The role of inertia for grid flexibility under high penetration of variable renewables - A review of challenges and solutions

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Abstract: Several studies show that grid-integrated renewable energy (RE) sources have the potential to replace conventional synchronous generators in the network. This means the grid will experience low conventional inertia that is currently provided by synchronous generators. Low, unpredictable and time-changing inertia in the power system, as a result of high penetration of non-synchronous RE sources, can cause rapid frequency oscillations. The rapid and unpredictable frequency oscillations are the major source of stability challenges in the power system. Therefore, this research presents a comprehensive literature survey on the role of inertia for grid flexibility under high penetration of non-synchronous RE sources to the power system. As inertia is becoming a time-changing quantity, inertia estimation techniques have been gaining popularity as solutions to stability challenges faced by the power system. Related to time-changing inertia, the following are discussed in this survey research. First, synthetic inertia provision in the network and the need for inertia estimation are intensively discussed. Second, the importance of prior knowledge of the system inertia, which will help operators to apply suitable control strategies to mitigate stability challenges, is also addressed. Third, the significance of co-existence, coordination and optimization of both conventional synchronous generator's inertia and synthetic inertia, as a key feature towards reliable and flexible grid in low inertia environment, are also emphasized. Finally, technical challenges, key issues, and further research needs are highlighted.

Keywords: Virtual/Synthetic Inertia, Inertia Estimation, Frequency Response, Inertia Monitoring, Rate of Change of Frequency, Renewable Energy Sources, Virtual Synchronous Generator

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Highlights

- Discussed challenges of low and time-varying inertia on the grid’s frequency stability.
- Explained significance of synthetic inertia to the grid’s frequency stability.
- Reviewed inertia estimation techniques in power systems extensively.
- Highlighted the need for coordination and optimization of inertia for grid flexibility.
- Emphasized the need for inertia monitoring for planning and operation of the grid.

Nomenclature

CHP	Combined heat and power
COI	Centre of inertia
DG	Distributed generation
ENTSO-E	European network of transmission system operators for electricity
ES	Energy storage
EU	European Union
EV	Electric vehicle
GW	Gigawatts
Hz	Hertz
Hz/s	Hertz per second
IEA	International energy agency
KHI	Kawasaki heavy industries
MW	Megawatts
MFAT	Ministry of foreign affairs and trade
NEM	National electricity market
PCC	Point of common coupling
PLL	Phase-locked loop
PMU	Phasor measurement units
PSO	Power system operators
PV	Photovoltaic
PWM	Pulse-width modulation
RE	Renewable energy
RoCoF	Rate of change of frequency
SA	South Australia
SG	Synchronous generator
SOC	State of charge
SVD	Singular value decomposition
VISMA	Virtual synchronous machine
VOC	Virtual oscillator control
VSG	Virtual synchronous generator
WECC	Western electricity coordination council

1. Introduction

Several factors have intensified the interests in finding low carbon energy sources for power generation. These factors include the growth of global energy demand and consumption, a global call for a low carbon economy, depletion of fossil fuel and geopolitics of the oil economy [1-3]. On this note, the vastly available renewable energy (RE) sources are a promising solution to the global energy demand crisis. As a result, their shares in the energy mix for power generation keep increasing [2, 4-6]. According to the global energy review by the International Energy Agency (IEA), the global share of RE sources into the power system was almost 13% by 2019 [7]. The global share of RE sources into the power system is expected to further rise to 45% by 2040 according to the renewables global status report [8]. Therefore, hybrid generation systems comprising conventional electric power generation sources and stochastic RE sources are inevitable in the power system [9, 10]. In this way, the rapidly growing stochastic RE sources, which have been intensively researched, are likely to replace some of the traditional synchronous generators.

Most of these RE sources such as solar PV, wind and fuel cell are linked to the power system using power electronic devices and, hence, decoupled from the rest of the power system [11]. Except for wind power generation that has a small amount of inertia, the rest of the RE sources including the linking power electronic devices do not provide a mechanical inertial response to the power system dynamics unlike the traditional power plants with synchronous generators [12-15]. For this reason, they are generally termed inertia-less RE sources. As the penetration of these inertia-less RE sources in the power system increases, the conventional generation units, which have huge rotating mass with large kinetic energy referred to as inertia, are being substituted. The substituted mechanical inertia is exclusively responsible for instant response to dynamics in the power system before controllers and operators take actions [16, 17]. The remaining mechanical inertia in the system after replacement with high penetration of RE sources may be inadequate to immediately and effectively respond to frequency oscillations when exposed to disturbances. The reduced inertia will, therefore, lead to a high rate of change of frequency (RoCoF) and large frequency deviations (peak and nadir) after a disturbance [18-20]. Similarly, since most of the RE sources are intermittent as they are weather dependent, changes in weather conditions will impact RE sources and, therefore, affect the number of committed synchronous generators into the network over time. This tendency, consequently, leads to challenges on the planning, operation and control of the power system networks [9, 21-23]. Subsequently, the stability and flexibility of the grid are at risk as the converter-based RE sources keep increasing in the network. This replacement of conventional synchronous generators is, however, changing the conventional property of the traditional power system. Consequently, the traditional stability of the power systems is put at risk.

Despite the challenges brought about by RE sources, many countries worldwide have intensively invested in alternative energy sources such as solar power, wind power, fuel cells, micro-turbines, combined heat and power (CHP), biogas, etc. This move is geared by the global agenda towards clean energy. Some countries, such as Denmark, Ireland and Germany have a high penetration of RE sources, comprising more than 20% in their grids [24]. In this perspective, PV and wind power generation are the fastest-growing power sources worldwide at the moment. Globally, PV power generation grows at an annual average rate of 15%, while wind power generation grows at an annual average rate of 10%. As it stands, the global installation for the new power generation technologies topped 620 GW for PV [25] and 651 GW for wind [26] by the end of 2019. This trajectory informs that there will be a continuous decrease of mechanical inertia from conventional synchronous generators in the power system as they get replaced by the non-synchronous RE sources.

Owing to this continuous decrease of mechanical inertia systems in the grid, as exhaustively studied in [21, 27-29], potential solutions have been proposed to address the related challenges. The solutions include running multiple synchronous generators lightly loaded while much of the power generation coming from RE sources [30]. Although this approach is a very effective method of providing adequate inertia during power imbalances, it is limited by the cost due to a substantial requirement of dedicated rotating reserves. On the other hand, another technique proposed is to use energy storage devices such as batteries, super-capacitors and flywheels operating together with proper control strategies to flexibly compensate for frequency deviations [31-33]. This approach has been of interest as the controlled ES systems respond quickly to frequency events in power systems. Control of both ES systems and other RE sources, which are linked to the grid for frequency support, are collectively referred to as virtual or synthetic inertia [34-38].

It is worth pointing out that virtual or synthetic inertia has become a point of interest and focus for modern and future grid stability and flexibility. The decrease of inertial machines such as synchronous generators and the increase of the stochastic renewable energy sources in the power system needs more research to ensure stability and flexibility of the modern and future power grid [9, 21]. The introduction of synthetic inertia into the power system causes the overall power system inertia to be a time-varying quantity. Therefore, the likeliness of inertia becoming a time-varying quantity in the network triggers more attention to the power system stability and reliability. As a result, for the safe and reliable operation of modern and future power systems with low and time-varying values of inertia, estimation and monitoring of inertia as well as an assessment of frequency response in power systems are essential. Prior knowledge of the value of inertia in the system will help in planning for frequency response in the system. By successfully assessing frequency response in the network, appropriate flexibility measures of the system can be planned. Generally, preceding information of the inertia values in the network will help power system operators (PSO) to plan and act either before the contingency or immediately after the contingency with appropriate measures.

In the context of frequency control as related to the increase of converter-based generation units, the "modern grid" is the grid with hybrid generation units (conventional synchronous generators and converter-based generation units). Though there are converter-based generation units integrated into the modern grid, the frequency is still dictated by synchronous generators. These converter-based generation units are termed "grid-following" [39]. On the other hand, the "future grid" will also comprise hybrid generation units with the exception that the network will solely be dominated by converter-based generation units. The frequency control will be dictated by converter-based generation units and digital/synthetic/virtual inertia. Therefore, the term "grid-forming converter" is often used [39].

The rest of the paper is structured as follows: the role of inertia in power system dynamics related to frequency stability and flexibility is reviewed and discussed in Section 2. On the other hand, the synthetic inertia approach, as dynamic frequency support for stability control in the network, is intensively analysed and discussed in Section 3. Furthermore, Section 4 comprehensively reviews and assesses different inertia estimation techniques in power systems. Moreover, a comprehensive discussion on synthetic inertia, its significance, related challenges and solution in the modern grid, as well as future trends and the possible way forward in this research direction, are presented in Section 5. At last, the conclusion of this comprehensive literature survey is drawn in Section 6.

2. The role of inertia in power system's frequency stability and flexibility

2.1. Inertia versus RoCoF: an overview

The fundamental power balance between the generated and consumed powers at all-time in the network is vital in maintaining the network frequency at its desired nominal value. Any power imbalance in the system such as disconnection of one or more generating units will lead to rotor swings of the remaining generators in the network. Due to this swing, kinetic energy stored in the rotating mass of the remaining generators in the network will instantly react to the change. This phenomenon is profoundly known as an inertial response [30, 40, 41]. In other words, inertia can be described as the stored rotating energy that responds instantly to grid disturbances by resisting changes to the grid frequency. Inertia plays a substantial role and influences the eigenvalues and vectors, which determine the stability of the grid after the occurrence of contingencies [42, 43]. During this inertial response time, only kinetic energy from rotating mass is conventionally responsible for frequency damping before activation of primary frequency control by the governor, which takes place several seconds after the contingency [44]. For a clear understanding of frequency stability, it is worth to recap on highlights of primary and secondary frequency controls.

- *Primary frequency control*

Primary frequency control is also called governor control. In the primary frequency control, the speed of the generating units is regulated to gain the balance between generation and load. The governor control, which is externally implemented from the synchronous generator, is designed in such a way that it changes the prime mover power to control output power from the generator. By changing the generator’s output power, the frequency of the grid is controlled. For instance, when the frequency drops due to load increase or generation decrease, speed governors of generating units are regulated to increase the remaining turbine mechanical power output in direct response to the frequency variations. Since the primary frequency control is a local control action to the generating unit, it does not restore the frequency to the pre-disturbance nominal value [30, 44].

- *Secondary frequency control*

Since the primary frequency control is a local control action to the generating unit, another control action is needed to restore the frequency to the nominal value. The secondary frequency control restores the frequency to pre-disturbance nominal (i.e., reference) value. It operates from a central system that provides a wide area control action to several generators to regulate the active power production for system frequency restoration to desired values. Specifically, secondary frequency control operates by changing the base generation of the generators in the system. In some cases, if the system frequency after imbalance is less than the nominal value, then some reserved generation units need to be started or the load needs to be decreased to maintain the generation and load balance in the network. On the contrary, if the system frequency is larger than the nominal value, then some generation units need to be stopped or the load needs to be increased to maintain the generation and load balance in the network.

It is a matter of fact that before the primary and secondary frequency controls are activated, the inertia of the network determines how fast or slow the frequency will change after the disturbance. To make this clear, the following well-known swing equation (1) is presented [30].

$$2H\frac{d\overline{\omega}_r}{dt} = \overline{T}_m - \overline{T}_e \tag{1}$$

The swing equation (1) can be transformed using Laplace transform from a function of time variable (t-domain) to a function of a complex variable (s-domain) to obtain (2) in which s denotes the Laplace transform operator.

$$\frac{\overline{\omega}_r}{\overline{T}_m - \overline{T}_e} = \frac{1}{2Hs} \tag{2}$$

The mathematical model of the swing equation presented in (2) is further represented in the block diagram in Fig. 1 where $\overline{\omega}_r$ is the per-unit rotor angular speed of the generator, $\overline{T}_m$ is the per-unit mechanical torque, $\overline{T}_e$ is the per-unit electrical torque and H is the inertia constant of the system in (s). The block diagram model in Fig. 2 is obtained by including the frequency-dependent loads with load damping constant of D in (Nms) and considering small deviations in mechanical power (ΔP_m) and electrical power (ΔP_e) in (W), and further replacing the small deviations in mechanical torque (ΔT_m) and electrical torque (ΔT_e) in (Nm) at steady state as explained in [30].

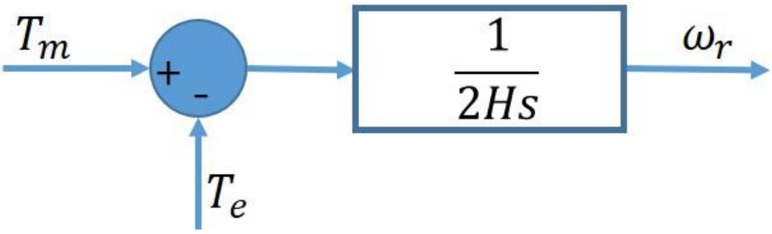


Fig. 1: Block diagram of the swing equation

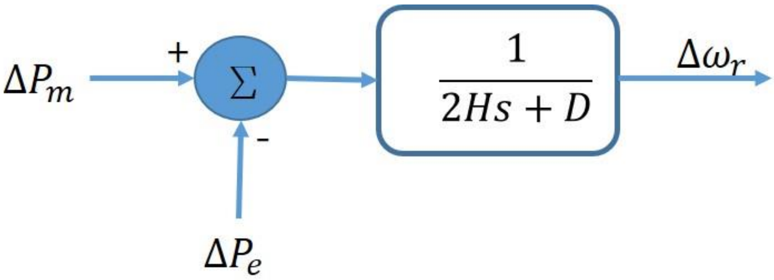


Fig. 2: Block diagram of the swing equation with damping constant

The target of (2) is to observe the system frequency (f) at the electrical output of the generator. Then, by using the number of the generator's field poles (np) and the relationship of the rotor speed ω_r in (rad/s) and rotor frequency f_r in (Hz), which is $\omega_r = 2\pi f_r$, the system frequency (f) in (Hz) is calculated as $f = np \times f_r/2$. To observe the system frequency response due to power mismatch and the impacts of inertia to the rate of change of frequency, the swing equation implemented in Fig. 2 is simulated using different values of network inertia constant *(H)* obtained from different literature works [45, 46]. The simulation results to demonstrate the impacts of different values of inertia constant to frequency response are presented in Fig. 3.

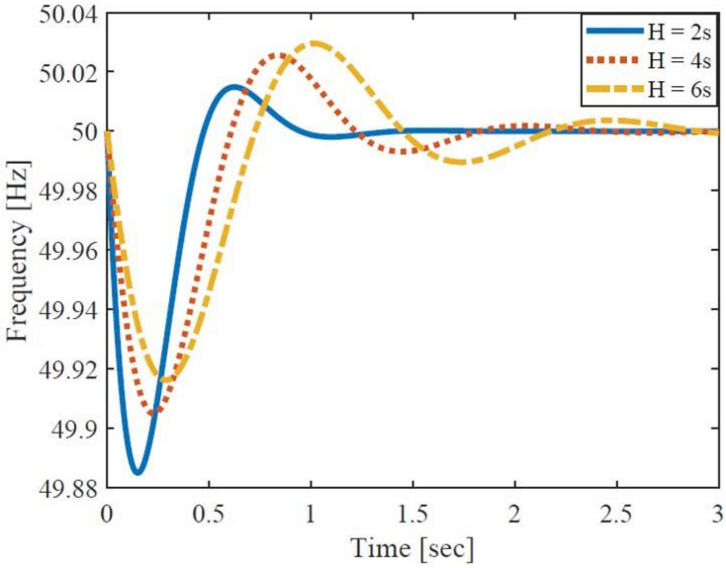


Fig. 3: Impact of inertia constant (H) to rate of change of frequency (RoCoF)

From Fig. 3, it can be well noted that different values of inertia constant *(H)* affect the rate of change of frequency (RoCoF) in the network. Increasing the value of system inertia *(H)* lowers the RoCoF when there is a disturbance in the network. This behaviour is essential as it allows ample time for governor control to be initiated before system frequency reaches unsafe high values. Subsequently, general observation from Fig. 3 is that the increase in system inertia decreases the rate of change of frequency in the network. In this way, the stability of the power system is guaranteed by high values of inertia in the network. Generally, to reduce the impacts of dynamics specifically frequency deviations in the power system, high inertia values in power systems are highly recommended [47]. Nevertheless, ever-increasing RE sources penetration into the grid, which displaces the conventional synchronous generator, reduces the mechanical inertia in the system. This prevailing trend leads to the importance of further extensive research on RoCoF, frequency peak and nadir [48, 49].

At this juncture, it is worth highlighting that the size of synchronous generator inertia in the system determines how fast or slow the frequency will change after disturbance. This means high values of synchronous generators inertia prevent the fast change of the system frequency after disturbance and vice versa [50]. This fact highlights the importance of allowing a sufficient amount of system inertia to fast track and reduce RoCoF and ensuring the stability of the network before the activation of primary frequency control.

2.2. Frequency stability challenges in low-inertia systems

As explained from the previous sub-section, a synchronous generator (SG) has the required inertia and damping capability, which instantly respond to frequency oscillations during power imbalance in the conventional grid [51]. This happens before the primary and secondary frequency controllers regulate the power balance in the system. However, a large scale integration of RE sources has led to a significant decrease of this conventional rotational inertia in the system, and therefore, increase RoCoF values in the power system [45]. For the low values of mechanical inertia in the system, any disturbance occurring in the system can result in very fast and large frequency variations. This fast frequency response is a risk for the secure operation of the power system. This is a significant challenge to the power system as a result of the high penetration of RE sources.

From a power system stability perspective, it is known that for secure and reliable operation of the power system, the system frequency should be maintained within acceptable limits even after contingencies [16]. To achieve this, the power balance in the system should be constantly observed and maintained. Nevertheless, the uncertainty of power output from stochastic and low-inertia RE sources may significantly disturb the power balance in the system and lead to unpredictable frequency oscillations [52, 53]. The unpredictable frequency oscillations may be fast and large enough to result in the triggering of protection systems before primary frequency controllers are activated. This situation may lead to cascading failures and possible blackouts [53].

As far as control is concerned, the primary frequency control scheme is activated few seconds after the inertia response to regulate the speed of the synchronous generators in the network. As the primary frequency control is not instant, the high RoCoF in the low inertia power system is generally a serious challenge to be addressed [54]. For instance, in 2010, Ireland was among the first countries to observe that high RoCoF values were serious problems in the power system. Therefore, penetration of non-synchronous RE sources was to be kept under 50% in order not to exceed the RoCoF of 0.5 Hz/s [55]. Owing to the high penetration of RE sources in their networks, other countries and regions have reviewed and updated their grid codes. For instance, the continuous operational frequency is between 49-51 Hz for Germany, GB, Norway and Denmark. For the lower frequency range of 47.5-49 Hz and the higher frequency range of 51-51.5 Hz, operation is allowed for a specific time according to respective TSO. Outside these lower and upper ranges, protective relays must disconnect within a minute [56]. To allow fast RoCoF, the maximum RoCoF for these networks is allowed to 2.5 Hz/s [57].

To reflect further on the severity of the fast RoCoF problem, there have been other real cases reported around the world. The reported cases are caused by low system inertia as a result of the recent high penetration of RE sources. A South Australia (SA) blackout on 28 September 2016 as reported in [58] is a good example. It is reported that, after disconnection of the SA system from the rest of the National Electricity Market (NEM), there was very low inertia in the remaining islanded SA system, which resulted in a very high RoCoF. The frequency dropped below 47 Hz very fast that triggered generator protection systems to operate and resulted in cascading failures before primary frequency controls had a chance to respond. The situation ended up in a blackout [55]. As a result of this event, low levels of inertia in large systems like the Australian system have been known to be a threat to the safe operation of the network. Yet, the highest penetration of solar photovoltaics in the southern part of Australia’s network, which is 58%, needs more attention to mitigating stability challenges in the country.

Furthermore, in 2011, the New Zealand network under the operation of Transpower noticed the frequency nadir of 47.5 Hz and RoCoF of 0.73 Hz/s on the North Island system following a significant disturbance. Based on this experience, the engineering planning team had to take precautions for establishing the plans for future integration of more wind and solar power into the network. Studies show that with the penetration of 1300 MW of inertia-less variable RE sources into the network, the RoCoF would increase to 2.1 Hz/s, which is unsafe RoCoF compared to 1.2 Hz/s for the network operation [59].

To illustrate more on the effects of high penetration of RE sources to the RoCoF in the network, a network model simulation with different levels of RE sources penetration as obtained from refs. [60, 61] was studied. Fig. 4 shows how RoCoF is significantly affected by the high penetration of RE sources. From Fig. 4, it is shown that the frequency response for the network with 0% penetration of RE sources is quite different from the frequency response with 40% penetration of RE sources. The frequency response with 40% penetration of RE sources exhibits much faster

RoCoF with the higher value of frequency nadir than the response without any penetration (i.e., 0% penetration of variable RE sources).

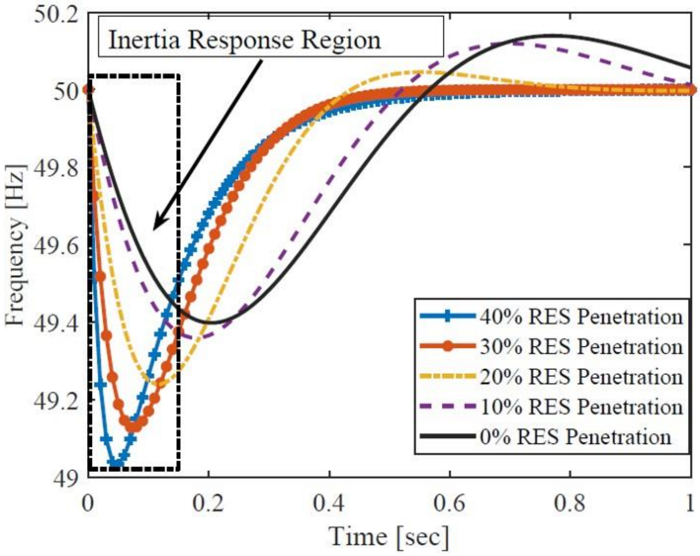


Fig. 4: Impacts of penetration of RE sources to the system frequency response

If more attention is put on the inertia response region of Fig. 4, it is obvious that the frequency response with 0% penetration of RE sources is slowly reaching the nadir point, giving ample time for the primary frequency control to take action to stabilise the network. This is contrary to when the levels of RE sources penetration are increased. As the levels of RE sources penetration are increased, the frequency response reaches the nadir value very fast. The fast reaching nadir value does not give enough time for the primary frequency control to act and protect the network. Therefore, the fast reaching nadir value might lead to serious stability problems in the network.

2.3. Towards 100% renewable grid

Despite the challenges related to the high penetration of RE sources, several studies such as [62-67] have anticipated that a reliable 100% renewable energy powered grid can be achieved in the near time to come. However, it should be clear that the concept of 100% does not essentially mean 100% converter or non-synchronous dominated grid. It should be noted that mainly converter-based renewable energy generation technologies such as wind turbines, PV solar and battery are the ones referred to as non-synchronous generation units. The rest of the renewable power generation units that comprise hydropower, geothermal, biogas, biomass, and solar thermal use the conventional synchronous generator. As the introduction of synthetic inertia in power system stability control is getting more attention, and hence, increases the level of its application into the grid, this trend indicates that there is a possibility of achieving 100% renewable grid soon as depicted in [68, 69]. Several countries have demonstrated this to be possible and feasible. The countries include Iceland with 100%, Norway (97%), Uruguay (97%), Costa Rica (93%), New Zealand (82%), Brazil (76%) and Canada (62%) to mention a few [69, 70]. According to the Government of Iceland, the 100% renewable energy power generation for the Iceland network comprises 73% hydropower and 23% geothermal power [71]. The two types of power generation units in Iceland are high inertia plants, therefore, the Iceland grid does not experience the problem of low inertia. Although the wind power sector grows in Norway, hydropower dominates the energy mix by comprising 91.8% of total RE sources in the country [72]. Therefore, with the high share of the hydropower generation in the energy mix with relatively high inertia, the problems with low inertia do not apply in the Norwegian grid. High shares of hydropower also apply to Costa Rica, Brazil and Canada. On the other hand, an interesting example of a country with a high RE share without solely hydropower dominance is Uruguay. Around 38% of electricity in Uruguay is supplied by wind, making it the second-largest in the world in terms of the percentage of this energy. Among countries with a close-to-100% renewable grid, Uruguay appears to be the least hydro-dependent one [8]. Continental wise, the level of penetration of RE sources is projected to increase year after year. For instance, the European Union (EU) anticipated that by 2050, 62% of its installed capacity will be from RE sources [73]. The same trends can be observed in America, Asia, and Africa.

Although there is a promising trajectory towards this transformation of the power grid, yet the challenges associated with this transformation cannot be underestimated [74, 75]. Measures related to grid planning, operation and control need to be taken to make the move smooth and viable [76]. Besides, the stochastic nature of wind and solar PV power generation, optimization, and coordination of synthetic inertia when co-existing with conventional inertia should be addressed. Wind and solar powers as the main promising sources of renewable power are variable and uncertain as determined by local weather conditions. [77, 78].

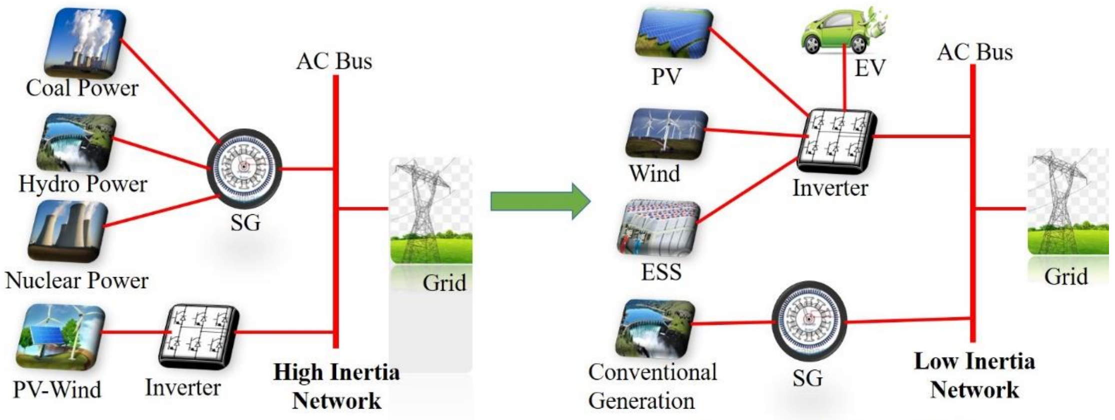
Moreover, PV energy sources generate dc power while wind power generators give ac power outputs at low and variable frequency, which is not consistent with system frequency [79]. Therefore, most of these new generation technologies are integrated into the grid through power electronic equipment such as converters and inverters. As the number of these distributed renewable generation units are increasing in the power system, the grid is likely to be dominated by the converter-based generation units soon [31, 80]. The fact that RES sources do not participate in frequency regulation operations due to lack of adequate reserves, their increasing share to the grid is challenging. Therefore, it is crucial to mimic the conventional synchronous generator inertial response behaviour in the power electronic-based converters as a solution to low inertia in the power system [81, 82]. The use of electronic converters as a means of mimicking inertial response is commonly referred to as synthetic inertia.

3. Synthetic inertia approaches for frequency control in grid

3.1. Virtual inertia topologies in the power system

Synchronous generators have been driving the traditional power systems in a unidirectional power flow for a long time. The introduction of distributed generation units and RE sources, as a result of intensive prioritization of clean energy sources, paved the way for a transformation of the network towards a new concept of a grid layout with flexible power flow [38]. As described in the previous sections, the evolution of the traditional power systems towards modern and flexible network has a price to pay for. The challenges related to this evolution need solutions to make the move smooth. One of the challenges is the high inertia of SGs, which resists sudden frequency change during power imbalances in the network, is being replaced. Despite the challenges related to the transformation, many studies have been carried out on the control of converters to integrate RE sources into the grid [83, 84].

However, more penetration of RE sources, which most of them do not contribute to inertia response in the network, replaces some of the SGs in the network. Consequently, this leads to a decrease of overall system mechanical inertia and, hence, an evolution from high inertia systems to low inertia system as pictured in Fig. 5. The significant decrease in overall system mechanical inertia causes frequency stability issues as discussed in [85]. With the reduced inertia in the network, power imbalances will result in large frequency deviations that are associated with large RoCoF that may lead to loss of stability of the network.



SG Dominated Grid **Converter Dominated Grid**

Fig. 5: Grid transformation from high to low mechanical inertia network

To respond to stability issues related to inertia challenges caused by high penetration of RE sources in the grid, the new concept of synthetic inertia is introduced into the power system [13, 33, 80, 84, 86-101]. Synthetic inertia is an artificially made frequency support service by controlling converters connecting RE sources to the grid. The term synthetic inertia is described by ENTSO-E as “the facility provided by a power park module or HVDC system to replace the effect of the inertia of a synchronous power generating module to a prescribed level of performance” [102]. Likewise, in the clarifying article by Robert Eriksson et al, synthetic inertia is defined as “the controlled response from a generating unit to mimic the exchange of rotational energy from a synchronous machine with the power system” [34]. Other literature works have used other name to refer to synthetic inertia. Common names are such as virtual, emulated, hidden and digital inertia [103-106].

Back in 2007, Beck and Hesse introduced a VIrtual Synchronous MAchine (VISMA) topology [35]. The VISMA topology was designed to introduce synthetic or virtual inertia to the network. The reason for introducing the topology was to make possible integration of more non-synchronous renewable generation units such as PV, wind and fuel cell systems to the grid. After the inventions of Beck and Hesse topology, many other topologies and approaches established by different studies followed [89, 99, 107, 108]. Among the many topologies was the Virtual Synchronous Generator (VSG) [81]. VSG refers to an inverter control to mimic a synchronous generator in the provision of synthetic inertia in the network [36, 37, 109, 110]. The main target of the VSG topologies is to emulate the behaviour of real synchronous machines in frequency control of the power network [111]. Mainly, the topologies are supported with algorithms that control inverters coupled to distributed generation units to provide an inertial response to grid frequency discrepancies [41]. The control strategies for VSG are designed to mimic both steady-state and transient characteristics of SGs. The VSG virtually comprise important attributes of a synchronous generator during the inertial response. For instance, the ES system for VSG imitates the flywheel of SG as it can absorb and provide power in case of imbalances. There are different control approaches, which are designed to implement VSG. Some of the approaches try to implement all the attributes of SG making the algorithms complicated [112-114]. However, there are approaches that consider only essential attributes of SG to be implemented in VSG and achieve the intended control goals. For instance, the iterative method of swing equation is considered in [88], droop control is implemented in [115] and power-sharing is made possible by VSG control in [116]. For an in-depth comparison of VSG and SG, interested readers are recommended to read [117].

Despite the similarities existing between VSG and SG, there are also some differences existing between them as:

- VSG controls do not give instantaneous inertial response as SGs do. VSGs provide an inertial response after a dead band limit [41, 118].
- VSG frequency response services depend solely on the capacity of the ES system associated with them and other control characteristics to emulate inertial response. In this way, they depend on the tuning of these parameters to respond to frequency events properly [41, 118].

Also, the VSG topologies experience some challenges for their application in the modern network as:

- VSG controls mainly rely on a phase-locked loop (PLL) to detect the grid voltage, phase angle and frequency. This is one of the main drawbacks in achieving a complete converter dominated grid as the presence of SG is still crucial to provide reference values [83].
- Another drawback of this invention is lacking power reserve for RE sources used in VSG to ride-through under large oscillations [119]. Although this problem has been addressed in [94, 99] by using ES systems, the limited capacities of ES systems are still challenging.

Table 1 categorises different topologies of synthetic/virtual inertia proposed by different researchers. For each category, the table summarises generalized advantages and disadvantages for each approach. Besides, related references for further reading are also provided for each topology.

Table 1: Categories of synthetic/virtual inertia technologies in power systems

Synthetic inertia category	Pros	Cons	Topologies included in the category	Ref.
Synchronous generator emulation	• Use inverter together with ES systems to mimic an SG behaviour • Imitate traditional behaviours of an SG in the operation of the power system with high penetration of the converter based RE sources • Able to self-synchronize in the grid	• Instability problems led by the use of PLL • Difficult to implement complex differential equations • Prone to numerical instabilities	Synchronverters VISMA Kawasaki Heavy Industries (KHI)	[81, 108, 120] [35-37] [15, 49]
Swing equation	• Control the inverter of a DG unit together with ES systems to support inertial response • Use the swing equation of the SG within the control algorithm to develop a virtual inertia	• Prone to numerical instabilities • Difficulty in obtaining accurate control parameters	Ise Lab topology Synchronous Power Controller (SPC)	[15, 49, 88] [121]
Frequency-power response	• Emulate the inertial response characteristics of an SG during power system dynamics • Use DGs as dispatchable sources • Implement control strategies with short-term energy buffers	• Not applicable for island mode • Inaccurate frequency derivative data from PLL • Instability due to sensitivity in noise	VSG VSYNC lab topology	[122] [15, 48
Other topologies	• Use conventional active power droop controls to implement inertial response for converter-based power systems by	• Respond slowly to transients	Droop-based topology Virtual oscillator control (VOC)	[82, 98, 123] [124]

imitating the behaviours of the Synchronous/Induction generators	Inducverters	[49, 125, 126]

3.2. Application of synthetic inertia for frequency stability in power systems

Several approaches have been proposed to imitate the inertial behaviour of SG involving a combination of RE sources, ES systems, power electronic converter and control algorithms as described in the previous sub-section. The simplified concept of how VSG is analogous to the conventional synchronous generator in the grid is presented in Fig. 6. To make it clearer from the figure, distributed generation (DG) is analogous to the prime mover in the conventional power system, while the inverter altogether with the controls (not shown in the figure) represent the VSG. The VSG can imitate the properties of a synchronous generator by utilizing the ES systems for feeding or absorbing power to or from the grid during power imbalances, respectively [117].

Using proper control algorithms to the inverter together with ES systems as proposed in [28, 31, 80, 87, 92, 115, 127, 128], distributed generation units can mimic the performance of synchronous generators such as damping, power droop and inertia. Fig. 7 shows a simplified general basic operating principle of the synthetic inertia provision by a VSG. From the figure, the algorithm to control the inverter in the provision of virtual inertia depends solely on the information from the grid. The phase-locked loop (PLL) is used to collect the grid information such as frequency response that is used to decide how much virtual inertia should be supplied to respond to the frequency change. Fig. 8 describes how virtual inertia provision is generally achieved in the network. The virtual inertia algorithm shown in Fig. 8 controls the ES systems to provide frequency support in terms of virtual inertia into the network for any power imbalance. K_{VI} represents the control gain of virtual inertia in (s) while K_P is the constant that emulates damping in the power network in (MW/Hz). Besides, T_{VI} stands for the time constant in (s) for the dynamic model of ES system. The control algorithm of the VSG model can be realized by using the swing equation, which is used to describe the relation of inertia, damping and rotor angular velocity of SG [100, 129, 130].

It is worth stressing that from the control principle of SG; it is noted that active power is regulated by controlling the power angle between the SG internal voltage and the voltage at the point of common coupling (PCC) of the grid. A similar control approach can be imitated for VSG to mimic the electromechanical dynamics of the SG to regulate the active and reactive power of the inverter.

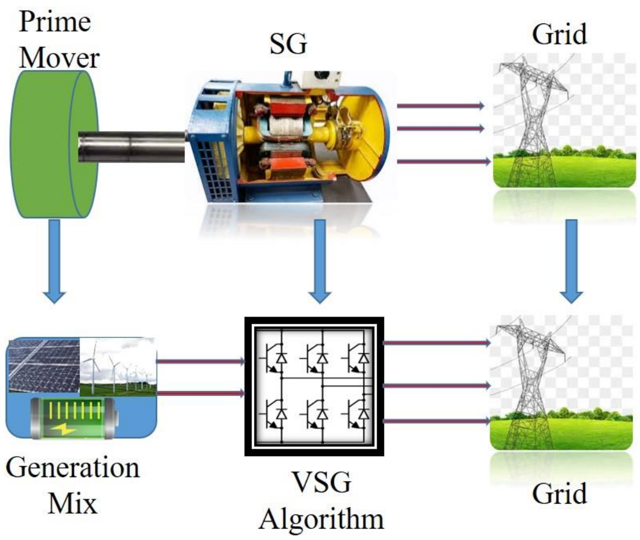


Fig. 6: Analogy of VSG with conventional SG

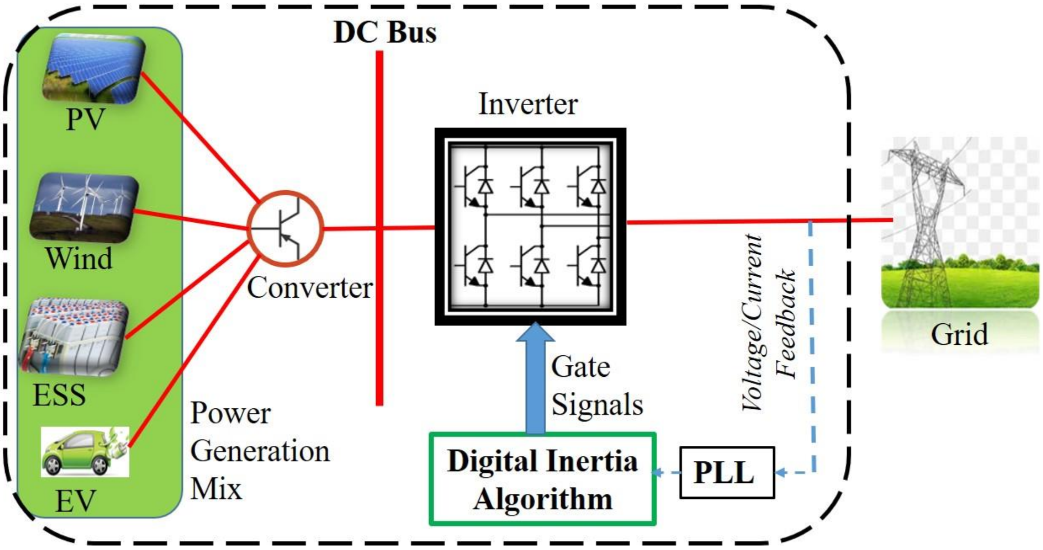


Fig. 7: General inverter-based virtual inertia emulation in grid

It is also known that the dynamics of an SG are governed by the swing equation as it ensures that stability is adhered to if accelerating power is zero [85]. Using a virtual inertia algorithm, the swing equation can be executed mathematically to implement the behaviour of an SG in the inverter. As mentioned in the previous sub-section, power converter with ES systems can be controlled to provide synthetic inertia in the grid as generally demonstrated in Fig. 7. The point of focus from Fig. 7 is the use of grid information to generate an algorithm for providing virtual power for frequency response. The derivative control of grid frequency is mainly used to provide virtual inertia component to the grid in case of more penetration of RE sources. In case of any power imbalance that leads to frequency deviation, the VSG control will deliver the desired virtual inertial power ΔP_{VSG} as shown in (3) [93]

$$\Delta P_{VSG} = K_{VI}\frac{d\Delta\omega}{dt} + K_P\Delta\omega \tag{3}$$

where $\Delta\omega = \omega - \omega_o$ and ω_o is the nominal frequency of the grid in (rad/s). Using the control gain of virtual inertia K_{VI} in (s), the product K_{VI} and derivative of frequency deviation $\frac{d\Delta\omega}{dt}$ in (rad/s^2) as $K_{VI}\frac{d\Delta\omega}{dt}$ is the power to be injected or absorbed depending on the position of frequency deviation from the nominal value. K_P is the constant that emulates damping in the power network.

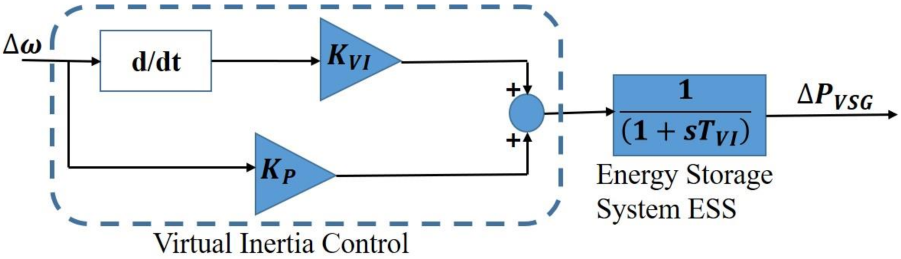


Fig. 8: Virtual Inertia provision and control in grid

To mitigate the problems related to increasing levels of RE sources connected to power systems and, hence, replacing conventional generators, synthetic inertia has shown much potential to reduce the problems [131, 132]. One of the important benefits of synthetic inertia in the power system is to encourage more penetration of RE sources. When VSG exists in the network with conventional synchronous machine inertia, this means the equivalent inertia in the network will comprise two components. The two components are conventional inertia (H_S) and synthetic/virtual inertia (H_{VI}). Therefore, the conventional equation to compute for equivalent inertia in the system can be further modified to include the synthetic inertia (H_{VI}) as presented in (4) [45].

$$H_{eq} = \frac{\underbrace{\sum_{i=1}^{N} H_i \times S_{B,i}}_{H_S} + \underbrace{\sum_{j=1}^{V} H_{VI,j} \times S_{B,j}}_{H_{VI}}}{S_B} \tag{4}$$

where, H_i and $S_{B,i}$ are the inertia constant in (s) and rated power in (MVA) of the *i*th synchronous generator, N is the total number of SGs connected to the network and S_B is the base power in (MVA) of the system. $H_{VI,j}$ and $S_{B,j}$ are virtual inertia in (s) constant and rated power in (MVA) of the *j*th virtual synchronous machine, V is the number of the virtual synchronous machine connected to the network.

3.3. *Case study of virtual inertia application for frequency stability in the power system*

To describe the application of virtual inertia on frequency stability in the power system, a complete model set-up representing the network with penetration of RE sources is given in Fig. 9. The network comprises both conventional synchronous generator inertia and synthetic inertia. To incorporate the penetration of RE sources, active powers from combined solar and wind power plants are increased by equivalently 20%. This penetration of RE sources replaces equally active power generation from the conventional generator. Therefore, inertia associated with this replaced conventional generation is also reduced from the network. Finally, the virtual inertia provision is activated with different levels of K_{VI} constant in the network to evaluate the improvement of frequency response as a result of increased penetration of RE sources.

Fig. 10 demonstrates network frequency responses with different case scenarios. To start with, the frequency response is simulated with the only conventional synchronous generator in place. Then, a low inertia scenario is activated with a 20% penetration level of RE sources and the SG inertia is reduced equivalent to the RESs active power added into the network. Finally, VSG is implemented with different levels of K_{VI} to study its impacts on frequency response in networks with penetration of RE sources.

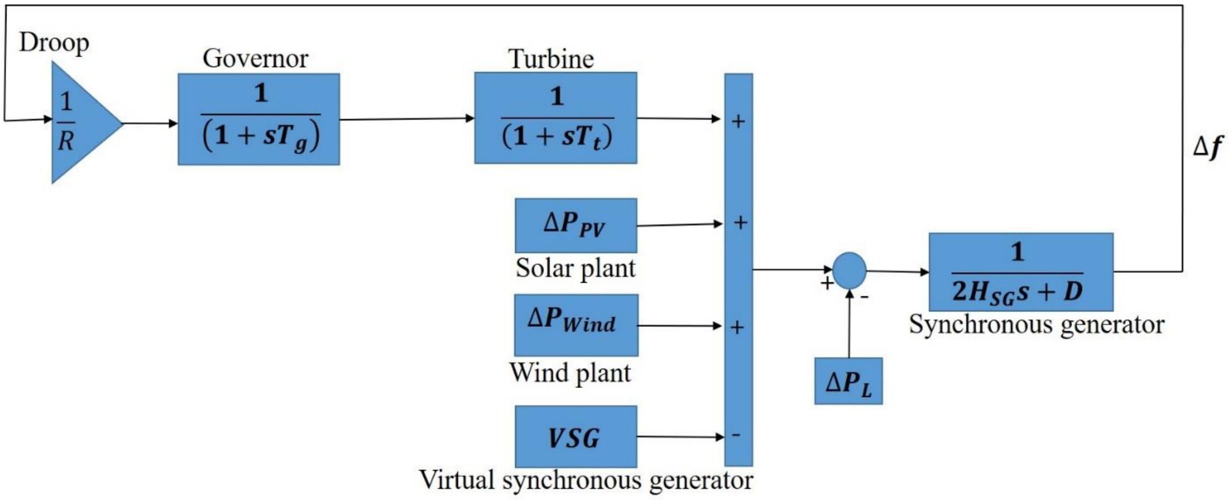


Fig. 9: Power system model to show the impact of VSG on the frequency response of a network with penetration of RE sources

From the simulations represented in Fig. 10, different scenarios are presented. The responses show how inertia affects frequency response in the network. To be more precise, it can be noted how the penetration of RE sources affects both RoCoF and the peak value of the frequency after disturbance. Finally, the introduction of VSGs, with different K_{VI} constants, displays the improvement in RoCoF, the frequency peaks and settling time as the figure signifies.

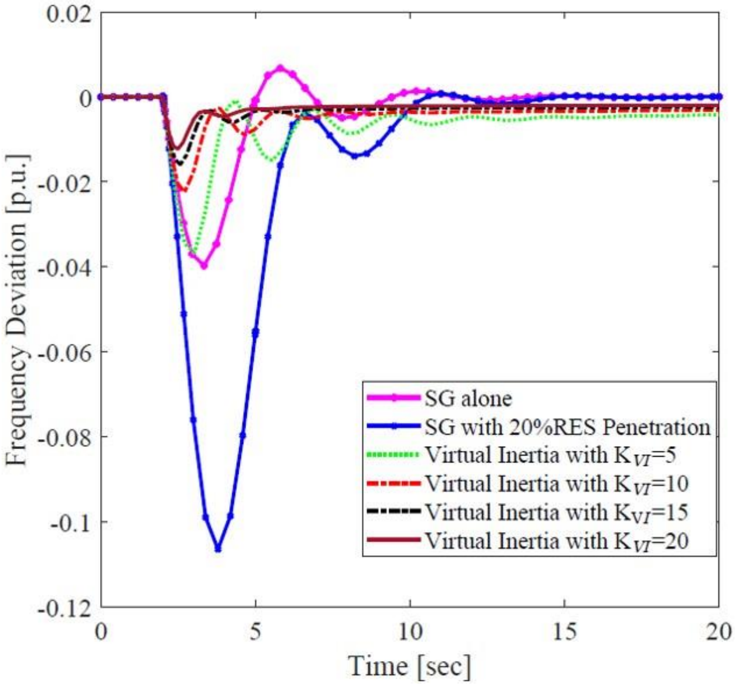


Fig. 10: Frequency responses with different scenarios of inertia in the power system

3.4. *Significance of synthetic inertia in frequency stability control*

So far, synthetic inertia has proven practical potential to stabilize frequency response in low inertia networks. The inertial response it provides by rapidly injecting/absorbing power to mitigate fast RoCoF events and out-of-limits frequency deviations is crucial as seen in Fig 10. The value of synthetic inertia is noticed during the response period of the system after imbalance. This inertial response period is very essential in frequency stability as it is described as the “buying” or “waiting” time before primary frequency control comes into action. Making this time adequately long is very important for the secure operation of the network. Delaying synthetic inertia provision beyond frequency nadir or peak may result in severe stability issues. Therefore, synthetic inertia controls should be designed in such a way that they provide their services before frequency peaks or nadirs to avoid frequency stability issues in the network.

To explicate the concept of when synthetic inertia has to take action in the stability and flexibility control of the power system after a contingency, the time scale of the frequency control for the conventional network is provided in Fig. 11. From the figure, the position at what time scale the synthetic inertia is supposed to come into play during frequency contingency is presented. Synthetic inertias are faster than primary frequency control but slower than the conventional SG inertia, which reacts instantly after power imbalances. Therefore, if coordination algorithms of SG inertia with synthetic inertia in the modern grid are developed, they will ensure the secure operation of the power system even with high penetration of non-synchronous RE sources.

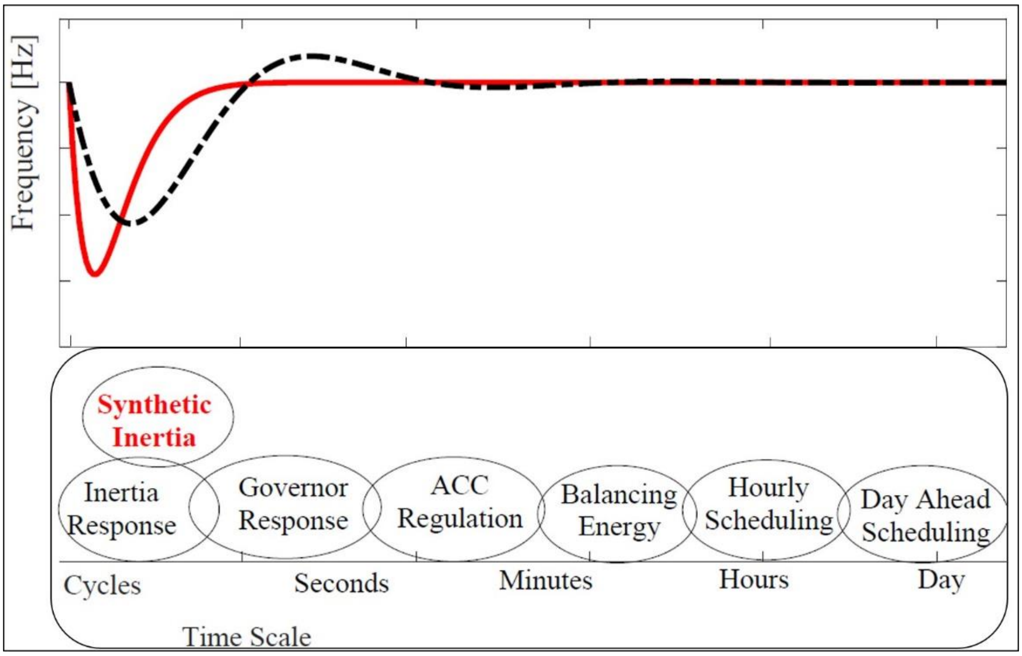


Fig. 11: Time frame in frequency control including synthetic inertia in the power system

To link with the response time of synthetic inertia, Table 2 shows how different ES systems with new power generation technologies, which are used with control techniques to provide synthetic inertia, can fast respond to frequency variations in the grid. Understanding different response times of these different technologies is crucial to achieving quality synthetic inertia provision designs in the power system. This discussion shows that synthetic inertia is essential in maintaining frequency stability in reduced mechanical inertia networks. Since primary controls can take up to seconds to be activated, synthetic inertias show that they can be activated before the primary frequency control.

Table 2: Synthetic inertia technologies with response times [133, 134]

Technology	Activation Time
Lithium Batteries, Flow Batteries, Super-Capacitor	10-20 ms
Lead-Acid Batteries	40 ms
Wind Turbine with Virtual Inertia Response	40 ms
Solar PV and ES systems	100-200 ms
Flywheels	≤ 4 ms

3.5. *Synthetic inertia vs fast frequency response debate*

To smoothly go through this part, it is good to recap on the inertia concept in the network. As described before, inertia is responsible for reacting instantly to system frequency changes as a result of any disturbance in the power balance in the network [34]. On the other hand, RE sources that are connected to the grid via converters do not contribute to instant inertial response as SGs do. In that regard, RE sources do not contribute to mechanical inertia in the system. Consequently, they do not instantly or naturally release or absorb energy as a result of frequency change. However, they depend on controllers, which control ES systems to release or absorb energy during frequency variation to mimic the performance of SGs [34]. Thus, from conventional frequency theories, mechanical inertia from SGs can directly determine the initial RoCoF, while synthetic inertia cannot. However, initial RoCoF in the network is used to determine how much synthetic inertia is needed to support the frequency during contingencies.

A debate, therefore, arises on how synthetic or virtual inertia is perceived in the network. There have been different opinions of the term depending on the context. Many studies do not make a clear distinction between virtual inertia and fast frequency response. After becoming aware of this misunderstanding, a research study [34] introduced a distinction between these terms to avoid their misuse. The term synthetic inertial response must, therefore, correspond to the controlled response from a generating unit to mimic the exchange of rotational energy from a synchronous machine with the power system. Any other form of fast controlled response can, then, be termed as fast frequency response. To elucidate more, synthetic inertial response is a subset of fast frequency response, which contains different responses based on frequency and RoCoF.

Finally, the explanations of synthetic inertia and fast frequency response from the European Network of Transmission System Operators for Electricity (ENTSO-E) and [34, 135] clearly defined these two terms as follows: “Synthetic inertia is the controlled contribution of electrical torque from a unit that is proportional to the RoCoF at the terminals of the unit; while fast frequency response is the controlled contribution of electrical torque from a unit, which responds quickly to frequency changes to counteract the effect of a reduced inertial response.”

4. Inertia estimation techniques in power system

It is well known that the inertia constant for the conventional power system, in general, is a constant and steady quantity. Based on the prior knowledge of the constant inertia value in the conventional network that is defined by (4), the frequency response of the network can be anticipated and assessed before a disturbance occurs in the network. However, inertia in modern and future networks with high penetration of RE sources will not only become low but also time-varying as clarified in the preceding sections. For this reason, it can be said the inertia in the modern grid is becoming a dynamic quantity. Therefore, dynamic inertia can be defined as a time-varying of the total inertia value in the power system caused by the extensive use of stochastic synthetic inertia to support frequency response in low mechanical inertia systems. The stability problems related to low and dynamic inertia in the network have been discussed in the previous sections. To account for stability problems related to low values and dynamic inertia, increased awareness regarding this quantity has been given priority in the network [136]. Prior estimation and monitoring of this quantity are essential for planning purposes and therefore for the secure operation of the power system. Since inertia affects the network frequency response just after the contingency, its prior understanding and management in the system are critical.

To attain this goal of understanding the value of inertia in the network, several studies such as [60, 61, 92, 137-139] have been conducted to establish algorithms to estimate the value of inertia constant in the network. Different methods of inertia estimation in the literature can be classified into three main categories, namely: offline, online, and predictive estimations. Different approaches are used interchangeably in these categories to estimate the inertia constant in the network. Of these three categories, most of the studies have been conducted on offline and online categories [60, 61, 137-142]. Very little has been done on predictive inertia estimation [143-146].

The inertia estimation has been made possible by significant advancements in measurement systems, which have been of potential in the power network for tracking real-time measurements of the entire network. As a result of this advancement in measurement technology, phasor measurement units (PMUs) have been widely installed to record operating conditions in power networks. The recorded information is very crucial for inertia estimation purposes in the network.

4.1. Offline inertia estimation approaches

Most of the offline estimation techniques are post-mortem approaches. This means the offline inertia estimation techniques are used to study and evaluate the values of inertia constant in the network after occurrences of contingencies. They can tell how much inertia was available during significant disturbance incidents [138]. Most offline approaches use historical data that is recorded using the PMU. Information such as active power and frequency behaviour post power imbalance events are used to estimate the inertia in the network. Some of the proposed techniques that use post-event disturbances can be found in [147, 148]. Of the offline studies, some studies [60, 61, 137, 138, 147] use records of major disturbances to establish the estimation algorithm, while other approaches [139, 142] use normal operating conditions of the network to establish estimates of inertia values in the network.

However, there are challenges associated with the offline inertia estimation process in the network. These challenges are results of poor frequency measurements, which are coupled with oscillatory components and noises mainly during transients [60]. Polluted frequency measurements lead to inaccurate calculation of RoCoF and, hence, poor inertia estimation. To address the problem, Refs. [61, 149] introduced some techniques to eliminate measurement noise and oscillations that distort the RoCoF calculations. On the other hand, locating the exact time of disturbance in the network has been another challenge to look at. When disturbance time is not exactly located in the network, the alignment of RoCoF and the corresponding disturbance (ΔP) will be inaccurate. This further leads to inaccurate inertia estimation in the network. This drawback motivated research work in [60] to be conducted on moving average filter and the research work in [149] to be focused on detrended fluctuation analysis to locate the time of disturbance in the network towards inertia estimation.

Nevertheless, most of the techniques introduced in this field do not precisely consider the effects of the penetration of RE sources in the estimation process. As pointed out in the previous sections, modern and future networks will be highly penetrated with inertia-less power generation units. The effects of the stochastic nature of these non-synchronous generation units have to be taken into consideration when estimating the inertia constant of the network. The problem associate with penetration of stochastic RE sources is the complexity introduced in the network that is not taken care of by the conventional equations to handle the dynamics of the modern network.

4.2. Online inertia estimation approaches

The need for real-time inertia estimation in the network has been gaining popularity for almost a decade now. The motive behind this move to online inertia estimation is the move to time-varying inertia values in the network due to the high penetration of RE sources and fast frequency response devices in the network. Due to this need, several online inertia estimation methods have been proposed in published works. The proposed methods have different techniques and algorithms in achieving real-time inertia estimation in the modern and future power system.

Most of the proposed methods use PMUs to record real-time measurements from the network. The recorded measurements are used for the online estimation of the inertia constant in different perspectives. Examples of the methods that use PMUs as sources of network measurements are such as [150-154]. Some of the approaches used for inertia estimation are such as dynamic regressor extension and mixing on time series data [155]. Other methods with time series modal approaches are proposed in [139, 152]. In ref. [153], a robust Kalman filter is used with the derivative of the linear discrete-time state-space form to online estimate the inertia of a network. Other methods such as that are proposed in ref. [156] use autoregressive data centred models, which can describe the dynamic evolution of the power system inertia. Furthermore, a method using a sliding discrete Fourier transform (SDFT) technique to online estimate the inertia of the network is proposed in [157]. On the other hand, ref. [158] used the approach of electromechanical oscillation modal extraction from synchronized ambient data to online estimate the inertia of the power system.

Like offline inertia estimation approaches, online approaches also face some challenges in the estimation process. First, measurement errors in PMU due to noise are the main source of large estimation errors. Although filtering techniques are employed in some methods, the accuracy is not satisfactory in some of the methods [139]. Second, most methods consider only inertia from synchronous generators in their analysis. Therefore, there is an underestimation of the total inertia of the network as the demand-side inertia contribution is not considered in most research works [159]. Third, some proposed methods are irrelevant for online applications as they take a long time to give inertia estimation from the time the imbalances are detected in the network. The time taken for modal analysis, execution, inertia extraction and finally sending the inertia value to operators is very long making them irrelevant for network protection. Normally, the protection decision needs to be made very quickly after the occurrence of the contingency in the network. Fourth, the huge network model and a large amount of time series data involved in most of the proposed methods lead to significantly large computational burdens. Updating the huge network models at high sampling rates and respectively updating a large amount of time series data make the methods very slow [160, 161].

4.3. Inertia prediction approaches

There is also an increasing need to forecast the values of inertia constant in the network. The instantaneous reaction of inertia after power imbalance in the network gives no time for frequency control schemes to safeguard the stability of the network [159]. Unanticipated low network inertia conditions and inadequate frequency response reserves could pose a serious risk to the reliability and security of the grid. Therefore, the anticipation of network inertia is becoming important in modern and future power systems. Prediction of time ahead network inertia is essential for PSO to plan for alternative sources of inertia in the network in anticipation of reduced inertia. Forecasting inertia values in the network will determine when the network will be at risk, and appropriate measure can be taken well in advance. As synthetic and other fast frequency response reserves are likely to be tradeable quantities in the future network, contractual arrangements to procure these services can be planned as inertia values can be forecasted in the network [49, 159]. However, there is not much research done on this area. Ref. [145] shows the need for the prediction of network inertia by proposing a prototype tool to forecast system inertia and to assess the sufficiency of frequency response reserves. Using the ERCOT network, inertia was forecasted, and fast frequency reserves could be planned well in advance. The need to predict system inertia as one of the major attributes to assess the operational impact of non-synchronous machines on a power grid is justified in this literature. Besides, ref. [144] proposes a short-term kinetic energy forecast using a decomposable time series model approach. Using the Nordic network, they could predict the kinetic energy of the network one hour ahead of time with a forecasting error of 5%. Also, a two-stage stochastic generation and primary frequency response scheduling model is proposed in [146] to predict the network inertia for primary frequency response adequacy under uncertain wind generation. Using the ARIMA model in scenario generation and reduction of wind power uncertainty, this research could forecast the inertia of the system one day ahead. However, this one-day ahead inertia prediction would need further research to justify. Furthermore, an artificial neural network approach to forecast the network inertia with high penetration of wind farms is recently proposed in [162]. As noted above, to ensure that the stability and flexibility of the modern and future grids are maintained, there is a need to research more on inertia prediction in the power system. The prediction of inertia values would be essential for predictive controllers in the power system.

4.4. General observations of system identification as used in inertia estimation techniques

Complicated interconnected power networks involving various stochastic components are very difficult to model and analyse using conventional mathematical models. Due to such complexities, modern grids become very difficult to be represented using conventional mathematical equations to fully model all stochastic elements in the network. Even the mathematical equations, which have been developed to represent these complicated stochastic networks, are also complex. Hence, they cannot be easily used to represent the time-varying behaviours in networks. Besides, complex equations are difficult to use in real applications such as control system design. Traditionally, mathematical modelling of power network involves formulating mathematical models of every single significant component individually in the network. The mathematical models using the single component modelling method result in large and complex overall models that are very difficult to analyse [79, 163].

Given the complexity of the modern and future power systems due to the high penetration of RE sources, system identification is the alternative approach to analyse the modern network [164-166]. System identification can be easily achieved using online recorded data of the network. Therefore, it can be said that an alternative way to represent complex modern networks is the data-centred system identification approach [167-169]. This approach has been useful to the power system industry in several ways. Initially, it can validate the complex system models by being able to modify the parameters of those models so that they best fit the actual measured performance of the network [170]. Moreover, the approach can also be used to benchmark system behaviour [165]. Real-time performance of the data-centred system identification approach can further provide system operators with valuable knowledge about the stability situation of the system [169]. In addition to its advantages, the system identification approach can be used even if the inside structure of the system is not known. The measured input and output data in the system identification approach provide useful information about the system behaviour [165, 166, 169]. Thus, mathematical models can be generated to explain the dynamics of the system of interest from observed input-output data.

To summarize the data-centred system identification and inertia estimation approach, Fig. 12 is presented. Inertia estimation based on the data-centred system identification approach solves the challenge of inertia estimation solely depending on recorded data for large disturbances only.

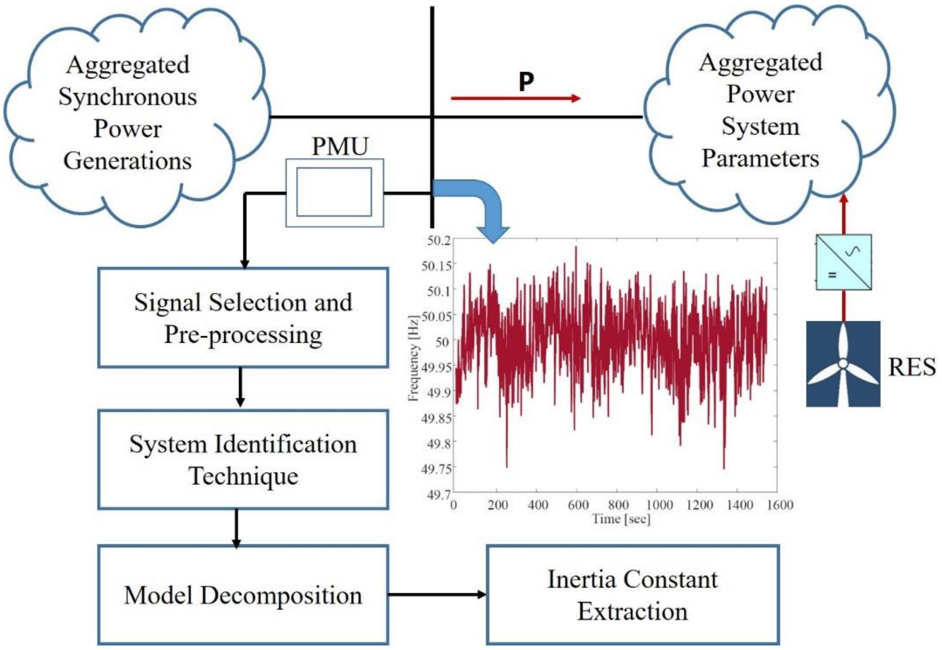


Fig. 12: Data-centred system identification and inertia estimation approach

PMUs that are presented in Fig. 12 can record a substantial volume of data in real-time. The recorded data contains adequate electromagnetic response information that is required for transient analysis [171]. The data recorded contain an input signal that is used as an exciting signal just enough to cause a response to the system. For this reason, normal ambient data of the network can be used for the continuous inertia estimation process. To be specific for the case of inertia estimation in the power system, the signals of interest are the active power and frequency changes as input and output signals, respectively. The two signals are sampled and then used for system model identification [172]. Some techniques such as linear regression and least-squares estimate are then used to decide the validity of the estimated model and optimize the parameters associated with the estimated model of the system. The identified system models are usually high order models, which are complex to analyse and compute. Therefore, some decomposition techniques such as singular value decomposition (SVD) are further used to not only simplify the analysis but also reduce the computation burden associated with the models [173]. From the decomposed model, inertia can be extracted and communicated to PSO for planning and control purposes.

Due to some improvements in addressing the challenges associated with the inertia estimation process, some studies have been put in place to estimate the inertia constants of some countries and regions. For instance, Ref. [61] used reliable data from PMU to estimate the inertia constant of the Great Britain network. In [60], frequency measurements from 10 disturbance based events were used to estimate the inertia constant of the Japanese power system. Furthermore, frequency measurements from a centre of inertia (COI) point in the network were used in [137] to estimate the inertia constant of the Western Electricity Coordination Council (WECC) system. Last but not least, the Nordic region network was researched for inertia estimation in [141] where a comparison of the following two approaches was done. The COI frequency for the whole network approach was compared by dividing the network into 12 areas, and the COI frequency for each area was used to estimate the inertia of the whole network. It was noted that the estimation using COI of the divided areas gave more accurate estimation compared with one COI for the whole network.

Table 3: Inertia estimation techniques used to estimate the inertia of different networks

Network	Inertia estimation approach	References	Year
Great Britain	• An offline approach using PMUs to record events from different locations of the network	[61, 174]	2014, 2016
Japan	• An offline approach using ten transient events	[60]	1997
Nordic	• An online approach using real-time measurements power plants in the Nordic network	[141]	2015
Western Electricity Coordination Council (WECC)	• An offline approach using several year historical data of frequency, load and outage events to determine the network inertia.	[137]	2004

Table 4: Inertia estimation techniques classifications [159]

Estimation category	Description/ application	Pros	Cons	Refs.
Offline	Inertia estimation techniques depending on large disturbances historical data of the network	• Can estimate inertia available at a specific disturbance • Can simultaneously estimate system inertia and determine the size of disturbance • Can use frequency and voltage responses to estimate system inertia • Can estimate inertia of multiarea interconnected networks	• The size of the disturbance to be known • Time of events to be known • Post-mortem approaches • Errors in RoCoF calculation due to noise affect accuracy • No continuous estimation	[61, 76, 138, 139, 147, 171, 175-178]
Online	Inertia estimation techniques that use real-time measurements of the network as inputs for estimations	• Can estimate real-time network inertia • Can use PMU measurements to estimate inertia • Give continuous inertia of the network • Can use normal operating conditions of the network	• Inaccuracy due to measurement errors • Slow and not reliable for online estimation due to long execution time • Impractical for online estimations due to large computational time because of large network models	[142, 150-152, 155, 158, 179]
Forecast	Inertia estimation techniques that predict the future system inertia to predict the frequency response of the network ahead of time	• Can plan stability control schemes well in advance • Determine when the network will be at risk • Plan procurement of synthetic inertia and fast frequency response reserves • Can increase situational awareness for more RE sources integration in the network	• Challenges to include inertia contribution from the demand side in the forecast • Limited to short-time forecast • Prediction accuracy affected by stochastic weather change and noise in the measurements	[143-146, 162, 180]

5. Discussion and Future Trends

5.1. *Overall summary of inertia behaviour in modern and future power system*

Fig. 13 summarizes the whole discussion of this literature survey. From traditional power systems theories, it is understood that inertia constants from synchronous generators in the system are generally constant. There is no substantial variation in inertia present in the system over time. As a result, this known conventional inertia constant can provide an adequate initial inertial response when imbalances happen in the system. In that way, conventional inertia provides enough time for primary controls to act on the contingency [16, 147].

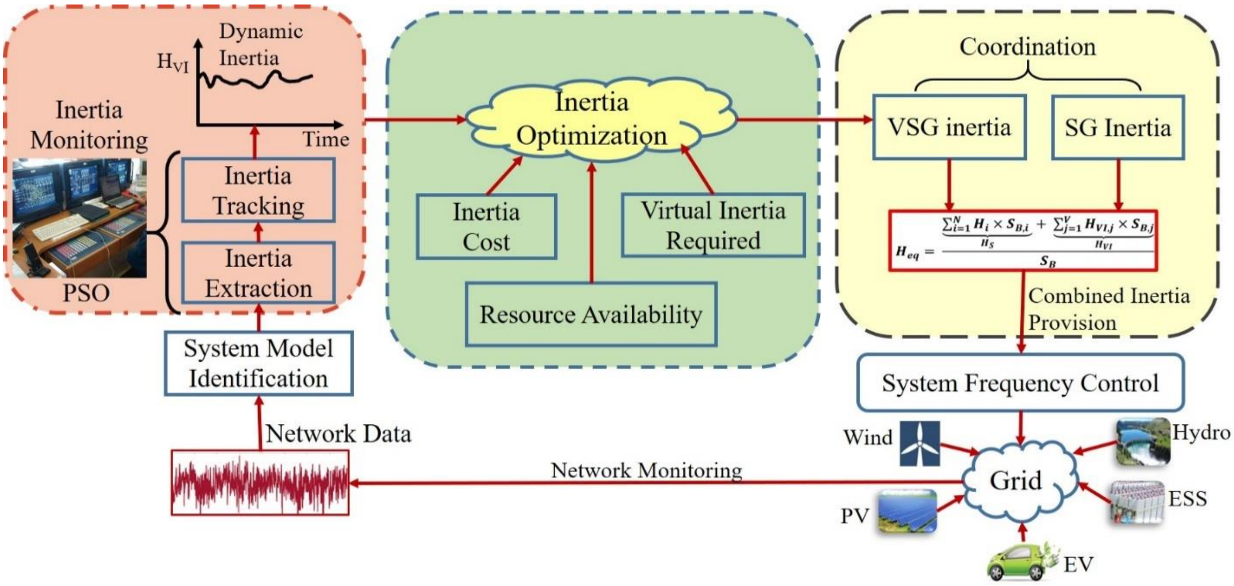


Fig. 13: Concept of inertia monitoring, coordination, and optimization in modern and future power systems

As stochastic RE sources keep on replacing more synchronous machines from the power system, some concerns need to be addressed. Many synchronous machines with their related inertia will be replaced when weather conditions favour provisions of RE sources. Nevertheless, power supply by stochastic RE sources to the grid depends primarily on resources availability such as irradiance, wind speed and state of charge (SOC). Consequently, integrated stochastic RE sources make power balancing in the grid more difficult. As a result of problematic power balancing, costs for power balancing are getting higher as more RE sources are integrated into the grid. The UK, for instance, spends £1 billion a year balancing the grid, and it was projected to double by 2021 [181]. Unfortunately, all these power balancing related costs are reflected in the customers’ energy bills [182, 183].

This trend is, therefore, raising the concern of continuous power imbalances in the system [121, 184]. In fact, in addition to power imbalance problems, the stochastic nature of RE sources is resulting in frequency control being unpredictable, hence, exposing power system stability at risk. The unpredictability of system frequency is due to the total system inertia becoming a time-variable quantity. Therefore, time-changing inertia in modern networks is becoming difficult to monitor and control, unlike in the traditional system [51, 147]. The generation mix dispatched at any point in time primarily affects the total inertia present in the system.

In connection to challenges brought by high penetration of stochastic RE sources, many power system operators (PSO) are concerned about how to deal with low and time-changing inertia issues in the future grid. This concern intends to establish adequate levels of inertia at any point in time to guarantee system stability by alerting PSO and give valued support for adaptive frequency control schemes [147, 185]. To this point, it is essential to model system inertia as a time-dependent variable that needs to be integrated with PSO and control for fast and guaranteed frequency control [16].

5.2. Inertia monitoring in modern and future power systems

As discussed in the preceding sections, RoCoF after a disturbance in the network is informative when discussing the impact of effective inertia on the stability of the power system. Before governor control is initiated, the frequency response due to power imbalance in the network is largely influenced by the system effective inertia (H). High inertia systems have low RoCoF $\left(\frac{\Delta f}{\Delta t}\right)$, which is very important for stability control in the power system [16]. High inertia values ensure governor controls are initiated before frequency reaches critical values. In contrast, low inertia systems have high RoCoF, which is risky for maintaining stability in power networks and can lead to cascading failures in the network. Since inertia is becoming a time-varying quantity due to penetration of stochastic RE sources, estimation and monitoring of time-varying inertia values in the network are crucial as described in Fig. 13. Prior knowledge of the time-varying inertia values in the network will be very useful in assessing the frequency response before contingencies happen in the network. This will further help to ensure planning, operation, stability control of the network as well as optimization of inertia values in the system. The prior estimation of inertia values at any given time would become a key input to adaptive control and security applications in the network.

5.3. Coordination of SG and VSG inertia in power networks

It has been observed that VSG are very supportive in frequency response in the networks with low inertia. The fast-virtual active power injection/absorption in the system by VSG to recover a system frequency following a disturbance is very crucial in the network. However, the fact that VSG inertia solely depends on the capacity of the ES systems behind them limits their applications. Consequently, conventional SG should be held in place to work together with VSG during disturbances. To avoid maloperation between SG and VSG inertias in the network, they need to be coordinated to operate smartly as seen in Fig 13. Besides, the coordination between SG and VSG inertias leads to the economical utilization of these two quantities for frequency support in the power system. If individual values of either SG inertia or VSG inertia are not adequate to damp the fast frequency response, then, they can be used simultaneously and in a coordinated way when disturbances occur. All this effort is to ensure that the operation of the network is not only reliable and secure but also economical.

If a scientific approach of coordination of SG and VSG is laid in place, it will encourage more penetration of VSG in the network for frequency control purposes. Interconnection techniques and specifications between SG and VSG should be developed to address inertial response, power control and frequency regulation. Additional research is required to standardize basic needs in these interconnection techniques and specifications. In this regard, areas to be looked at are regulation policies, size and operation technology of VSG, reserve margins and synthetic inertia to be considered as a tradeable commodity to mention a few research aspects.

5.4. Optimization of VSG in networks

Accurately predicting the network inertia values in advance is a fundamental aspect in planning for frequency response. This aspect introduces another concern of optimal values of synthetic inertia from inertia emulating resources as highlighted in Fig. 13. Achieving optimal inertia values would assist to accurately control stability issues for weather-related power imbalances in the network. Although there have been several proposed control algorithms to make RE sources and ES systems participate in inertial response in the grid [90, 120, 186], none of them has been able to accurately propose an optimal value of synthetic inertia provision during imbalances. There is a need for developing a systematic approach to determine optimal virtual inertia values in responding to frequency events in power systems. These optimal values of virtual inertia will co-exist with well-established conventional mechanical inertia in the grid for frequency stability control.

Furthermore, VSG has been introduced to emulate the inertial behaviour of a conventional synchronous generator. To achieve inertial emulation, inverter-based DERs used as VSG need some kind of temporary energy storage systems similar to that of the rotating mass of the rotor of a synchronous generator. Due to limitation in temporary and dynamic energy storage systems, VSG provides constant values of inertia and damping constants during grid dynamics to decrease frequency deviation and the RoCoF [13-15]. However, the use of more flexible and optimal values of virtual inertia constants for frequency response in modern and future power systems would be more advantageous [92]. Therefore, VSG with control techniques that would provide dynamic and optimal values of inertia and damping constants would address this challenge in frequency control. Incorporating wind and PV data would also be useful in this research direction to attain accurate inertia constant estimation for proper power system operation and planning [187, 188].

5.5. Future Trends

As the move towards more renewable energy resources integration to the grid is limited by reduced mechanical inertia, more penetration of stochastic RE sources can lead to stability issues in the grid. With this challenge, there should be a limit of stochastic RE sources capacity to be integrated into the grid. However, the introduction of synthetic inertia has been a potential move towards replacing mechanical SG inertia and, therefore, increasing the penetration of stochastic RE sources to the grid. If further studies and improvements are performed in the virtual inertia research area, they would promise attainment of a more renewable and flexible grid in the near time to come.

To make the move attainable, there is a need to focus on different challenges, which are still unsolved in this research direction. It is noted that most of the stochastic RESs are interfaced to the grid via power electronic converters. The fast control algorithms on converters allow stochastic RE sources with ES systems to respond to system dynamics faster than primary frequency control of conventional power plants. Since power electronic converters depend on the speed of the controllers, there is a serious concern that they may not be effective instantly after the contingency. In other words, power imbalances in the system cannot be naturally addressed by a power electronic converter, which is subject to delays. Consequently, the natural synchronous generators instant inertial response is still of most importance. Therefore, there is a need to carry out more research in this area to make synthetic inertia respond as fast as possible.

Another area to focus on is the limitation of reserve power delivery from RE sources to provide primary frequency control. This has been a serious limitation for stochastic RE sources, especially when they are operated at their maximum power points. If more research is done in making the RE sources participate in primary frequency control by ensuring sufficient reserve margin, it would be a significant contribution towards more penetration of RE sources in the power system. Adequate reserve margin can help power system ride-through during power contingencies. On the contrary, the currently existing insecurity due to incapability of reserve power delivery by RE sources is a major limiting factor for more penetration of RE sources. Enough reserve power delivery by RE sources would ensure RE sources participation in the primary frequency control. Therefore, this aspect needs to be addressed in future research works.

Moreover, existing stability theories, which were established several decades back such as the swing equation, do not hold when incorporating both SG and VSG response to frequency change. The conventional equations do not reflect the new stochastic generation units and new dynamic loads, which are recently penetrating the network. This issue also needs a dedicated platform to develop new theories, which will consider all stochastic behaviours of the modern and future grid with the presence of both SG and VSG. If this platform is well achieved, it will ensure flexibility and reliability of the grid with more penetration of RE sources.

Also, the inertia that is primarily provided by the conventional synchronous generators is apparently treated as a free resource. As the power network is now transitioning to converter based, there is a need for conventional inertia and synthetic inertia to be treated as tradeable commodities. A proper market framework for these resources is an effective approach to ensure their availability for power system stability control and power quality management. This is also an open area for more research to be done.

Finally, weather forecasting studies related to power imbalances, as a key factor in system stability studies, is another research area to work on. As more power generation units in the network are weather dependent therefore stochastic, there is a need to focus on the weather forecast and integrate this data to PSO to plan for power balances in the network. Predicting power imbalances due to weather forecast in the network is useful for the controller design to ensure stability control of the network is maintained.

6. Conclusion

This paper has presented an intensive review of the role of inertia for ensured stability and flexibility of the modern and future grid. The challenges related to low inertia in the network have been reviewed. Various proposed solutions to address these challenges have been discussed. Further possible research areas to address the challenges in future networks have been proposed. In short, to fully enjoy the benefits and opportunities of the new power generation technologies, the conventional grid must transition to a dynamic interactive real-time infrastructure that is more flexible and efficient to accommodate stochastic generation units. The benefits of a flexible grid, which include management of power balance, enhanced network reliability and optimized asset utilization, are guaranteed with proper control of the parameters of the network such as frequency. As conventional synchronous generators are getting replaced in the grid transformation, synthetic inertia is a centre of discussion for this grid transformation. Therefore, proper estimation, monitoring, coordination, optimization, and management of synthetic inertia related to conventional mechanical inertia may guarantee the achievement of a flexible modern renewable grid soon. To achieve this massive transformation, research areas with challenges suggested in future trends need to be researched more to get useful solutions for implementation. These altogether can ensure the attainment of a complete renewable grid, which is environmentally friendly.

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