Received 20 April 2020; revised 29 July 2020 and 22 September 2020; accepted 3 October 2020. Date of publication 9 October 2020; date of current version 9 November 2020.

Digital Object Identifier 10.1109/OAJPE.2020.3029767

Energy Quality: A Definition

XIAO-PING ZHANG[1] (Fellow, IEEE), AND ZUANHONG YAN[2] (Member, IEEE)

[1]Department of Electronic, Electrical and Systems Engineering, School of Engineering, University of Birmingham, Birmingham B15 2TT, U.K.

[2]China Southern Power Grid Electric Power Research Institute, Guangzhou 510530, China

CORRESPONDING AUTHOR: X.-P. ZHANG (x.p.zhang@bham.ac.uk)

This work was supported in part by the Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/N032888/1 and Grant EP/L017725/1.

ABSTRACT In literature, variations and distortions, and interruptions of voltages (or voltage waveforms) and currents (or current waveforms) have been considered in the framework of power quality (or voltage quality). With the massive penetration of renewable energy into power systems, variations including fluctuations and intermittences of output powers of these renewable sources are of great concerns. It is evidenced that with the high penetration of renewable energy, variations of renewable energy have increased the costs of UK's balancing markets by 39% in this spring and summer (NGESO, 2020). Therefore, there are needs to introduce a technical framework, namely, 'energy quality' to (a) define the quality of power waveforms; (b) propose measures/indices to characterize the variations (fluctuations and intermittences) of powers and power flows; (c) present methods to improve energy quality. Finally, research directions of energy quality are highlighted to encourage more R&D as well as international collaborations in terms of standards and grid code developments.

INDEX TERMS Power quality, voltage quality, energy quality, energy filter, energy filtering, waveforms, renewable energy, wind energy, wave energy, solar energy, variations, fluctuations, intermittency, average power, energy spectrum, total power distortion (TPD), standard power deviation (SPD), coefficient of variation, standard deviation, grid code, energy storage, power system oscillation, frequency response, frequency control.

I. INTRODUCTION

ELECTRICITY would progressively become the central energy carrier, growing from a 20% share of final consumption to an almost 50% share by 2050, and renewable power would be able to provide the bulk of global power demand (86%) economically [1]. With the massive penetration of renewable energy into power systems, power variations including fluctuations and intermittences are of great concerns. Large power variations ask for more capacity redundancy of transmission equipment and cause problems in the power system, including forced oscillation, thermal recursion, frequency and voltage disturbances and increase stability risks. When renewable power is injected into a weak grid, active power variation can also lead to voltage instability at the point of common coupling. For this reason, smoothed power flows with less fluctuations or intermittences not only help achieve power balance and frequency stability, but also help enhance voltage stability in weak grid.

With the rapid development of renewable energy and power electronics based power sources, it is necessary to quantitatively measure and set requirements on the variations of power flows. Although Power Quality is a well defined concept to measure and set requirements on a voltage and current waveform, so far, there is no such a counterpart to describe the quality of a power waveform. Therefore, there are needs to introduce a technical framework, namely, 'energy quality' [2] to define the quality of power waveforms of these renewable energy sources. In the past, quite some research activities have been conducted to test the frequency response capability, ramping rate or limits to the rate of change of power levels of machines with different capacity in different time scales, power balancing of power systems with renewable energy sources [18], [19], [23]–[26]. These works are in line with the scope of this paper, which are in echo with the development of a new framework of energy quality.

UK's electricity system is experiencing lower inertia and larger, more numerous losses than ever before [26], and hence

National Grid Electricity System Operator (NGESO) has proposed that faster acting frequency response products are needed because system frequency is moving away from 50Hz more rapidly as a consequence of imbalances. Over the next few years, NGESO aims to deliver a new suite of faster-acting frequency response services to support operations as the electricity system is decarbonized and to ensure that these new services enable a level playing field for all technologies that will mitigate this risk. Coinciding with the reduced demand due to the COVID-19 pandemic and high level of renewables output, the GB electricity system has seen a balancing cost of £ 718 million this spring and summer 2020, which is 39% higher than the expected cost in this period. It is evidenced that with the high penetration of renewable energy, variations of renewable energy have increased the costs of balancing markets. This required the NGESO to take a large number of actions to balance the system and ensure system operability. In this situation, methods and tools are needed to characterize, measure and control the variations and hence reduce the balancing costs.

China is the world's largest renewable power capacity installer and renewable energy producer, the largest manufacturer and exporter of wind turbines and solar PV panels, and continues rapid growth in renewable energy. The technical requirements of renewable power integration in China are mainly given by two key national standards: GB 38755-2019 "Guidance of Power System Security and Stability" [18] and GB/T 19963-2019 "Technical requirements of windfarm integration into power system" [19]. In [18], the power system should be with sufficient flexibility to achieve power balance, and renewable power stations should increase their ability of active control of real power, by coordinated or equipped with gas power stations, pumped-hydro storage, battery storage and other flexible resources when necessary. Suppressing and monitoring measures should be taken on renewable power stations and connected transmission lines with risks of sub/super oscillation. In addition, under normal operation, the per unit static limit of real power transfer based on the average power should be between 1.15-1.20. In [19], it has been proposed that when the active output power of a windfarm is above 20% of rated power, the windfarm should achieve continuous and smooth control of its active output power. Also there are limits to the change of power level of windfarms within 1 min and 10 min, and the change of power level should meet the demands of power system stability. Furthermore, the suggested values of limits of the change of power level of windfarms in different time scales are specified. Both of these have been recently upgraded in 2019 to meet new technical characteristics of the power system with increasing penetration of renewables. These upgraded standards (e.g. limits to the rate of change of power levels of machines with different capacity in different time scales) are very relevant to the aspects of energy quality discussed in this article, but not yet fully extended and presented in the framework of energy quality. Further developments of grid code/standards based on the framework of energy quality to systematically harmonize contradictions between the uncertainty of renewable energy and the security stability requirements of the power system are encouraged.

In [23], the challenges caused by the integration of wind energy and the proposed solutions methodologies have been reviewed. Among the various challenges, the generation uncertainty, fault ride-through capability, socioeconomic, environmental, and electricity market challenges have been reviewed, which can be addressed in the framework of energy quality. The solutions used and proposed methods to mitigate the impact of these challenges, such as energy storage systems, wind energy policy, and grid codes reviewed and discussed are very relevant to solutions for energy quality improvements.

In [24], [25], grid codes about wind power integration around the world including grid codes of Denmark, Ireland, the U.K., Germany, Spain, China, the U.S., Canada, and other countries have been reviewed and compared. The most important aspects of these grid codes are concerning frequency regulation, fault ride through, ramping rate, market balancing, etc.

From the above description, it is clear that power/power flow waveforms from renewable energy sources are of great interest in terms of technical dynamic response capability/performance and market operations and system planning, which also have impact on the operation, control and security of power systems. The nature of these technical issues is related to the time dependent and locational related power/power flow waveforms of power sources (in particular, renewable energy sources), power demands and power flows, and these are better to be measured, characterized and evaluated in the framework of energy quality.

This paper proposes measures/indices to characterize the variations including fluctuations and intermittences. In addition, if there are energy quality issues, what are the methods to improve energy quality? Are there international standards needed?

The paper is organized as follows. The concept of energy quality is defined in Section II, which also shows the differences between power quality and energy quality and hence explains why energy quality is needed. Energy quality problems are classified in different time scales in Section III. The measures to characterize the variations, fluctuations and intermittences in the framework of energy quality are proposed in Section IV. The methods of improving energy quality are discussed in Section V while the needs for international standards and power grid code developments are highlighted in Section VI. Finally conclusions are drawn and future research directions of energy quality are highlighted to encourage more R&D as well as international collaborations in terms of standards and grid code developments.

II. DEFINITION OF ENERGY QUALITY

In literatures, variations and distortions of voltage and current waveforms have been considered in the framework of power quality (or voltage quality) [3]–[5], [20], [27].

With the massive penetration of renewable energy into power systems, variations including fluctuations and intermittences of output powers from these renewable sources are of great concerns. The initial concept of ''energy quality'' and differences between ''power quality'' and ''energy quality'' were proposed in [2]:

'Power Quality' is mainly concerned with the quality of voltage and current waveforms as shown in [3]–[5], [20], [27], while 'Energy Quality' is mainly concerned with the quality of power or power flow waveforms vs time. Power quality is different from the proposed energy quality in the paper in different aspects as follows.

A. DIFFERENT PRIMARY CONCERNS/FOCUSES

The primary concerns/ focuses of power quality are mainly voltage and current wave forms [3]–[5], [20], [27], which are represented largely in harmonic voltage and current phasors. Powers in the context of power quality are very much related to distorted voltage and current waveforms [28] and it is clear that the focuses are voltage and current waveforms. While the primary concerns/ focuses of energy quality are mainly power and power flow waveforms and their variations over time.

B. DIFFERENT MOTIVATIONS

The fundamental motivation for development of Energy Quality was particularly associated with the increasing penetration of random and fluctuating renewable energy sources [18], [19], [23]–[26]. In this situation, we need a new framework to measure the fluctuations of powers and power flows and value the low fluctuating powers and power flows in electricity market environments. So the fundamental motivation for energy quality is that it allows electricity market operators to characterize the fluctuations of powers and power flows easily and hence price the services provided by different fluctuating renewable energy sources in the market environments, and this means that the fluctuations of powers and power flows in the framework of energy quality can be easily implemented in the electricity market environments as ancillary services. While power quality is mainly considered in the technical framework and it is difficult to be considered in the electricity market environments.

C. DIFFERENT DRIVERS

The major driver for energy quality is very much associated with a new framework need for dealing with the fluctuations and deviations of power or power flows vs time in the market environments. While in market operations, the measures of power and power flow fluctuations are in favor of the concept of energy quality. However the primary driver for power quality is very much associated with the supply quality in terms of voltage and current waveforms, which is not particular related to fluctuations of renewable energy generation. It is evidenced that in the IEEE standard, neither renewable energy generation nor power/power flow fluctuations were mentioned [28]. Without the fluctuating renewable energy generation sources, the concept of energy quality would not be needed.

D. ARE POWER QUALITY AND ENERGY QUALITY CORRELATED?

1) In the conventional power system, there was very little share of renewables. In such a system, although power quality issues are raised here and there due to concerns in voltage/current waveforms, the active power flows are very much consistent, steady and controllable at both the generation and demand sides. So, for the traditional power system, even though there are serious ''power quality'' problems, the ''energy quality'' is usually pretty good.
2) Comparatively, when power is mostly generated by renewable energy sources, even the system has a perfect power quality with perfect sinusoidal voltage/current waveforms and there are no harmonics, it could have a very poor Energy Quality since the active power generated by wind and solar is intermittent and heavily fluctuating.
3) In other words, power quality and energy quality are not directly correlated. The two frameworks have different primary concerns/focuses, drivers and motivations. It should be pointed out that both frameworks could not cover everything by themselves, and both concepts are needed and useful to characterize the operations and performances of future renewable energy dominated power systems. The two frameworks will help each other and bring strength and prosperity of our power & energy system subjects.

E. THE PRACTICES AND DEVELOPMENTS

The practices and developments in power & energy industry indicate that power balancing of power systems with renewable energy sources have been considered in different time scales to deal with the variations of high penetration of renewable energy [18], [19], [23]–[26]. For example, requirements of the rate of power variations in different time scale were given in some recently updated grid codes [18], [19]. These works are in echo with the development of a new framework of energy quality.

F. THE PROPOSED DEFINITION

The preliminary ideas about the ''energy quality'' were presented in an IEEE conference [21] and CIGRE meeting [22], respectively. The feedback received from the power engineering communities was positive and encouraging.

This paper is to generalize this concept and provide the following definition of ''Energy Quality'':

(1) Energy Quality is mainly concerned with the quality of power flow waveform in power networks, output power waveforms of power generation sources as well as power demand waveforms (profiles) over time.

(2) The difference between 'Power Quality' and 'Energy Quality' is that the former is mainly concerned with

the quality of voltage and current waveforms while the later is mainly concerned with the quality of power flows, power generation and power demand waveforms (or profiles).

(3) 'Energy Quality', which is time dependent and locational related, can be measured at different locations in different time scales from seconds to long-term period. It characterizes time dependent locational power waveform (or profile) behaviors so as to value their behaviors and/or services in regarding to their time dependent and locational related characteristics and performances. And hence Energy Quality is very much related to the characterization of frequency and power variations/deviations and power balancing in terms of technical performances and market values.

III. CLASSIFICATIONS OF ENERGY QUALITY

Energy Quality can be measured in different time scales such as seconds, minutes, hours and days, years, etc to characterize power waveform behaviors so as to value their behaviors and/or services in regarding to time dependent features. According to the different time scales of energy quality problems, they may be considered to be:

(1) Short-term power variations: This considers the power waveforms typically in the time scale of seconds (or even milliseconds), up to minutes. Hence this will look at transients of power waveforms. Fig. 1 shows the wind output powers of two DFIGs when power fluctuations in seconds and variations in minutes are caused due to the mechanical oscillation and change of wind speed. The period of natural changes of wind speed and mechanical oscillations of wind turbine tower is in this time scale. This may cause forced oscillations in power system [6].

(2) Mid-term power variations: This considers the power waveforms in the time scale of minutes, up to hours. This is related to spinning reserve and non-spinning reserve time frame.

(3) Long-term power variations: This considers the power waveforms in the time scale of half hour, up to days or a week, or a month, or up to a year. As an example, Fig. 2 shows the regional solar power generation in six consecutive days during summer and winter respectively where the intermittency is also demonstrated. This time scale is particularly related to electricity market operations [7]. The output power waveforms and power demand waveforms can be split into 48 half-hour energy blocks (or even shorter energy blocks of each 15-min) and these energy blocks will demonstrate different values during the day. The basic principle is that these energy blocks are more valuable during the peak national demand periods than those energy blocks during the minimum national demand periods. The UK's national peak demand pricing is just a simple example of such an approach. With the differentiation

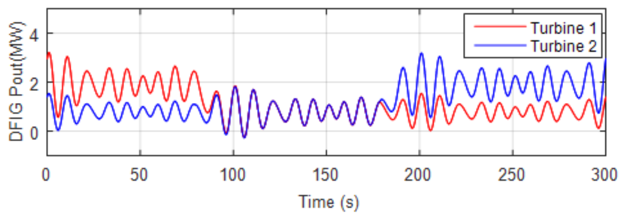

FIGURE 1. **Power variations of two DFIGs.**

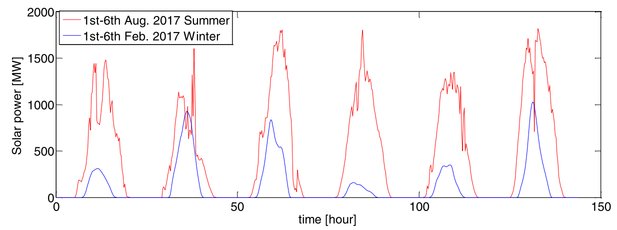

FIGURE 2. **Regional solar power generation in six days during summer and winter.**

of these energy blocks in the time scale of either each half hour or each 15-min (or even shorter), energy sources/demands/energy storage services can be valuated/priced based on waveforms (or profiles) during the day. It should be mentioned that in terms of pricing of electricity, primary consideration is kWh though under some conditions kVARh should be considered. For example, in the UK, excess kVArh charges apply when a half hourly (HH) metered LV or HV designated site's reactive power consumption (measured in kVArh) exceeds 33% of the active power (measured in kWh).

(4) Very long-term power variations: This considers the power waveforms in the time scale of from a year, up to 10-20 years. This time scale is particularly related to power system planning.

Power variations consist of power fluctuations and power intermittences. Power fluctuations cover short-term power variations and mid-term power variations in the time scale from seconds to hours. Intermittences cover long-term and very long-term power variations in the time scale from days to years.

IV. MEASURES AND CHARACTERIZATION OF ENERGY QUALITY

In order to characterize energy quality, measures/indices are introduced to characterize energy quality. Key aspects of energy quality (but not limited with) include: average power level, energy spectrum, total power distortion (*TPD*) and standard power deviation (*SPD*).

A. AVERAGE POWER/AVERAGE POWER LEVEL

The first aspect of energy quality, the average power (or average power level) for a power waveform within a time period (or a time window) of T, is defined mathematically as

$$\bar{P}_T(t) = \frac{1}{T}\int_{t-T}^{t} p(\tau)\cdot d\tau \tag{1}$$

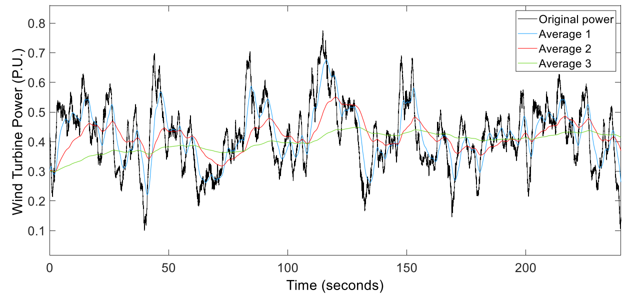

FIGURE 3. Wind power waveform and 3 average waveforms.

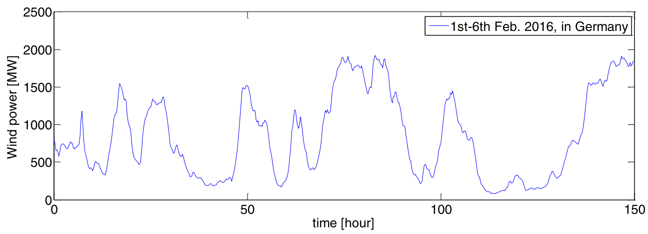

FIGURE 4. Average power waveform with a time window of 15-min.

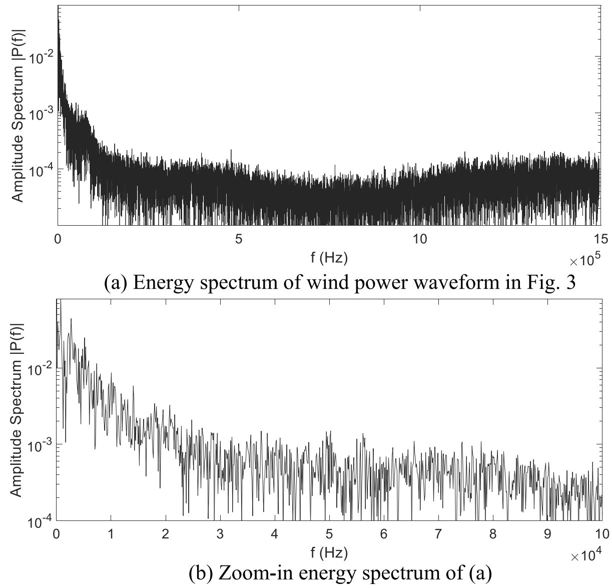

FIGURE 5. Energy spectrum of wind power waveform.

where $p(\tau)$ is the output power waveform vs time. The energy quality can be measured by the average power and standard power deviation to be introduced later in this section.

Fig. 3 shows the fast variations of wind turbine output power waveform and 3 average power waveforms with 3 different time windows (scales). The sampling time for the original wind power measurements is $\Delta t = 9$ ms, while the 3 time windows for average power waveforms, which are referred to as average 1, average 2 and average 3, respectively in Fig. 3, are set to $T = 2\Delta t$, $T = 10\Delta t$, $T = 50\Delta t$, respectively. The original measured power waveform is in black color. It can be seen that as the time window increases, the average power waveform is flattened.

For the purpose of characterization of the intermittency of a renewable energy source, T is usually set in the range minutes to hours, and of course this depends on the needs of applications. Fig. 2 shows the average power waveform with a time window of 15-min. The zero average power level means the renewable power source is not available at that time, for instance, solar power generation at night. The power level can characterize the availability of a power source, and it is desirable to maintain the power level as close as possible to its rating power of 1.0 p.u.. Large variations will certainly bring burdens to power grid operations and may need additional equipment and generation capacity to compensate the variations, for example, energy storage systems may be needed to smooth the variations.

It raises problems to the balance of power systems when the power level of large-scale energy sources changes too fast. Actually, technical requirements to limit the rate of change of power level have already been proposed in some latest standards and grid codes. More details are discussed in Section VI.

B. ENERGY SPECTRUM

The second aspect of energy quality is the frequency domain characteristics of power waveforms, which is described by the magnitude spectrum of the Fourier transform of them, called Energy Spectrum. It is presented in mathematical formulation as follows:

$$F_T(\omega, t) = \left| \int_{t-T}^{t} p(\tau) e^{-j\omega\tau} d\tau \right| \tag{2}$$

The energy spectrum $F_T(\omega, t)$ is a measure of the power waveform over a finite period of time T. It indicates how the energy carried by a power waveform over a period of time is distributed in the frequency domain. Fig. 5 shows the energy spectrum of wind power waveform shown in Fig. 3, which indicates the rich wide range of frequency spectrum. The energy spectrum is important and useful since the frequency domain characteristics of a power waveform are closely related to many technical issues with the power system, such as frequency response/regulation/reserve, power balancing for market operations, power system planning, forced oscillations [8], energy storage dimensioning [9], [10], etc.

C. TOTAL POWER DISTORTION (TPD) OF CONTINUOUS POWER WAVEFORM

For periodic power fluctuation and a power fluctuation within a time duration of T, the fluctuation can be described by the Total Power Distortion (*TPD*), which can be considered as an extension of the conventional concept, the total harmonic distortion (*THD*), to the waveforms of output powers from renewable energy sources, power demands, and power flows in power grids. It is well known that *THD* of a voltage is defined, mathematically, as

$$THD = \frac{\sqrt{\sum_{k=2}^{\infty} V_k^2}}{V_1} = \sqrt{\frac{\lim\limits_{T\to\infty} \frac{1}{T}\int_{t-T}^{t} v(\tau)^2 d\tau}{V_1^2} - 1} \tag{3}$$

where V_k is the rms value of the k-th order harmonic of the voltage waveform, V_1 is the rms value of the fundamental component, and $v(\tau)$ is the voltage waveform. The period T cannot go to infinity but could be set to a large value. For a periodic voltage/current waveform, its frequency spectrum is discrete, in which the fundamental frequency component is the desired component and the other high-order harmonics are the distortion.

It should be pointed out here:

(1) In most cases, a power waveform may not be periodic, thus the discrete frequency spectrum is replaced with a continuous power spectral density.
(2) For an ideal power waveform, its average power level is to be a DC constant, and all the other harmonics, regardless of frequencies, are regarded as part of the distortion, which provides zero long-term output power.

Considering the above, the Total Power Distortion (*TPD*) of a power waveform in a period time of T is defined, mathematically, as

$$TPD_T(t) = \frac{\sqrt{2\int_{0^+}^{\infty} S_T(\omega,t)\,d\omega}}{\bar{P}_T(t)} \tag{4}$$

where

$$S_T(\omega,t) = \frac{1}{T}\left|\int_{t-T}^{t} p(\tau)e^{-j\omega\tau}d\tau\right|^2 \tag{5}$$

where $S_T(\omega,t)$ is the power spectral density of the power waveform.

According to the Parseval's theorem of the power spectral density, the integration of spectral density and frequency is equal to the integration of the square of the waveform to time, so it can be derived that

$$2\int_{0^+}^{\infty} S_T(\omega,t)\,d\omega = \int_{-\infty}^{\infty} S_T(\omega,t)\,d\omega - \int_{0^-}^{0^+} S_T(\omega,t)\,d\omega = \frac{1}{T}\int_{t-T}^{t} p(\tau)^2\cdot d\tau - \bar{P}_T^2(t) \tag{6}$$

Substitute (5) into (4), we have

$$TPD_T(t) = \sqrt{\frac{\frac{1}{T}\int_{t-T}^{t} p(\tau)^2\cdot d\tau}{\bar{P}_T^2(t)} - 1} = \sqrt{\frac{T\cdot\int_{t-T}^{t} p(\tau)^2\cdot d\tau}{\left(\int_{t-T}^{t} p(\tau)\cdot d\tau\right)^2} - 1} \tag{7}$$

Equation (7) gives a useful method to calculate *TPD* from the real-time measuring of power flow waveforms, power out waveforms from energy sources and power demand waveforms. A larger *TPD* indicates a more significant fluctuation around the average power level, and in other words, the power waveform is more distorted from its average power level.

In industrial applications, *TPD* could be noted as total demand distortion (*TDD*) and total generation distortion (*TGD*) in particular at the demand side and generation side, respectively. For example, *TGD* is useful to measure the fluctuations and intermittences of solar, wind and wave power generation, and *TDD* is useful to measure those of massive scale of charging power of electric vehicles. The standards and indications of *TGD* and *TDD* would be different since equipment and application scenarios at generation and demand sides are of vital differences, but they share the same mathematical basis.

D. COEFFICIENT OF VARIATION c_V AND STANDARD DEVIATION σ

In statistics, the coefficient of variation c_v is defined as the ratio of the standard deviation σ to the mean value [11].

$$c_v = \frac{\sigma}{\mu} = \frac{\sqrt{E(X^2)-\mu^2}}{\mu} = \sqrt{\frac{E(X^2)}{\mu^2} - 1} \tag{8}$$

where $E(X^2)$ is the mean value of the squares of data. For the power waveform as a continuous time function from (t-T) to t, we have

$$E\left(X^2\right) = \frac{1}{T}\int_{t-T}^{t} p(\tau)^2\cdot d\tau \tag{9}$$

$$\mu = \bar{P}_T(t) = \frac{1}{T}\int_{t-T}^{t} p(\tau)\cdot d\tau \tag{10}$$

$$\sigma = \sqrt{E(X^2)-\mu^2} \tag{11}$$

Substitute (8), (9) and (10) into (7), it can be found that *TPD* and c_v are actually the same, and hence we have

$$TPD_T(t) = c_v = \frac{\sigma}{\mu} = \frac{\sqrt{E(X^2)-\mu^2}}{\mu} = \sqrt{\frac{E(X^2)}{\mu^2} - 1} \tag{12}$$

It should be pointed out here that the Standard Power Deviation (*SPD*) and the average power can together characterize energy quality of power waveforms in terms of the severity of fluctuations or intermittencies.

E. TPD OF DISCRETE DATA OF POWER

In previous sections, the *TPD* of continuous power waveform has been proposed to measure and characterize the power fluctuation within a period of time T. When measuring and characterizing power waveform over a long time duration, it is inconvenient and unusual to describe the power in a continuous time function, but it would be more likely presented in a group of sampled, averaged, and discrete data. Therefore, it is necessary to derive the discrete expression of *TPD* so as

TABLE 1. Comparison between energy quality and power quality.

	Power quality analogy	Energy quality	Continuous form	Discrete form
Magnitude	Voltage /current magnitude or RMS value	Average Power level	$\bar{P}_T(t) = \frac{1}{T}\int_{t-T}^{t} p(\tau)\cdot d\tau$	$\bar{P}_N = \frac{1}{N}\sum_{i=1}^{N} p_i$
Harmonics	Voltage Spectrum	Energy Spectrum	$F_T(\omega,t) = \left\lvert\int_{t-T}^{t} p(\tau)e^{-j\omega\tau}d\tau\right\rvert$	$F_T(\omega,t) = \left\lvert\sum_{n=1}^{N} p_n e^{-j\omega n}\right\rvert$
	THD	TPD	$TPD_T(t) = \sqrt{\frac{T\cdot\int_{t-T}^{t} p(\tau)^2\cdot d\tau}{(\int_{t-T}^{t} p(\tau)\cdot d\tau)^2} - 1}$	$TPD_N = \sqrt{\frac{N\cdot\sum_{i=1}^{N} p_i^2}{(\sum_{i=1}^{N} p_i)^2} - 1}$

to use *TPD* to characterize the power intermittency. As has been shown in Section IV.C, *TPD* is equal to the coefficient of variation c_v. Thus, for a group of discrete power data $\{p_i \,|i = 1, 2, \ldots, N\}$, the *TPD* is presented in the discrete form as

$$TPHD_N = \sqrt{\frac{\frac{1}{N}\sum_{i=1}^{N} p_i^2}{(\frac{1}{N}\sum_{i=1}^{N} p_i)^2} - 1} = \sqrt{\frac{N\cdot\sum_{i=1}^{N} p_i^2}{(\sum_{i=1}^{N} p_i)^2} - 1} \tag{13}$$

F. COMPARISON BETWEEN TPD OF ENERGY QUALITY AND THD OF POWER QUALITY

Comparison between *TPD* of Energy Quality and *THD* of Power Quality is summarized in Table 1.

G. ENERGY QUALITY APPLICATION: CASE STUDIES

Two case studies are presented here as examples of the application of Energy Quality indices. Real data of renewable power generation is presented and its energy quality is analyzed quantitatively.

In the first case, Fig. 6 shows the wind power generation of a Germany wind farm connected to 50Hertz transmission grid in four different days. The power data was averaged and sampled every 15min. Table 2 presents the energy quality indices, from which we could see this wind farm generated most power on the 4$^{\text{th}}$ of July with the highest average power level on that day. Standard Power Deviation (*SPD*) represents the absolute volume of fluctuations, and *TPD* represents the relative volumes of it. The wind power generation on the 4$^{\text{th}}$ of July had the largest *SPD* so it put the biggest burden on transmission capacity to tolerate power fluctuation. The wind power generation on the 2$^{\text{nd}}$ of July had the largest *TPD*, which means it was relatively the most fluctuating power flow among these four.

TABLE 2. Energy quality indices of wind power generation in four day.

Day (in 2020)	Jul 01	Jul 02	Jul 03	Jul 04
Average Power level （MW）	4.60	2.47	2.42	6.80
Standard Power Deviation （MW）	1.37	0.99	0.57	1.39
TPD	0.30	0.40	0.23	0.21

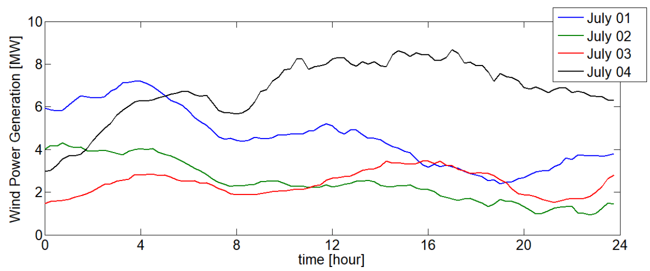

FIGURE 6. Power flows of a Germany wind farm in four different days.

TABLE 3. Energy quality indices of wind power generation under different sampling rate.

Sampling time	every 5s	every 1min	every 25min
Average Power level （MW）	12.61	12.61	12.61
Standard Power Deviation （MW）	0.85	0.75	0.67
TPD	0.068	0.059	0.053

In the second case, Fig. 7 shows the power generation of a wind farm in Spain under different sampling rate of the power data. Table 3 presents the energy quality indices in this case. Results show that the average power level is irrelevant with the sampling rate, but *SPD* and *TPD* of a power flow would decrease as the sampling time becomes longer, because power variations with a bandwidth higher than the sampling rate would be removed by the sampling. For this reason, it is noted that the requirements of *SPD* and *TPD* should be proposed in regard to the given sampling rate of power data. The selection of the sampling rate would better match the time scale of power flows which is of interest. For example, when the primary frequency regulation is considered, the time scale is about 1s to 30s and the desired sampling time would be no more than 1s to deliver enough detailed information about power variation during transients. In other cases when long-term electricity market behaviour is considered, a very high sampling rate is not necessary.

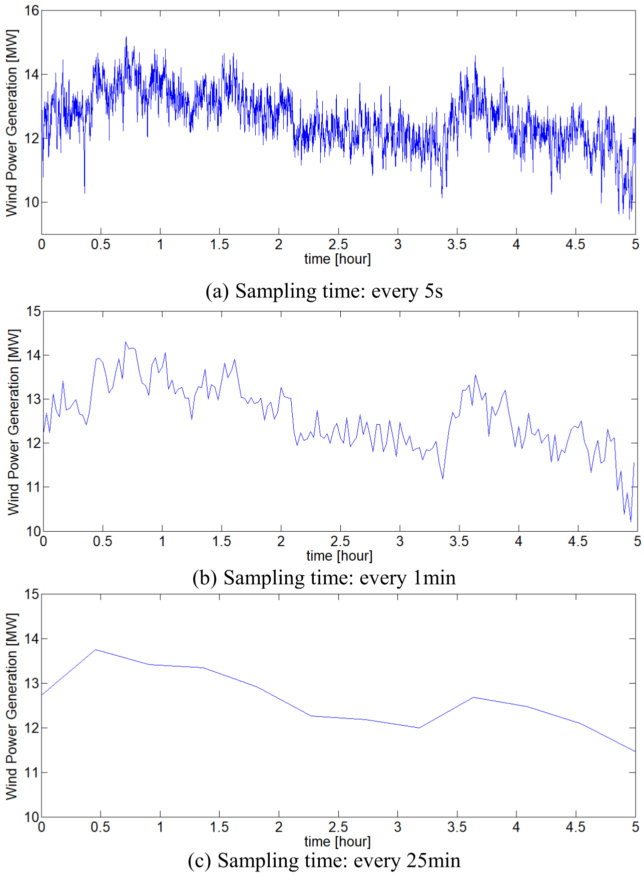

FIGURE 7. Wind power generation of a wind farm in Spain under different sampling rate.

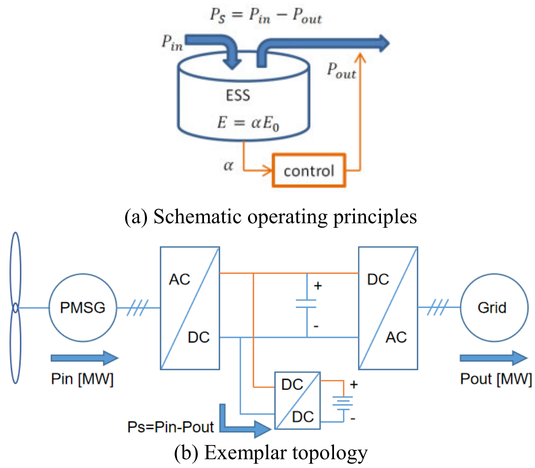

FIGURE 8. Operating principles and exemplar topology of SEF.

V. METHODS FOR IMPROVING ENERGY QUALITY

There are two causes of energy quality problems, both of which are mainly raised by the increasing penetration of renewable energy sources. Firstly, it comes from the uncertainty of renewable power generation, which brings stochastic change of power level and fluctuations and intermittences of power flows. Secondly, it comes from the control system stability and electromagnetic transients of renewable power generators, which brings risks of power oscillations in a large frequency range of 1-1000 Hz [12]–[14], called wide frequency range oscillation. The former problem is based on normal operations of renewable energy sources, while the latter is more often triggered by faults and significant disturbances. Accordingly, energy storage control and power oscillation damping control are two approaches to improve energy quality.

Besides the power oscillation damping control in different frequency range, in this section, we introduce a group of energy storage systems called Energy Filters to improve the energy quality in power system. By these examples, we encourage more studies and applications of different forms of energy storage in power system to make it more reliable, flexible and friendly to renewable integration.

In power systems, power filters are conventionally used to improve the power quality of voltages and currents. By contrast, energy filters are basically either energy systems with energy filter control capability or special energy storage systems with energy filter control to improve the energy quality of power flows. For instance, these filters could be developed based on SMES, flywheels, ultracapacitors, and batteries, independently from its control methods. Like filters used in signal processing, the energy filters also have their transfer functions, cut-off frequencies and Bode plots.

A very brief introduction of different kinds of energy filters is given below and more details are presented in [2], [15]. High-order and adaptive energy filters can be achieved based on very much the same hardware structures but only by changing the control methods and control objectives.

A. SERIES ENERGY FILTER (SEF)

A series energy filter can achieve direct control of the output power. This feature makes it different from the parallel energy filter. The output power of a SEF is filtered and separated from the fluctuating input power flow by the energy storage device and control. Fig. 8 shows the operating principles and exemplar topology of SEF where P_{in} and P_{out} are the input and output power of SEF, P_s is the output power from the energy storage system, and E_0, E and α are the energy storage capacity, actual energy storage and charging status, respectively. The exemplar topology is a PMSG based wind power generation system with full rated conversion and battery storage. The battery storage on the DC link is under SEF control and it smooths the output power to the grid when the input wind power is heavily fluctuating. This exemplar case is a SEF because the output power is directly controlled by the grid-side converter.

Fig. 9 shows an example case of the input and output power of a SEF when the input frequency equals to the cut-off frequency of the first-order SEF, in which there is a 45 degree phase shift between the input and output power as indicated by the filter theory.

There two features for the SEF. The first feature of the SEF is that it directly controls its output power. The second

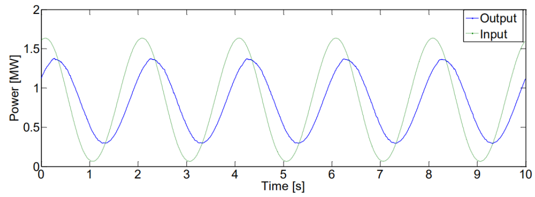

FIGURE 9. **The output power P_{out} and input power P_{in} of the SEF $f_{in} = f_{cut}$.**

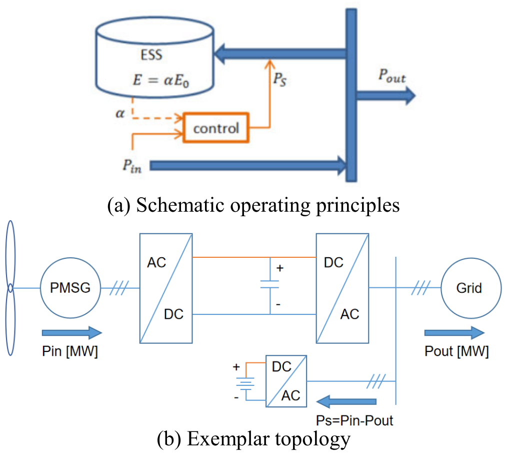

FIGURE 10. **Operating principles and exemplar topology of PEF.**

feature and also a big advantage is that it doesn't need to measure its input power. These two features are important when compared with the parallel energy filters. A SEF is virtually operated as a low-pass filter of power flows with its cut-off frequency. The high-frequency fluctuation of the unknown input power is filtered out while the output power is smoothed.

B. PARALLEL ENERGY FILTER (PEF)

By contrast with the SEF, the output power of a PEF is not directly controlled and the input and output power are not separated but more in coherence. Also, the input power must be measured in order to control a PEF. The smoothed output power could be regarded as a summation of the fluctuating input power and the compensating power from the EES, both of which are connected to the power bus in parallel. Fig. 10 shows the topology and an exemplar case of PEF. The exemplar case of PEF is a parallel system of wind power generation and battery storage interfacing with the power grid as shown in Fig. 10 (b). The variables P_{in}, P_{out}, P_s, E_0, E and α are the same as those in Fig. 8.

Fig. 11 shows the simulated output and input power of a PEF. Since in this case the frequency of the input sinusoidal power flow is 10 times of the cut-off frequency of the PEF, the output power flow is much more smoothed than that in the former case shown in Fig. 9.

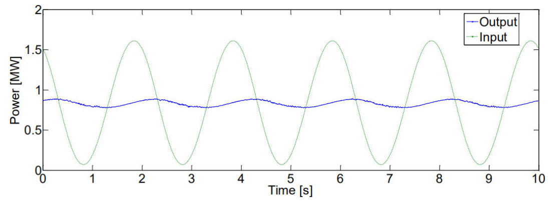

FIGURE 11. **The output and input power of the PEF f_in = 10f_cut.**

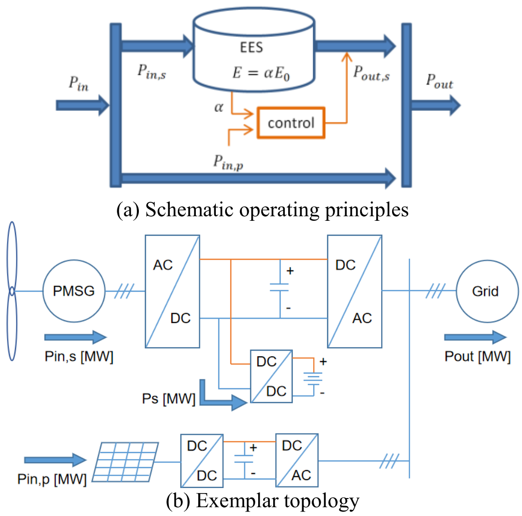

FIGURE 12. **Operating principles and exemplar topology of HEF.**

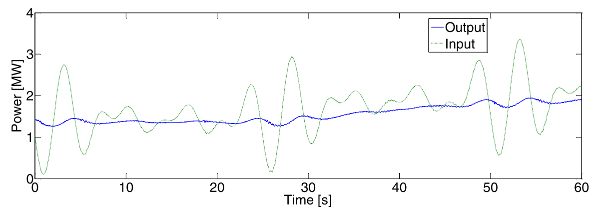

FIGURE 13. **The total output power Pout and input power Pin of the first-order HEF.**

C. HYBRID ENERGY FILTER (HEF)

For the SEF and PEF, the fluctuating input power can go through only one pathway. Comparatively, an HEF has two pathways for the input power. Fig. 12 shows the topology and an exemplar case of the HEF where $P_{in,s} - P_s + P_{in,p} = P_{out}$. Fig. 13 shows an example of the total input and output power of a first-order HEF, and as can be seen the fluctuating power flow is very much smoothed after the energy filter.

The exemplar case of HEF is shown in Fig. 12(b). It consists of a wind power generation unit with DC-link battery storage and a solar power generation unit. It could be taken as a mix of SEF and PEF. In this case, the wind power generation unit is the series pathway while the solar power generation unit is the parallel pathway. As a hybrid, the HEF takes advantages from both the series and parallel forms, which has the most powerful topology and control capability among the three energy filters in this paper.

D. ENERGY FILTERS AND SUPPRESSION OF POWER OSCILLATIONS

Enormous studies have been done on power oscillation damping control. In the past, this is a problem of system angular stability in the first place, yet it also deserves a place in the framework of energy quality. Unlike stochastic renewable power flows continuously injected by external sources, power oscillation is triggered by faults or significant disturbances of power system usually when parameters of components or controllers of power electronics devices are mismatched. Although not all power oscillations lead to system instability, a lightly damped oscillation can lead to malfunction of the system protection and should be effectively damped.

Traditionally Power System Stabilizer (PSS) of synchronous generators is a classical solution to inter-area and low-frequency oscillations [16]. In the modern power system, damping control of sub/super synchronous oscillation and high-frequency oscillation is mainly based on power electronics devices, including FACTS, HVDC, power converters of renewable power generators, energy storage and so on. Latest studies indicate that control parameters of renewable power generators have significant impacts on the risks of wide frequency range oscillations [17]. In a renewable rich power system in the future, advanced power oscillation damping control and methods to optimize the control parameters to minimize the oscillation risks are expected. Energy filters, which are primarily proposed for smoothing power waveforms of renewable energy sources, can have the great potential in the damping of power system oscillation of wide frequency range. In addition, with the application of energy filters, the fluctuations of power waveforms can be smoothed and minimized so as to reduce the risk of system oscillations.

VI. THE NEEDS FOR INTERNATIONAL STANDARDS AND GRID CODE DEVELOPMENTS FOR ENERGY QUALITY

In the past, quite some research activities have been conducted to test the frequency response capability, ramping rate or limits to the rate of change of power levels of machines with different capacity in different time scales, power balancing of power systems with renewable energy sources [18], [19], [23]–[26].

Power waveforms from renewable energy sources are of great interest in terms of technical response capability/performance and market operations and system planning, which also have impact on the operation, control and security of power systems. The nature of these technical issues is related to the time dependent and locational related power waveforms of power sources (in particular, renewable energy sources), power demands and power flows, and these are better to be measured, characterized and evaluated in the framework of energy quality. The following R&D activities are needed:

(1) Coherent measures/indices in the framework of energy quality in terms of average power, standard power deviation and total distorted power at different time scales will need to be developed, and hence standards and grid codes will need to be developed accordingly.

(2) Time dependent location related energy quality modeling and analysis of renewable power waveforms are needed to assess the value of energy provided by renewable energy sources and hence improve the efficiency of energy market operations.

(3) Time dependent location related energy quality modeling and analysis of renewable power waveforms are needed to assess the value of energy provided by renewable energy sources and hence improve the accuracy of power system planning.

(4) A unified method in the framework of energy quality is needed to test the fast dynamic active power/frequency response capability, price the frequency response services under competitive market operations. In addition, ramping rate of power and rate of change of power and frequency needs to be specified.

(5) Energy quality standards and grid codes are needed to reduce power fluctuations of renewable energy sources and hence reduce the risks of power system oscillations.

(6) Synchronized measurement, monitoring and control systems and computing tools for energy quality are needed. Certainly PMUs can be used and extended for energy quality purpose straight way.

VII. CONCLUSION

The increasing penetration of renewable energy in power system brings stochastic power flows, uncertainties of energy market operations and power system planning and risks of wide frequency range oscillations and stability. These variations including fluctuations and intermittences of power waveforms are with natural contradictions to the needs of power system efficiency, security and stability. In this article, in contract to the concept of power quality used to measure characteristics of voltage and current waveforms, a framework of Energy Quality has been established to measure characteristics of power waveforms of generation sources, demands and power flows, hence value/differentiate the technical performances and price their services provided in terms of their quality, i.e. energy quality. The energy quality of a power waveform is assessed in terms of the following aspects: 1) what is the average power level; 2) how the carried energy is distributed in frequency domain; 3) how soon and heavily the power or power flow is changed & fluctuated. Measures/indices of energy quality, including average power level, energy spectrum, *TPD* and *SPD* have been defined in mathematical expressions to quantitatively assess these aspects. The proposed indices are also applicable to frequency. In addition, along with the newly defined indices in this paper, rate of change of power and frequency and/or power ramping rate should be considered together in the energy quality framework.

In different time scales, high energy quality requirements would help enlarge power system stability margin, achieve the effective power balance, facilitate the efficient operation of electricity market, and make better use of machine and converter capacities, etc. For power waveforms with low energy quality, energy filters and associated control will be able to smooth the power waveforms under normal operations and damp wide frequency range system oscillation under faults conditions, respectively.

To harmonize contradictions between high share of renewable power and power system efficiency, security & stability, further efforts are encouraged to be paid on the development of monitoring & control systems, computing tools and pricing methods as well as standards/grid codes in the framework of energy quality. As energy quality is an emerging area, it is unlikely that everything can be covered in a single paper. Rather it is felt that this paper is to stimulate further discussions about the topic in the power community.

REFERENCES

[1] (Apr. 2019). *Global Energy Transformation*. IRENA. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf

[2] Z. Yan and X.-P. Zhang, ''General energy filters for power smoothing, tracking and processing using energy storage,'' *IEEE Access*, vol. 5, pp. 19373–19382, 2017.

[3] R.C. Dugan, M.F. McGranaghan, H. W. Beaty, *Electrical Power Quality*. New York, NY, USA: McGraw-Hill, 1996.

[4] M. Bollen, *Understanding Power Quality Problems: Voltage Sags and Interruptions*. Hoboken, NJ, USA: Wiley, 1999.

[5] J. Arrillaga, N.R. Watson, S. Chen, *Power System Quality Assessment*. Chichester, U.K.: Wiley, 2000.

[6] C. Su, Y. Hu, Z. Chen, and W. Hu, ''Mitigation of power system oscillation caused by wind power fluctuation,'' *IET Renew. Power Gener.*, vol. 7, no. 6, pp. 639–651, Nov. 2013.

[7] H. Wu, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, ''Demand response exchange in the stochastic day-ahead scheduling with variable renewable generation,'' *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 516–525, Apr. 2015.

[8] Y. Liu, P. Ju, J. Chen, Y. Zhang, and Y. Yu, ''Contrastive analysis of general and special forced oscillations of power systems,'' *CSEE J. Power Energy Syst.*, vol. 1, no. 1, pp. 61–68, Mar. 2015.

[9] A. Blavette, D. L. O'Sullivan, T. W. Lewis, and M. G. Egan, ''Dimensioning the equipment of a wave farm: Energy storage and cables,'' *IEEE Trans. Ind. Appl.*, vol. 51, no. 3, pp. 2470–2478, Jun. 2015.

[10] S. Henninger, J. Jaeger, and H. Rubenbauer, ''Dimensioning and control of energy storage systems for renewable power leveling,'' in *Proc. IEEE/PES Transmiss. Distrib. Conf. Exposit. (T&D)*, Dallas, TX, USA, May 2016, pp. 1–5.

[11] (Apr. 2020). *Coefficient of Variation*. [Online]. Available: https://everipedia.org/wiki/lang_en/Coefficient_of_variation

[12] A. E. Leon and J. A. Solsona, ''Sub-synchronous interaction damping control for DFIG wind turbines,'' *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 419–428, Jan. 2015.

[13] L. Sainz, L. Monjo, M. Cheah-Mane, and J. Liang, ''Assessment of subsynchronous oscillations in AC grid-connected VSC systems with type-4 wind turbines,'' *IET Renew. Power Gener.*, vol. 13, no. 16, pp. 3088–3096, Dec. 2019.

[14] Y. Zhang, X. Chen, and J. Sun, ''Impedance modeling and control of STATCOM for damping renewable energy system resonance,'' in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Cincinnati, OH, USA, Oct. 2017, pp. 3295–3302.

[15] Z. Yan and X.-P. Zhang, ''Adaptive energy filters smoothing renewable power fluctuations at different power levels,'' in *Proc. 15th IET Int. Conf. AC DC Power Transmiss. (ACDC)*, Coventry, U.K., 2019, pp. 1–5.

[16] Y. Yu, S. Grijalva, J. J. Thomas, L. Xiong, P. Ju, and Y. Min, ''Oscillation energy analysis of inter-area low-frequency oscillations in power systems,'' *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 1195–1203, Mar. 2016.

[17] M. Cespedes and J. Sun, ''Impedance modeling and analysis of grid-connected voltage-source converters,'' *IEEE Trans. Power Electron.*, vol. 29, no. 3, pp. 1254–1261, Mar. 2014.

[18] *Guidance of Power System Security and Stability*, document GB 38755-2019, Beijing, China, Dec. 31, 2019.

[19] *Technical Requirements of Windfarm Integration into Power Systems*, document GB/T 19963-2019, Beijing, China, 2019.

[20] G. T. Heydt, *Electric Power Quality, Stars in a Circle Pubns*. Stars in a Circle Pubns, May 1991.

[21] X. P. Zhang, ''Fundamental challenge of energy system with high penetration of renewable energy: Energy quality,'' keynote speech presented at the 2017 Int. Electr. Energy Conf. (CIEEC), Beijing, China, Oct. 2017,

[22] X. P. Zhang, ''Energy quality,'' keynote speech presented at the CIGRE UK Future Power Netw. Seminar, Mar. 26, 2018, ARUP, London, UK.

[23] S. D. Ahmed, F. S. M. Al-Ismail, M. Shafiullah, F. A. Al-Sulaiman, and I. M. El-Amin, ''Grid integration challenges of wind energy: A review,'' *IEEE Access*, vol. 8, pp. 10857–10878, 2020.

[24] Y.-K. Wu, S.-M. Chang, and P. Mandal, ''Grid-connected wind power plants: A survey on the integration requirements in modern grid codes,'' *IEEE Trans. Ind. Appl.*, vol. 55, no. 6, pp. 5584–5593, Nov. 2019.

[25] E. Nycander and L. Soder, ''Review of European grid codes for wind farms and their implications for wind power curtailments,'' in *Proc. 17th Int. Wind Integr. Workshop*, Stockholm, Sweden, Oct. 2018.

[26] NGESO. (2020). *UK's Balancing Mechanism*. [Online]. Available: https://www.nationalgrideso.com/industry-information/balancing-service

[27] *IEEE Recommended Practice for Monitoring Electric Power Quality*, IEEE Standard 1159–2019, 2019.

[28] *IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions*, IEEE Standard 1459–2010, 2010.

XIAO-PING ZHANG (Fellow, IEEE) is currently a Professor of Electrical Power Systems with the University of Birmingham, U.K. He is also the Director of Smart Grid, Birmingham Energy Institute, and the Co-Director of the Birmingham Energy Storage Center. He coauthored the monograph ''*Flexible AC Transmission Systems: Modelling and Control*,'' (Springer, 2006 and 2012). He coauthored the book ''*Restructured Electric Power Systems: Analysis of Electricity Markets with Equilibrium Models*,'' (Wiley-IEEE Press, 2010). His research interests include modeling and control of HVDC, FACTS and renewable energy, distributed generation control, energy market operations, power system planning, and global power and energy internet. He has been chairing the IEEE PES WG on Test Systems for Economic Analysis. He has been the IEEE Distinguished Lecturer on HVDC, FACTS, and wave generation.

ZUANHONG YAN (Member, IEEE) received the joint B.Eng. degree from the Huazhong University of Science and Technology, Wuhan, China, and the University of Birmingham, Birmingham, U.K., in 2012, the M.Sc. degree from The University of Manchester, Manchester, U.K., in 2013, and the Ph.D. degree from the University of Birmingham, in 2018. He is currently a Research Fellow with China Southern Power Grid Electric Power Research Institute. His research interests include renewable energy integration and control and energy storage application.