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Power Quality Indices for Transient Disturbances

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***Abstract*—For reasonable power quality assessment of transient disturbances in electric power systems, new transient power quality indices are developed based on a signal processing technique, time-frequency analysis. Based on the time-frequency distribution of a transient disturbance, a set of time-frequency based power quality indices are developed. In this paper, the instantaneous disturbance energy ratio, normalized instantaneous disturbance energy ratio, instantaneous frequency, and instantaneous K-factor are suggested for transient power quality assessment. Time-frequency based power quality indices allow one to quantify the effects of transient disturbances with high-resolution and accuracy.**

***Index Terms*—Instantaneous disturbance energy ratio, instantaneous frequency, instantaneous K-factor, normalized instantaneous disturbance energy ratio, power quality, power quality index, time-frequency analysis, transient disturbance.**

I. INTRODUCTION

POWER quality is a quality of service (QoS) issue for customer and electric power service providers and it covers a variety of transient electromagnetic phenomena in electric power distribution systems [1]. Recently, the increasing number of nonlinear loads and power electronic devices for utility and customers are becoming sources of degradation of electric power quality via the generation of disturbances, e.g., impulsive transients, transient oscillations, interruptions, sag, harmonic distortion, interharmonics, etc. [2], [3]. The disturbances corrupt the power system waveforms, which are to be maintained at a fixed amplitude and frequency. Hence, definitions, standards and evaluations are required for power quality issues. The ITIC standard [4] or IEEE 519 [5] is an example of transient power quality treatment and practice.

For assessment purposes, power quality indices are utilized to represent the degree of the quality degradation in a quantitative manner. Hence, various types of power quality indices are defined, either in the time domain or the frequency domain, depending on the purpose of the application. In the time domain, the crest factor, peak and RMS values are defined, while total harmonic distortion (THD), distortion index (DIN), K-factor and telephone influence factor (TIF), etc. are defined in the frequency domain in terms of the Fourier series coefficients [6]. The problem of applying various power quality indices based on the periodicity of disturbance to transient power quality phenomena has been carefully addressed in [6] and [7], which provide a strong motivation for this paper. Hence, it is necessary to devise a measure of power quality to capture the "transient" characteristics of disturbance signals in power systems. Owing to the continual changes in system configurations and load conditions, the "time-varying" harmonic problem has been addressed [8] and a statistical solution has been suggested [9].

In order to analyze the transient and time varying nature of the disturbance signals in power systems, signal processing techniques have been employed for assessment, detection, localization and classification purposes [10]–[12] and [13]. Recently, the wavelet transform [14], [15] and the short-time Fourier transform [16] have been frequently utilized in the study of power quality, which are characterized by the "time & scale" and "time & frequency" localization of the transient signals, respectively.

One of the most interesting applications is the assessment of power quality by re-defining the power quality indices for transient events using signal processing techniques. G. Heydt *et al.* recognized the limitations of the traditional power quality indices [6] and suggested a new definition and application of power quality indices based on the short-time Fourier transform for aperiodic signals [17]. However, as discussed in [18], the short-time Fourier transform requires a time localization window with time duration ΔT which prohibits a more general application of the power quality indices to "*nonstationary*" signals [19]. In addition, the potential applicability of time-frequency analysis to transient power quality is mentioned in [18]. In this paper, we utilize "time-frequency analysis", which encompasses the short-time Fourier transform as a special case, to provide a unified definition of various power quality indices and their application to transient disturbance signals.

We introduce the general concepts of power quality indices and discuss the limitation of the Fourier approach in Section II. Also in Section II, the main tool of this paper, time-frequency analysis, is introduced. In Section III, the evaluation process of the time-frequency based power quality indices is discussed: the original disturbance waveform is separated into the fundamental component and disturbance component for time-frequency analysis. The obtained time-frequency distributions allow one to define a set of transient power quality indices in a unified way. In Section IV, the applicability and validity of the proposed transient power quality indices is carefully investigated by applying them to real-world disturbances. Using two transient capacitor switching disturbances and one sub-transient voltage sag disturbance we successfully demonstrate the efficacy of the various time-frequency based transient power quality indices. The conclusion is drawn in Section V.

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II. FOURIER ANALYSIS VERSUS TIME-FREQUENCY ANALYSIS FOR POWER QUALITY

As the power of a periodic signal is preserved in both the time and frequency domain via Parseval's theorem, one can develop Fourier coefficient based power quality indices to properly assess the contributions of the harmonics for a periodic disturbance. Based on the Fourier coefficients, various types of frequency-domain power quality indices can be obtained. The most typical power quality index is total harmonic distortion (THD) defined as follows:

$$\mathrm{THD}_v = \frac{1}{|v_1|}\sqrt{\sum_{k=2}^{k=\infty} |v_k|^2}. \tag{1}$$

Once the Fourier coefficients are calculated, the THD can be directly calculated. One can re-interpret the THD as the square root of the power content ratio of the harmonics to the fundamental frequency. Therefore, THD is typically employed to assess the relative amount of harmonic power associated with a periodic disturbance signal. Besides the THD, various types of other power quality indices are defined based on the Fourier series coefficients such as the K-factor and distortion index, etc. [6], [7].

However, the evaluation of the Fourier series requires a periodicity of the disturbance signal with respect to the fundamental frequency $(\omega_0/2\pi)$. Hence, the treatment of transient disturbances, whose periodicity with respect to the fundamental frequency cannot be defined, via the Fourier series based power quality indices is inappropriate from a signal analysis point of view and will result in errors [7]. Therefore, we will utilize time-frequency analysis, which provides simultaneous time and frequency information for the analysis and assessment of transient disturbance signals.

Time-frequency analysis is motivated by the analysis and representation of nonstationary signals whose spectral characteristics change in time. Various types of time-frequency distributions, e.g., the spectrogram, Wigner-Ville distribution and Choi-Williams distribution [20], reduced interference distribution (RID) [21], etc., have been proposed for improvement of the time-frequency resolution. The various types of time-frequency distributions have been generalized by L. Cohen with the following equation known as "Cohen's class" [22]

$$\mathrm{TFD}_x(t,\omega;\phi) = \frac{1}{4\pi^2}\int\!\!\int\!\!\int x^*\left(u-\frac{\tau}{2}\right)x\left(u+\frac{\tau}{2}\right) \times \phi(\theta,\tau)e^{-j\theta t - j\tau\omega + j\theta u}\,d\theta\,d\tau\,du \tag{2}$$

where $\phi(\theta,\tau)$ is the kernel of the time-frequency distribution and is different for each member of the class. The signal $x(t)$ is the analytic (complex) version of the signal to be analyzed. The variable τ denotes a time domain shift, and θ a frequency domain shift. For a given signal $x(t)$, (2) yields a distribution function $\mathrm{TFD}_x(t,\omega;\phi)$ of time and frequency for a given kernel, $\phi(\theta,\tau)$. The characteristics of the distribution function depend on the choice of kernel, $\phi(\theta,\tau)$, but the main idea of time-frequency analysis is to find a representation, $\mathrm{TFD}_x(t,\omega;\phi)$, of a nonstationary signal as a function of "time (t)" and "frequency (ω)".

The time-frequency representation of a signal is not an unique one; it depends on the selection of the kernel, ϕ. For the selection of the kernel, we will focus on the time and frequency marginal properties of the time-frequency distribution. The marginal properties are expressed by the following equations [21].

Time marginal

$$\int \mathrm{TFD}_x(t,\omega;\phi)d\omega = |x(t)|^2, \quad \text{if } \phi(\theta,\tau=0)=1. \tag{3}$$

Frequency marginal

$$\int \mathrm{TFD}_x(t,\omega;\phi)dt = |X(\omega)|^2, \quad \text{if } \phi(\theta=0,\tau)=1 \tag{4}$$

where $X(\omega)$ is the Fourier transform of the time-domain signal $x(t)$. Therefore, with the kernel requirements such that $\phi(\theta,\tau=0)=1$, and $\phi(\theta=0,\tau)=1$, the time-frequency distribution collapses to the absolute-value squared Fourier transform for the frequency marginal and the absolute-value squared time-domain signal for the time marginal. Note that "Parseval's theorem" provides physical validity of the Fourier based-classical power quality indices for periodic disturbance waveforms. Likewise, the time and frequency marginal properties confirm the physical validity of the time-frequency based transient power quality indices, which will be derived in the next section.

The definition of Cohen's class provided in (2) is a bilinear transformation so that interference terms will appear if a signal is composed of multiple components [20], [21]. The time-frequency characteristic of the interference term for a given signal depends upon the selection of the kernel. Hence, the arguments regarding the selection of proper kernel in time-frequency analysis are also applicable to the case of power quality analysis. As the disturbance signal in power systems is characterized by the presence of multiple frequency components over a short time duration, interference is also problematic and a high resolution time-frequency distribution is required [20], [21]. Among the various types of time-frequency distributions, the reduced interference distribution (RID) [21] has been shown to exhibit the most suitable properties for the analysis of the transient disturbance events in power systems [23]. Therefore, in this paper, we will choose reduced interference distribution (RID) [21], which satisfies time and frequency marginal properties with reduced interference characteristics.

III. TIME-FREQUENCY BASED POWER QUALITY INDICES

A flowchart of the algorithm for time-frequency based power quality indices is provided in Fig. 1. Each step will be discussed in detail in this section. For the discussion of the transient power quality assessment, the time-frequency based transient power quality indices are defined in Step 3. In Step 4, the principal average is introduced to quantify the time-varying transient power quality indices.

Step 1) **Generation of the time-frequency distribution** Based on the definition of the time-frequency distribution provided in (2), the first step starts with generation of the time-frequency distribution.

However, the dominance of the 60 Hz component impedes the high-resolution observation of the

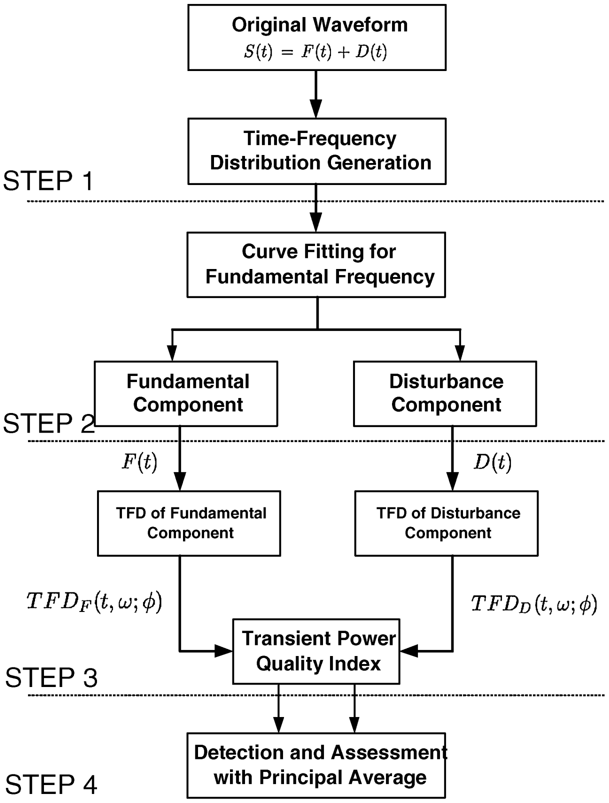

Fig. 1. Algorithm process of the time-frequency based transient power quality assessment.

time-frequency distribution of the disturbance due to a limited dynamic range available for the disturbance component of the signal. Hence, in the next section we will introduce a set of power quality assessment evaluation algorithms to represent the time-frequency distribution of the transient disturbance by first isolating the disturbance signal from the fundamental frequency component. Furthermore, one can detect the existence of the transient disturbance via the time-frequency based power quality indices as discussed in the next section.

Step 2) **Separation of the fundamental and disturbance waveforms**

Assign the fundamental frequency component of signal as $F(t)$ and disturbance signal as $D(t)$ such that the original waveform of the signal $S(t) = F(t) + D(t)$. As the fundamental frequency $(\omega_0/2\pi)$ in power systems is fixed at 60 Hz or 50 Hz, one can estimate the disturbance waveform $\hat{D}(t)$ by subtracting an estimate of the fundamental waveform $\hat{F}(t)$ from the original waveform $S(t)$ as follows:

$$\hat{D}(t) = S(t) - \hat{F}(t) \tag{5}$$

where $\hat{F}(t; A, \theta) = A_0 \cdot \cos(\omega_0 t + \theta)$. The amplitude of the fundamental frequency components is evaluated from the time-frequency distribution at the fundamental frequency, $\mathrm{TFD}_S(t, \omega_0)$, and the phase θ_0 of the fundamental frequency is obtained by a curve fitting routine as follows:

$$\{\theta_0\} = \arg_\theta \min |S(t) - \hat{F}(t)|^2. \tag{6}$$

The isolation of the disturbance signal, $D(t)$, enables one to obtain greater resolution for the disturbance signal by eliminating the dominant fundamental frequency component in the time-frequency distribution.

Step 3) **Frequency weighting and calculation of the time-frequency based power quality index**

After the separation of the fundamental frequency component $\hat{F}(t)$ and the disturbance signal $\hat{D}(t)$, one can generate time-frequency distributions of the individual signals from (2) as depicted in Fig. 1. We denote the time-frequency distribution of disturbance as $\mathrm{TFD}_D(t, \omega; \phi)$ and that of the fundamental component as $\mathrm{TFD}_F(t, \omega; \phi)$. After obtaining the time-frequency distributions of the fundamental $\mathrm{TFD}_F(t, \omega; \phi)$ and disturbance $\mathrm{TFD}_D(t, \omega; \phi)$, one can define time-frequency based power quality indices in a unified manner. There exist various ways of defining the power quality indices, however, the object of this paper is to modify the classical power quality indices defined in terms of Fourier coefficients so that the transient power quality is to be assessed as a function of time.

1) Instantaneous Distortion Energy Ratio: The instantaneous distortion energy ratio $(\mathrm{IDE}(t))$ is defined as follows in terms of the time-frequency distributions of the disturbance and fundamental frequency components:

$$\mathrm{IDE}(t) = \left\{ \frac{\int \mathrm{TFD}_D(t, \omega; \phi) d\omega}{\int \mathrm{TFD}_F(t, \omega; \phi) d\omega} \right\}^{1/2} \times 100\%. \tag{7}$$

The definition of the $\mathrm{IDE}(t)$ can be interpreted as a "*time-varying*" power quality assessment determined by the time-frequency localized energy ratio of the disturbance events to the fundamental frequency energy. In other words, $\mathrm{IDE}(t)$ is the transient version of the total harmonic distortion (THD) given in (1). Note that in $\mathrm{IDE}(t)$, the energy of the disturbance is calculated not just from the harmonics but from all continuous frequencies. Therefore, we do not have to confine the disturbance energy to harmonics, and it is the reason why the index is named "instantaneous distortion energy ratio," not "harmonic" factor.

2) Normalized Instantaneous Distortion Energy Ratio: Instead of the total harmonic distortion (THD), the power contribution of a periodic disturbance may be represented by the distortion index (DIN), alternatively. The concept of the distortion index (DIN) is very close to that of the total harmonic distortion (THD); however, the distortion index is defined in terms of the harmonic power divided by the total power in the waveform itself

$$\mathrm{DIN}_v = \frac{\sqrt{\sum\limits_{k=2}^{k=\infty} |v_k|^2}}{\sqrt{\sum\limits_{k=1}^{k=\infty} |v_k|^2}}. \tag{8}$$

This feature is an advantageous aspect of the distortion index (DIN) over the total harmonic distortion (THD) where the absence of the fundamental frequency components fails in the evaluation of the index. Hence, the transient disturbance energy $\mathrm{TFD}_D(t,\omega;\phi)$ can be normalized by the sum of the transient disturbance itself and fundamental energy $\mathrm{TFD}_F(t,\omega;\phi)$ as follows:

$$\begin{aligned}\mathrm{NIDE}(t) &\\ &= \left\{\frac{\int \mathrm{TFD}_D(t,\omega;\phi)d\omega}{\int \mathrm{TFD}_D(t,\omega;\phi)d\omega + \int \mathrm{TFD}_F(t,\omega;\phi)d\omega}\right\}^{1/2}\\ &\quad \times 100\%. \end{aligned}\tag{9}$$

Therefore, the normalized time-varying instantaneous disturbance energy ratio corresponds to the transient version of DIN_v defined by the Fourier coefficients. Note that the $\mathrm{NIDE}(t)$ increases with the transient disturbance energy, however, it cannot exceed a maximum value of 100%. The relation between the THD and DIN still holds true for $\mathrm{NIDE}(t)$ and $\mathrm{IDE}(t)$, as indicated in the following:

$$\begin{aligned}\mathrm{NIDE}^2(t) &= \frac{1}{1+\frac{\int \mathrm{TFD}_F(t,\omega;\phi)d\omega}{\int \mathrm{TFD}_D(t,\omega;\phi)d\omega}}\\ &= \frac{\mathrm{IDE}^2(t)}{1+\mathrm{IDE}^2(t)}.\end{aligned}\tag{10}$$

A large amplitude transient disturbance may result in a large value of $\mathrm{IDE}(t)$; however, for $\mathrm{NIDE}(t)$, the maximum value is bounded by 100% so that the variations of the transient power quality index is limited. Due to the relation between the $\mathrm{NIDE}(t)$ and $\mathrm{IDE}(t)$ shown in (10), for a relatively small disturbance, e.g., less than 30%, $\mathrm{IDE}(t)$ will have close value to $\mathrm{NIDE}(t)$. We recognize that $\mathrm{IDE}(t)$ and $\mathrm{NIDE}(t)$ correspond to the square root of an appropriate energy ratio; however, to avoid awkward phraseology, we will simply use the term "energy ratio" throughout this paper.

3) Instantaneous Frequency: The time-frequency based transient power quality indices discussed above interpret the effects of the disturbance in terms of transient energy. However, the same transient disturbance energy might have different effects on the power system depending on the local frequency content. By exploring the frequency localization via the time-frequency distribution, one can define a measure of the severity of the transient disturbance in terms of frequency.

The instantaneous frequency is calculated from the time-frequency distribution as follows [22]:

$$\mathrm{IF}(t) = \frac{\int \omega \cdot \mathrm{TFD}_S(t,\omega;\phi)d\omega}{\int \mathrm{TFD}_S(t,\omega;\phi)d\omega}. \tag{11}$$

Therefore, the instantaneous frequency is a first-order moment, where each frequency component in $S(t)$ is weighted by the energy associated with that component at the time of interest. Consequently, a disturbance with higher frequency content will result in higher value of instantaneous frequency than a disturbance with lower frequency content. Hence, the instantaneous frequency is very sensitive to the onset of a transient event, which is usually composed of high frequency components. This sensitive feature of the instantaneous frequency allows one to utilize it for the detection of the onset of a variety of transient disturbance events.

4) Instantaneous K-Factor: The K-factor is a measure of the harmonic content generation of a load and is especially useful for transformer ratings [6]. To generalize the K-factor to a transient disturbance, the square (2nd order) of the normalized frequency is weighted by the relative amount of energy associated with that frequency at the time of interest. Hence, one can define the instantaneous K-factor $\mathrm{IK}(t)$ as follows:

$$\mathrm{IK}(t) = \frac{\int {\omega_N}^2 \cdot \mathrm{TFD}_S(t,\omega;\phi)d\omega}{\int \mathrm{TFD}_D(t,\omega;\phi)d\omega + \int \mathrm{TFD}_F(t,\omega;\phi)d\omega} \tag{12}$$

where the normalized angular frequency ω_N is

$$\omega_N = \frac{1}{2\pi} \cdot \frac{\omega}{60\ \mathrm{Hz}}. \tag{13}$$

Based on the definition of the instantaneous K-factor $\mathrm{IK}(t)$ provided in (12), the value of $\mathrm{IK}(t)$ under the normal steady state conditions, will remain 1. The value of the $\mathrm{IK}(t)$ is more sensitive to any transient variation of the waveform compared to the instantaneous frequency provided in (11), because, $\mathrm{IK}(t)$ has a squared frequency, ω^2, dependence, while $\mathrm{IF}(t)$ has just a linear frequency, ω, dependence.

Step 4) **Calculation of the principal average of transient power quality indices**

The transient power quality indices provide useful information about the time-varying signature of the transient disturbance for assessment purposes. However, if the time-varying signature can be quantified as a single number, it would be more informative and convenient for an assessment and comparison of transient power quality. Therefore, we define a "*principal average*" of the transient power quality indices, $\overline{\mathrm{TFPQ}}$ as an average of the time-frequency based power quality index function $\mathrm{TFPQ}(t)$ over a fundamental period T_0 as follows:

$$\overline{\mathrm{TFPQ}} = \frac{1}{T_0}\int_{t_0-T_0/2}^{t_0+T_0/2} \mathrm{TFPQ}(t)\,dt \tag{14}$$

where $t_0 = \arg\max_t\{\mathrm{TFPQ}(t)\}$. The selection of the time interval center for the evaluation of the principal average $\overline{\mathrm{TFPQ}}$ is determined by the time index of the local peak value of the $\mathrm{TFPQ}(t), t_0$. Consequently, the principal average of transient power quality indices is the local average over a T_0 sec. duration which is centered at the local peak value of the $\mathrm{TFPQ}(t)$.

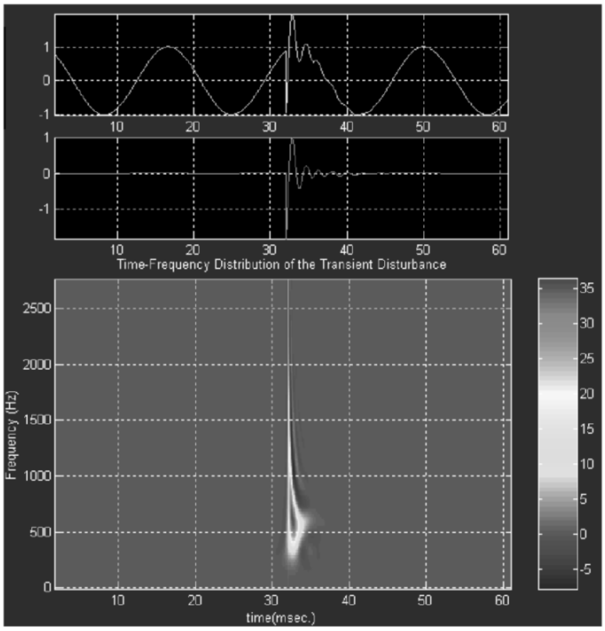

Fig. 2. Time-frequency distribution of a fast capacitor switching disturbance.

IV. APPLICATION EXAMPLES

In this section, we will consider three real-world samples of disturbance waveforms to illustrate the time-frequency based power quality indices defined in the previous section. The first two samples are fast and slow capacitor switching disturbances. Then, a sub-transient disturbance, voltage sag is characterized by the time-frequency based power quality indices. In the following subsections, each disturbance example will be discussed individually. The real-world disturbance waveform data illustrated in this section were provided courtesy of EPRI (Electric Power Research Institute).

A. Transient Capacitor Switching Disturbances

In Fig. 2, a fast capacitor switching disturbance is provided with the time-frequency distribution, and the corresponding transient power quality indices are shown in Fig. 3. The waveform at the top of Fig. 2 is the original waveform and the waveform in the middle is the extracted disturbance waveform obtained by (5). The time-frequency distribution of the fast capacitor switching disturbance is provided in the bottom of Fig. 2. The fast capacitor switching is caused by a restrike on opening; if a contactor does not successfully open during the deenegizing process, an arc is generated by re-energizing the capacitor. It is known that the disturbance generated by the capacitor switching restrike on opening exhibits a transient oscillation with natural frequency determined by the capacitance and inductance of the system. Therefore, the disturbance signal is more transient and oscillatory than normal capacitor energizing, which will be considered next.

The time-frequency distribution in Fig. 2 shows that the transient energy of the disturbance occupies approximately 500 Hz to 1000 Hz during 32–33 ms. The instantaneous disturbance energy ratio $\mathrm{IDE}(t)$ in Fig. 3(c) shows a peak value 231.9% at 32.04 ms while the peak of the normalized instantaneous disturbance energy ratio $\mathrm{NIDE}(t)$ in Fig. 3(d) shows a peak value 91.83% at the same time. The principal averages, $\overline{\mathrm{IDE}(t)}$ and $\overline{\mathrm{NIDE}(t)}$, are 17.64% and 13.56%, respectively. The instantaneous frequency in Fig. 3(e) shows a peak value of 2.695 kHz at 32.09 ms. and the principal average of the instantaneous frequency $\overline{\mathrm{IF}(t)}$ is 115.65 Hz. The instantaneous K-factor shows a peak value 10.14 at 32.24 ms. and the principal average of the instantaneous K-factor $\overline{\mathrm{IK}(t)}$ is 1.65.

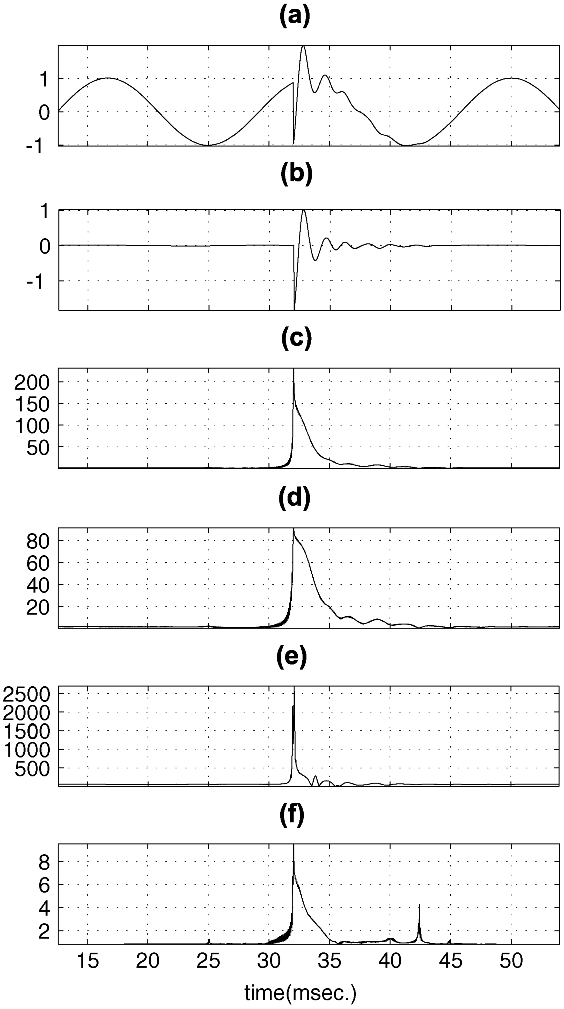

Fig. 3. Time-frequency based transient power quality indices of the fast capacitor switching: (a) Disturbance waveform. (b) Separated disturbance waveform. (c) Instantaneous disturbance energy ratio $(\mathrm{IDE}(t))$. (d) Normalized instantaneous distortion energy ratio $(\mathrm{NIDE}(t))$. (e) Instantaneous frequency $(\mathrm{IF}(t))$. (f) Instantaneous K-factor $(\mathrm{IK}(t))$.

In Fig. 4, a slow capacitor switching disturbance is considered with the corresponding time-frequency distribution, and the corresponding transient power quality indices are shown in Fig. 5. The slow capacitor switching provided in Fig. 4 comes from a normal capacitor switching for the correction of power factor. Hence, the disturbance caused by the slow capacitor switching is intuitively expected to be less significant than the fast capacitor switching disturbance discussed before.

The time-frequency distribution in Fig. 4 shows that the transient energy of the disturbance occupies between 200 Hz and 600 Hz during 12–15 ms. The instantaneous disturbance energy ratio $\mathrm{IDE}(t)$ in Fig. 5(c) shows a peak value 33.67% at 13.00 ms, while the peak of the normalized instantaneous disturbance

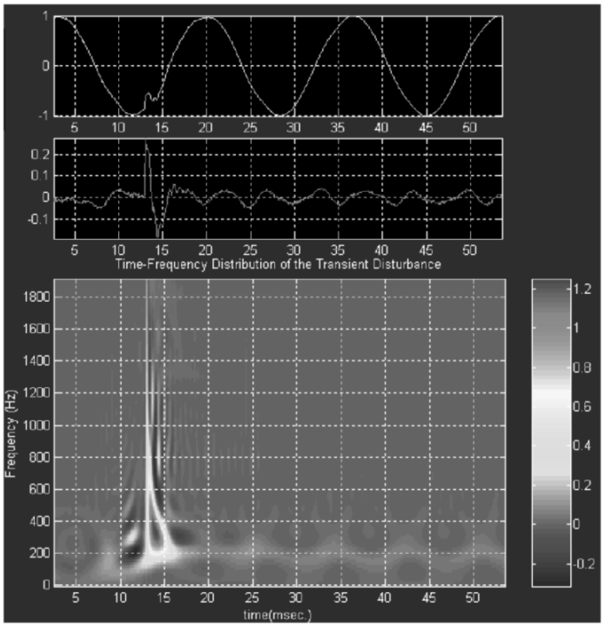

Fig. 4. Time-frequency distribution of a slow capacitor switching disturbance.

energy ratio $\mathrm{NIDE}(t)$ shows a peak value 31.91%. The principal average of the $\overline{\mathrm{IDE}(t)}$ and $\overline{\mathrm{NIDE}(t)}$ are 6.26% and 6.19%, respectively. The instantaneous frequency shows peak value 253.1 Hz at 12.87 ms. and the principal average of the instantaneous frequency $\overline{\mathrm{IF}(t)}$ is 64.35 Hz. The instantaneous K-factor shows a peak value 1.73 at 13.92 ms. and the principal average of the instantaneous K-factor $\overline{\mathrm{IK}(t)}$ is 1.11.

The transient power quality index peak values indicate that the fast capacitor switching is a more severe transient event than the slow capacitor switching in terms of $\mathrm{IDE}(t), \mathrm{NIDE}(t), \mathrm{IF}(t)$, and $\mathrm{IK}(t)$. This result can be confirmed by the shorter time duration and higher frequency content of the disturbance observed on the time-frequency distribution in Fig. 4. The ratio of the instantaneous peak values between the fast to the slow capacitor switch vary depending on the power quality indices : approximately 11 $(2695/253.1 = 10.65)$ times higher peak $\mathrm{IF}(t)$ and 3 $(91.83/31.91 = 2.88)$ times higher peak $\mathrm{NIDE}(t)$. However, in terms of principal average values, the fast capacitor switching disturbance has, approximately, 2 times higher values than the slow capacitor switching case.

B. Sub-Transient Disturbance: Voltage Sag

The application of the time-frequency based transient power quality indices are not only limited to purely transient disturbances. A sub-transient voltage sag disturbance caused by a motor starting is provided with the corresponding time-frequency distribution in Fig. 6 and corresponding transient power quality indices in Fig. 7. The waveform at the top of Fig. 6 is the original waveform and the waveform in the middle is the extracted disturbance waveform. Voltage sag is an event that exhibits a transient decrease of RMS value of the waveform which is very critical for adjustable speed drives (ASD), programmable logic controllers, microprocessors, etc.

The pattern of the time-frequency distribution is somewhat different compared with the previous two transient disturbance examples; the time-frequency distribution shows that the disturbance energy occurs at the fundamental frequency 60 Hz from 30 ms., with the amplitude slowly decreasing with time. The instantaneous disturbance energy ratio $\mathrm{IDE}(t)$ shows an abrupt increasing peak value 25.36% at 39.20 ms while the peak of the normalized instantaneous disturbance energy ratio $\mathrm{NIDE}(t)$ shows a peak value 24.58% at the same time. The peak value of the $\mathrm{IDE}(t)$ is associated with the depth of the sag; 80% of the nominal amplitude results in the value of approximately 20% instantaneous disturbance energy ratio. The slow recovery of the voltage sag is observed by the decreasing values of the $\mathrm{IDE}(t)$ and $\mathrm{NIDE}(t)$ in Fig. 7. The principal average values of the $\overline{\mathrm{IDE}(t)}$ and $\overline{\mathrm{NIDE}(t)}$ are 21.33% and 20.82%, respectively.

The instantaneous frequency exhibits a peak value 155.3 Hz at 30.81 ms., which is the exact time of the start of the voltage sag. The value of instantaneous frequency and its time index demonstrates that the instantaneous frequency is a powerful tool for accurate detection of the voltage sag initiation, which has been traditionally treated by RMS values or wavelet transforms. The principal average of the instantaneous frequency is very close to 60 Hz, i.e., $\overline{\mathrm{IF}(t)}$ is 59.76 Hz. The instantaneous K-factor shows peak value 21.26 at 30.16 ms. The principal

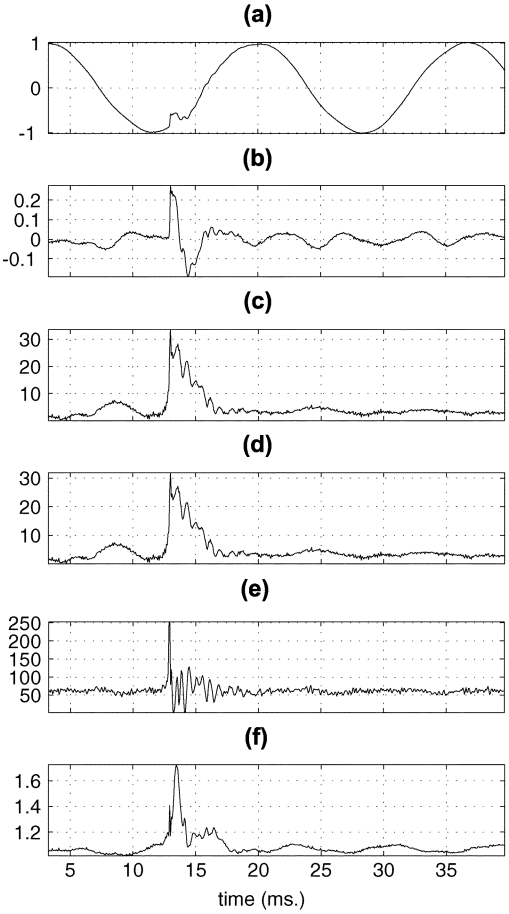

Fig. 5. Time-frequency based transient power quality indices of the slow capacitor switching: (a) Disturbance waveform. (b) Separated disturbance waveform, (c) Instantaneous disturbance energy ratio $(\mathrm{IDE}(t))$. (d) Normalized instantaneous distortion energy ratio $(\mathrm{NIDE}(t))$. (e) Instantaneous frequency $(\mathrm{IF}(t))$. (f) Instantaneous K-factor $(\mathrm{IK}(t))$.

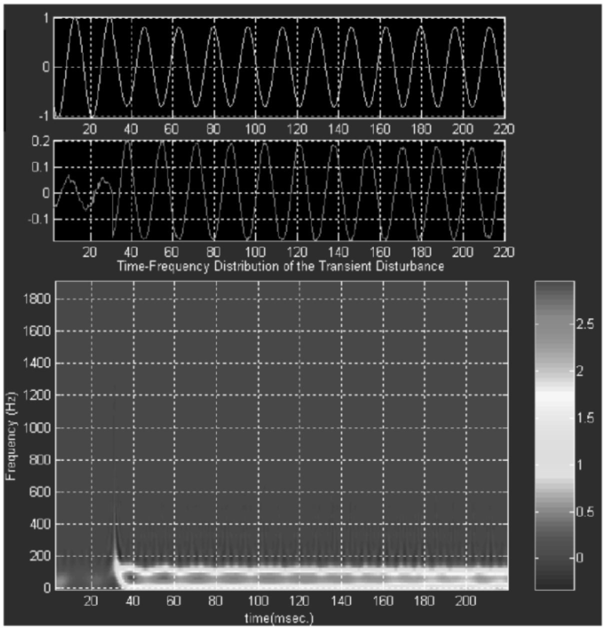

Fig. 6. Time-frequency distribution of a voltage sag disturbance.

average of the instantaneous K-factor $\overline{\mathrm{IK}(t)}$ is 1.08, which implies very small variation of the frequency content as is true for the case of voltage sag.

In terms of the principal averages of the instantaneous frequency and instantaneous K-factor, the voltage sag does not affect the frequency very much which remains very close to the fundamental frequency and its normalized value of 1. However, the variations of the amplitude are reflected in the values of the disturbance energy ratio. In the case of a voltage sag, sub-transient disturbance, the peak values are relatively smaller than for the corresponding transient disturbances; moreover, the differences between the peak value and principal average values of energy are relatively smaller compared to the transient cases due to the longer time duration of the voltage sag. This example of transient power quality assessment for voltage sag confirms the fact that the time-frequency based power quality indices, $\mathrm{IDE}(t)$ and $\mathrm{NIDE}(t)$, are very informative regarding sub-transient disturbances.

Furthermore, the frequency domain power quality indices, the instantaneous frequency and instantaneous K-factor, provide accurate and sensitive detection of the time of occurrence of the voltage sag as shown in Fig. 7. It is difficult to make an accurate estimate of sag time with classical RMS methods, however, the time-frequency based power quality indices, $\mathrm{IDE}(t)$ and $\mathrm{NIDE}(t)$, provide an accurate and sensitive analysis of the voltage sag phenomena. Note that in Fig. 7(e) and (f), the times of the maximum values of $\mathrm{IF}(t)$ and $\mathrm{IK}(t)$, 30.81 ms. and 30.16 ms., respectively, are close to the actual beginning time of the sag at 30.80 ms. observed in the time domain, whereas the times of the maximum values of $\mathrm{IDE}(t)$ and $\mathrm{NIDE}(t)$, 39.20 ms., are retarded with respect to the actual beginning time of the sag.

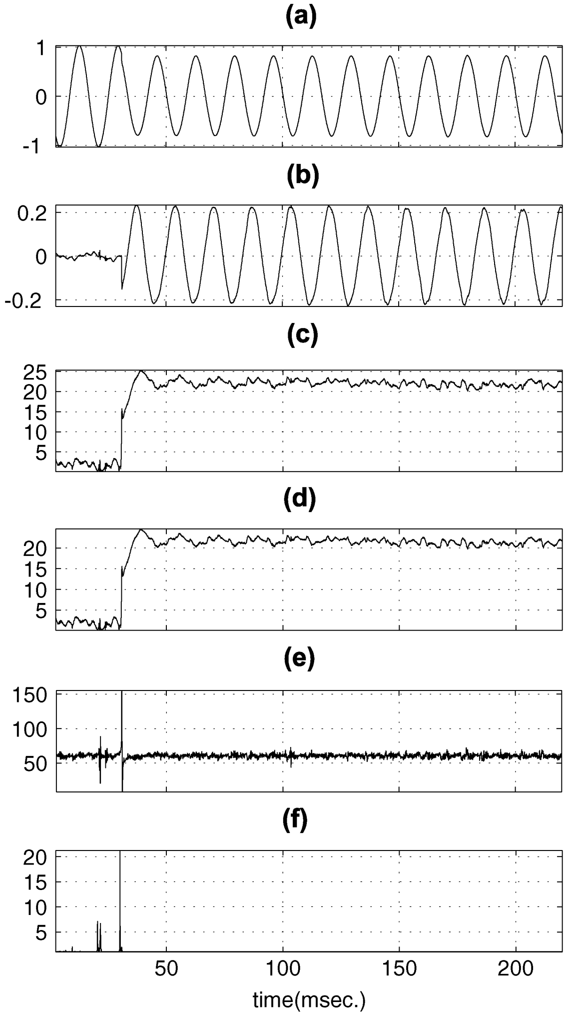

Fig. 7. Time-frequency based transient power quality indices of voltage sag: (a) Disturbance waveform. (b) Separated disturbance waveform. (c) Instantaneous disturbance energy ratio $(\mathrm{IDE}(t))$. (d) Normalized instantaneous distortion energy ratio $(\mathrm{NIDE}(t))$. (e) Instantaneous frequency $(\mathrm{IF}(t))$. (f) Instantaneous K-factor $(\mathrm{IK}(t))$.

TABLE I
SUMMARY OF TRANSIENT POWER QUALITY INDICES FOR THE EXAMPLES

		Fast cap. switching	Slow cap. switching	Motor starting
Type of disturbance		Transient	Transient	Sub-transient
IDE	peak time (ms.)	32.04	13.00	39.20
	peak value (%)	231.92	33.67	25.36
	principal average	17.64	6.26	21.33
NIDE	peak time (ms.)	32.04	13.00	39.20
	peak value (%)	91.83	31.91	24.58
	principal average	13.56	6.19	20.82
IF	peak time (ms.)	32.09	12.87	30.81
	peak value (Hz)	2695	253.1	155.3
	principal average	115.65	64.35	59.76
IK	peak time (ms.)	32.24	13.92	30.16
	peak value	10.14	1.73	21.26
	principal average	1.65	1.11	1.08

In Table I, a summary of the various power quality indices is provided for the three examples discussed in this paper. Comparing the disturbance examples in terms of their respective time-frequency based transient power quality indices, one can determine and compare the transient power quality in a quantitative way. It is difficult to tell which is the "best" power quality index, because they have different parameter dimensions; Hz (or equivalently rad./sec. for angular frequency notation) for $\mathrm{IF}(t)$, dimensionless energy percentage for $\mathrm{IDE}(t)$, $\mathrm{NIDE}(t)$, and dimensionless frequency squared for $\mathrm{IK}(t)$. However, if one determines a dimension or purpose for the transient power quality, one can select a corresponding time-frequency based transient power quality index. If one needs an assessment of transient power quality in terms of energy, one can choose $\mathrm{IDE}(t)$ or $\mathrm{NIDE}(t)$. If one needs an assessment of transient power quality in terms of frequency, one can choose $\mathrm{IF}(t)$ or $\mathrm{IK}(t)$. If one needs an assessment of transient power quality in terms of a specific frequency spectrum (for example, telephone interference factor), one can customize the time-frequency based transient power quality indices once one has calculated $\mathrm{TFD}_D(t,\omega)$ and $\mathrm{TFD}_F(t,\omega)$. Note that irrespective of power quality index selection, the time-frequency based power quality indices provide time-varying frequency signatures of the transient disturbance.

V. CONCLUSION

In this paper, power quality assessment for transient disturbance signals has been carefully treated by time-frequency analysis. The limitations of the traditional Fourier series coefficient based power quality indices, which inherently require periodicity of the disturbance signal, have been resolved by use of time-frequency analysis. Utilizing the time and frequency localization of the time-frequency distribution, the following time-frequency based power quality indices are proposed: the instantaneous disturbance energy ratio, normalized instantaneous disturbance energy ratio, instantaneous frequency, and instantaneous K-factor. The first two power quality indices characterize the disturbance in terms of energy, while the latter two power quality indices characterize the disturbance in terms of frequency deviation. Furthermore, the application of the time-frequency based power quality indices can be extended to the assessment and detection of sub-transient and periodic disturbances. In this paper, the efficacy of the time-frequency based power quality indices has been demonstrated by the use of real-world disturbance examples.

The time-frequency based power quality indices discussed in this paper can be interpreted as a generalization of the classical power quality indices. The Fourier series based power quality indices are a specific case of time-frequency based power quality indices for a periodic case without time resolution, which has been shown both theoretically and numerically for THD. Besides the time-frequency based transient power quality indices developed in this paper, one can develop other transient power quality indices by calculating appropriate moments of the time-frequency distribution. The time-frequency based transient power quality indices discussed in this paper are expected to play an important role in resolving various assessment and measurement issues for transient phenomena in power systems. The power quality indices proposed in this paper can be extended to disturbance evolution assessment, which could become a subject of future research in power systems.

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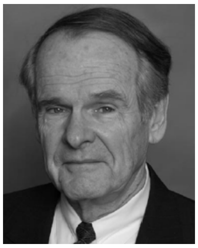

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