Foundations and Challenges of Low-Inertia Systems

(Invited Paper)

Federico Milano
University College Dublin, Ireland
email: federico.milano@ucd.ie

Florian Dörfler and Gabriela Hug
ETH Zürich, Switzerland
emails: dorfler@ethz.ch,
ghug@ethz.ch

David J. Hill* and Gregor Verbič
University of Sydney, Australia
* also University of Hong Kong
emails: dhill@eee.hku.hk,
gregor.verbic@sydney.edu.au

***Abstract*—The electric power system is currently undergoing a period of unprecedented changes. Environmental and sustainability concerns lead to replacement of a significant share of conventional fossil fuel-based power plants with renewable energy resources. This transition involves the major challenge of substituting synchronous machines and their well-known dynamics and controllers with power electronics-interfaced generation whose regulation and interaction with the rest of the system is yet to be fully understood. In this article, we review the challenges of such *low-inertia* power systems, and survey the solutions that have been put forward thus far. We strive to concisely summarize the laid-out scientific foundations as well as the practical experiences of industrial and academic demonstration projects. We touch upon the topics of power system stability, modeling, and control, and we particularly focus on the role of frequency, inertia, as well as control of power converters and from the demand-side.**

Keywords*—Low-inertia power systems, frequency stability, rate of change of frequency (RoCoF), converter-interfaced generation (CIG), grid-forming control, MIGRATE, RE-SEVE, CSIRO.

I. INTRODUCTION

In an effort to render the electric power system more sustainable, increasing shares of wind and solar generation are being deployed all around the world. The goal is to replace fossil fuel and nuclear based generation by renewable resources. Hence, the total global installed capacities for wind and solar resources have increased by a factor of about 6 for wind [1] and a factor of 40 for solar power [2] in the past decade.

Due to the physical characteristics of these resources and the fact that they are typically connected via power electronics to the system, their interaction with the grid is substantially different from the interaction of the traditional plants that use steam and hydro turbines. While the rotating parts of the synchronous machines inherently provide inertia to the system, this is not the case for the resources that are connected via power electronics. The consequence is that in the case of disturbances and supply/demand imbalances, the inertia that slows down the natural reaction of the system and buys the controllers and the operator time to take actions is significantly reduced because the resulting rate of change of frequency is much higher in systems with low inertia.

This paper focuses primarily on frequency and inertia issues. We note, however, that replacing synchronous machines by non-rotational sources has more general consequences. Power electronics converters introduce faster dynamics than conventional controllers for both active and reactive power support. This may create unexpected couplings and control approaches based on time-scale separations may become more brittle and increasingly less valid. Likewise, system control tasks predominantly provided by synchronous generators (such as voltage support and oscillation damping) have to be increasingly shouldered by non-synchronous devices.

Large-scale low inertia power systems have been merely a theoretical concept up until just a decade ago but have now become a reality. Some countries already have solar and/or wind generation capacity able to cover more than 100% of the demand. And some power systems around the world are facing the challenges caused by low inertia. The following are relevant real-life examples.

- Australia [3]: The level of combined wind and solar capacity is rapidly increasing and has reached 20% in the National Electricity Market. However, the grid is isolated with a long linear or 'stringy' topology (over 5000 km synchronous) which leads to special difficulties. Furthermore, a multiple of the already existing renewable capacity has additionally been proposed. There are already concerns about inertia distribution.
- Central Europe [4]: A task force comprised of European system operators studied the frequency behavior for the European system for decreasing system inertia. The main conclusion is that in the interconnected mode the system still shows acceptable frequency behavior even with significantly reduced inertia. However, in the case of split operation after a disturbance, the resulting imbalance combined with low inertia could result in unstable system behavior.
- Nordic grid [5]: With the combination of increasing renewable generation penetration and shutting down nuclear power plants, the operators of the Nordic grid list low inertia as one of the three main future challenges faced by their system. Proposed solutions include technical measures but also imposing operational requirements such as on minimum available kinetic energy.
- Ercot grid [6]: The generation capacity in the Ercot system is composed of 20% wind generation, which covers around 15% of the total electric energy consumption on average but up to 54% of instantaneous power. Given plans for further expansion of the wind generation capacity, Ercot is actively evaluating market based solutions to ensure sufficient availability of inertia in the system.

- EirGrid and SONI [7]: The installed all-island wind capacity is currently 3320 MW and is planned to increase up to 4050 MW before 2020. Despite this huge potential, wind intermittency limits the capacity credit of wind. In 2016, 22% of the total annual energy was generated by wind.

Many of the challenges related to low-inertia power systems have been highlighted in recent reviews and magazine articles [8]–[14]. While many of these issues are well recognized by now, what is still lacking is a scientific foundation for the modeling, analysis, and control of low-inertia systems. In particular, this methodology needs to be scientific to be applicable to grids generally. To address the stability issues of the past, two distinct research approaches have emerged: system theoretic (analytic) and computational (simulation based). Each has merits and can be used to complement each other. The main advantage of system-theoretic approaches is the capability to study sensitivity questions and draw general conclusions; the limitation is that the system model requires several simplifications, e.g. a small-signal model with simplified controllers, and so might be inaccurate for some features that have an important impact on the system performance following a disturbance.

Simulation-based approaches, on the other hand, are less restricted by modeling limitations. Their focus is the assessment of power system performance for a particular scenario. This allows obtaining quantitative conclusions for that particular scenario, but makes general conclusions difficult. Examples of these simulation-based studies are the reports for the Western USA system [15] and the all-island Irish system [8], that conclude with *ad hoc* statements of renewable energy sources integration limits, e.g. figures of 30% and 65%, respectively.

While the many reported studies provide useful insight into the immediate challenges, they do not offer a systematic guidance for the maximum non-synchronous and/or renewable-resource instantaneous generation limit that a given grid can accommodate from the frequency performance point of view. Also, many existing future-grid scenario studies have focused on simple power balancing using a copper plate model of the transmission network [16], and have used a range of assumptions, e.g. existing market model, that might change in the long term. Those studies have not taken into account network related issues, such as system stability. Issues like dynamics related to inertia are usually not considered outside the power systems area and this can be seen as a broader scientific issue.

There are many novel paradigms and issues for which a scientific basis still needs to be developed or is currently emerging, such as the role of the spatial inertia distribution (for contingencies, planning, and dispatch), novel control strategies for grid-forming power converters (such as virtual synchronous machine emulation or virtual oscillators), the role that fast DC energy storage has to play, questions concerning the modeling assumptions, time-scale separations and so on. These lead to many questions; at a high level the role of a regulated frequency in a low-inertia power system can even be questioned.

The many issues for low-inertia systems can be translated into specific analytic questions such as: (i) what are rigorous non-synchronous generation limits with respect to all kinds of stability and frequency performance, and how does this depend on grid structure; (ii) how to optimally place and control distributed energy resources (DER) to be available for anticipated low inertia situations; (iii) what are device-level control specifications to guarantee stability and robustness in an interconnected system; (iv) where are the most vulnerable sites for low inertia, and so on. It is the opinion of this group of authors that the required methodology has still to be developed, and a scientific foundation and consensus still needs to emerge. We also believe that to properly address these questions, major programs of research will be required. And indeed there are already a few projects directed to address these bigger questions including MIGRATE [9] and RE-SERVE [10] in Europe and the Australian Future Grid Project (CSIRO) [11] to name some close to the authors.

This paper aims to give a broad survey of both the issues related to low-inertia power systems as well as the solutions that have been put forward thus far. We review many of the ongoing research efforts, put them into context, and relate them to one another. We also raise open questions that have yet to be addressed or whose answers are still contested and debated. It is important to clarify that this article does not aim to be comprehensive in its scope, nor does it present all viewpoints and facets on the topic of low-inertia power systems. Our exposition and treatment is colored by our own research interests and experiences. In particular, we focus on transient and frequency stability as well as converter control as the core scientific challenges of low-inertia power systems, we only superficially discuss other relevant and related aspects (such as voltage stability, reactive power support, CIG-induced oscillations, and so on), and we do not discuss specific technologies or regulatory and economic questions.

We also wish to emphasize that our focus is on high-voltage AC transmission systems, but similar topics are pursued in the microgrids literature, see for example [17]–[19]. Microgrids are different from transmission grids in many aspects (voltage levels, time-scales, line characteristics, grid topology, system operation, etc.), and, in comparison to the latter, do not have to be compatible with a legacy-system. In another problem scenario, 100% CIG-dominated high-voltage AC grids are already existing, e.g., in Germany, to interconnected offshore wind power plants through HVDC [20]–[22]. The issues are slightly different than in low-inertia utility grids due to the ubiquitous presence of HVDC and the complete absence of synchronous machines; see the survey [20]. Finally, similar low-inertia issues are also encountered in railway AC power systems; see [23] and references therein. However, due to the vastly different characteristics, it is unclear whether knowledge and insights carry over to AC power transmission grids. Hence, we believe that low-inertia AC power transmission systems require an independent and yet-to-be developed scientific foundation.

The remainder of the paper is organized as follows. Section II focuses on the changing role of frequency in a low-inertia system. Section III addresses more general issues related to modeling, power system stability, operation, and control. Section IV reviews and relates the solutions that have been proposed to address these issues. Finally, Section V concludes the paper.

II. FREQUENCY IN A LOW-INERTIA SYSTEM

A. *Time scales of frequency control in conventional systems*

The main functions of synchronous machines are to generate active power, regulate the frequency and the voltage, and provide kinetic energy. The rotor of a synchronous machine is effectively a *flywheel* whose inertia is crucial to compensate for fluctuations and disturbances (e.g., load/generation variations or contingencies) in the short term (up to 5 s). After that, the primary and the secondary frequency regulations take over by varying the active power generated by the machines. This takes place on time scales of tens of seconds (primary frequency control) and minutes (secondary frequency control). Tertiary control, when implemented, and generator rescheduling are slower and take place on time scales of the order of tens of minutes and hours, respectively. A synoptic scheme that represents the different time scales associated with frequency dynamics and control is shown in Fig. 1.

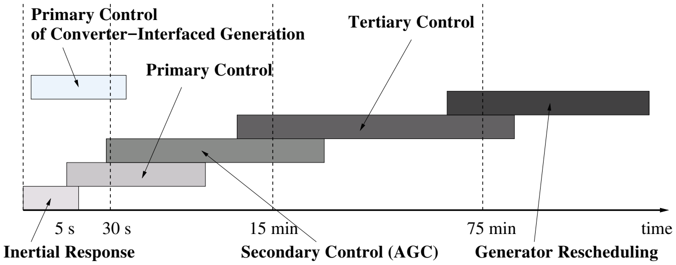

Fig. 1. Typical time scales of frequency-related dynamics in conventional power systems as well as typical time scale of frequency control that can be provided through CIG.

The inertia of synchronous machines impacts the dynamic behavior of the system only in the first instants after a contingency or the occurrence of a power unbalance. Provided there is sufficient reserve, in fact, primary, secondary and tertiary regulations and generation rescheduling can be implemented regardless of the fact that the system includes high or low inertia, or any inertia at all. Of course, most converter-interfaced generation (CIG) is also non-dispatchable and usually modelled in terms of stochastic processes, such as for wind speed. These facts complicate the regulation and power dispatch, but their impact is in time scales larger than that of the inertial response of synchronous machines.

Another aspect that is worth mentioning at this point is that CIG has also a rather different mechanism to provide reactive power support compared to conventional AVRs of synchronous machines. The main difference is that the voltage control obtained through converters can be consistently faster than that of the AVRs. The low inertia problem will be thus very likely accompanied by the need to design also a voltage and/or reactive power control that does not produce unintended, e.g. unstable, dynamic couplings in the time scale of the inertial response of synchronous machines.

B. *Response of synchronous machines to power unbalances*

Let us focus exclusively on the crucial time scale ranging from zero to a few seconds after a disturbance. Neglecting for now network topology, a conventional system where generation is attained with synchronous as well as non-synchronous generation can be represented as

$$M\dot{\omega}(t) = p_{\rm s}(t) + p_{\rm ns}(t) - p_{\rm l}(t) - p_{\rm j}(t)\,, \tag{1}$$

where M is the total inertia of the synchronous machines, $\omega(t)$ is the average frequency of the system, and $p_{\rm s}$ and $p_{\rm ns}$ represent the powers of the synchronous and non-synchronous generation, respectively; and $p_{\rm l}$ and $p_{\rm j}$ are load demand and losses in the transmission system, respectively. In (1), $p_{\rm ns}$ represents both CIG, which is assumed to have frequency and voltage control capability, and other non-synchronous generation that does not provide control, e.g. type A wind turbines. It is straightforward to observe that the bigger M, the higher the kinetic energy of the system and, thus, the lower the frequency deviations and the higher the ability of the system to compensate power unbalances due to contingencies and/or load variations. On short time scales, the controls of synchronous machines do not affect the power balance (1), but converters may do so under certain assumptions; see below for details.

It is also interesting to note that, since a large quota of $p_{\rm ns}$ comes from stochastic energy sources, e.g. wind power plants and solar photo-voltaic, the unbalances of the power are expected to be larger and more frequent when $p_{\rm ns}$ is non-zero, which is likely the reason why the penetration of renewable sources is often associated with the “low inertia” issue. However, any non-synchronous generator, even if fully deterministic, will contribute to reduce M and, hence, to increase frequency fluctuations.

At this point it is worth highlighting another aspect: on short time scales, synchronous machines affect the power balance (1) through instantaneously available physical storage (in this case the kinetic energy stored in the rotating masses) but not through their primary control due to slow actuation. For CIG the situation is the opposite: the analogous instantaneous physical storage of a power converter is the energy stored in its DC-side capacitor; see the energy storage in Fig. 3. The latter is negligible in comparison with the rotational inertia of synchronous machines. On the other hand, power electronic sources can be actuated on much faster time scales than synchronous machines and thus contribute to power balancing provided that they are equipped with a fast DC energy supply. Thus, the lack of physical inertia can be potentially compensated through fast DC-side energy storage, such as batteries, flywheels or super-capacitors. We will revisit and further detail these themes throughout the paper.

C. *Time scale of frequency control of CIG*

A feature of most non-synchronous generation is to be based on a power electronic interface. This is the case for most wind power plants (either type C or type D wind turbines which are based on partial and full scale, power converters, respectively), and PV solar, which require a DC/AC converter to be connected to the grid. Power converters are generally fast and can thus allow non-synchronous generators to provide a primary frequency control faster than conventional power plants [24], [25]. On the other hand, since power converters do not respond “naturally” to power unbalances, the very first instants after a contingency might not be fully covered. This situation is illustrated in Fig. 1. The risk, which is also the main concern of systems operators, e.g. EirGrid in Ireland or ENTSO-E in continental Europe, is that the response of CIG might not be effective enough in the first seconds or, even, first hundreds of milliseconds, which is where the inertial response of the synchronous machines has its most relevant impact on system dynamics.

Another anticipated issue is that the reserve and thus the ability to provide primary frequency control with CIG is limited [26], e.g., in terms of power and energy. The latter expectation is based on the current practice to operate CIGs at their maximum power point. Note, however, that the problem would persist even if CIG is operated with a given reserve (e.g., 10% below the maximum power point). The stochastic nature of most CIG, in fact, prevents guaranteeing a given reserve and security margin in the system.

D. Decoupling of frequency and power balance in 100% non-synchronous systems

In a hypothetical system where there are no synchronous machines at all, $M \approx 0$ and the frequency is completely decoupled from the power balance of the system:

$$0 = p_{\mathrm{ns}}(t) - p_{\mathrm{l}}(t) - p_{\mathrm{j}}(t) \tag{2}$$

In this case, no element of the grid responds "naturally" to power variations and a control system has to be in place to keep the power balance at every instant. In practice, at least for the time being, the 100% non-synchronous generation is not a realistic scenario for large systems. Large hydro power plants, in fact, will likely always be based on synchronous machines. Also, substituting all existing conventional power plants with CIG will certainly require a few decades. However, it is possible that, for short periods, the percentage of synchronous generation can be very small or, even, null, especially, when parts of the grid are islanded. It is interesting to note that this scenario, has never happened so far, except maybe for small islands, even if the installed capacity of non-synchronous generation would allow satisfying the whole demand.

A relevant case is the Irish system, where the TSO, EirGrid, has decided not to pass the limit of 65% CIG. A penetration of renewable generation of 60% was effectively hit in 2017 [27] and there are plans to increase the limit up to 75%. However, due to the lack of inertial response of CIG (at least, in the current set up), there is no plan for now to allow a 100% CIG, even if the wind available in a given period could accommodate such an operating condition.

In a recent article in the IEEE Power & Energy magazine [27], the authors indicate real-world cases of instantaneous penetration of non-synchronous generation higher than 65%. For example, in 2015, the Danish system showed an instantaneous penetration of 140% of CIG. This value, however, should not be interpreted as the fact that the Danish grid operated as in (2). The Danish grid is connected to the rest of the ENTSO-E system, which includes a large percentage of synchronous generation and, thus, a high inertia. So, despite the penetration of wind power in Denmark, the overall power balance is still governed by (1). Rather, the case of the Danish system leads to another issue deriving from CIG, namely, local fluctuations of frequency. This issue is thoroughly discussed in Subsection II-I.

It is relevant to note that CIG penetration and the effective level of the inertia present in the system are certainly correlated but one cannot be univocally determined from the other. In common practice, e.g., EirGrid approach, the definition of non-synchronous generation takes into account exclusively the instantaneous power produced. So, for example, a machine of 100 MW is accounted for the same as a 1000 MW unit producing 100 MW. The two scenarios have the same CIG but different inertia and, hence, different dynamic responses. While purposely provocative, this example indicates that high CIG does not necessarily imply a low-inertia operating condition.

It is still an intriguing thought experiment to think about the role of frequency in (2) without synchronous machines as appear in (1). In a system without machines, frequency is not anymore a *physical* variable attached to synchronizing rotating machinery, but the electrical frequencies and the frequencies of controller-internal clocks asymptotically synchronize throughout the grid [28], [29]. An example are the oscillator-based control strategies for inverters discussed in Section IV. Certainly, this notion of a globally synchronized frequency signal is much more fragile due to the fast time constants and volatile fluctuations encountered in an inertia-less system. A more detailed discussion is presented in Section IV.

E. Inertial response vs. primary frequency control

The power balances in (1) and (2) lead to significant consequences from the point of view of the system response and, in turn, of the regulation of the frequency. We briefly outline below the impact on power system security and control. Further discussions on these issues and proposed solutions are provided in Sections III and IV, respectively.

1) Low inertia likely implies low security: For synchronous machines, the distinction between rate of change of frequency (RoCoF) and primary frequency control is "physical". Primary frequency control can be slower than the inertial response as the latter is instantaneous and guaranteed. Non-synchronous devices, on the other hand, do not respond to power variations, unless forced to by a specifically designed control. In other words, the inertial response of CIG must be implemented as a control loop and is thus subject to delays, malfunctioning, saturation, unexpected coupling with other dynamics possibly leading to instabilities, etc. A system with low inertia is thus intrinsically *less secure* than a system with high inertia.

2) Alternatives to frequency-based controllers: Equation (2) clearly indicates that if there is no synchronous machine, the variation of the frequency is actually *immaterial* for the determination of the power imbalance. This has led many researchers to look for strategies to balance the power through controllers that do not rely on the measure of the frequency [30], [31]. However, such controllers tend to rely on communication systems and are, in general, not fully reliable nor easy to implement. No clear alternative candidate to substitute the frequency as the main signal to regulate the power balance has been identified yet and this is what mostly prevents, for the time being, the 100% instantaneous penetration of non-synchronous generation in real-world power systems.

F. Frequency of the centre of inertia

So far, we have treated the frequency as it were a unique, common quantity for the whole system. This is a common approximation when studying primary frequency control. For

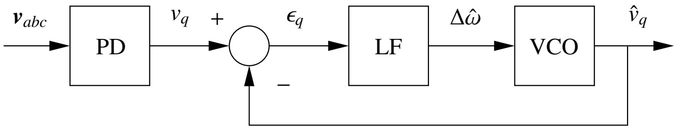

Fig. 2. Basic scheme of a standard PLL.

example in [32] a single bus model with aggregated machine model is utilized. When considering a unique frequency for the system, one usually refers to the frequency of the center of inertia (COI), which is computed based on the rotor speeds and inertia constants of the synchronous generators connected to the system [33]. Assuming a set $\mathcal{G}$ of synchronous generators, the expression to compute the COI is

$$\omega_{\mathrm{COI}} = \frac{\sum_{j \in \mathcal{G}} M_j \omega_j}{\sum_{j \in \mathcal{G}} M_j}, \tag{3}$$

where ω_j are the electrical rotor speeds, and M_j are the normalized inertia constants. The utilization of ω_{COI} is currently limited to simulations, where its property to avoid generator angle drifting can be exploited to reduce the integration step and thus improve efficiency [34]. In practical applications, however, ω_{COI} has no utilization, for now, because its calculation requires the availability of measurements of all synchronous machine rotor speeds. As a matter of fact, system operators do not estimate the COI frequency on-line but, rather, measure the frequency at some relevant, e.g. a *pilot* bus of the system. The behavior of the frequency of the pilot bus, however, does not represent the average frequency of the system as it follows the dynamics of the closest synchronous generators.

The inertia-weighted nature of the COI in (3) makes this quantity particularly suited to study inter-area oscillations among machine clusters. Local variations of the machines, especially those characterized by a small inertia, are lost. The "averaging" property of the COI is not necessarily a drawback from the control point of view of CIG, as it is further discussed in Subsection II-I.

G. Phase-Lock Loop Controllers

The primary frequency control of synchronous machines is naturally based on the measure of the rotor angular speed of the machine itself. Since the dynamic response of synchronous machines imposes frequency variations, the rotor speeds are clearly the "right" measurements to use for frequency control.

The situation changes substantially when it comes to defining the frequency signal for CIG, which depending on the mode of operation (see Section III-C1) do not necessarily impose the frequency at the point of connection - unlike synchronous machines. In this case, the local bus frequency is a brittle signal that has to be estimated by means of available measurements, e.g. for the purpose of grid-following power converter control (see Section III). The available measurements are the AC voltages at the point of connection and the outputs of the Phase-Locked Loops (PLLs) which are the typical devices utilized for the frequency estimation.

An illustrative scheme of the fundamental-frequency model of a synchronous reference frame PLL is shown in Fig. 2. This scheme is composed of the following three main parts:

i. The Phase Detector (PD), which measures the vector of three-phase voltage at the bus of connection, $\boldsymbol{v}_{abc}(t)$. The voltage is then converted from abc representation into $\alpha\beta$- and dq-reference frames, and the q-axis component $v_q(t)$ is computed.
ii. The Loop Filter (LF), which takes the error $\epsilon_q(t)$ between the measured q-axis voltage, $v_q(t)$, and the one estimated by the PLL, $\hat{v}_q(t)$. While there exist several different configurations of the LF, they are generally based on a tracking controller, e.g. a PI controller.
iii. The Voltage-Controlled Oscillator (VCO), which takes the bus frequency deviation, $\Delta\hat{\omega}(t)$ and provides the estimation of the bus voltage q-axis component $\hat{v}_q(t)$. The VCO typically consists of a pure integrator to avoid steady-state errors in $\hat{v}_q(t)$, and impose that, in steady-state, $v_q(t) = 0$.

Finally, the PLL output is typically also low-pass filtered before used in CIG control applications. We note that there are many different implementations of the PLL (see, for example, [35]–[37]) where the main differences are in the LF block. Most commonly, LF consists of a PI controller, e.g. the synchronous-reference frame PLL. The most relevant feature, common to all PLL designs, is that the output of the LF is an estimation of the frequency deviation at the bus of connection, namely, $\Delta\hat{\omega}(t)$ in Fig. 2. The bus frequency estimation is thus given by $\omega_0 + \Delta\hat{\omega}$, where ω_0 is the synchronous speed.

Since the input quantity v_q undergoes fast electromagnetic transients, the PLL can show numerical issues and provide a frequency estimation affected by jumps and discontinuities following discrete events in the system such as faults or line outages. Moreover, PLLs introduce a non-negligible delay which can limit the performance of the controllers that depend on the frequency estimation of the PLL. Recent publications have recognized the impact of PLLs in the regulation provided by non-synchronous devices [38], [39], but also the potential instabilities that these devices can cause to electronic converters [40], [41]. More details on the impact of PLLs are discussed in Sections III and IV.

H. Other Synchronization Techniques

A majority of clock-distribution devices cannot meet the requirements of the system clock frequencies. Hence, various improvements of PLL-based clock drivers have been proposed in the literature: a robust fuzzy-logic design based on a gradient descent method and a genetic algorithm in [42] can offer a performance comparable to analytically derived PLLs; smoother estimation of the signal parameters in the presence of noise and harmonics can also be achieved through in-loop filters and window functions [43], as well as by introducing the transport delay method [44].

Among the several alternative solutions to PLLs that have been proposed in recent years, we cite two of them: (i) the Kalman Filter-based synchronization method (KFSM) [45]–[47]; and (ii) the Recursive Discrete Fourier Transform (RDFT) [48]–[50]. Both these technique are discrete and have interesting properties and, for specific applications, can be preferred to the standard analogue PLL. However, the dynamics of the frequency estimation of both of these approaches is not smooth. Moreover, the RDFT requires an amplitude detector as the fundamental frequency, during the transient, deviates from its nominal value. An advantage of the KFSM is that the system is linear, and so the Kalman filter gain can be computed off-line [51] and is able to slightly reduce, in certain noise conditions, the estimation delay that is typical of all PLLs implementations.

I. Frequency Divider

So far we have discussed the frequency of the COI, which is a continuous quantity and provides the "overall" frequency trend, and PLL which provides local and inevitably noisy frequency estimations. A method to compute these ideal frequency signals has been recently proposed in [52], where the authors proposed the *frequency divider formula* (FDF). This formula is based on the augmented admittance matrix of the system and on the assumption that the frequency along the impedances of transmission lines varies as in a *continuum matter* where synchronous machine rotor speeds define boundary conditions.

A detailed discussion on the assumptions and hypotheses behind the FDF are beyond the scope of this paper. Full details are provided in [52]. For illustration, we briefly outline the expression and the features of the FDF. We start with

$$\Delta\boldsymbol{\omega}_B = \mathbf{D}\Delta\boldsymbol{\omega}_G \ . \tag{4}$$

where $\Delta\boldsymbol{\omega}_G$ are machine rotor speed deviations, $\Delta\boldsymbol{\omega}_B$ are the frequency deviations at system buses, and $\mathbf{D}$ is a matrix that only depends on the network topology, transmission line parameters and synchronous machines internal reactances. Based on the FDF, [53] and [54] show how the delays introduced by PLLs can affect the ability of non-synchronous devices to properly regulate the frequency. The effect of fast dynamics of machine magnetic fluxes is also shown to lead to potential instabilities. A comparison of the transient behavior of different PLL implementations is given in [55].

Interestingly, [56] and [57] show that the COI signal, due to its averaging properties, often leads to an overall smoother frequency response and better control provided by CIG than what can be obtained using PLL estimations. This consideration could be further developed in the future as, in a recent publication, it has been shown that the frequency of the COI can be estimated based on the FDF and the knowledge of synchronous machine inertia constants [58]. This byproduct of (4) may allow implementing coordinated area primary and secondary frequency controllers sharing an average value of the frequency signal rather than utilizing a local one.

Another relevant consequence of (4) is that the frequency of distribution networks with no synchronous generation, i.e. without any device that imposes the frequency at buses has to be the same at every bus at every instant. This property of the frequency is what can lead to the successful implementation of virtual power plants, namely, power plants that are composed of different sources (wind, PV solar, etc.) at different locations of the distribution system but coordinated together to provide ancillary services [59]–[61].

J. Need for a novel definition of the frequency

Based on the discussion above, it appears that the frequency and RoCoF in low-inertia systems must be carefully evaluated, especially in the first instants after a contingency. Other time scales, which are relevant for primary, secondary and other frequency controls are not significantly affected by the amount of inertia in the system.

It is interesting to note that the current definition of the frequency provided by the ENTSO-E Commission Regulation (EU) 2016/631 of 14 April 2016 Establishing a Network Code on Requirements for Grid Connection of Generators, assumes a conventional power system with adequate level of inertia. The definition of frequency, in fact, reads as follows:

> *Frequency means the electric frequency of the system expressed in hertz that can be measured in all parts of the synchronous area under the assumption of a consistent value for the system in the time frame of seconds, with only minor differences between different measurement locations.*

Such a definition needs to be updated in order to take into account the high dynamic conditions that will characterize the upcoming power systems with very high or 100% RES penetration. In this regard, in [62], a new definition is proposed:

> *Frequency means the electric frequency of the system expressed in hertz that can be measured in all parts of the synchronous area under the assumption of a consistent value for the system, with only minor differences between different measurement locations in quasi steady-state conditions.*

In the definition above, two concepts have been modified with respect to the one provided by ENTSO-E. First, the definition of frequency, and thus the assumptions therein, should be valid for any time frame, not only for the time frame of seconds, which might be too long for RoCoF and inertial response. Then, [62] shows that, during transients, frequency variations between different measurement locations can significantly impact the frequency control of CIG. Therefore, the assumption that only minor differences exist is applicable only in quasi steady-state conditions.

III. ISSUES ARISING

A. Modeling

1) Converter Modeling: The dynamics of a conventional power system are dominated by synchronous machines and their controls. In a low-inertia system, we need an accurate representation of power electronic converters, their controls, and their limitations – especially on the short time scales. There certainly are elaborate models of power converters, the primary energy sources behind them (wind turbines etc.), as well as the devices needed to provide a (virtual) inertial response such as flywheels, batteries, super-capacitors, and so on [24], [63]–[66]. However, this level of detail is probably not useful for power transmission system models and their use for analysis and control design.

The appropriate level of granularity lies somewhere between detailed device-level models and coarse-grain models of low-inertia sources given by controllable voltage (or current or power) sources with outer control loops as employed in the microgrid literature [67]–[71]. Similar to traditional model reduction in power systems based on time-scale separation [72], one may also conceive a hierarchy of models for low-inertia systems. Such time-scale based modeling and model reduction is standard when averaging power electronics models [73], on the system level it has been pursued for microgrids [74]–[76], and results for low-inertia power grids are reported in [77]. Another model reduction based on aggregation of parallel inverter sources has been considered in [78].

A conclusion from the microgrid literature is that the dominant dynamics of power electronics (PE) sources are given by the time constants of the outer control loops, e.g. PLL time constants, droop gains, or virtual oscillator parameters. For transmission grids, the reports [4], [79] highlight the effects of control lags and measurement delays (especially of PLLs) and predict lower integration limits than related studies where these delays are not modeled [80].

Aside from these control layers, the model reduction in [77] also stresses the dominant converter DC charge dynamics of a converter and their analogy to the mechanical swing dynamics of a synchronous machine. However, this analogy is only formal, as the capacitor on the DC side is designed and sized for reducing the DC voltage ripple. Thus, the energy stored in the DC capacitor for the converter is negligible with respect to that stored by the inertia of synchronous machines. To make the aforementioned analogy viable and practically useful, it is necessary to connect a sufficiently large energy storage device to the DC side of the converter.

This analogy between synchronous generators and CIG and the duality of DC voltage and mechanical frequency has been widely discussed in recent years [9], [24], [81], [82] and explicitly used for converter control in [83]–[87]. Similarities and, more importantly differences have to be carefully defined to avoid (unfortunately very common) misunderstandings. A synchronous generator is a device that intrinsically embeds three functions:

1) an energy source, namely the mechanical power coming from the turbine;
2) an energy conversion from mechanical to electrical through the magnetic coupling between rotor and stator; and
3) an energy storage, namely, the rotating mass (effectively, a flywheel) of the rotor and the turbine.

The converter, on the other hand, only provides the energy conversion from DC to AC, through the power electronic switches. *De facto*, the converter is a controllable DC/AC transformer. As a consequence, the converter requires an energy source and an energy storage to properly resemble the synchronous machine. Fig. 3 illustrates the discussion above.

From the control point of view, both devices offer two degrees of freedom. There are, however, crucial differences. The synchronous machine controls the mechanical power and the field voltage, which lead to primary frequency and primary voltage control, respectively. The converter also has two input quantities, i.e. the d-axis and q-axis components of the pulse-width modulation (PWM) control, which directly actuate the d-axis and q-axis components of the AC current. One of these components is typically utilized to regulate the grid-side AC voltage, thus implementing the primary voltage control of the converter. Depending on the configuration and the converter topology, the other component can be used, for example, to regulate the DC voltage or current flowing through the converter. Finally, the active power injection and the energy balance across the converter's DC storage (DC-side capacitor) are regulated through the control of the energy source connected to the converter.

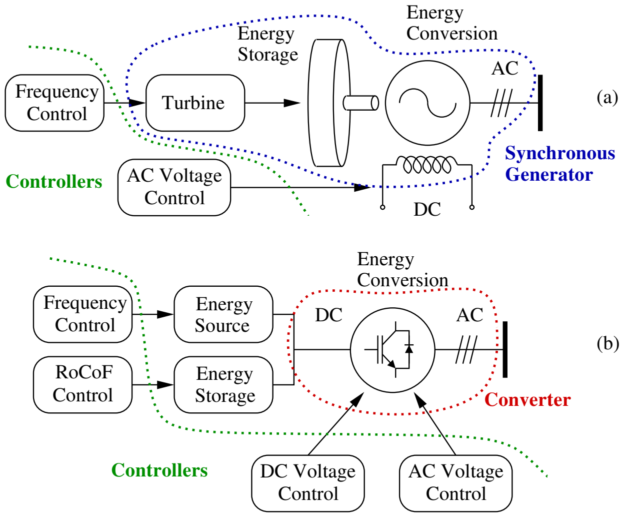

Fig. 3. Energy conversion, energy storage and controllers of (a) synchronous machines and (b) power electronic converters.

Recall that any control formulated in a dq-frame requires an angle reference for this dq-frame. Whether this angle reference is extrinsic, e.g. obtained from the grid angle though a PLL, or intrinsic, e.g. by means of a frequency control loop, is related to the taxonomy of *grid-forming* and *grid-following* operation modes; see Section III-C. These terms refer to whether the control of the energy source and/or the converter provide frequency control or not, respectively. In recent years a variety of other solutions have been proposed. The grid-forming operation mode can be implemented in several ways, e.g. through a frequency-power droop characteristic, emulation of the synchronous machine dynamics, or virtual oscillator behavior; see Sections III-C and IV-A for further details. Recent approaches also exploit the aforementioned formal duality of DC voltage and mechanical frequency and control the converter output frequency via the DC voltage [83]–[87].

It is also important to note that, while the mechanical inertia is an inseparable part of the synchronous generator, a converter requires a fast DC-side energy storage and a specific control to respond to the variation of the frequency, e.g. RoCoF control or emulated virtual inertia. As a matter fact, the DC-side energy storage can even embed both RoCoF and primary frequency controls together, if the DC-side energy source itself is not dispatchable, as for wind or solar PV.

Overall, CIG requires four controllers, two for the DC-AC conversion itself through PWM, one for the DC energy source, and one for the DC energy storage. How these controllers are handled, however, is quite flexible and a variety of possibilities have been explored, even though more in theory than in practice, in recent years. This is, in turn, the main difference between the synchronous machine and the converter: the converter is a modular and nearly fully actuated device that allows for a variety of control solutions and actuation on very fast time scales. Furthermore, multiple storage devices and/or energy sources, in fact, can be connected to the DC side. We refer to the Sections III-C and IV-A for further details.

Finally, the need for protections and limiters for the synchronous machine is well known, e.g. the over- and under-excitation limiters. These, however, tend to be relatively slow and are often delayed on purpose as the machine can stand quite significant over-currents for a short time. On the other hand, [9], [88], [89] stress the importance of modeling saturation limits, e.g. for over-currents, in power converters especially for analyzing post-contingency behavior where overloads are likely to be encountered.

2) Inertia Variability: The level of inertia present in the system at any point in time is heavily dependent on the generation mix dispatched for that particular day and time [32], [90], [91], e.g., many synchronous machines may be disconnected when the weather forecast favors renewable generation. In [90], the time-dependent system inertia in Germany for the year 2012 is computed and presented based on an aggregated system model. It is reported that total system inertia at one point in time can be half of the value of other times. With infeeds from inverter-connected resources varying up to 50% of total load, this of course is not unexpected but again demonstrates the highly time dependent nature of system inertia. The authors of [90] kindly provided the data and script to generate Fig. 4 which similarly shows the volatile temporal variations of the aggregated inertia constant in Germany for the last quarter of 2013.

In systems with mostly synchronous machines, the variations in the level of inertia present in the system are limited given the fact that the inertia constants of different machines are not widely different. More importantly, the resulting level of total system inertia would be sufficient to provide the initial inertial response in case of severe disturbances. With the replacement of synchronous machines by non-synchronous resources, system inertia becomes time-dependent and a function of expected wind and solar power output as that determines the level of resources needed to cover the remaining net load. Hence, the parameter of naturally occurring system inertia is increasingly becoming a variable subject to a significant level of variability and dependent on weather conditions. Most importantly, without the explicit consideration of the level of inertia of the dispatched plants, situations may arise when the system is not capable of providing acceptable inertial response.

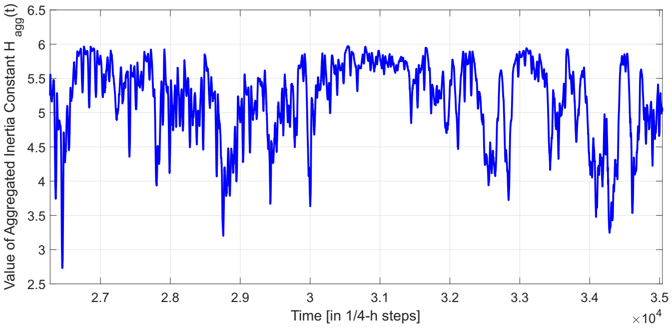

Fig. 4. Temporal variation of the aggregated inertia in Germany for the last quarter of 2013 (data and script kindly provided by the authors of [90]).

Utilities with extensive amounts of wind and solar generation capacity in the system have recognized that they need to actively plan for having sufficient inertia in the system and cannot assume any more that the plants dispatched via standard market procedures will naturally provide the required level of inertia. For example, already in 2012 ERCOT discussed the need for a new Fast Responding Regulation Service (FRRS) [6]. An important recommendation included in the report is the initiation of a Synchronous Inertia Response Service. On a similar note, [92] discusses Fast Frequency Response (FFR) for the Australian Energy Market Operator as an option to overcome the low inertia issues in their system. While the discussion on how electricity markets may deal with the issue of low inertia is out of scope of this paper, the fact that utilities consider finding market based solutions to establish a sufficient level of inertia at any point in time, indicates that it is necessary to model system inertia as a time-dependent variable that needs to be integrated as a lower-bounded variable into the dispatch modeling.

B. *Power System Stability*

1) Impact on all levels and time-scales: Power system stability assessment and stabilization approaches have been major parts of power system dynamics for many decades. The IEEE Power System Dynamic Performance Committee (PSDPC) dates back to 1967 and now has two subcommittees on Power System Stability and Power System Stability Controls. Over the 1990s and early 2000s many meetings (and a lot of debate) between CIGRE and IEEE ended in a joint statement of definitions and classifications for power system stability [93]. The primary definition stated:

> *Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.*

There are some points to note. The definition refers to the whole interconnected system so leaves room for some less relevant parts to be "unstable", e.g. a remote motor stall, and still interpret the overall system to be stable depending on priorities. Secondly, the whole framework for stability envisaged an initial steady operating point, a disturbance and asks whether the system returns to a possibly different steady operating point. Then three main classifications were defined by giving priority to respectively angles, frequency and voltages further divided into small-disturbance and large-disturbance versions and further again into short-term and long-term versions (except for angles). Theoretically these concepts can be described and analyzed by appropriate linearized and nonlinear models and concepts of Lyapunov stability theory, partial stability and bifurcation theory. Practically, the classification works because for most situations the natural dynamics has a convenient time-scale separation for angles, frequency and voltage issues.

While these more specific classifications and the methods that applied to them have made a solid platform for power system dynamic analysis there have always been some things to keep in mind about possible shortcomings:

- It is easy to find specific situations where the separation between the separate stability types is not clear, e.g. short term voltage dips in the transient region [94];
- The whole view of stability was focused on dynamics, particularly generator dynamics, and the actual grid structure was given little attention by theoreticians. Of course, different structures were of no concern to a utility with its own grid;
- Aggregated load dynamics were generally poorly known; theories [95] did not consider robustness adequately;
- Power electronic dynamics were not explicitly considered and just part of the aggregated dynamics;
- In fact the only dynamics considered was for time scales above 5 ms or so, i.e. electro-mechanical dynamics and slow load dynamics; in this time scale the classical phasor approximation can be used;
- There was never given a satisfactory solution to predicting and arresting cascading collapse; beyond a certain tipping point the blackout was inevitable, and recovery became the priority.

Despite these features and qualifications, the whole subject was one with a healthy mix of theoretical basics and practical application over many decades. There have been signs for some years that this might need to be revisited in the light of the major technological changes described above. In particular, it is the opinion of the authors that the following demand some attention in definitions and classification of stability:

- The equilibrium-disturbance-equilibrium view of stability appears inadequate to cover many stability type situations of today as the system responds to generation volatility and faster power movements;
- The influence of grid structure interacting with the more diverse dynamics seems useful to study further; the issue of where devices are physically in the network is crucial to answering questions in vulnerability, resilience and so on;
- With greater penetration of CIG, the dynamic time scales and variables of interest have changed and may affect the classifications; until the newer phenomena are clearly studied and classified, the more wholistic system concept of stability should be given more prominence.

In fact at the time of writing, the IEEE PSDPC has a task force in the early stages of considering new issues but apparently with more emphasis on the CIG aspect, and this includes reduced grid inertia and faster dynamics. There is nothing definite that can be said at this stage but certainly the classifications will be added to so that phenomena associated with converters are explicitly represented. This is not without debate since the phenomena involve angle synchronism, i.e. in the PLL, and oscillatory behavior and further can be regarded as problems to be fixed within the converter rather than real system issues. The impact of converter dynamics in stability is illustrated elsewhere in the paper.

At the system level in terms of the main conventional stability types, there have been numerous papers considering the impact of renewable power in specific situations. Generally these papers show that increased penetration of CIG has an affect in the studied systems, but with no general conclusions of whether the effect is positive or negative in any general guideline sense. Some researchers do explicitly consider sensitivity questions related to inertia in a computational way and so can arrive at some more general statements – see for example [96], [97]. However, variations to the grid topology are generally not considered. Such variations can be studied via Monte Carlo approaches; see the techniques developed in [98] to study transient stability in low-inertia grids.

For transient stability an interesting study was carried out on a 18205 bus model of the USA Western Electricity Coordinating Council (WECC) system when all conventional sources have been replaced with CIG [80]. The only rotating machines directly connected to the network are wound rotor induction generator wind turbines and induction motor loads so the total system inertia is close to zero. Traditional contingency analysis showed somewhat surprising stability but also the conclusion that coordinated wide-area converter control action may have to be incorporated to enhance the reliability of the system.

The impact of solar power on voltage stability has been a major consideration at all voltage levels and can mostly be considered as not related to inertia. However the impact of wind power penetration in particular has been studied on voltage stability of transmission and sub-transmission grids [99], [100]. Here the replacement of conventional power by wind power and addition of such power sources are seen to raise new voltage issues, i.e. traditional voltage support from generators is lost and the higher losses in subtransmission mean the power variability and voltage control imposed at the PCC cause voltage variations or possibly excessive voltage control movements, e.g. OLTC taps, elsewhere in the grid.

The above mentioned theories for all types of stability have filled too many books and papers to report completely here, but most of it is in need of revision and expansion to accommodate the new dynamics and devices. Lyapunov based theory for angle stability [101] is based on conventional generators and aggregate loads. One approach based on so-called network-preserving models (NPM), which were initially introduced [102] to solve a longstanding problem of finding a rigorous Lyapunov function, has a load model equation which can equally represent a zero inertia CIG [103]. This can be a basis for analytical studies. As loads increasingly feature storage and demand-response mechanisms, these will need to be represented in models. This is work in progress by one of the authors (Hill) of this paper. Also CIG dynamics will require new analytical and computational approaches to give more general conclusions – comments elsewhere in the paper already highlight some steps taken here by the authors.

In practice, there are new situations to guard against as large CIG interact with grids. An event which occurred in

Europe in 2006 followed strong winds causing wide-scale wind plant shutdown with consequent frequency nadir leading to under-frequency load shedding all with huge disruption to the grid. The initial fault was caused by dispatcher mismanagement. The resulting uncontrolled wind power plant shutdown and re-start sequences, almost triggered a probably fatal split of the Eastern European grid areas from Germany [104].

A recent incident in Australia [3] similarly followed a freak storm where the shutdown of wind power played a role in leading to a blackout. The root cause of the blackout event, however, was the outage of three 275 kV transmission lines and not wind power as such. The resulting voltage dips and the improperly tuned low-voltage ride-through (LVRT) threshold of the wind farms in the area led to the additional outage of nine wind farms, which in turn outed the crucial Heywood interconnector. The rule-set by which the wind turbines were operated could obviously be improved to avoid their automatic but untimely shutdown for self-protection. However, the same would be true for conventional turbines that shut-down for self-protection in other major blackout events. As mentioned, the analysis and prevention of such cascading events already needed more work in conventional systems. In both USA ERCOT and China new sub-synchronous oscillations related to wind power-grid interaction have emerged [105], which are so unfamiliar that data-based solution methods have been proposed over model-based techniques. Maybe this indicates a new approach that can be pursued of a computational kind. In fact, there has been a recent line of work towards data-based stability assessment aimed at dealing with complexities like scale, time delays, and data loss among others [106]–[108].

A further impact on stability only indirectly related to inertia is the loss of normal short-circuit current from conventional generators, and CIG tends to have limits on short-circuit currents, which means normal protection to preserve stability will not work effectively [109]. This changes the models again and also strategies for protection and control.

2) Frequency Response: Fig. 5 shows the response of a conventional power system to a fault, in this case loss of generation. This figure or elements thereof can be found in any power system text book as a coarse-grain illustration of (i) the power system frequency dynamics (such as inertial response as well as oscillations when zooming into the figure), (ii) the relevant associated performance metrics, e.g. RoCoF, frequency nadir, and restoration time), and (iii) the main frequency-restoring control actions on the primary and secondary level.

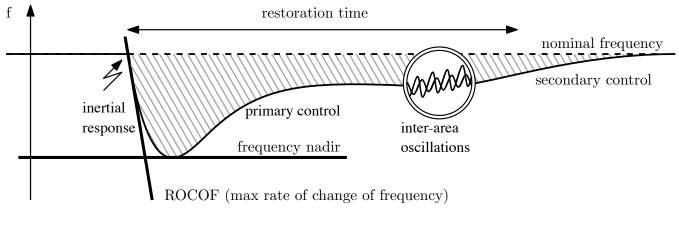

Fig. 5. Post-fault behavior of a conventional power system dominated by the dynamics of synchronous machines and their controls (adapted from [110]).

Our grasp of frequency stability and associated control actions are based on our understanding of the behavior of power systems as displayed in Fig. 5. For example, protection is triggered based on RoCoF values, load-shedding is initiated based on frequency nadirs, and controls are tuned based on such post-contingency step-responses. Of course, when zooming into the post-fault dynamics, less benign and more irregular behavior is revealed, especially in the initial transient. In what follows, we continue to work with the classical, albeit stylized, post-fault Fig. 5 keeping in mind that it is a coarse-grain plot of the underlying complex nonlinear dynamics.

Extrapolating to low-inertia systems: How do we expect such post-fault curves to change in low-inertia systems? By extrapolating from simplified power system swing equation models, we certainly expect that lower levels of inertia lead to steeper RoCoF slopes and low-frequency nadirs, as hinted at in all articles and TSO reports cited in Section I. As a potential and often advocated remedy, frequency control is shouldered increasingly by fast-ramping devices such as loads and converter-interfaced sources resulting in a much faster primary control response – possibly together with controlled virtual inertia – though there are severe limitations on the device-level implementation; see Section III-C for further details. These intuitive insights are confirmed in more detailed studies from Eirgrid and ENTSO-E [111] which recommend relaxing the limits on RoCoF and frequency nadir as well as remedial RoCoF control actions such as emulation of virtual inertia. Concerning contingencies giving rise to post-fault plots as in Fig. 5: as more bulk generation is replaced by distributed generation, we expect many more but likely smaller contingencies from loss of generation [112]. On the other hand, future grids are potentially susceptible to even larger faults caused by HVDC lines [113]. For more granular dynamics, e.g. oscillations, one may speculate that the spatial distribution of rotational inertia is very relevant and not just the total system inertia, as shown in the case studies [90], [110], [114].

The extrapolation fallacy: One can continue exploring such scenarios and extrapolate from current knowledge to future low-inertia systems. Inevitably such thought experiments lead to the conclusion that the familiar Fig. 5 is representative mostly of synchronous machines, their physical dynamics, and their controls. Extrapolating from this status-quo is a good starting point to understand frequency stability and control in low-inertia systems; see for example the Irish case study [115]. However, we should not expect a similar behavior for a power system with very few (or no) synchronous machines, with dynamics on much faster time-scales, and different frequency control mechanisms. On the far end of the extrapolation is a zero-inertia system where ”frequency” may have no more meaning. For example, the case study in [110] shows that the familiar performance indicators (RoCoF, frequency nadir, or damping ratio) or the total (virtual or rotational) system inertia are not necessarily a representative of benign system dynamics. We also note many of the CIG control, system stability, and inertia placement studies (reviewed later in Section IV) do not start from the familiar post-fault plot in Fig. 5 but consider a more generic disturbance behavior as in Fig. 6. In conclusion, we caution the reader to over-extrapolate from Fig. 5 to a low-inertia system.

C. Power System Operation and Control

In the following paragraphs, we discuss how the transition to power-electronics-based generation impacts the system-level

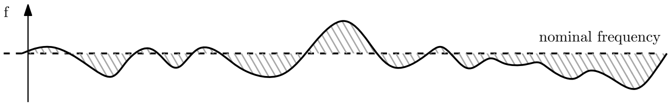

Fig. 6. Hypothetical post-fault response of a low-inertia system [110].

and device-level operation and control.

1) Operation of Low-Inertia Sources: As discussed in Section III-A, the usual dynamics of a power system are largely a consequence of the natural dynamics caused by the physical principles of the synchronous machines and their controls. These dynamics have been leveraged in the past to define operational approaches that balance and stabilize the system [116]. CIG however lacks these natural dynamics and therefore also the natural interaction with the grid and other grid resources. Given this missing natural coupling between CIG and the grid, the interaction of these resources with the grid are determined by the chosen control approach. In general, different modes of operation can be identified but as of now there is no unique and/or widely accepted terminology and distinction between these modes. In fact, many of them are even contradictory and depend on the perspective taken by the researcher and his/her main research focus, e.g. power electronics or power systems.

Two common modes that are usually distinguished are the grid-forming mode and the grid-following or grid-feeding mode [117]–[120]. In the grid-forming mode the CIG regulates the voltage magnitude at its terminal and the frequency to specific setpoints, similar to a synchronous machine. In the grid-following/grid-feeding mode, the grid regulates the frequency and the voltage while the CIG stays synchronous and provides a set amount of power simply following the imposed voltage and frequency. As discussed in [121], from the systems perspective additional modes of operation are conceivable, namely modes which provide regulation of either the frequency or the voltage magnitude and following the other.

Operating CIG in grid-feeding mode is only possible if there are other resources that do form voltage and frequency. As a large share of the generation resources in the system are still synchronous machines that form a relatively stiff AC grid, it is possible to operate all CIG as grid-feeding devices. However, as the penetration of renewable resources connected via power electronics increases, at least some of these will be required to participate in the process of forming frequency and voltage.

Works that have studied the requirements for low- or no-inertia systems, e.g. [9], [88] have been drawing the conclusions under the premise that CIG is operated either in grid-forming or in grid-following mode. Grid-forming converters are usually represented as an ideal AC voltage source with a low-output impedance, whereas the grid-feeding units are modeled as an ideal current source connected to the grid in parallel with a high impedance. Hence, the feeding converter should be perfectly synchronized with the AC voltage at the connection point, in order to regulate accurately the active and reactive power exchanged with the grid [122]. In [122], the concept of a grid-supporting mode was introduced which incorporates additional high level control loops to the grid-forming and grid-following modes to regulate an AC voltage vector via the power output.

As elaborated above, due to the degree of freedom of the controls of converters also a partial grid-forming mode is theoretically conceivable, assuming that these concepts actually lead to practically useful converters. Given this range of potential operating modes, the following questions are all open: what role each converter in the system should have, i.e. in what mode it should operate, how many should be operating as grid-forming devices or any other mode, and how these operation modes classify as grid service.

One reason for the ambiguity of the prevalent control mode classifications is the emphasized focus on the structural aspect of the control, i.e. a strict hierarchy of inner and outer control loops with a predefined set of operational functions. While such an approach meets the implementation criteria for state-of-the-art PE, it overdetermines the scope of the problem and is incompatible with some of the novel control approaches, e.g. *matching control* reviewed in Section IV-A. Furthermore, it might not give a full insight into the converter nature under different operation modes (see [123]) and could be susceptible to control parametrization, as shown in [121], [124]. Hence, a classification that can properly capture and classify the already proposed control concepts is still to be elaborated.

2) Control of CIG: In current power systems, the majority of CIG is controlled as grid-following sources as defined in Section III-C1; see the reviews [113], [125], [126]. While this mode of operation is economically very efficient, it heavily relies on the assumption of a stiff AC grid whose constant voltage and frequency can be tracked via a PLL. As discussed, without rotating machines, all converters will no longer be able to remain "followers". Thus, future low-inertia grids require also grid-forming sources that provide a reference and support for frequency and voltage, black-start capabilities, as well as a stable and robust synchronization mechanism – all capabilities that are nowadays offered primarily by synchronous machines. We refer to [9], [14], [88] for a more in-depth discussion.

Limitations of converter control: An important aspect to take into account when designing converter controllers is their dynamic interaction with the rest of the system. In a conventional grid, the fast electrical transmission line dynamics are dominated by the comparatively slow electro-mechanical dynamics and actuation of synchronous machines and thus practically negligible. As opposed to synchronous machines the physical dynamics of converters are on similar time scales as the transmission line dynamics, and their controls are also significantly faster than synchronous generator controls, up to the order of milliseconds. Such a quick response may lead to the expectation that primary frequency control can be improved if CIG is a relevant quota of the overall generation. This conclusion, however, has to be taken with caution as the faster the controllers of the converters, the more likely their dynamic coupling with the grid. Such a coupling, unfortunately, has been shown to be often unstable [21]. For transmission systems, where the R/X ratio is low, there is however a relatively large margin for the design of converter controllers, which can be actually faster than traditional synchronous machine ones, even if not as fast as the converter would allow. In medium and low voltage distribution systems, however, where the R/X ratio is higher than that of transmission grids, the unstable coupling of converter controllers and line dynamics can considerably limit the effectiveness of CIG control [127].

Two further important aspects that limit the operation and control of power converters are actuation delays induced by signal processing (e.g., PPL) and control loops on the order of up to 100 ms as well as tight limitations on the converter currents that cannot be violated, e.g., in a post-contingency response. These aspects are inherent limitations of *any* converter control architecture that cannot be circumvented, but they are more or less pronounced depending on the particular control strategy. We will frequently revisit these themes below.

Virtual inertia emulation: The transition from grid-following to grid-forming converter operation is primarily a control problem. An obvious and often advocated baseline solution is to design grid-forming converters by *emulating* synchronous machines, their inertial response, and their control mechanisms. In the simplest case, the speed-droop-control characteristic of a synchronous machine is emulated, which proved to be a successful approach for microgrids dating back to the early 1990's [67]. Recently, a plethora of strategies has been proposed to emulate synchronous machine models of various degrees of fidelity under names such as *synthetic inertia* or *virtual synchronous machine*; see the articles [66], [128], [129] and the EU Project VSYNC [130] for detailed reviews.

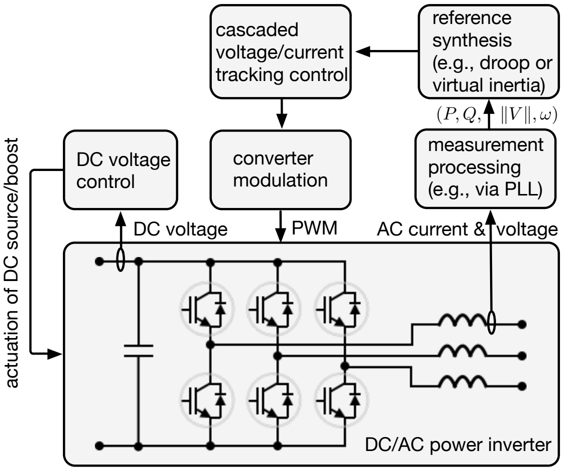

Fig. 7. Prototypical device-level implementation of virtual inertia

Virtual inertia emulation strategies are based on measurements of AC quantities such as injected power, frequency, and amplitude. For example, *inverse droop* and related strategies measure the AC frequency through a PLL and accordingly proportionally adapt the converter power injection based on a linear droop characteristic. The latter is encoded in a micro-controller whose outputs are tracked by the converter modulation typically through a cascaded control architecture. This signal processing and control architecture is schematically illustrated in Fig. 7. A more complex reference model (upper right block in Fig. 7) can be used if the emulation of further machine characteristics such as inertia or rotor/stator/AVR is desired. Finally, droop control and machine emulation can also be implemented in a grid-forming fashion by measuring the injected power (typically through a low-pass filter to ensure appropriate damping [131]) and accordingly adapting the converter modulation frequency. We also remark a first-order droop (or power-based) mechanism is sufficient to ensure stable synchronization that does not need any virtual inertia (in the form of second-order mechanical dynamics) [132]. Indeed, many virtual inertia strategies are tuned to effectively have a nearly zero inertia constant [81], [133], which results in a more well-behaved closed-loop behavior without severe overshoots.

Limitations of virtual inertia emulation: Notice that each of the blocks in Fig. 7 is by itself a non-trivial signal processing entity, see for example the PLL in Fig. 2, thereby increasing the complexity and end-to-end actuation delay in the control loop. For such and related implementations, the time delays resulting from measuring and processing AC quantities render the benefits of (otherwise fast) power converter control often ineffective [4], [88], [128]. Another limitation of inertia emulation are the converter current limits during post-contingency dynamics: recall that a synchronous machine can be heavily overloaded and provide short-circuit current during a fault, but a similar response is not desirable for a converter with very narrow limits on the admissible current overshoots [9], [88]. As mentioned before, current saturation is an inherent limitation of any converter control architecture often causing instability see e.g. [134], [135] for the case of droop control. However, in the authors' experience, these limitations are especially pronounced when emulating synchronous machine dynamics. For this reason the virtual inertia constants are often tuned to zero, as mentioned above. Furthermore, the inverter's DC-side storage element is mostly excluded in the model and the control design for the converter/grid interactions, which limits the control performance (droop and emulation strategies typically become unstable unless a stringent time-scale separation between AC and DC dynamics is enforced [133]) and also misses a key insight: namely, the DC bus voltage reflects the power imbalance and serves as valuable control signal; see Section III-A1. Finally, droop control and machine emulation are known to have a rather narrow stable region of attraction and slow dynamics compared to other (oscillator-based) control strategies [136], [137].

In summary, the often advocated virtual inertia emulation strategy is a valuable baseline solution to grid-forming converter control. Under nominal (not faulty) conditions, it recovers the dynamic input-output behavior of a controlled synchronous machine and is thus compatible with the legacy power system. However, this solution is not a magic bullet and has limitations when it comes to stabilizing post-contingency dynamics subject to current limits, time delays, and far away from a small-signal regime. As a final thought, it also seems to be a naive and wasteful approach to force a converter (a fully actuated, modular, and very fast control system) to behave like a (under-actuated, rigidly controlled, and comparatively slow) synchronous machine that does not make use of the converters' key resources and strengths. Thus, multiple alternative approaches to grid-forming converter control have been proposed which we will review in Section IV-A below.

IV. STATUS OF SOLUTIONS

A. Device-Level: Control of Power Converters

At the heart of low-inertia systems is the change in generation technology. Aside from device-level challenges for CIG and storage technologies, the relevant system-level questions are concerned with how (possibly distributed) low-inertia sources are interfaced with the larger utility grid.

1) Grid-Forming Control Strategies: We first focus on solutions that have been put forward for grid-forming converter control. In Section III-C, we have already reviewed the general limitations of converter control: interactions with line dynamics, control-induced delays, and tight current limits. As discussed above, multiple control approaches are based on *virtual inertia emulation* that control an inverter to have a similar terminal behavior as a synchronous machine [66], [81], [128], [129], [133], [138]–[140]. While these strategies are successful and generally viable under nominal conditions, they are limited in their applicability for post-contingency stabilization; see Section III-C. Since emulation strategies are a broad and active research area, there is hope that these obstacles can be overcome. Certainly, the simplest emulation strategy, *droop control*, has seen many applications in microgrids [67], [69], [71], and, thanks to its simplicity, droop may see further extensions to make it more robust and more widely applicable.

A related strategy, at least on the surface, is *matching control* [77], [83]–[87]. This control strategy starts from the generator/converter analogies illustrated in Fig. 3 and controls the DC-AC energy exchange of a converter by matching the electro-mechanical energy exchange of a synchronous machine. The key ingredient is to recognize the duality of converter DC voltage and the generator rotor frequency and to accordingly control the converter modulation analogous to the generator's rotating magnetic field. Matching control requires only measurements of the DC voltage and no other inner loops thereby bypassing the control-induced delays of other strategies. It also exposes an architectural feature of the inverter which is independent of the particular control strategy: namely, the DC voltage needs to be stabilized by the primary DC energy source to guarantee a power balance across the converter without depleting the DC capacitor. This feature is implicit in all other converter control strategies relying on a stiff DC voltage control and time-scale separations [133].

Yet another set of control strategies is *virtual oscillator control*, where converters are controlled as nonlinear limit-cycle oscillators, e.g. as van-der-Pol oscillators, interacting with the converter terminal signals. The idea of virtual oscillator control dates back to [141], [142], and it has been further theoretically investigated and experimentally validated in [143]–[147], among others. It has been shown in theory and experiments that virtual oscillator control reduces to droop-control near a quasi-steady state, but the former has faster, global, and more robust convergence properties [136], [137], [147]. We note that oscillator-based control strategies have proved to be powerful approaches in theory and experiments, but their foundations still need to be further developed to include, for example, voltage and frequency regulation capabilities.

2) Role of Measurements and Delays: The ongoing transition from conventional synchronous machines to PE-interfaced generation introduces new issues from the perspective of signal processing. While the inherent physical processes of a synchronous machine provide natural means of synchronization and inertia without any delays immediately slowing down the system dynamics, the behavior of converter units is purely based on the nature of control algorithms, and involves the measurement of the 3-phase voltage and current waveforms at the converter terminal. The lack of "inherent synchronization" is compensated for by the deployment of dedicated synchronization units, primarily PLLs, that take these measurements as inputs to determine the frequency. Finally, a set of control blocks take these processed measurements as inputs to determine the settings for the PWM. Hence, the control of a converter entails a chain of signal processing steps which in summary inevitably leads to inherent and unavoidable delays in the control of CIG.

Furthermore, as already discussed in Section II-G, PLLs are inherently sensitive to noise which can potentially cause instabilities. Indeed, the PLL-based techniques might be inadequate for synchronization of multiple units in a low-inertia system that is prone to fast frequency variations. Hence, there is a need to consider alternative synchronization strategies. Options include for example the replacement of the PLL with a controller that emulates the self-synchronizing nature of an *induction machine*, such as presented in [123] or similarly to substitute the PLL with a *virtual synchronous machine* emulation as in [148]. Another alternative is to modify the existing *synchronverter* control strategy in order to provide self-synchronization [149]. The emulation of a machine via a controller further allows the integration of some additional "grid-friendly" properties of the actual generators, such as virtual inertia and power and frequency oscillation damping.

Another alternative towards obtaining the information of frequency balance in a converter-based system can be derived from the *matching control* principles, e.g. [77], [87], described in Section II-E. The conclusion is that similar to the rotational frequency of a synchronous machine, the voltage measurement on the DC side of a converter can equally indicate the instantaneous power imbalance (see Fig. 3). The importance of this local control signal was also recognized and highlighted in back-to-back converter applications of DFIG-based wind power generators [24], [150], as well as in the nonlinear modeling of droop-controlled HVDC transmission systems, with their dynamics reduced to the DC-side capacitors [151].

While the vast majority of control strategies propose decentralized operation of individual converter units based on locally attainable signals, the existence of a more global, wide area-like configuration could also be an option, e.g. actively recomputed converter setpoints dispatched from a centralized entity. For both options, depending on what type of measurements are needed and how they are being communicated and processed, the potential time delays in a converter-based system could vary from several milliseconds to up to a few seconds, thus drastically affecting the system stability margins. The introduction of additional control loops that on one hand provide additional features, but also require additional measurements, further exacerbate the time delay issue. An example are frequency control strategies based on *adaptive* inertia and damping regulation such as presented in [17], [152]–[157], which include an explicit RoCoF measurement as a control input. However, attempts to measure RoCoF during a short phasor measurement unit (PMU) window have inherent time delays and noise-related issues [158].

In view of the overall faster time scales in the system dynamics of low-inertia systems, the impact of signal delays can become of crucial importance for the overall stability of these systems. The inclusion of time delays however reformulates the converter model from a traditional differential-algebraic equation (DAE) form into a set of delay differential-algebraic equations (DDAEs). This, among other reasons, leads to the need to devise new stability approaches.

B. New Stability Analysis

The integration of time delays, but even more general the issues raised in Section III-B, require attention to many modeling and analysis questions regarding stability and there has been some progress.

Due to the transcendental nature of the resulting DDAEs, several general-purpose techniques have been proposed for recasting the small-signal stability analysis of large-scale DDAEs into a finite spectrum of critical, low-frequency eigenvalues, most notably the Chebyshev discretization scheme and Padé approximants [159]–[162]. Using such a model the impact of time delays on stability of a system with an all converter-interfaced generation was investigated in [163] confirming that the stability margin depends heavily on the measurement delay. However, the implementation of a detailed converter model [164], together with multiple, e.g. [162], [165], [166], and varying time delays, e.g. [167]–[169], still needs be realized to carry out extensive stability analysis studies.

At the system level it is suggested here that more emphasis should already have been placed on grid structure, i.e. the grid topology as well as “where things are” in the grid, in order to analyze stability. There are new concerns such as critical sites, e.g. for CIG [99], and the recent attention to locate vulnerable sites for failure and attack [170], which make it even more compelling. In other areas of science the role of network topology has been given much more emphasis in determining dynamic properties. In complex networks science – which refers to power grids as an example – the topology, node dynamics and coupling strengths are all given equal weight.

Different topologies have dramatically different capabilities for synchronization. These ideas have inspired a recent line of work [171]–[176] on power system stability where structure is given much more prominence. Further in [172], [174], the equilibrium-based paradigm for stability is not used and allows for the continuous disturbance type analysis - see Section III-B discussion. In [176], the idea presented in [80] is translated into an analytic question, namely to give stability conditions in terms of CIG dynamics, load dynamics and network structure for small-disturbance stability. Another approach to stability analysis than Lyapunov theory is so-called input-to-state stability (ISS) which emphasizes the relation between the size of the response to the size of the disturbance. This approach has been used in [177] to analyze the impact of wind power. (This approach was anticipated in the 2004 stability definitions paper [93], but has not been widely used.) Fig. 5 and Fig. 6 illustrate the change from equilibria-event based to continuous disturbances and synchronization and ISS methods provide ways to deal with the latter.

The complex networks approach has been used to explore vulnerability and cascading collapse in several results see [170], [178] and the references within. In [178], a new method for the analysis of the power system vulnerability is proposed. Based on complex network theory and the Max-Flow theorem, a new vulnerability index is adopted to identify the vulnerable lines in a power grid. These methods can be used to specifically address CIG related issues in further work.

Taking the computational approach as another way to get general conclusions about how structure affects stability, some work [179] on how inertia placement relative to area power export/import was inspired by the Australian Future Grid project and some earlier results [96], [97]. Considering the well-known two area test system [116] and varying CIG and tie-line power flows some guidelines were obtained that were then used on a study of the five-area linear model of the Australian NEM. This work needs to be extended to consider a range of typical structures for large grids.

The Future Grid project used scenario analysis to assess stability across large numbers of scenarios defined by hourly operations and inter-seasonal variations in renewable generation. In [180], a framework is proposed for fast stability scanning using a novel feature selection algorithm and a novel self-adaptive PSO-k-means clustering algorithm. To achieve the computational speed-up, the stability analysis is performed only on a small number of representative cluster centroids instead of on the full set of operating conditions. As a case study, the small-signal stability and steady-state voltage stability scanning of a simplified model of the Australian National Electricity Market with significant penetration of renewable generation is carried out. Compared to an exhaustive time series scanning, the proposed framework reduced the computational burden up to ten times, with an acceptable level of accuracy.

C. Distributed Control

Classical frequency control is achieved by a mix of local and centralized synchronous generator control [116]. As the dominance of large synchronous generators gives way to more distributed and less controllable CIG (and with lower inertia) the whole control problem changes towards one referred to as ’end-to-end’, i.e. all generation, network and demand-side distributed energy resources (DER) will need to play a role - see discussion in Section III-B2. This requires use of so-called distributed control to implement in a coordinated way. There has recently been much scientific attention to this subject (some under other headings including multi-agent systems and game theory). It is interesting to note that some of these new control paradigms mobilize control actions on a faster time-scale than conventional generators, i.e. milliseconds, and so can be usefully deployed even in a system with substantial synchronous generation. However, they become more essential as the CIG level rises.

There are ways to achieve some contribution to control from the kinetic energy of the turbines in wind turbine generators (WTGs). This can be utilized to support power system frequency during contingencies – see some recent work by the authors [181], [182] and references within from the early 2000s. In [182] the frequency support capability of WTGs operating at the maximum power point (MPP) to prevent secondary frequency dips, provoked from switching between normal operating mode and the frequency support mode, is formulated. A time-variable droop characteristic is proposed for frequency support from WTGs, which is quite effective in preventing large frequency excursions and facilitates smooth recovery of the kinetic energy of WTGs.

Distributed control for low-inertia systems based on converter design has also been considered recently [77]. As in related research for microgrids, the models go back to first principles and allow novel concepts for converter control design to be considered. In [77], starting from a detailed nonlinear first-principle model of a low-inertia power system, including detailed power converter models and the power grid with no phasor approximation, arguments from singular perturbation theory are used to obtain a tractable model for control design. Results on frequency stabilization via decentralized nonlinear droop control are presented [67], [69], [71].

These generator side improvements notwithstanding, there appears to be a large untapped resource on the demand-side if the associated challenge of coordinating large numbers of agents can be met. The subjects of distributed control, multi-agent systems and game theory all provide ways to deal with this. It is already well-known and demonstrated in test facilities that use of fast demand modification (direct or in response to incentives) can be very effective in frequency control [183]–[185]. The study of this idea using methods of distributed control theory has progressed recently [186]–[191].

In [190], frequency regulation of power systems is studied by using both automatic generation control (AGC) and load-side control. A switched distributed controller is designed for each load bus in a transmission network which achieves the dual goals of being fully responsive and non-disruptive [192]. The controllable loads work together with generators to restore the system frequency quickly after a real power mismatch occurs in the grid. A consensus-based distributed loadside controller is designed. Peer-to-peer communication between loads is used to achieve an average consensus according to which controllable load reacts to the frequency deviation. To achieve minimum disruption, the load-side controller shifts its duties to AGC slowly after the frequency goes back into an ideal region, and hence, controllable loads will restore to their nominal conditions gradually. A switching signal is designed to detect time instants when the load-side controller should work in the mode of frequency restoration or in the mode of load restoration. Ongoing work is extending these results to allow greater granularity in the control agents [193] and more sophisticated event-triggering methods for switching between modes [194].

Storage technologies, such as batteries, have higher ramping capability than conventional generators, and so they can be used to achieve better dynamic tracking performance when following a rapidly changing frequency control signal. However, storage units are energy constrained. In [191] a method is given for decomposing the target signal into a different signal for each generator and each storage unit, depending on their characteristics and on the storage energy levels. Faster units receive signals with higher ramping rates. The method is particularly suitable when the energy/power ratios vary by orders of magnitude. The energy content of the storage unit signals is managed through a term penalizing energy level deviation in the dispatch cost function. A distributed implementation of the method approaches the dispatch of its centralized counterpart. Using a population of 1000 units it is shown that the distributed implementation is (i) up to 700 times faster than the centralized implementation, therefore allowing for real-time implementation with a large number of units; and (ii) robust to loss of communication links.

Related to the above methods are similar approaches to achieving distributed voltage control in the presence of high levels of CIG [195]. The schemes generally deploy conventional control agents (switched capacitors, OLTC) with load control aggregators.

The emergence of cost-effective "behind-the-meter" DER, in particular rooftop solar PV and battery storage, and the advancement of sensor, computer, communication and energy management technologies are changing the way electricity consumers source and consume electric power. A scenario called "Rise of the Prosumer" has featured strongly in Australia considerations of future grids [11], [196]. The opportunities offered by demand side resources have also been recognized by the Australian Energy Market Commission [197], who argue that consumers with PV-battery systems can provide network support and ancillary services that were traditionally confined to the domain of large generators. Indeed, [198], [199] showed that a high penetration of prosumers, consumers equipped with rooftop solar and battery storage, changes the demand profile in ways that significantly improve the system loadability [198] and frequency performance [199].

Using prosumers as an efficient source of flexibility to support system security, including inertia and frequency support, however, requires bridging the gap between large-scale demand response aggregation, e.g. [200], and the management of individual home-level production, e.g. [201], [202], given the task-oriented nature of energy usage [203]. A major challenge is to align the objectives of many households aiming to minimize cost and maximize comfort with the objectives of an aggregator that aims to minimize the cost of electricity purchased in a pooled wholesale market. Next, the highly diffuse nature of DER requires distributed approaches to ensure scalability.

Several distributed optimization techniques have been proposed in recent years to address the challenges arising in smart grids (see the recent survey [204] for a comprehensive overview). In the context of demand response aggregation, the usual approach is to decompose the optimization problem in terms of devices, e.g. [200], which neglects the underlying home energy management. To address that, [205] proposed a scalable on-line distributed algorithm which can aggregate several thousand of households with a mixture of discrete and continuous energy levels, which can be coupled with an incentive compatible mechanism to ensure that the consumers follow their allocations and prevents collusion.

D. Inertia Placement

Data shows that the rotational inertia level is not only temporally varying but also spatially not uniformly distributed across the grid [32], [90], [91]. For a given contingency, the resulting post-fault dynamics are thus not only a function of the total system inertia but also of the spatial distribution of inertia across the grid which again depends on the current dispatch point. We are thus faced with the questions of how much inertia we actually need to withstand a contingency, where in the system has it the most beneficial effect, how we can value the contribution of virtual inertia, and how to trade-off between virtual inertia and damping subject to finite actuation capacity.

Several authors have recently investigated such *virtual inertia and damping allocation* questions relying on optimization-based approaches. In such a formulation a cost function is minimized over the virtual inertia and damping parameters that characterize the transient performance of a linearized system model and subject to budget and capacity constraints on the available virtual inertia and damping. The proposed performance criteria include the classic power system metrics in Fig. 5 such as spectral criteria on the eigenvalues and eigenvectors for oscillation damping [114], [206], approximate time-domain criteria on RoCoF, nadir, and restoration time [32], [115], [207]. Another class of approaches starts from the observation that the post-fault response of a low-inertia system does not have to take a similar shape as in Fig. 5 and the associated criteria may not be sensible optimization objectives. Rather these approaches parameterize the inertia allocation in terms of system norms measuring the amplification of disturbances to selected performance outputs in terms of the $\mathcal{H}_2$ [110], [208], [209] the $\mathcal{H}_\infty$ metric [210], [211], or combinations thereof with time-domain metrics [212].

Common outcomes of all these studies are that total system inertia is a poor characterization of performance and resilience, but the geographic location in the grid is very significant - another situation where grid structure must be explicitly used. In fact, a low-inertia system with strategically placed virtual inertia and damping can outperform (in the optimization metric) a conventional system. There is no intuitive geographic allocation pattern emerging from the different case studies, but [208] provides an analytic result for a simplified swing equation model: the optimal allocation of virtual inertia is aligned with the expectation of a fault to take place, which suggests robust $\max - \min$ optimization framework or a uniform allocation for uniform fault probabilities. The study [110] concludes that inertia should be dominantly allocated near generation buses where frequency measurements are most reliable, and that it is important to penalize the control effort.

Finally, [212] emphasizes that the results very much depend on the model fidelity and the nature of the disturbance. However, care should be taken when interpreting these results and asking for an *optimal* placement. Indeed, all studies show that the optimal allocation of inertia and damping strongly depends on the chosen optimization criteria and constraints. To conclude, the post-fault response of a low-inertia system is *tune-able* and not passive as in a conventional system. Hence, it is up to the designer to choose the right optimization criteria.

All of the above investigations are of theoretical nature analyzing stylized models such as swing equations with variable inertia coefficients. Important open questions include how inertia should actually be dispatched on different time-scales. There is a range of open problems related to unit commitment, dispatch, control, and of course economic aspects all related to inertia that require much more attention. An interesting study in this direction [213] analyzes the dispatcher's trade-off between aggregated inertia and worst-case contingency.

E. Practical Situations

We now present two real-life examples where low inertia is already a serious issue, namely the all-island Irish transmission system and the Australian National Electricity Market. Both systems are islands, but while the former is meshed, the latter is stringy.

1) All-Island Irish Transmission System: The all-island Irish transmission system is composed of two TSOs, EirGrid and NISO. This network is peculiar as it is a relatively small system (about 5 GW of peak load) and it is connected to the rest of the world, namely the Great Britain network, only through two HVDC cables (Moyle interconnector in Northern Ireland and East-West interconnector). The small size coupled with the high penetration of wind power would allow experimenting instantaneous penetration of non-synchronous generation up to 100%. However, "only" up to the 65% of non-synchronous generation instantaneous penetration is enforced. This limit has been defined by EirGrid and SONI in April 2018, based on a comprehensive stability analysis. The Irish system is the first in the world that can handle such a level of variable renewable energy on the grid at any given time.

One of the main issues of the Irish system that prevents higher levels of penetration is the East-West interconnector, which is a 500 MW High Voltage Direct Current (HVDC) link between the electricity transmission grids of Ireland and Great Britain. Such interconnector is one of the largest voltage sourced converter (VSC) HVDC links in operation worldwide, but while 500 MW is about 10% of the total peak load of EirGrid, it is less than 1% of the peak load of the National Grid in Great Britain. The disconnection of the East West interconnector is a relatively likely event and is effectively the largest and most critical contingency that can affect the Irish grid [214]. As a matter of fact, a power plant is specifically dedicated to take over in case of the disconnection of the largest infeed. Another relevant, although less likely, event is the loss of wind power generation due to network faults. However, this issue can be significantly mitigated if not solved by means of an effective implementation of the fault-ride through capability of wind power plants [215], [216] and proper freqeuncy control of wind power plants [217]. Both issues above are directly related to frequency stability and, in particular, to the frequency excursion and RoCoF following the loss of the largest infeed or of generation (see equation (1)). To date, the Irish system is thus one of the systems where low inertia is one of the major issues that the TSO has to solve to ensure the stability of the grid.

Fig. 8 shows the minimum frequency following the loss of the largest infeed versus the kinetic energy stored in conventional generators and the load divided by the dispatched power of the largest infeed [214]. The abscissa is one of the operational metric defined by EirGrid to identify the impact of non-synchronous generation on the transient response of the Irish system. Based on simulations results and experience, EirGrid defines that safe values for the ratio between the kinetic energy and the power of the largest infeed are above 30 MWs/MW. Hence, corrective measures to increase the stability of the system are either to ensure a minimum amount of conventional synchronous machines (including possibly synchronous compensators) or enable emulated inertia, i.e. RoCoF control, by means of wind power plants.

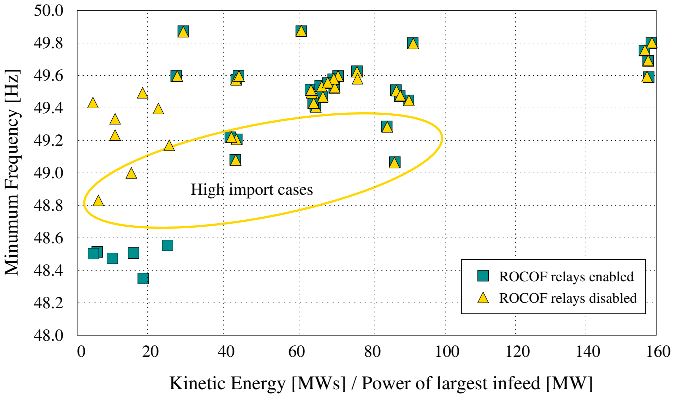

Fig. 8. Minimum frequency following the loss of the largest infeed versus the kinetic energy stored in conventional generators and the load divided by the dispatched power of the largest infeed (adapted from [214]).

2) Australian National Electricity Market (NEM): The NEM consists of five interconnected states – Queensland, New South Wales (including the Australian Capital Territory), Victoria, South Australia, and Tasmania. The NEM is one of the world's longest interconnected synchronous power systems, stretching from Port Douglas in Queensland to Port Lincoln in South Australia and across the Bass Strait to Tasmania – a distance of around 5000 km. In addition to that, the network topology is stringy, with a limited interconnection capacity between the states. South Australia, for example, is only connected to Victoria by one 220 MW HVDC line (Murraylink) and one double-circuit 650 MW HVAC line (Heywood interconnector).

Given the very high penetration of wind and solar (30% and 15% of installed capacity, respectively), a loss of the interconnector can be a serious operational issue, as evidenced by the 2016 South Australian blackout. In that regard, the South Australian system is very similar to the Irish system. The other similarity is its size – it has the maximum demand of 3.1 GW, with a combined wind and solar (mostly rooftop PV) energy penetration of 40%. Because the interconnection to Victoria is synchronous, the maximum instantaneous penetration can be higher than in Ireland. In 2015-16, the maximum instantaneous penetration (excluding exports) was 119% for wind and 38% for rooftop PV. However, the loss of the Heywood interconnector in such situations can result in a lack of inertia. The Australian Energy Market Operator (AEMO) has therefore introduced a new system strength measure, requiring a minimum of three synchronous generating units to be operating at all times to ensure a minimum amount of inertia. The Australian Energy Market Commission is now discussing a possibility of introducing a market for inertia.

F. Integration Studies

1) PMU-based monitoring and forecasting: The EU project MIGRATE[1] [9] addresses the impact of high penetration of PE devices, e.g. HVDC connections and non-synchronous generation, on high voltage transmission systems. The project focuses on how to increase the penetration of such devices while maintaining a minimum stability margin of the transmission system. To this aim, MIGRATE first defines the modifications to the dynamic behavior of the power system and the potential interactions between PE controllers. The goal is to define proper control strategies that should help TSOs to increase the level of PE penetration without modifying the structure of existing controllers and grid codes. The software solutions are tested in the Scottish Power and Landsnet (Iceland) networks.

The most innovative goal of the MIGRATE project is to revisit the control strategies on the device and system level (converter-internal control, primary and secondary voltage and frequency – in terms of system adequacy – control, as well as tertiary reserves) so as to be able, firstly, to operate the network with no synchronous generators (100% PE penetration) and, secondly, operate the network at very high PE penetration with both control strategies (the existing one and the new one). Proper revisited protection schemes, power quality evaluations and network code recommendations accompany the definition of such new controllers.

The low-inertia issues are among the challenges posed by the high penetration of PE devices that are tackled by the MIGRATE consortium. Based on the experience of Irish, British and Nordic partners, it is recognized that there is a possible correlation between inertia variations and the non-uniform frequency variations observed in the British and Nordic power systems. A new monitoring and forecasting approach for area inertia, assuming a non-uniform distribution of system inertia, will be developed and implemented, e.g. by Scottish power, so as to help TSOs better operate (including operational planning) their network under high PE penetration. In particular, a method will be developed to estimate area inertia (or inertia of a single generating unit) based on PMU measurements in the few seconds following a system disturbance.

2) Integration of electric and communication systems: The EU project RESERVE[2] focuses on the integration of novel communication systems, e.g. 5G, and the electric grid, in particular, at the distribution voltage level, with high penetration of renewable energy resources. The project considers both frequency and voltage stability issues and both low inertia and 100% non-synchronous generation scenarios. With respect to frequency stability, the main goal of RESERVE is to define, through measures and proof-of-concept simulations, the frequency control that can be achieved through renewable energy sources (RES). With the proper communication system, it is expected that RES will be able to provide a faster control and possibly lead to a system as stable as the current asset based on conventional power plants.

One of the goals of RESERVE is to provide a proper theoretical background for frequency measures and estimation as well as the impact of measure delays and noise is defined first. The most relevant results achieved so far are related to this task [52], [53], [56], [218] and have led to a new definition of frequency to be proposed for ENTSO-E network codes (see Subsection II-J).

Future work to be carried out within the RESERVE consortium will investigate the issues in the power system operation caused by a large integration of RESs, and propose corrective

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[1] Webpage: `www.h2020-migrate.eu`

[2] Webpage: `www.re-serve.eu`

actions – specifically based on the integration of energy storge devices and communication networks – to adapt the frequency regulation strategy. Next, a stability analysis involving non-synchronous generation that provides frequency regulations will be carried out, considering different scenarios and penetration levels of non-synchronous and/or renewable generation. Finally, the project aims at drafting ancillary service definitions and network codes for validation, harmonisation and standardisation within the countries of the European Community.

3) Scenario-based approach: The Future Grid Research Program funded by the CSIRO[3], has the aim to explore possible future pathways for the evolution of the Australian grid out to 2050 by looking beyond simple balancing. The motivation for the program was provided by the transition of power systems to future grids dominated by variable renewable generation and the prosumeration of the demand, which requires a major departure from conventional power system planning, where only a handful of the most critical scenarios is analyzed.

Following an industry based forum which led to report [11], a University Research Cluster was formed to give a more computational basis to future grid questions. Some of the results related to inertia are now briefly described.

As an alternative to “system theoretic” approaches for inertia placement described in Section-IV-D, [199] proposes a computational scenario-based sensitivity analysis to asses the renewable integration limits with respect to frequency performance. While “system theoretic” approaches provide theoretically proven performance guarantees, they come with their own limitations. First, the small-signal state-space system model might be inaccurate for large-disturbance frequency stability analysis. Second, the generic inverter-interfaced generator models are simplified by necessity, so several important features that have an important impact on the system performance following a disturbance – e.g. fault-right through capability or primary frequency response provided by wind turbines – are omitted.

Finally, the problem of optimal inertia placement cannot be separated from market dispatch given that the ability of an inverter-interfaced generator depends on its current dispatch level, which, in turn, depends on the market dispatch, as demonstrated in [199]. In addition to that, if prosumers are used as a source of flexibility [198], [199] including them in system dispatch is important. To account for a wide range of possible future evolutions, [199] uses scenario-based sensitivity analysis, which provides a systematic approach to capture the impact of a wide range of emerging technologies on the behavior of future grids. The framework is generic and uses chronological time series analysis to capture the inter-seasonal variations in renewable generation so the stability performance can be assessed over a long horizon. An important feature of the framework is a generic demand model which considers the impact of prosumers [198].

The model is formulated as a bi-level program in which the upper-level unit commitment problem minimizes the total generation cost, and the lower-level problem maximizes prosumers’ aggregate self-consumption. Unlike in the existing bi-level optimization frameworks that focus on the interaction between the wholesale market and an aggregator, the coupling is through the prosumers’ demand, not through the electricity price. That renders the proposed model market structure agnostic, making it suitable for future grid studies where the market structure is potentially unknown [219]. The lower-level objective is motivated by the emerging situation in Australia, where rooftop PV owners are increasingly discouraged from sending power back to the grid due to very low PV feed-in-tariffs versus increasing retail electricity prices.

In this setting, an obvious cost-minimizing strategy is to install small-scale battery storage, to maximize self-consumption of local generated energy and offset energy used in peak pricing periods. Moreover, self-consumption within an aggregated block of prosumers is a good approximation of many likely behaviors and responses to other future incentives and market structures, such as (peak power-based) demand charges, capacity constrained connections, virtual net metering across connection points, transactive energy and local energy trading, and a (somewhat irrational) desire for self-reliance.

The main result of [199] is captured in Fig. 9 which shows the minimum rate of change of frequency (RoCoF) for different levels of nonsynchronous instantaneous penetration (NSIP) for several scenarios. The red line clearly delineates the NSIP limit assuming a critical RoCoF of $-0.5\,\mathrm{Hz\,s^{-1}}$. Observe that the NSIP limit depends on the location of the contingency, which confirms the findings of the studies summarized in Section-IV-D. To address that, [199] proposes several solutions, including a dynamic region-based minimum inertia constraint in the market dispatch model. In addition to that, the paper shows that synchronous condensers, emulated inertia and wind turbine deloading provide a viable alternative to the inertia provided by synchronous generation.

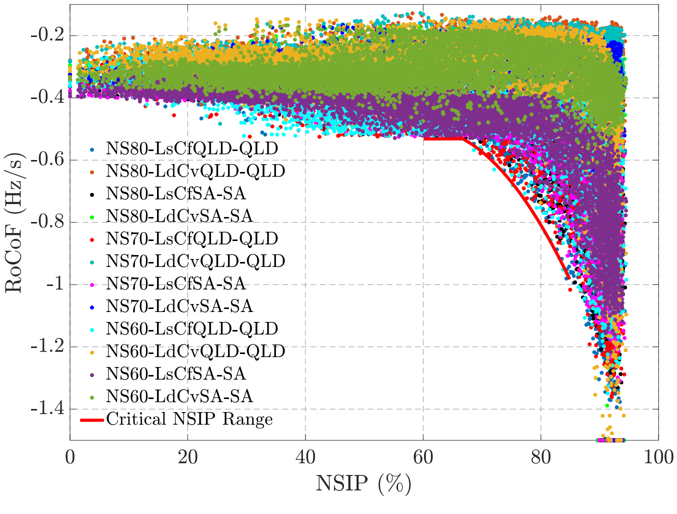

Fig. 9. Minimum RoCoF following a credible contingency for different levels of CIG instantaneous penetration in an Australian case study [199].

V. CONCLUSIONS

In this invited survey paper, an overview of the issues expected for low-inertia power systems – regarded as equivalent to high penetration of CIG – is given along with some research proceeding and required to deal with them. Given that high

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[3] Webpage: `www.futuregrid.org.au`

CIG levels has impact on almost everything from planning to operations, modeling, stability and control, there has been a need to focus on some aspects. Inevitably there has also been some emphasis given to work in and connected to the authors' own institutions in the areas of dynamics and control. Some emphasis has also been given to the relative roles of analytic, computational and practical aspects.

The later sections contain many suggestions for further work, which can be summarized as follows:

- New models are needed which balance the need to include key features without burdening the model (whether for analytical or computational work) with uneven and excessive detail;
- New stability theory which properly reflects the new devices and time-scales associated with CIG, new loads and use of storage;
- Further computational work to achieve sensitivity guidelines including data-based approaches;
- New control methodologies, e.g. new controller to mitigate the high rate of change of frequency in low inertia systems;
- A power converter is a fully actuated, modular, and very fast control system, which are nearly antipodal characteristics to those of a synchronous machine. Thus, one should critically reflect the control of a converter as a virtual synchronous machine; and
- The lack of inertia in a power system does not need to (and cannot) be fixed by simply "adding inertia back" in the systems.

This group of authors believes that these are the core scientific challenges to be addressed in low-inertia systems. There are also many important points to be made concerning issues that we only superficially touched upon such as the effects of low-inertia grids on conventional generation, voltage stability and reactive power support by converters, the economic aspects of inertia and conventional generation dispatch, as well as the role of FACTS devices, HVDC, and synchronous condensers. Ultimately, the techniques above will serve to define proper network codes and, hopefully, to increase the instantaneous penetration and the capacity credit of CIGs.

Finally the authors generally advocate a more scientific approach to technical and bigger questions where analytical and computational approaches can give new guidelines and methodologies which can respond to the greater levels of uncertainty and change expected in future grids.

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