Chapter

A Review of Virtual Inertia Techniques for Renewable Energy-Based Generators

Ana Fernández-Guillamón, Emilio Gómez-Lázaro, Eduard Muljadi and Ángel Molina-Garcia

Abstract

Over recent decades, the penetration of renewable energy sources (RES), especially photovoltaic and wind power plants, has been promoted in most countries. However, as these both alternative sources have power electronics at the grid interface (inverters), they are electrically decoupled from the grid. Subsequently, stability and reliability of power systems are compromised. Inertia in power systems has been traditionally determined by considering all the rotating masses directly connected to the grid. Thus, as the penetration of renewable units increases, the inertia of the power system decreases due to the reduction of directly connected rotating machines. As a consequence, power systems require a new set of strategies to include these renewable sources. In fact, 'hidden inertia,' 'synthetic inertia' and 'virtual inertia' are terms currently used to represent an artificial inertia created by inverter control strategies of such renewable sources. This chapter reviews the inertia concept and proposes a method to estimate the rotational inertia in different parts of the world. In addition, an extensive discussion on wind and photovoltaic power plants and their contribution to inertia and power system stability is presented.

Keywords: frequency control, grid stability, inertia, power systems, inverter-interfaced renewable energy sources

1. Introduction

Imbalances between generation and consumption cause frequency variations in a power system [1]. To maintain frequency in its nominal value, power systems rely on synchronous machines connected to the grid, which store kinetic energy automatically extracted in response to a sudden power imbalance [2]. However, due to the new environmental policies and the limited fossil fuel reserves, conventional generators are being replaced by renewable energy sources (RES)-based generators [3]. Among the different RES available, the most promising for electrical power generation are PV and wind power installations, which are inverter-interfaced RES (II-RES) [4]. However, the massive penetration of II-RES into the grid can involve several issues that should be taken into account [5]. First, as they depend on weather conditions, these sources are intermittent and uncertain, placing stress on power system operation [6]. Moreover, as they are connected to the grid through inverters which electrically decouple them from the grid [7], the effective inertia of the power system can be reduced [8]. This inertia reduction affects the system reliability, compromising the frequency stability [9]. The rotational inertia is related to both nadir (minimum frequency) and rate of change of frequency (ROCOF) [10]. In fact, larger nadirs and faster ROCOFs are obtained in low rotational inertia power systems, subsequently making them more sensitive to frequency deviations [11, 12]. As a result, over the last decade, several frequency control techniques have been proposed to facilitate the massive penetration of wind and PV resources into the grid [13]. In addition, recent contributions investigated the use of smart inverters with voltage and frequency support to enhance grid stability [14]. Such solutions are commonly referred to as hidden, synthetic or virtual inertia [15].

This chapter focuses on the current and future inertia concept for power systems. A methodology to estimate the current rotational inertia of power systems based on their electricity generation mix is proposed. In addition, the possibilities of wind and PV power plants to contribute to inertia and participate in frequency control are also presented. The rest of the chapter is organized as follows. The inertia analysis and swing equation of generators and current and future power systems are presented in Section 2. In Section 3, the inertia constant estimation methodology is explained, comparing the results to a previous report published by the European Network of Transmission System Operators for Electricity (ENTSO-E). Section 4 reviews different frequency control techniques for PV and wind power plants. Finally, Section 5 gives the conclusion.

2. Inertia analysis in power systems

2.1 Inertial response of a synchronous generator: inertia constant

Rotating masses of a synchronous generator store kinetic energy E_{kin} following Eq. (1), where J is the moment of inertia and ω_r is the rated rotational frequency of the machine [16]:

$$E_{kin} = \frac{1}{2}\ J\omega_r^2. \tag{1}$$

Moment of inertia J *is a measure of the resistance of an object to changes in its rotational motion* [17]. However, in power systems, it is common to express inertia constant H instead of moment of inertia J. Actually, the inertia constant of a generator determines the time interval during which an electrical generator can supply its rated power only by using the kinetic energy stored in its rotating masses. H is defined following Eq. (2), being S_r the rated power [18]:

$$H = \frac{E_{kin}}{S_r} = \frac{1}{2}\ \frac{J\ \ \omega_r^2}{S_r}. \tag{2}$$

Work in [10] reviews the inertia constants H of conventional power plants proposed in recent decades, which range between 2 and 10 s.

In power systems, the motion of each turbine-generator group is expressed as Eq. (3), where T_m and T_e are the mechanical torque of the turbine and the electromagnetic torque of the generator, respectively:

$$2\ H\ \frac{d\omega_r}{dt} = T_m - T_e, \tag{3}$$

However, as $P = T \cdot \omega$ and considering the initial status as 0:

$$P = P_0 + \Delta P = (T_0 + \Delta T) \cdot (\omega_{r0} + \Delta\omega_r), \tag{4}$$

where $\Delta P = \Delta P_m - \Delta P_e$ and $\Delta T = \Delta T_m - \Delta T_e$. Moreover, for small variations:

$$\Delta P \simeq T_0 \cdot \Delta\omega_r + \Delta T \cdot \omega_{r0}, \tag{5}$$

and in steady state:

$$\begin{aligned} T_{m0} &= T_{e0}, \\ \omega_{r0} &= 1\ \text{pu}. \end{aligned} \tag{6}$$

In consequence, considering small variations around the steady state, Eq. (3) can be rewritten as in Eq. (7) [19]:

$$2\ H\ \frac{d\Delta\omega_r}{dt} = \Delta P_m - \Delta P_e. \tag{7}$$

Furthermore, some electrical loads connected to the grid are also frequency-dependent, working as a load resource under frequency deviations (i.e., synchronous machines). In this way, the electrical power of those loads can be expressed as:

$$\Delta P_e = \Delta P_L + D \cdot \Delta\omega_r, \tag{8}$$

where ΔP_L is the power change of those loads independent from frequency deviations and D is the damping factor (load-frequency response). Subsequently, by including the damping factor in Eq. (7), it is modified to Eq. (9), which is usually referred to as *swing equation* and represents the motion of a synchronous generator:

$$2\ H\ \frac{d\Delta\omega_r}{dt} = \Delta P_m - (\Delta P_L + D \cdot \Delta\omega_r). \tag{9}$$

2.2 Aggregated swing equation: application to power systems

To apply the swing Eq. (9) to a power system, all synchronous generators are grouped in an equivalent rotating mass. This is carried out by determining the equivalent inertia constant H_{eq} of such generators:

$$H_{eq} = \frac{\sum_{i=1}^{SG} H_i \cdot S_{B,i}}{S_B}, \tag{10}$$

where H_i and $S_{B,i}$ are the inertia constant and rated power of synchronous generator i, SG is the total number of synchronous generators connected to the grid and S_B is the rated power of the power system.

In the same way, loads are reduced to an equivalent one with damping factor D_{eq}. If the power system under analysis is stable, an inaccurate value of D_{eq} will not have a significant impact on the study. However, under disturbance situations, the value of D_{eq} can be a major contribution [20]. As variable frequency drives become more common, the equivalent damping factor is expected to decrease [21].

2.3 Hidden and virtual inertia emulation from RES: modified equivalent inertia constant

In recent decades, several policies have promoted the penetration of RES-based generation units, which have replaced synchronous generators directly connected to the grid [22]. However, as some of them are II-RES (i.e., wind and PV), power systems with a high penetration of those RES require new frequency control strategies that emulate the behavior of conventional power plants under power imbalance conditions [23]. Such techniques are commonly referred to as hidden, synthetic, emulated or virtual inertia [15]. By including this emulation of inertia into power systems, equivalent inertia H_{eq} would be modified. Thus, it would have two different components: (i) synchronous rotating inertia coming from synchronous (conventional) generators H_S and (ii) emulated/virtual inertia coming from II-RES H_V [24, 25]. Thus, Eq. (10) would become:

$$H_{eq} = \frac{\overbrace{\sum_{i=1}^{SG} H_i \cdot S_{B,i}}^{H_S} + \overbrace{\sum_{j=1}^{VG} H_{V,j} \cdot S_{B,j}}^{H_V}}{S_B}, \tag{11}$$

where VG is the number of II-RES connected to the grid through emulation/virtual control methods and H_V is the inertia constant of the emulated/virtual generation unit. This modified equivalent inertia expressed in Eq. (11) is graphically illustrated in **Figure** 1, based on [26]. As can be seen, there are three different links between the generation units and the grid frequency: (i) rotational synchronous inertia from conventional generators, (ii) hidden inertia from VSWT and (iii) virtual inertia from PV. This is because modern VSWT have rotational inertia stored in their blades, drive train and electrical generator [27]. However, due to the inverter and maximum power point tracking (MPPT) strategy, they cannot automatically provide this inertia to the grid [28–31], being thus considered as 'hidden' from the power system point of view [32]. In fact, VSWT have inertia constants comparable to those of conventional generators, as summarized in **Figure** 2. In consequence, it is considered that the inertia provided by VSWT is 'emulated' [33].

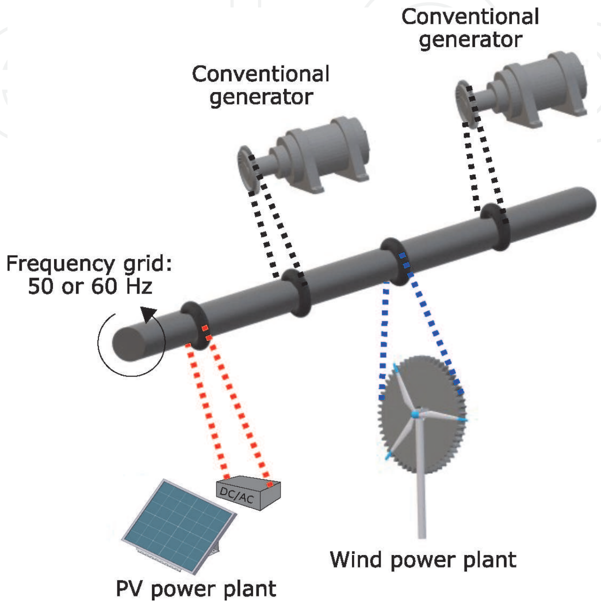


Figure 1.
Power system with synchronous, hidden and virtual inertia.

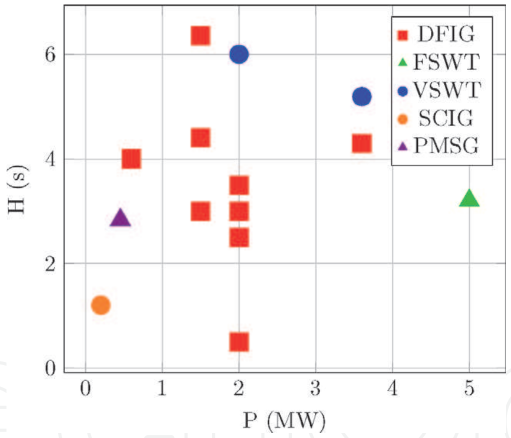


Figure 2.
Inertia constant values H *for different wind turbine technologies.*

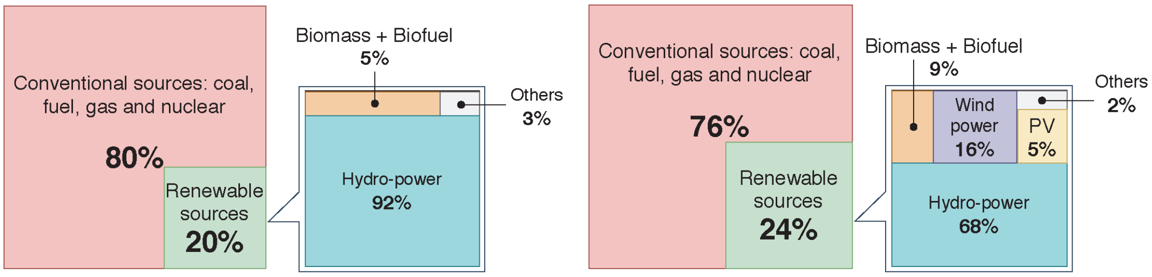
On the other hand, PV has no rotating masses [30]. Thus, PV power plants cannot store kinetic energy and their inertia constant is $H \simeq 0$ [31]. Consequently, they cannot provide inertia unless it is synthetic/virtual, thus being usually referred to as 'emulated synthetic/virtual inertia' provided by such PV power plants [34, 35].

Due to the repercussions of II-RES with regard to the rotating inertia of power systems [36], they should start providing active power support under disturbances [37]. The specific literature includes several technologies that allow II-RES to participate in frequency control by providing additional power under disturbances [38–40].

3. Inertia estimation for power systems

Energy global statistics are provided by the International Energy Agency (IEA). Considering Eq. (10) and the electricity supply within a year presented in [41], it is possible to calculate the equivalent inertia H_{eq} in different regions of the world. According to each technology, the inertia constant H of conventional units is estimated as the mean value of those presented in [10] (i.e., $H_{coal} = 4$ s, $H_{oil} = 4$ s, $H_{gas} = 5$ s, $H_{nuclear} = 4$ s, $H_{hydro} = 3.25$ s). It is considered that II-RES are not participating in frequency control (i.e., not contributing to the system inertia).

Figure 3 depicts the generation mix change between 1996 and 2016. Over these two decades, the total electricity consumption increased by more than 80%. However, in the same time period, RES electricity generation only increased by 4%. Based on the approach previously described to estimate H_{eq}, **Figure 4** depicts the change between the inertia constant for the different continents between 1996 and



(a) (b)

Figure 3.
Generation mix in the world: change between 1996 and 2016. (a) Generation mix in 1996. (b) Generation mix in 2016.

2016. As can be seen, the inertia reduction in Asia, the USA and South America was negligible (between 2.5 and 3%), whereas in Europe it decreased by nearly 20%.

In line with the inertia reduction suffered, RES supply in Europe increased by nearly 20% (refer to **Figure 5**). Actually, ENTSO-E has already focused on the high

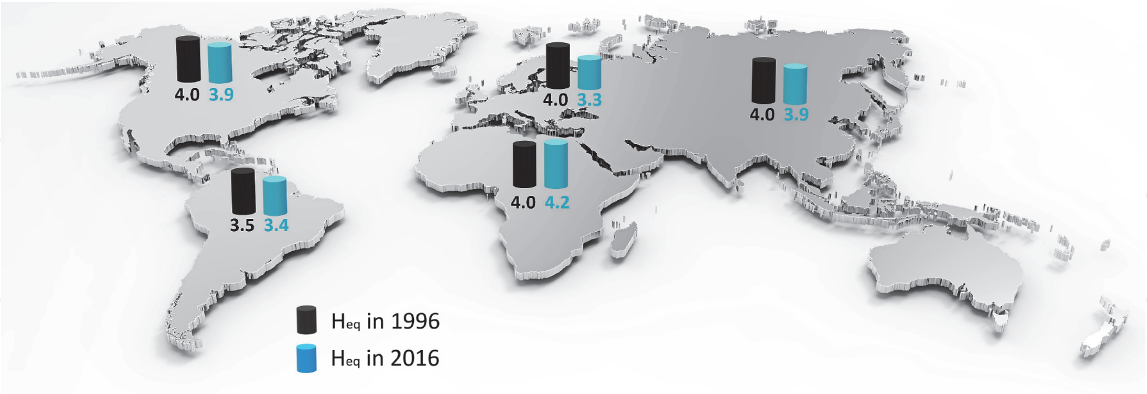
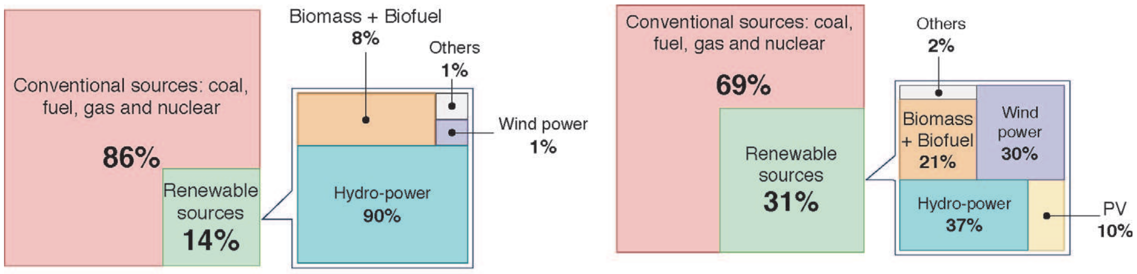


Figure 4.
Estimated equivalent inertia constants in the world by continent: change between 1996 and 2016.



(a) (b)

Figure 5.
Generation mix in Europe: change between 1996 and 2016. (a) Generation mix in 1996. (b) Generation mix in 2016.

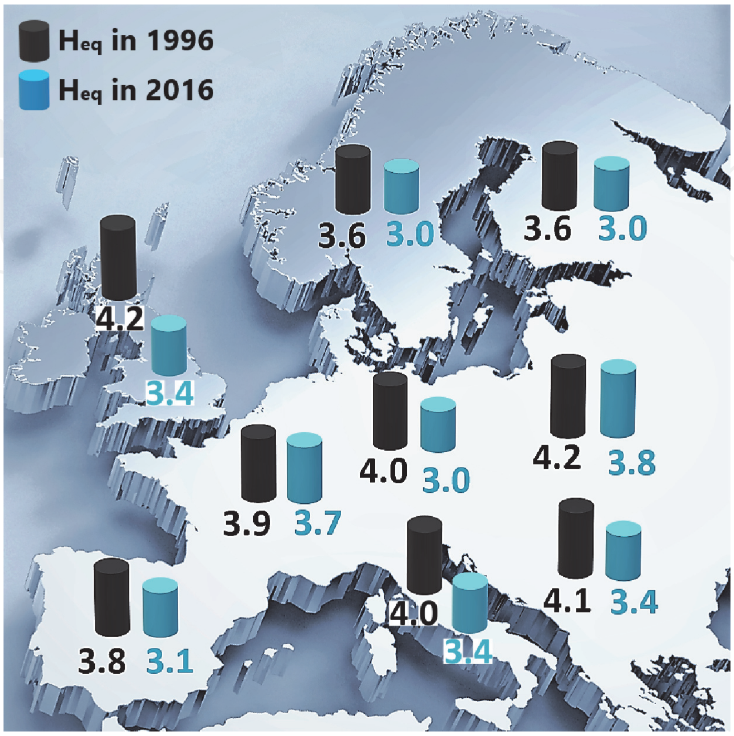


Figure 6.
Equivalent inertia constants estimated in EU-28: change between 1996 and 2016.

RES integration-low synchronous inertia problem. In one of their published reports, ENTSO-E estimated the evolution of system inertia for different TYNDP scenarios for 2030 in Europe and certain countries (i.e., the United Kingdom, France and Germany), considering that II-RES do not contribute to inertia [42]. In those estimations, H_{eq} depends on the percentage of hours in a year that II-RES are working. Thus, it is possible to compare the H_{eq} estimated in this chapter with the values obtained by ENTSO-E.

The transition of H_{eq} in a number of European countries can be seen in **Figure 6**. In [42], considering RES current generation rate: (i) H_{eq} of Europe is within range 3.8–4.5 s; (ii) H_{eq} of the United Kingdom is within range 3–4 s; (iii) H_{eq} of France is 5 s and (iv) H_{eq} of Germany is 3.5 s. Some discrepancies can be observed. The main cause of these is the values of the inertia constant of conventional plants. In fact, if the maximum value of H for all conventional plants is considered (i.e., $H_{coal} = 5$ s, $H_{oil} = 5$ s, $H_{gas} = 5$ s, $H_{nuclear} = 4$ s, $H_{hydro} = 4.75$ s), the H_{eq} results are nearly the same as those presented in [42].

4. II-RES frequency control strategies

4.1 Preliminaries

To maintain frequency within an acceptable range, generation and load in the power system must be continuously balanced [43]. In fact, frequency variations from the nominal value can cause several problems including under-/overfrequency relay operations and disconnection of some loads from the grid, among others [44]. Thus, frequency stability is an essential issue for power systems [45].

With the increase in II-RES, the equivalent inertia constant of power systems is reduced, subsequently obtaining (i) larger frequency deviations after an imbalance and (ii) higher ROCOF [7, 46]. As a consequence, II-RES should start providing active power support under disturbances [37].

4.2 PV power plant frequency control strategies

In order to provide additional active power during imbalanced situations, PV power plants can integrate different solutions, mainly based on two principal approaches: energy storage systems (ESS) or de-loading control strategies. Moreover, the technical challenge is more severe with PV power plants than with wind generation, since PV systems cannot provide any inertial response unless special countermeasures are adopted [47].

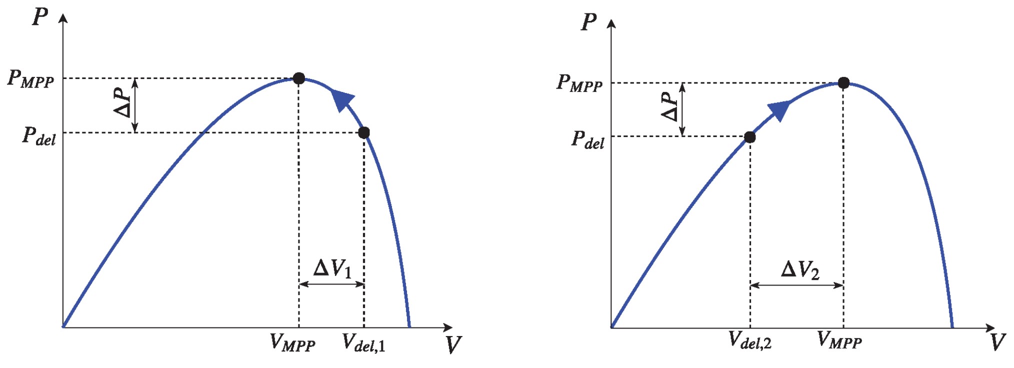
With regard to ESS, different solutions have been proposed in the literature to be applied to PV systems. Although the relevant benefits of ESS to power system's operation is widely recognized, some significant challenges can be identified: (i) the selection of a suitable technology to match the power system application requirements, (ii) an accurate evaluation of the energy storage facilities estimating both technical and economic benefits and (iii) a cost decreasing to a realistically acceptable level for deployment [48]. Among the different ESS, the battery energy storage is considered by some authors as the oldest and most mature ESS [49]. In work [50], it is concluded that the Li-Ion batteries are those that best suit frequency regulation services. Batteries are limited in power, though present a high storage ratio [51–53]; on the other hand, supercapacitors have high levels of power with low energy storage ratio. As a consequence, the battery-supercapacitor combination is proposed as an interesting ESS solution [54]. Indeed, these technologies can help to solve the problem of the ‘intermittent’ nature of solar PV supply [55]. Additional solutions for PV installations based on supercapacitors can be found in [56, 57]. Flywheels are another solution widely proposed as ESS, being applied from very small micro-satellites to large power systems [58]. Work in [59] points out a great benefit of flywheels backing up solar PV power plants, mainly focused on the cloud passing, which can cope with the high cycles of the flywheel technologies. Indeed, flywheels excel in short duration and high cycle applications [60]. Moreover, flywheels have a high efficiency, usually in the range between 90% and 95%, with an expected lifetime of around 15 years [61]. Different solutions propose hybrid ESS coupled to PV power plants [53], such as a battery hybridization with mechanical flywheel [62].

PV power plants usually work at the maximum power point (MPP) according to ambient temperature T and solar irradiation G [63]. However, they can work below their MPP, having thus some active power reserves (headroom) to supply in case of a frequency deviation. This approach is usually referred to as de-loading technique and is commonly proposed for PV installations [64, 65]. In this way, the PV plant is operated at P_{del}, below P_{MPP}, so that some power reserves $\Delta P = P_{MPP} - P_{del}$ are available [66, 67]. As can be seen in **Figure 7**, P_{del} can be related with two different voltages: (i) over the maximum power point voltage, $V_{del,1} > V_{MPP}$, and (ii) under the maximum power point voltage, $V_{del,2} < V_{MPP}$. However, due to stability problems, the de-loaded voltage corresponds to the higher value $V_{del,1}$ [68]. This V_{del} is then added to the MPP controller reference, in order to also de-load the inverter. This controller for de-loaded PV is modified in [69], such that the release of the reserve is directly linked to both (i) the frequency excursion and (ii) the availability of the reserve in the PV system. This controller is also proposed in [70].

4.3 Wind power plant frequency control strategies

Wind power plants can also participate in frequency control by using different solutions. Apart from the use of ESS or working with the de-loading control strategy, wind turbines can provide inertial response as conventional generators due to the rotational inertia of the blades and generator [10].

With regard to ESS, wind power plants can also include batteries [71], supercapacitors [72] and flywheels [73]. ESS are considered an alternative to compensate the lack of short-term frequency response ability of wind power plants [74]. The utility-scale battery ESS helps to reduce the ROCOF, providing frequency support and improving the system frequency response [75]. A battery ESS based on a state-machine-based coordinated control strategy is developed in [76] to support



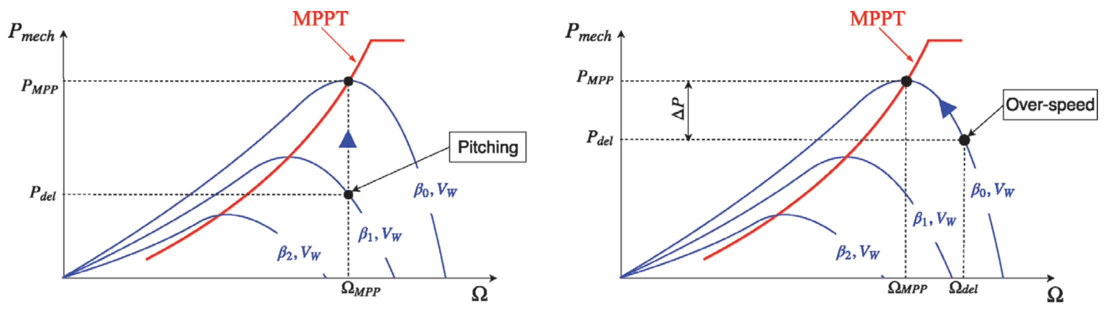
(a) (b)

Figure 7.
De-loading techniques for PV power plants. (a) $V_{del.1} > V_{MPP}$*. (b)* $V_{del.2} < V_{MPP}$*.*

frequency response of wind power plants, including both primary and secondary frequency control. A real-time cooperation scheme by considering complementary characteristics between wind power and batteries is discussed in [77] to provide both energy and frequency regulation, considering the battery life cycle. The combination of battery and supercapacitor is considered in [78] as an effective alternative to improve the battery lifetime and enhance the system economy. In this way, an enhanced frequency response strategy is investigated in [79] to improve and regulate the wind frequency response with the integration of ultra-capacitors. With the aim of smoothing the net power injected to the grid by wind turbines (or by a wind power plant), some authors propose to use flywheels [80, 81]. Flywheels are also proposed to dynamically regulate the system equivalent inertia and damping, enhancing the frequency regulation capability of wind turbines [38, 82] and also the entire grid [83]. A coordinated regulation response of the turbine power reserves and the flywheels while participating in primary frequency control is described in [84]. Finally, other works include not only frequency response but also voltage control by using flywheels [85, 86].

In line with PV installations, wind turbines also work in the MPP according to the wind speed v_w. As a consequence, the de-loading technique is considered as a solution to provide additional active power in imbalanced situations with wind turbines, by operating them in a suboptimal point through the de-loaded control mode [87]. Wind turbines have two different possibilities to operate with the de-loading technique (refer to **Figure 8**) [32]: (i) pitch angle control and (ii) overspeed control. The pitch-angle control increases the pitch angle from β_0 to β_1 for a constant v_w; in this way, the supplied power P_{del} is below the maximum power P_{MPP}, being thus a certain amount of power ΔP that can be supplied in case of frequency contingency (**Figure 8(a)**) [88–91]. When this additional power ΔP is provided, the pitch angle has to be reduced from β_1 to β_0. The overspeed control increases the rotational speed of the rotor, shifting the supplied power P_{del} towards the right of the maximum power P_{MPP} (**Figure** 8**(b)**) [87, 92, 93]. As in the pitch-angle control, P_{del} is below P_{MPP} [71]. When the additional power ΔP is supplied, the rotor speed has to be reduced from Ω_{del} to Ω_{MPP}, releasing kinetic energy [39, 87, 92, 93].

In order to provide an inertial response, at least one supplementary loop control is introduced into the power controller to increase the generated power by the wind power plant. This additional loop is only activated under power imbalances (i.e., frequency deviations), supplying the kinetic energy stored in the blades and generator to the grid as an additional active power for a few seconds [94]. The droop control provides an additional active power ΔP proportional to the frequency excursion Δf (see **Figure 9**), as the primary frequency control of conventional power plants. The increase in the active power output then results in a decrease in



(a) (b)

Figure 8.
De-loading techniques for wind power plants. (a) Pitch control. (b) Over-speed control.

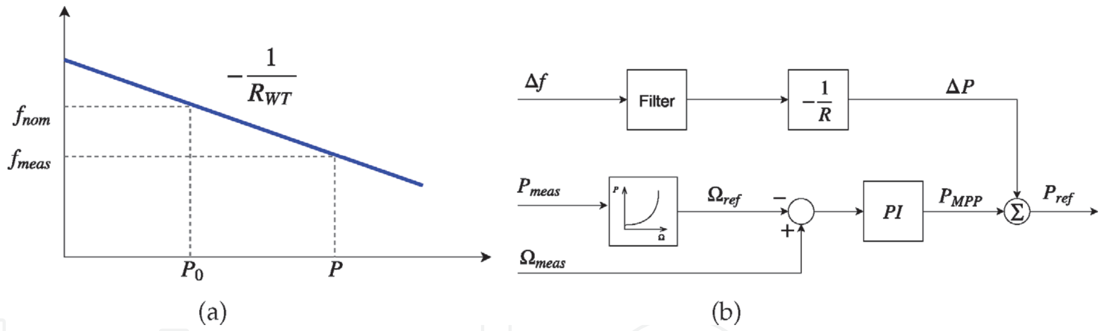


Figure 9.
Droop control for VSWTs. (a) Droop characteristic. (b) Block diagram of droop control.

the rotor speed [95–99]. ΔP can be estimated following Eq. (12), being R_{WT} the droop control setting of the wind turbine:

$$\Delta P = -\frac{\Delta f}{R_{WT}} \tag{12}$$

The hidden inertia emulation technique is based on emulating the inertial response of traditional synchronous generators. Two possibilities are found in the specific literature, as presented in **Figure 10**: (i) one loop, where the additional power is proportional to the ROCOF [100–102], and (ii) two loops, where the additional power is proportional to the ROCOF and the frequency deviation. The second strategy causes the frequency to return to its nominal value [103–105]. In both cases, the rotor and generator speeds are reduced to release the stored kinetic energy.

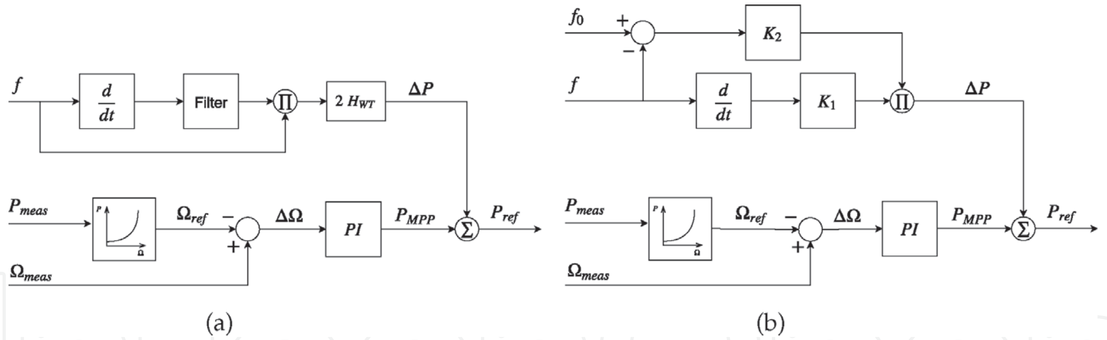


Figure 10.
Hidden inertia emulation controllers. (a) One loop. (b) Two loops.

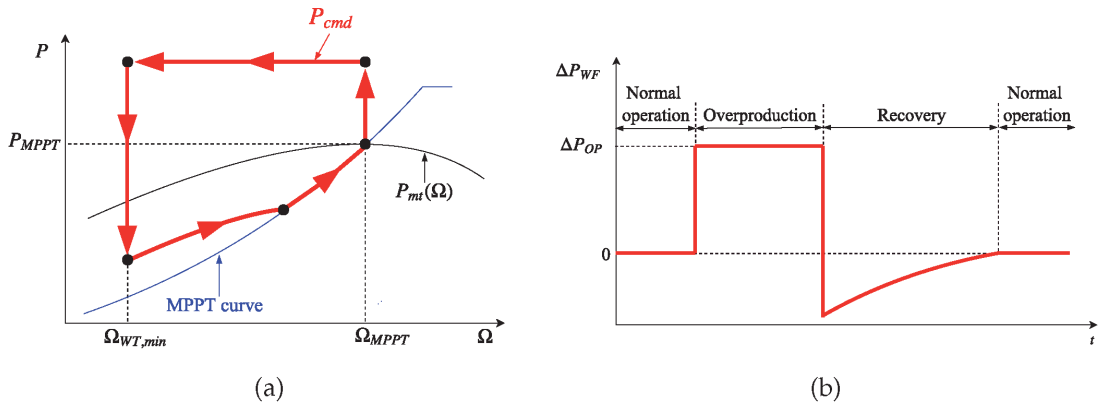


Figure 11.
Fast power reserve emulation technique [106]. (a) $P - \Omega$ curve. (b) Power variation.

The fast power reserve approach is similar to the hidden inertia emulation technique: an additional power is initially supplied, which makes the rotor speed to decrease. However, in this technique, the additional active power ΔP has been defined as a constant value independent of the system configuration and frequency deviation [106–110] or variable (depending on the frequency deviation or minimum rotor speed limits) [43, 111, 112]. The rotational speed decrease is then recovered through a recovery period, which can cause a secondary frequency dip due to the sudden decrease of the power generated by the wind power plant. As a consequence, different recovery periods have been proposed in the last decade to avoid this secondary frequency drop [43, 106, 108–111, 113, 114], even coordinating this period with ESS [115]. **Figure 11** shows the fast power reserve emulation control proposed in [106].

5. Conclusions

In this chapter, we have conducted an extensive literature review of inertia of power systems. A methodology to estimate the inertia constants of different power systems is proposed and verified with the inertia constant results of ENTSO-E. The contribution of wind and PV power plants as 'hidden inertia' and 'virtual inertia,' respectively, to participate in frequency control has also been discussed, providing significant information for their participation in frequency control.

Acknowledgements

This work was supported by the Spanish Education, Culture and Sports Ministry (FPU16/04282), Spanish Economy and Competitiveness Ministry and European Union FEDER, which supported this work under Project ENE2016-78214-C2-1-R.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

DFIG	double-fed induction generator
ESS	energy storage systems
ENTSO-E	European Network of Transmission System Operators for Electricity
FSWT	fixed-speed wind turbine
HAWT	horizontal axis wind turbine
II-RES	inverter-interfaced renewable energy sources
PMSG	permanent magnet synchronous generator
PV	photovoltaic
RES	renewable energy sources
ROCOF	rate of change of frequency
SCIG	squirrel cage induction generator
VSWT	variable speed wind turbine
WPP	wind power plant

Author details

Ana Fernández-Guillamón[1*†], Emilio Gómez-Lázaro[2†], Eduard Muljadi[3†]
and Ángel Molina-Garcia[1†]

1 Department of Automatics, Electrical Engineering and Electronic Technology,
Universidad Politécnica de Cartagena, Cartagena, Spain

2 Renewable Energy Research Institute and DIEEAC-EDII-AB, Universidad de
Castilla-La Mancha, Albacete, Spain

3 Department of Electrical and Computer Engineering, Auburn University,
Auburn, AL, USA

*Address all correspondence to: ana.fernandez@upct.es

† These authors are contributed equally.

References

[1] Babahajiani P, Shafiee Q, Bevrani H. Intelligent demand response contribution in frequency control of multi-area power systems. IEEE Transactions on Smart Grid. 2018;**9**(2): 1282-1291

[2] D'hulst R, Fernandez JM, Rikos E, Kolodziej D, Heussen K, Geibelk D, et al. Voltage and frequency control for future power systems: The ELECTRA IRP proposal. In: 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), IEEE. 2015. pp. 245-250

[3] Fernández-Guillamón A, Das K, Cutululis NA, Molina-García Á. Offshore wind power integration into future power systems: Overview and trends. Journal of Marine Science and Engineering. 2019;**7**(11):399

[4] Shah R, Mithulananthan N, Bansal R, Ramachandaramurthy V. A review of key power system stability challenges for large-scale PV integration. Renewable and Sustainable Energy Reviews. 2015;**41**(Supplement C): 1423-1436

[5] Cvetković M, Pan K, López CD, Bhandia R, Palensky P. Co-simulation aspects for energy systems with high penetration of distributed energy resources. In: AEIT International Annual Conference; 2016. IEEE. 2017. pp. 1-6

[6] Wang Y, Meng J, Zhang X, Xu L. Control of pmsg-based wind turbines for system inertial response and power oscillation damping. IEEE Transactions on Sustainable Energy. 2015;**6**(2):565-574

[7] Junyent-Ferr A, Pipelzadeh Y, Green TC. Blending hvdc-link energy storage and offshore wind turbine inertia for fast frequency response. IEEE Transactions on Sustainable Energy. 2015;**6**(3):1059-1066

[8] Yang S, Fang J, Tang Y, Qiu H, Dong C, Wang P. Synthetic-inertia-based modular multilevel converter frequency control for improved micro-grid frequency regulation. In: 2018 IEEE Energy Conversion Congress and Exposition (ECCE); IEEE. 2018. pp. 5177-5184

[9] Delille G, Francois B, Malarange G. Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system's inertia. IEEE Transactions on Sustainable Energy. 2012;**3**(4):931-939

[10] Fernández-Guillamón A, Gómez-Lázaro E, Muljadi E, Molina-García Á. Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. Renewable and Sustainable Energy Reviews. 2019;**115**:109369

[11] Dehghanpour K, Afsharnia S. Electrical demand side contribution to frequency control in power systems: A review on technical aspects. Renewable and Sustainable Energy Reviews. 2015; **41**:1267-1276

[12] Nguyen HT, Yang G, Nielsen AH, Jensen PH. Combination of synchronous condenser and synthetic inertia for frequency stability enhancement in low inertia systems. IEEE Transactions on Sustainable Energy. 2018;**10**(3):997-1005

[13] Groß D, Bolognani S, Poolla BK, Dörfler F. Increasing the resilience of low-inertia power systems by virtual inertia and damping. In: Bulk Power Systems Dynamics and Control Symposium (IREP). 2017

[14] Ustun TS, Aoto Y. Analysis of smart inverter's impact on the distribution network operation. IEEE Access. 2019;**7**: 9790-9804

[15] Vokony I. Effect of inertia deficit on power system stability-synthetic inertia concepts analysis. In: 2017 6th International Youth Conference on Energy (IYCE); IEEE. 2017. pp. 1-6

[16] Ulbig A, Borsche TS, Andersson G. Impact of low rotational inertia on power system stability and operation. IFAC Proceedings Volumes. 2014;**47**(3): 7290-7297

[17] Serway RA, Jewett JW. Physics for Scientists and Engineers with Modern Physics. Cengage Learning: Brooks/ Cole; 2018

[18] Uriarte FM, Smith C, Van Broekhoven S, Hebner RE. Microgrid ramp rates and the inertial stability margin. IEEE Transactions on Power Systems. 2015;**30**(6):3209-3216

[19] Fernández-Guillamón A, Vigueras-Rodríguez A, Molina-García A. Análisis y simulación de estrategias agregadas de control de frecuencia entre grandes parques eólicos y aprovechamientos hidroélectricos [MS thesis]. Universidad Politécnica de Cartagena; 2017

[20] Huang H, Li F. Sensitivity analysis of load-damping characteristic in power system frequency regulation. IEEE Transactions on Power Systems. 2013; **28**(2):1324-1335

[21] Tielens P, Van Hertem D. The relevance of inertia in power systems. Renewable and Sustainable Energy Reviews. 2016;**55**:999-1009

[22] Fernández-Guillamón A, Vigueras-Rodríguez A, Molina-García Á. Analysis of power system inertia estimation in high wind power plant integration scenarios. IET Renewable Power Generation. 2019;**13**(15):2807-2816

[23] Muñoz-Benavente I, Hansen AD, Gómez-Lazaro E, García-Sánchez T, Fernández-Guillamón A, Molina-García Á. Impact of combined demand-response and wind power plant participation in frequency control for multi-area power systems. Energies. 2019;**12**(9):1687

[24] Gu H, Yan R, Saha TK. Minimum synchronous inertia requirement of renewable power systems. IEEE Transactions on Power Systems. 2017; **33**(2):1533-1543

[25] Tielens P, Van Hertem D. Receding horizon control of wind power to provide frequency regulation. IEEE Transactions on Power Systems. 2017; **32**(4):2663-2672

[26] Kroposki B, Johnson B, Zhang Y, Gevorgian V, Denholm P, Hodge B-M, et al. Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy. IEEE Power and Energy Magazine. 2017;**15**(2):61-73

[27] Du P, Matevosyan J. Forecast system inertia condition and its impact to integrate more renewables. IEEE Transactions on Smart Grid. 2018;**9**(2): 1531-1533

[28] Muyeen S, Takahashi R, Murata T, Tamura J. A variable speed wind turbine control strategy to meet wind farm grid code requirements. IEEE Transactions on Power Systems. 2010;**25**(1):331-340

[29] Zhao J, Lyu X, Fu Y, Hu X, Li F. Coordinated microgrid frequency regulation based on DFIG variable coefficient using virtual inertia and primary frequency control. IEEE Transactions on Energy Conversion. 2016;**31**(3):833-845

[30] Hosseinipour A, Hojabri H. Virtual inertia control of PV systems for dynamic performance and damping enhancement of dc microgrids with constant power loads. IET Renewable Power Generation. 2017;**12**(4):430-438

[31] Tielens P. Operation and control of power systems with low synchronous inertia [PhD thesis]. KU Leuven; 2017

[32] Yingcheng X, Nengling T. Review of contribution to frequency control through variable speed wind turbine. Renewable Energy. 2011;**36**(6): 1671-1677

[33] Fischer M, Engelken S, Mihov N, Mendonca A. Operational experiences with inertial response provided by type 4 wind turbines. IET Renewable Power Generation. 2016;**10**(1):17-24

[34] Tang ZX, Lim YS, Morris S, Yi JL, Lyons PF, Taylor PC. A comprehensive work package for energy storage systems as a means of frequency regulation with increased penetration of photovoltaic systems. International Journal of Electrical Power & Energy Systems. 2019;**110**:197-207

[35] Yang L, Hu Z, Xie S, Kong S, Lin W. Adjustable virtual inertia control of supercapacitors in PV-based ac microgrid cluster. Electric Power Systems Research. 2019;**173**: 71-85

[36] Li W, Du P, Lu N. Design of a new primary frequency control market for hosting frequency response reserve offers from both generators and loads. IEEE Transactions on Smart Grid. 2017;**9**(5):4883-4892

[37] You R, Barahona B, Chai J, Cutululis NA, Wu X. Improvement of grid frequency dynamic characteristic with novel wind turbine based on electromagnetic coupler. Renewable Energy. 2017;**113**:813-821

[38] Attya A, Dominguez-Garcia J, Anaya-Lara O. A review on frequency support provision by wind power plants: Current and future challenges. Renewable and Sustainable Energy Reviews. 2018;**81**:2071-2087

[39] Wang S, Tomsovic K. A novel active power control framework for wind turbine generators to improve frequency response. IEEE Transactions on Power Systems. 2018;**33**(6):6579-6589

[40] Ziping W, Wenzhong G, Tianqi G, Weihang Y, Zhang H, Shijie Y, et al. State-of-the-art review on frequency response of wind power plants in power systems. Journal of Modern Power Systems and Clean Energy. 2018;**6**(1): 1-16

[41] International Energy Agency. Total primary energy supply (TPES) by source, year and country. Available from: https://bit.ly/34YTcda. [Accessed: 17 October 2018]

[42] ENTSO-E. High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS). Available from: https://bit.ly/2x5fZrh

[43] Fernández-Guillamón A, Sarasúa JI, Chazarra M, Vigueras-Rodríguez A, Fernández-Muñoz D, Molina-García Á. Frequency control analysis based on unit commitment schemes with high wind power integration: A Spanish isolated power system case study. International Journal of Electrical Power Energy Systems. 2020;**121**:106044

[44] Bevrani H, Daneshmand PR. Fuzzy logic-based load-frequency control concerning high penetration of wind turbines. IEEE Systems Journal. 2012; **6**(1):173-180

[45] Ozer B, Arikan O, Moral G, Altintas A. Extraction of primary and secondary frequency control from active power generation data of power plants. International Journal of Electrical Power & Energy Systems. 2015;**73**:16-22

[46] Nedd M, Booth C, Bell K. Potential solutions to the challenges of low inertia power systems with a case study concerning synchronous condensers. In: 2017 52nd International Universities Power Engineering Conference (UPEC); IEEE. 2017. pp. 1-6

[47] Wang X, Yue M. Design of energy storage system to improve inertial response for large scale PV generation.

In: 2016 IEEE Power and Energy Society General Meeting (PESGM). 2016. pp. 1-5

[48] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy. 2015; **137**:511-536

[49] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: A critical review. Progress in Natural Science. 2009;**19**(3): 291-312

[50] Akram U, Nadarajah M, Shah R, Milano F. A review on rapid responsive energy storage technologies for frequency regulation in modern power systems. Renewable and Sustainable Energy Reviews. 2020;**120**:109626

[51] Marcos J, Storkël O, Marroyo L, Garcia M, Lorenzo E. Storage requirements for PV power ramp-rate control. Solar Energy. 2014;**99**:28-35

[52] Salim NB, Aboelsoud H, Tsuji T, Oyama T, Uchida K. Load frequency control of two-area network using renewable energy resources and battery energy storage system. Journal of Electrical Systems. 2017;**13**(2):348-365

[53] Zhao Z, Xiao H, Yang Y. Improved coordinated control strategy of hybrid energy storages in PV power smoothing. Energy Procedia. 2018;**145**:151-156

[54] Cabrane Z, Ouassaid M, Maaroufi M. Analysis and evaluation of battery-supercapacitor hybrid energy storage system for photovoltaic installation. International Journal of Hydrogen Energy. 2016;**41**(45): 20897-20907

[55] Chandra A. Supercapacitors: An alternate technology for energy storage. Proceedings of the National Academy of Sciences. 2012;**82**:79-90

[56] Taghizadeh M, Hoseintabar M, Faiz J. Frequency control of isolated WT/PV/SOFC/UC network with new control strategy for improving SOFC dynamic response. International Transactions on Electrical Energy Systems. 2015;**25**(9): 1748-1770

[57] You S, Liu Y, Tan J, Gonzalez MT, Zhang X, Zhang Y, et al. Comparative assessment of tactics to improve primary frequency response without curtailing solar output in high photovoltaic interconnection grids. IEEE Transactions on Sustainable Energy. 2018;**10**(2):718-728

[58] Mousavi GS, Faraji F, Majazi A, Al-Haddad K. A comprehensive review of flywheel energy storage system technology. Renewable and Sustainable Energy Reviews. 2017;**67**: 477-490

[59] Amiryar ME, Pullen KR. A review of flywheel energy storage system technologies and their applications. Applied Sciences. 2017;**7**:286(1-21)

[60] Pullen KR. The status and future of flywheel energy storage. Joule. 2019; **3**(6):1394-1399

[61] Akinyele D, Rayudu R. Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessments. 2014;**8**:74-91

[62] Barelli L, Bidini G, Bonucci F, Castellini L, Fratini A, Gallorini F, et al. Flywheel hybridization to improve battery life in energy storage systems coupled to res plants. Energy. 2019;**173**: 937-950

[63] Xin H, Liu Y, Wang Z, Gan D, Yang T. A new frequency regulation strategy for photovoltaic systems without energy storage. IEEE Transactions on Sustainable Energy. 2013;**4**(4):985-993

[64] Alatrash H, Mensah A, Mark E, Haddad G, Enslin J. Generator emulation controls for photovoltaic inverters. IEEE Transactions on Smart Grid. 2012;**3**(2):996-1011

[65] Zarina P, Mishra S, Sekhar P. Deriving inertial response from a non-inertial PV system for frequency regulation. In: 2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES); IEEE. 2012. pp. 1-5

[66] Zarina P, Mishra S, Sekhar P. Photovoltaic system based transient mitigation and frequency regulation. In: 2012 Annual IEEE India Conference (INDICON); IEEE. 2012. pp. 1245-1249

[67] García-Gracia M, El Halabi N, Ajami H, Comech MP. Integrated control technique for compliance of solar photovoltaic installation grid codes. IEEE Transactions on Energy Conversion. 2012;**27**(3):792-798

[68] Moutis P, Vassilakis A, Sampani A, Hatziargyriou N. DC switch driven active power output control of photovoltaic inverters for the provision of frequency regulation. IEEE Transactions on Sustainable Energy. 2015;**6**(4):1485-1493

[69] Mishra S, Zarina P, Sekhar P. A novel controller for frequency regulation in a hybrid system with high PV penetration. In: 2013 IEEE Power and Energy Society General Meeting (PES); IEEE. 2013. pp. 1-5

[70] Zarina P, Mishra S, Sekhar P. Exploring frequency control capability of a PV system in a hybrid PV-rotating machine-without storage system. International Journal of Electrical Power & Energy Systems. 2014;**60**:258-267

[71] Ziping W, Wenzhong G, Tianqi G, Weihang Y, ZHANG H, Shijie Y, et al. State-of-the-art review on frequency response of wind power plants in power systems. Journal of Modern Power Systems and Clean Energy. 2017:1-16

[72] Xiong L, Li Y, Zhu Y, Yang P, Xu Z. Coordinated control schemes of super-capacitor and kinetic energy of DFIG for system frequency support. Energies. 2018;**11**(1):103

[73] Jauch C, Hippel S. Hydraulic–pneumatic flywheel system in a wind turbine rotor for inertia control. IET Renewable Power Generation. 2016; **10**(1):33-41

[74] Wen J, Liu J, Long Y, Yao W. Solution to short-term frequency response of wind farms by using energy storage systems. IET Renewable Power Generation. May 2016;**10**:669-678

[75] Gonzalez-Longatt FM, Alhejaj SM. Enabling inertial response in utility-scale battery energy storage system. In: 2016 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia). 2016. pp. 605-610

[76] Tan J, Zhang Y. Coordinated control strategy of a battery energy storage system to support a wind power plant providing multi-timescale frequency ancillary services. IEEE Transactions on Sustainable Energy. 2017;**8**(3):1140-1153

[77] He G, Chen Q, Kang C, Xia Q, Poolla K. Cooperation of wind power and battery storage to provide frequency regulation in power markets. IEEE Transactions on Power Systems. 2017;**32**(5):3559-3568

[78] Bai L, Li F, Hu Q, Cui H, Fang X. Application of battery-supercapacitor energy storage system for smoothing wind power output: An optimal coordinated control strategy. In: 2016 IEEE Power and Energy Society General Meeting (PESGM). 2016. pp. 1-5

[79] Tan Y, Muttaqi KM, Ciufo P, Meegahapola L. Enhanced frequency response strategy for a pmsg-based

wind energy conversion system using ultracapacitor in remote area power supply systems. IEEE Transactions on Industry Applications. 2017;**53**(1): 549-558

[80] Gayathri NS, Kar IN. Smoothing of wind power using flywheel energy storage system. IET Renewable Power Generation. 2017;**11**:289-298

[81] Díaz-González F, Sumper A, Gomis-Bellmunt O, Bianchi FD. Energy management of flywheel-based energy storage device for wind power smoothing. Applied Energy. 2013;**110**: 207-219

[82] Yao J, Yu M, Gao W, Zeng X. Frequency regulation control strategy for PMSG wind-power generation system with flywheel energy storage unit. IET Renewable Power Generation. June 2017;**11**:1082-1093

[83] Zhao H, Wu Q, Hu S, Xu H, Rasmussen CN. Review of energy storage system for wind power integration support. Applied Energy. 2015;**137**:545-553

[84] Díaz-González F, Hau M, Sumper A, Gomis-Bellmunt O. Coordinated operation of wind turbines and flywheel storage for primary frequency control support. International Journal of Electrical Power Energy Systems. 2015;**68**:313-326

[85] Ahmadi R, Ghardashi F, Kabiri D, Sheykholeslami A, Haeri H. Voltage and frequency control in smart distribution systems in presence of der using flywheel energy storage system. IET Conference Proceedings. January 2013: 1307-1307

[86] Ghosh S, Kamalasadan S. An energy function-based optimal control strategy for output stabilization of integrated DFIG-flywheel energy storage system. IEEE Transactions on Smart Grid. 2017; **8**(4):1922-1931

[87] Zhang X, Zha X, Yue S, Chen Y. A frequency regulation strategy for wind power based on limited over-speed de-loading curve partitioning. IEEE Access. 2018;**6**:22938-22951

[88] Moutis P, Loukarakis E, Papathanasiou S, Hatziargyriou ND. Primary load-frequency control from pitch-controlled wind turbines. In: 2009 IEEE Bucharest PowerTech; IEEE. 2009. pp. 1-7

[89] Ma H, Chowdhury B. Working towards frequency regulation with wind plants: Combined control approaches. IET Renewable Power Generation. 2010;**4**(4):308-316

[90] Moutis P, Papathanassiou SA, Hatziargyriou ND. Improved load-frequency control contribution of variable speed variable pitch wind generators. Renewable Energy. 2012;**48**: 514-523

[91] Žertek A, Verbič G, Pantoš M. Optimised control approach for frequency-control contribution of variable speed wind turbines. IET Renewable Power Generation. 2012; **6**(1):17-23

[92] Castro LM, Fuerte-Esquivel CR, Tovar-Hernández JH. Solution of power flow with automatic load-frequency control devices including wind farms. IEEE Transactions on Power Systems. 2012;**27**(4):2186-2195

[93] Vidyanandan K, Senroy N. Primary frequency regulation by deloaded wind turbines using variable droop. IEEE Transactions on Power Systems. 2013; **28**(2):837-846

[94] Alsharafi AS, Besheer AH, Emara HM. Primary frequency response enhancement for future low inertia power systems using hybrid control technique. Energies. 2018; **11**(4):699

[95] Ye H, Pei W, Qi Z. Analytical modeling of inertial and droop responses from a wind farm for short-term frequency regulation in power systems. IEEE Transactions on Power Systems. 2016;**31**(5):3414-3423

[96] Fakhari Moghaddam Arani M, Mohamed YAI. Dynamic droop control for wind turbines participating in primary frequency regulation in microgrids. IEEE Transactions on Smart Grid. 2018;**9**(6):5742-5751

[97] Lertapanon P, Wangdee W. Analysis and modeling of wind turbine generators considering frequency controls. In: 2017 International Electrical Engineering Congress (iEECON); IEEE. 2017. pp. 1-4

[98] Huang L, Xin H, Zhang L, Wang Z, Wu K, Wang H. Synchronization and frequency regulation of DFIG-based wind turbine generators with synchronized control. IEEE Transactions on Energy Conversion. 2017;**32**(3):1251-1262

[99] Deepak M, Abraham RJ, Gonzalez-Longatt FM, Greenwood DM, Rajamani H-S. A novel approach to frequency support in a wind integrated power system. Renewable Energy. 2017; **108**:194-206

[100] Gonzalez-Longatt F, Chikuni E, Stemmet W, Folly K. Effects of the synthetic inertia from wind power on the total system inertia after a frequency disturbance. In: Power Engineering Society Conference and Exposition in Africa; Citeseer. 2012. pp. 9-13

[101] Bonfiglio A, Invernizzi M, Labella A, Procopio R. Design and implementation of a variable synthetic inertia controller for wind turbine generators. IEEE Transactions on Power Systems. 2019;**34**(1):754-764

[102] Liu K, Qu Y, Kim H-M, Song H. Avoiding frequency second dip in power unreserved control during wind power rotational speed recovery. IEEE Transactions on Power Systems. 2018; **33**(3):3097-3106

[103] Morren J, de Haan SWH, Kling WL, Ferreira JA. Wind turbines emulating inertia and supporting primary frequency control. IEEE Transactions on Power Systems. February 2006;**21**:433-434

[104] Díaz-González F, Hau M, Sumper A, Gomis-Bellmunt O. Participation of wind power plants in system frequency control: Review of grid code requirements and control methods. Renewable and Sustainable Energy Reviews. 2014;**34**:551-564

[105] Dreidy M, Mokhlis H, Mekhilef S. Inertia response and frequency control techniques for renewable energy sources: A review. Renewable and Sustainable Energy Reviews. 2017;**69**:144-155

[106] Tarnowski GC, Kjar PC, Sorensen PE, Ostergaard J. Variable speed wind turbines capability for temporary over-production. In: Power & Energy Society General Meeting, 2009. PES'09. IEEE. 2009. pp. 1-7

[107] Keung P-K, Li P, Banakar H, Ooi BT. Kinetic energy of wind-turbine generators for system frequency support. IEEE Transactions on Power Systems. 2009;**24**(1):279-287

[108] El Itani S, Annakkage UD, Joos G. Short-term frequency support utilizing inertial response of DFIG wind turbines. In: 2011 IEEE Power and Energy Society General Meeting; IEEE. 2011. pp. 1-8

[109] Hansen AD, Altin M, Margaris ID, Iov F, Tarnowski GC. Analysis of the short-term overproduction capability of variable speed wind turbines. Renewable Energy. 2014;**68**:326-336

[110] Hafiz F, Abdennour A. Optimal use of kinetic energy for the inertial support

from variable speed wind turbines. Renewable Energy. 2015;**80**:629-643

[111] Kang M, Kim K, Muljadi E, Park J-W, Kang YC. Frequency control support of a doubly-fed induction generator based on the torque limit. IEEE Transactions on Power Systems. 2016;**31**(6):4575-4583

[112] Fernández-Guillamón A, Villena-Lapaz J, Vigueras-Rodríguez A, García-Sánchez T, Molina-García Á. An adaptive frequency strategy for variable speed wind turbines: Application to high wind integration into power systems. Energies. 2018;**11**(6):1-21

[113] Liu K, Qu Y, Kim H-M, Song H. Avoiding frequency second dip in power unreserved control during wind power rotational speed recovery. IEEE Transactions on Power Systems. 2017; **33**(3):3097-3106

[114] Fernández-Guillamón A, Vigueras-Rodríguez A, Gómez-Lázaro E, Molina-García Á. Fast power reserve emulation strategy for VSWT supporting frequency control in multi-area power systems. Energies. 2018;**11**(10):2775(1-20)

[115] Wu Z, Gao DW, Zhang H, Yan S, Wang X. Coordinated control strategy of battery energy storage system and PMSG-WTG to enhance system frequency regulation capability. IEEE Transactions on Sustainable Energy. 2017;**8**(3):1330-1343