, by partially reducing or increasing load (industrial, commercial, and residential) as a function of system conditions (or based on price signals), larger shares of VIBRES can be more efficiently integrated (Gils, 2014; Hummon et al., 2013; Pfeifer et al., 2018). In many countries, energy use in the transport sector—as well as the heating and cooling sector—is of a similar order of magnitude to electricity demand, and consequently there is large flexibility potential in those energy sectors that are gradually becoming more electrified. There is an

increasing trend in loads to include power electronic interfaces to the grid. Examples include light-emitting diodes, variable-speed drives, computer and electronic power supplies, and electric vehicle chargers. These devices are using power electronics to increase energy efficiency, but they can also be more easily and finely controlled than resistive loads. These could better support a high VIBRES system if they had grid-supporting capabilities, such as reacting to a grid frequency events. ERCOT, with a large share of VIBRES, uses demand response as a mitigation measure following disturbances (Matevosyan, 2019).

#### *4.2.3 Additional system ancillary service*

With additional shares of VIBRES, power systems might need additional sources of system flexibility that could be acquired with additional ancillary service requirements (Andreotti et al., 2010; Kroposki et al., 2010). These could include, but are not limited to, dynamic flexibility reserves and/or reserve ramping products. Allowing inverter-based power generators (such as wind and solar power plants) and flexible demand to contribute to such services assists in the goal of increasing shares of VIBRES.

#### *4.2.4 Distributed inverter voltage and frequency ride-through*

Most of today's distributed VIBRES disconnect from the power system (particularly if connected at lower voltage levels and with a smaller installed capacity) when a change in frequency and/or voltage exceeds limitations that are relatively more stringent than those for generation connected to the bulk power system. In a scenario with a large share of distributed VIBRES, the loss of these sources after a system disturbance could exacerbate the scenario on the system—i.e., a cascading event—by magnifying the original disturbance (Kaestle & Vrana, 2011; Kenyon & Mather, 2018). Within the California Independent System Operator territory, the Angeles Forest fault event in April 2018 led to the loss of at least 130 MW of rooftop distributed solar generation, whereas the Palmdale Roost Forest event in May the same year resulted in the loss of at least 100 MW (NERC and WECC Staff, 2019). The exact loss is challenging to determine because these resources operate beyond utility visibility, and the generation loss is registered only through a load increase. Distributed generation that can ride through frequency and voltage deviations would provide an additional capability that is needed under high shares of renewable energy. Voltage and frequency ride-through has already begun to be implemented in distributed VIBRES, and rules such as Rule 21 in California (Brown, 2017), VDE-AR-N 4105 in Germany (VDE, 2019), IEEE 1547-2018 (Nagarajan, 2018) and EC regulation (EU) 2016/631 (Commission Regulation (EU) 2016/631 of 14 April 2016, 2016) require distributed VIBRES to have voltage and frequency ride-through capability.

#### *4.2.5 Distributed wind and solar curtailment*

Many of today's small distributed VIBRES are behind the meter and thus invisible to the system operator. The possibility for operators to curtail distributed resources with controllable inverters would help increase shares of variable renewable energy in isolated power systems. Regulatory changes to allow such control over customer-sited VIBRES as well as enhancements in bulk power and distribution management systems will be needed to enable the curtailment of distributed VIBRES. Distributed energy resource management systems are being developed with the capability to implement curtailment in distributed VIBRES equipped with smart inverters (Enbala, 2018).

### **4.3 Commercial**

#### *4.3.1 Network expansion*

Interconnecting and expanding grids can enhance the integration of larger shares of variable renewable energy sources by reducing their combined variability and uncertainty (Bloom et al., 2017). Depending on the system size, network expansion could be performed at the transmission and/or distribution level. Network expansion might reduce the need for renewable curtailment, balancing resources, and storage (Steinke et al., 2013) and thus reduce the system operating cost while enhancing system reliability.

#### *4.3.2 Voltage-regulating devices*

Voltage-regulating devices can be used to control the voltage in the distribution network—for example, by reducing high voltages that could be caused by distributed solar PV. Options include synchronous condensers, static synchronous compensators (STATCOM), static volt-ampere reactive (VAr) compensators, volt/VAr control of PV inverters, and fixed or switched shunt capacitors. The different options present different capital and operational costs and differing steady-state versus dynamic capabilities, which must be considered as part of any decision process. An interesting development in voltage regulation with large quantities of distributed VIBRES is the capability of these devices to participate in voltage support, indicating that a large network of voltage-supporting devices (under appropriate control) are being installed only because of the nature of the interfacing device (inverters).

#### *4.3.3 Wind and solar forecasting*

Performing and using wind and solar power forecasts to inform power system operational decisions is useful for any shares of VIBRES to reduce the need for wind and solar curtailment as well as increase the operational value of other system elements, including other electricity generators and energy storage devices. Additional sensors and measurements might be needed in future systems to improve wind and solar power forecasts. Wind and solar power forecasting remains an active area of research (Antonanzas et al., 2016; Foley et al., 2012; Ren et al., 2015).

#### *4.3.4 Utility-scale wind and solar curtailment*

Communications and controllability of wind and solar power allows for the integration of larger shares of variable renewable energy sources, especially in the presence of distributed VIBRES, which might not be able to be controlled by the operator (Bird et al., 2014; Denholm & Mai, 2017). Today, most utility-scale wind and solar power plants can be operated to provide down-reserves through curtailment; however, in a future power system with much higher VIBRES shares, they might need to also provide up-reserves. Operating wind and solar power plants below rated power output enables providing up-reserves, which can increase their use because thermal power plants—which would otherwise be needed to provide those services (Gevorgian & O'Neill, 2016; Kiviluoma et al., 2014)—could then be decommitted. One example of this in current practice is Xcel Energy Colorado, which uses wind power plants to provide both up- and down-regulation reserves.

### **4.4 System-wide mitigation measures**

#### *4.4.1 Energy storage*

Similar to demand response, energy storage of different types (battery, thermal, pumped hydro, H<sub>2</sub>, etc.) can provide an arbitrage opportunity over time that the system operator can use (directly or indirectly, depending on market regulations) to integrate a larger share of variable renewable energy sources that do not necessarily generate electricity when consumers demand it. Storage is more valuable in geographically smaller power systems because these systems have less geographic

smoothing of variable renewable power. There is a very close coupling between energy storage penetrations and the rate of renewables curtailment as VIBRES penetration rates increase.

#### *4.4.2 Short-circuit analysis and protection coordination*

An important component of addressing the short-circuit analysis and protection coordination challenges under very high or 100% VIBRES power systems is to develop generic models for inverter-based generation resources that can capture their response during faults. The most accurate approach for doing so uses proprietary inverter models, which are simulated in an electromagnetic transient (EMT) program, along with an EMT model of the power system. The main drawback of this approach is that proprietary models of all the required inverter-based resource controls might not be accessible. EMT modeling might also be constrained by the amount of data required to develop an accurate EMT model of the power system being studied, and the computational burden also needs to be carefully considered. An alternative approach developed recently is to use iterative phasor-based models that simulate the nonlinear response of inverter controls (EPRI, 2015; IEEE/NERC Task Force on Short-Circuit and System Performance Impact of Inverter Based Generation, 2018). An advantage of this approach is that these models can be used in traditional steady-state phasor-based models used for calculating fault currents, which obviates the need to develop and use detailed EMT models.

In addition to accurately calculating the short-circuit currents, relays might need to be upgraded or replaced so that they can correctly respond to faults while differentiating between faults and normal overloads under low fault currents in very high or 100% VIBRES-based systems. Because of their sensitivity, line current differential and pilot wire schemes can be good choices for such systems (IEEE/NERC Task Force on Short-Circuit and System Performance Impact of Inverter Based Generation, 2018). Similarly, inverter-based renewable generation resources can be required to support negative-sequence directional relaying (IEEE/NERC Task Force on Short-Circuit and System Performance Impact of Inverter Based Generation, 2018). Another potential option for fault detection is traveling wave analysis (Velaga et al., 2019), where the wave front caused by a fault is measured, as opposed to fault current magnitude itself. These high frequency transients can be used to distinguish not only between normal and faulted operation, but also between different types and locations of faults. Grid codes related to the modeling requirements for short-circuit analysis and the performance of protective relays might also need to be modified.

#### *4.4.3 Markets adapted for high variable renewable systems*

Traditional marginal cost-based markets present a challenge for high VIBRES shares because of the near-zero marginal cost of generation from VIBRES, which depresses energy prices (Sensfuß et al., 2008; Trötscher & Korpås, 2008), making it difficult to recover capital costs in systems that operate for significant periods of time with a 100% VIBRES share. Products such as guarantees of origin, power purchase agreements, and other long-term contracts can provide the necessary income to wind and solar PV owners today, but they do not guarantee sufficient flexibility when VIBRES dominates energy production. An increasing use of electricity in the transport and heat sectors can improve power prices, especially during low-price periods; however, their increased use is presently impeded by flat energy-based grid tariffs and electricity taxes that do not reflect power price variations. Capacity markets might be another viable option, but they are not straightforward enough to define the requirements and payment structures for flexible capacity in future VIBRES-dominated markets. In a market with 100 % VIBRES, the prices will no longer be set by fuel prices of thermal generation but rather by the willingness to pay for electricity. If little flexibility is available, one can imagine high volatility scenarios where the prices either are zero or very high (defined by price caps or the value of lost load). The demand side could therefore play a dominant role in the short-term markets, where indirectly or directly flexible consumers react to variations in available power (O'Connell et al., 2014; Strbac, 2008). Storage can also help flatten the price (Green & Staffell, 2015), and their bids should

reflect the expected value of storing energy for later use, as is already the case in the hydro-dominated Nordic power system (Fosso et al., 1999).

Because a substantial part of new VIBRES, such as distributed PV, is developed at the end users, there is now increasing interest for local markets (Hvelplund, 2006; Ilic et al., 2012). Local markets also have a benefit of enabling access to other parts of the energy system, such as heat and transport. Local markets are currently being analyzed and tested based on different designs (Mengelkamp et al., 2017), such as peer-to-peer trading (*P2P-SmarTest Project*, 2015) and different algorithm-based pricing schemes (Trong et al., 2016). In any design case, local markets must be able to 1) interact with the overlaying markets and 2) provide sufficient price signals for investments in generation. For 1), it is necessary for the local markets to handle bottlenecks in the distribution grid in an effective manner and to avoid curtailment of end-user generation that otherwise could have been sold to the overlaying market. Thus, a distribution system operator might need to play an active role in these markets to mitigate bottlenecks both during operation and through grid investments. For 2), it is still a question whether local markets will create the necessary incentives for investments in local generation. For generation owned by the end user, this might not be a problem because only the power surplus and deficit need to be traded. On the other hand, generation companies are fully exposed to the market prices and might therefore prefer long-term contracts for the bulk energy in future markets and use the short-term market for trading imbalances. Such consequences of different local and system-wide market designs on cost-recovery for generators, storage, and flexibility providers as well as for the economics of the whole system are not yet well-covered in the existing literature and are an area of ongoing research.

#### 4.4.4 Black-start support

Given the experience of using synchronous generators powered by fossil fuels or hydropower for black-starts, the presence of these resources in a very high or 100% VIBRES-based grid can simplify black-start procedures. If such units are unavailable, however, or if it is desired to use VIBRES to provide black-start support, then the latter must satisfy the black-start requirements listed in Section II.B.3. Battery storage might well play a critical role in enabling black-start capability with VIBRES because storage is always available if charged.

Typically, small batteries are used to start diesel generators for system restoration. In recent years, large battery storage units have been used to kick-start gas turbines. For example, in Germany, a 15-MW /15-MWh battery energy storage plant was used to kick-start a gas turbine. The power to the gas turbine was provided by the battery plant over a microgrid that was not serving any load (*Expanded 15MWh German battery park demonstrates successful black start | Energy Storage News*, 2017). Similarly, a 33-MW/20-MWh battery energy storage plant was used to kick-start a 44-MW combined-cycle gas turbine in the Imperial Irrigation District in California (*California battery's black start capability hailed as 'major accomplishment in the energy industry,'* 2017). These examples show the potential for battery storage to form the grid and support the energization of cold loads. The potential for voltage source converter-based (VSC-based) high-voltage DC (HVDC) lines to provide black-start support if the grid at one end of the HVDC experiences a blackout has also been demonstrated. It was shown in (Jiang-Hafner et al., 2008) that VSC-HVDC was able to act as a stiff voltage source and maintain the grid frequency while energizing a 250-MVA transformer- and 10 MW of auxiliary load of a generation plant at the end of a 200-km long, 330-kV transmission line. The VSC-HVDC was able to manage the inductive inrush currents and the reactive charging currents while energizing the transformer and the plant auxiliary loads over a long transmission line. On the other hand, black-start operation using multiple inverters has been engineered to realize system restoration from distributed resources with decentralized control that will increase system resilience, but further research and development is essential to ensure compatibility with present-day systems and maintain system reliability (Lu et al., 2019; Seo et al., 2018).

This discussion suggests that VIBRES backed by battery storage or HVDC can be used to provide black-start support, although detailed studies or field demonstrations of full black-start capabilities with integrated storage and VIBRES are lacking. Moreover, work remains to understand the economics of obtaining black-start support from these resources. Research on developing market mechanisms to incentivize developers of these resources to commit the capacity to provide black-start support in grids is also required.

## Conclusion

As VIBRES shares increase in power systems across the world as result of a variety of economic, environmental, and political factors, the traditional measures and approaches to power system operation require reexamination. The variable and uncertain nature of these VIBRES will require new methods in dispatch to maintain appropriate reserves for power system regulation. The protection systems in place today, which are designed around the characteristics of synchronous generators, will require amendment under large shares of VIBRES with different fault characteristics. The lack of marginal cost necessitates a new approach to the governing economics of power systems. The technical disparities between the power electronics used for these resources and traditional synchronous generators require the development of novel control schemes for interoperability, new approaches for black-start capabilities, and distributed control approaches for the much larger quantity of generating assets. In particular, grid-forming controls and characteristics leveraged through VIBRES must be further developed for high instantaneous power shares.

The dynamic challenges that VIBRES introduce to power system stability are often overlooked as part of (energy-balancing) work on 100% renewable power systems, where hourly load and generation matching has been the primary focus. Contemporary research-and-development efforts are focused on technical and market solutions that will enable 100% VIBRES power systems, and these are reflected in the power system studies as well.

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