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Empirical mode decomposition application for short-term flicker severity

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Abstract: In this article, an approach based on empirical mode decomposition (EMD) is suggested in order to calculate short-term flicker severity, Pst, in power systems. EMD is a new signal processing method used for the analysis of nonlinear and nonstationary signals. Pst is an important quantity in the electric power quality index defined by the International Electrotechnical Commission. In the suggested approach, the voltage signal is separated into intrinsic mode function components using EMD. These components are used for calculating the voltage flicker amplitude and frequency, and Pst is calculated as a result of the statistical evaluation of flicker amplitude. EMD is thought to be efficient in finding the flickers and calculating Pst due to power to find the changes in the oscillating signal envelope of EMD. Simulations are made using an input signal modulated with single and multiflicker frequency. Simulations show that the approach is usable in the calculation of Pst and it gives good results.

Key words: Short term flicker severity, empirical mode decomposition, intrinsic mode function, voltage flicker, power quality

1. Introduction

Power quality (PQ) has gained much attention because of nonlinear loads. Due to their nonlinearity, loads cause fluctuations in the voltage waveform and can greatly change the load currents in an electrical distribution system. The most important feature of the voltage fluctuations is the flicker seen in light sources. Flicker is defined as an instable effect of brightness and spectral distribution fluctuating over time of a light stimulus on the eye, according to European Union EN61000-3-3 standards. Flicker is separated into two groups: short term and long term. The characteristic of flicker changes according to load type and dimension [1].

Voltage fluctuations and flicker shorten the life of electronic devices, impair the operation performance of motors and generators, and cause equipment to malfunction. Moreover, they impair the efficiency of the light source and cause memory loss and processing errors for computers [2].

Pst is a valid and important index of power quality according to International Electrotechnical Commission (IEC) standards. Calculating Pst accurately is a method used for the monitoring of power quality. Parameters related to flicker can be measured easily after the frequency and amplitude of voltage fluctuations are obtained accurately. IEC and IEEE standards recommend methods for flicker measurement and describe the function and design features of Flickermeter [3,4].

To determine the Pst, the Flickermeter suggested in the IEC standards can be divided into two main parts. The first part performs the electrical model of the lamp-eye-brain chain regarding voltage amplitude fluctuations

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for flicker sensitivity, known as instantaneous flicker level (IFL). The second part consists of statistical evaluation of IFL [5]. The evaluation reveals the characteristics value of short-term flicker severity Pst in 10 min intervals.

Many classification algorithms have been developed by researchers for the classification of power quality disturbances. A novel hybrid algorithm based on the applications of principle component analysis, discrete wavelet transform, and fast Fourier transform (FFT) in order to detect possible PQ disturbances such as voltage sag, flicker, harmonics, transients, DC component, and electromagnetic interference is presented in [6]. The potential of a relatively recent method of ensemble empirical mode decomposition (EMD)-based support vector machine (SVM) classification for analyzing nonlinear and nonstationary power disturbances is applied in [7,8]. A relatively new method known as EMD for the classification of the analyzed power quality disturbances developed by Huang et al. is proposed [9]. A new noise-assisted analysis method, called ensemble EMD, and the effect of ensemble EMD on time-frequency analysis behaviors are proposed in [10].

Several methods have been suggested to determine the level of flicker and to calculate the Pst. Some of these methods are fast FFT, FFT-based methods, square demodulation (SD), and wavelet transform (WT). These methods usually benefit from frequency region decomposition of the voltage waveform [11–14].

In these approaches, IEC Flickermeter digital performance is usually compared [15] and realistic results are obtained as a result of numerical confusion. Apart from these methods, Teager energy operator (TEO) and Hilbert transform (HT) have been used recently to analyze the voltage flicker. TEO can determine the signal amplitude changes quickly. However, this method is sensitive to noise and this also reduces the accuracy by increasing the frequency of flicker [16,17]. In HT, a complex signal is obtained after the HT of the original signal and this signal is used for removing the voltage flicker envelope. This causes the numerical complexity [18–20].

New analysis methods are required for the identification of voltage flicker and calculation of Pst. EMD is used for the analysis of the nonlinear and unstable signals and it gives good results [21]. This method is a new signal transformation based on instantaneous frequency.

In this paper, an approach based on EMD is suggested in order to calculate amplitude and frequency of voltage flicker and to obtain Pst. In this method, the signal is first decomposed at different frequencies by EMD, taking an account of the local oscillation into consideration. Secondly, HT is applied to each IMF component obtained from EMD. Flicker frequency and amplitude is calculated after the flicker envelope is obtained. Pst is calculated in accordance with the suggested method of IEC and the Pst error is obtained.

2. EMD

With the EMD model, a signal is decomposed into different frequencies by taking into consideration the local oscillations. Each IMF represents an oscillation in the signal. It can be considered as a harmonic component in this respect. However, unlike harmonic components, IMF amplitudes and frequencies are not constant and may vary over time. IMF corresponds to different frequency bands; however, there are predetermined frequency bands. The first IMF component obtained from EMD is the component that has the highest frequency in the original signal. The second IMF component has a lower frequency than first IMF.

According to Huang, IMFs that have the same length as the original signal have two important features:

1. The number of extrema points and zero crossing points must be equal to or different from each other with a single unit maximum;
2. The mean value of the envelope defined as a local maxima and the envelope defined as a local minima must be zero [21].

The original signal, which has the sum of the components of the IMF and the mean value, is shown in Eq. (1).

$$x(t) = r_n(t) + \sum_{j=1}^{n} c_j(t) \tag{1}$$

Here $x(t)$ is the signal being analyzed, n is the number of scale, $c_j(t)$ is the IMF in the jth scale, and $r_n(t)$ is the residue signal that remains from the repetitions (approximation oscillation).

IMFs are obtained as follows by the EMD method [21–25]. The examined signal is $x(t)$:

Step 1: All maximum and minimum points in $x(t)$ are found and marked. An upper envelope $u(t)$ and a lower envelope $v(t)$ are obtained by combining the found top extremum and lower extremum points with interpolation.

Step 2: m_1, the mean envelope of $x(t)$, is obtained by averaging the upper and lower envelopes.

Step 3: A new signal (h_l) is obtained by subtracting the mean envelope from the $x(t)$ signal using Eq. (2):

$$h_1 = x(t) - m_1 \tag{2}$$

Step 4: If the obtained h_l does not provide the IMF feature, the first 3 steps continue to be applied to h_l signal. This is called a sifting process. In the next step, it is treated as the data and h_{ll} is obtained. After repeated siftings in this manner up to k times, h_{lk} is obtained using Eq. (3):

$$h_{1k} = h_{1k-1} - m_{1k} \tag{3}$$

Step 5: After a stoppage criterion is selected, the first IMF component is obtained from c$_l$ $= h_{lk}$. Two different stoppage criteria can be used as the stoppage criterion of the sifting process [21]. The first stoppage criterion is determined using the Cauchy convergence test. This criterion requires the normalized squared difference between two successive sifting operations, defined in Eq. (4). If SD$_k$ is smaller than a predetermined value, the sifting processes are stopped.

$$SD_k = \frac{\sum_{t=0}^{T} \left|h_{k-1}(t) - h_k(t)\right|^2}{\sum_{t=0}^{T} h_{k-1}^2(t)} \tag{4}$$

The second stoppage criterion is based on the agreement of the number of zero crossings and extrema. The S-number is pre-selected. Sifting processes are stopped only after S consecutive times, when the numbers of extrema points and zero crossing points are equal or differ at most by one.

The first IMF component c$_l$ is subtracted from the input data, and its residue signal r$_l$ is obtained. c$_l$ shows the highest frequency component in the flicker signal. r$_l$ is handled as a new data series and a new sifting process is started. The processes are repeated for all residue signals until r$_n$ takes the value smaller than a pre-determined value or it becomes a monotonic function. Lastly, the remaining m signal is called a residue signal. r$_n$. r$_n$ is given in Eq. (5)

$$r_1 = x(t) - c_1$$

$$r_n = r_{n-1} - c_n \tag{5}$$

HT is applied to the IMF components obtained as a result of EMD, and flicker amplitude and frequency are obtained.

3. Short-term flicker severity Pst

3.1. Voltage flicker model

It is very important to obtain voltage flicker in order to calculate the Pst accurately. Voltage flicker is expressed by adding the amplitude-modulated fluctuation to amplitude modulation harmonic components. The modulated signal can be shown as the sum of sinusoidal components. Mathematically, if the harmonic components are ignored, voltage flicker can be explained by Eq. (6) [26]:

$$\begin{aligned} u(t) = A_0\left(1+\sum_{i=1}^{N} m_i\cos(2\pi f_i t+\phi_i)\right)\cos(2\pi f_0 t+\varphi_0) \\ = (A_0 + A_0 v(t))\cos(2\pi f_0 t+\varphi_0) \\ = A(t)\cos(2\pi f_0 t+\varphi_0) \end{aligned} \tag{6}$$

Here A_0 represents the signal amplitude, f_0 represents the main frequency, φ_0 represents the starting phase angle, and m_i represents flicker amplitude. f_i and ϕ_i are voltage flicker frequency and starting phase angle, respectively. $A_0\,\mathrm{v(t)} = A_0\sum_{i=1}^{h} m_i\cos(2\pi f_i t+\phi_i)$ is the flicker envelope.

Due to the voltage, the flicker envelope is modeled as amplitude-modulated, the number of extreme points of the voltage flicker envelope is equal to the number of zero-crossing points. In order to obtain the flicker envelope if Eq. (6) is squared before applying EMD to break the symmetry (+/− equal in terms of the lack of), and if m_i^2 and $m_i m_j$ terms are ignored as $m \ll 1$, Eq. (7) is obtained:

$$u^2(t) \cong \frac{A_0^2}{2} + A_0^2\sum_{i=1}^{N} m_i\cos(2\pi f_i t+\phi_i) + \frac{A_0^2}{2}\cos(2\pi 2 f_0 t+\varphi_0) + A_0^2\cos(2\pi 2 f_0 t+\varphi_0)\sum_{i=1}^{N} m_i\cos(2\pi f_i t+\phi_i) \tag{7}$$

Here the flicker envelope expressed with the $A_0^2\sum_{i=1}^{N} m_i\cos(2\pi f_i t+\phi_i)$ term in (7), and as a result, EMD is obtained.

3.2. Calculation of Pst

After the flicker envelope is obtained, HT is used in order to calculate flicker frequency and amplitude. Pst is calculated in accordance with the suggested method in IEC. When the flicker component is removed, it is passed through the detectable weighting filter on which weighting coefficients are calculated. This filter is usually consists of serial 3 filters. The first filter is a filter which has a 0.05 Hz cutoff frequency first-order high-pass. The second filter is the Butterworth filter, which has a 35 Hz cutoff frequency sixth-order low-pass. These filters remove DC components and the components that are two times higher than the existing network frequency. The third filter gives a bandpass response centered at 8.8 Hz. The obtained signal is passed through squaring and smoothing blocks. The squaring multiplier simulates nonlinear eye-brain perception by squaring the weighted flicker signal. The smoothing block consists of a first order low-pass filter with a 300 ms time constant. The storage effect in the brain is simulated with the help of this filter and the instant flicker level (IFL) is obtained. Lastly, IFL is passed through statistical evaluation [3].

Obtaining Pst by EMD can be shown with the algorithm in Figure 1. In statistical evaluation, for a signal in the time domain the cumulative probability $p(l)$ of signal level l over a period of T time is calculated from Eq. (8). The graphical representation of $p(l)$ is called the cumulative probability function (CPF) [5].

$$p(l) = \frac{\text{total time of where signal level } \geq l}{T} \tag{8}$$

First, five evaluation points on the CPF curve and weighting coefficients corresponding the points are chosen in order to obtain short-term flicker severity Pst using Eq. (8). Short term shows the 10 min observation period and it is calculated using Eq. (9) [3]:

$$P_{st} = \sqrt{\sum_i k_i P x_i} = \sqrt{0,0314P_{0.1} + 0,0525P_{1s} + 0,0657P_{3s} + 0,28P_{10s} + 0,08P_{50s}}$$

$$\begin{aligned} P_{50s} &= (P_{30} + P_{50} + P_{80})/3 \\ P_{10s} &= (P_6 + P_8 + P_{10} + P_{13} + P_{17})/5 \\ P_{3s} &= (P_{2.2} + P_3 + P_4)/3 \\ P_{1s} &= (P_{0.7} + P_1 + P_{1.5})/3 \end{aligned} \tag{9}$$

where k_i ith weighting coefficient, P_{xi} CPF curve level exceeds % x_i of the observation period. Here, 0.0314, 0.0525, 0.0657, 0.28 and 0.08 values are the weighting coefficients. $P_{0.1}$, P_1, P_3, P_{10}, and P_{50} factors are the flicker levels exceeding 0.1%, 1%, 3%, 10% and 50% of the observation period time duration. Fifteen supporter evaluation points on CPF are used in order to find the 5 evaluation points [3].

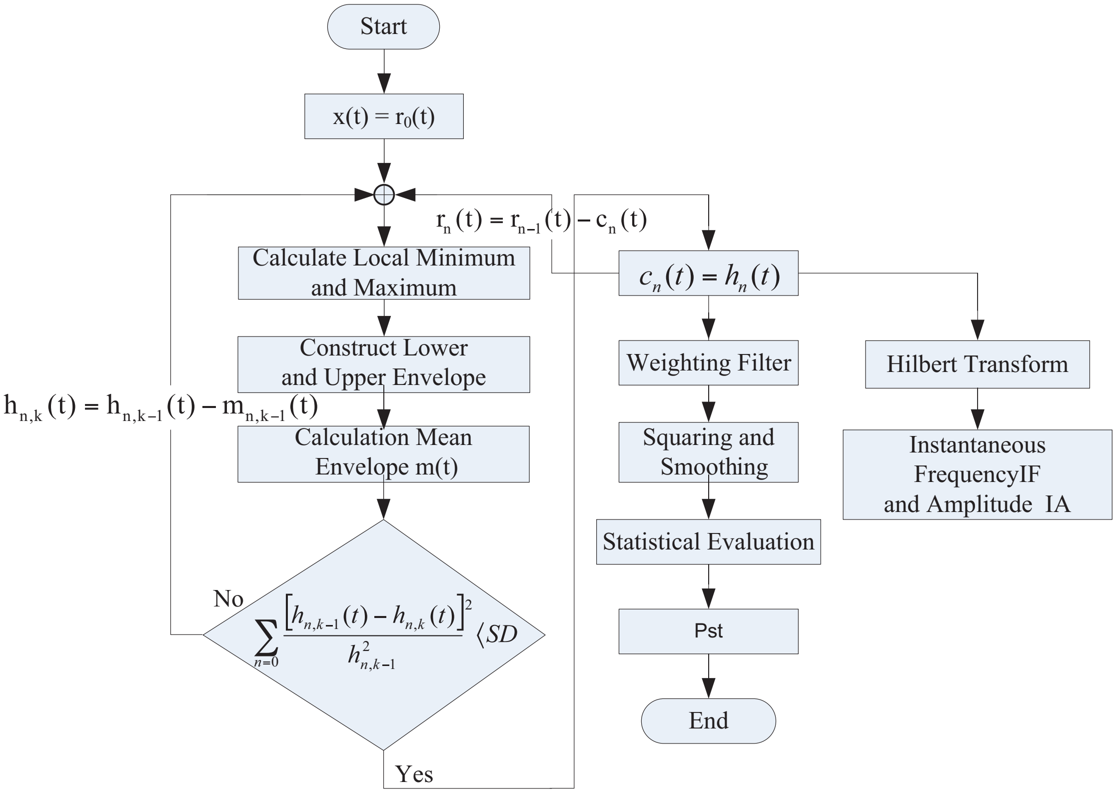

Figure 1. Algorithm of Pst.

4. Simulations

Simulations are performed in Matlab. The flicker-contaminated data was obtained by digitizing a California Instruments, BPS-30, 3-phase, 30 kVA programmable disturbance generator, which was fed with waveform files. The waveform files contain csv data that contains pure sinusoids added by flicker envelopes at various frequency and amplitudes. The IEC responses for sinusoidal fluctuations that result in unity instant flicker level are given for a 230 V/50 Hz system in [3]. Table 1 provides the response of IEC for a 230 V/50 Hz system given in the Flickermeter standard 61000-4-15 [3]. Simulated data are produced at 50 Hz system frequency as given in Eq. (6) with various flicker frequencies and the corresponding d values in Table 1. The short-term flicker severity Pst is calculated according to the IEC-recommended method. Single frequency, multiple frequency, and harmonic flicker signals are tested for the method mentioned above. For all the identified samples, the amplitude of the voltage signal is normalized to unity. Voltage waveform sampling frequency is taken as 10 kHz. Clearly, a sampling frequency above the Nyquist rate is necessary to contain all the necessary information of the analog signal. In our case, the flicker is a subharmonic with a frequency lower than 50 Hz. However, the transient waveform may contain nonsinusoidal shapes, which naturally contain a much higher frequency content. In order to capture all the subtle envelope shape variations and take their effects into account, a high sampling rate of 10 kHz is chosen. It was experimentally observed that the numerical results do not change for higher sampling rates; however, the possibly sharper flicker envelopes were not faithfully reconstructed with sampling rates below 5 kHz. The proportion of flicker amplitude to source signal amplitude m$_i$ is called the flicker amplitude. In order to calculate flicker frequency and amplitude, HT is used after the flicker envelope is obtained. When the flicker component is removed, it is passed through a detectable weighting filter in order to calculate Pst. The obtained signal is passed through squaring and smoothing blocks and the IFL is obtained. Lastly, Pst is obtained by evaluating the IFL statistically.

Table 1. Comparison of IFL values for EMD and SD methods.

f(Hz)	IFL			f(Hz)	IFL		
	d(%)	EMD	SD		d(%)	EMD	SD
5.0	0.398	1.012	1.013	12.0	0.312	0.986	0.986
5.5	0.360	1.016	1.016	13.0	0.348	0.982	0.982
6.0	0.328	1.015	1.016	14.0	0.388	0.976	0.976
6.5	0.300	1.000	1.001	15.0	0.432	0.973	0.973
7.0	0.280	1.000	1,001	16.0	0.480	0.975	0.975
7.5	0.266	1.005	1.006	17.0	0.530	0.975	0.975
8.0	0.256	1.002	1.003	18.0	0.584	0.981	0.979
8.8	0.250	1.000	1.000	19.0	0.640	0.984	0.982
9.5	0.254	1.001	1.002	20.0	0.700	0.990	0.988
10.0	0.260	0.994	0.994	21.0	0.760	0.991	0.987
10.5	0.270	0.994	0.995	22.0	0.824	0.999	0.989
11.0	0.282	0.991	0.992	23.0	0.890	0.998	0.989
11.5	0.296	0.988	0.998	24.0	0.962	1.005	0.995

4.1. Voltage signal with single flicker frequency

The amplitude expression modulated by single flicker frequency is shown in Eq. (10).

$$u(t) = A_0[1 + m\cos(2\pi f t + \phi_1)]\cos(2\pi f_0 t + \varphi_0) \tag{10}$$

Here $A_0 = 1$, $\phi_1 = 0$, $f_0 = 50$ Hz, and $\varphi_0 = 0$. In order to do a simulation analysis similar to real situations, flicker frequency f and amplitude m are adjusted according to the voltage fluctuation value when the IFL is 1. The IFL value is expected to be near 1 at the end of the simulation using values in the Flickermeter standard [3]. Twenty-five frequency components are chosen, which are around the most sensitive 8.8 Hz frequency. The relationship between the chosen flicker amplitude m and voltage fluctuation d is $m = \frac{1}{2\sqrt{2}}d$ [17].

Firstly, the voltage signals with single frequency flickers are taken as $m = 0.176$ and $f = 8.8$ Hz. The voltage signal with a single flicker frequency is given in Figure 2. One gets 6 IMF components IMF1 to IMF6 and residue IMF7 by EMD to the below-voltage signal modulated with a single flicker frequency. The IMF components that are obtained from EMD are shown in Figure 3. To determine the amplitude and frequency of the flicker signal, HT is applied to the second IMF component. These are given in Figures 4 and 5, respectively.

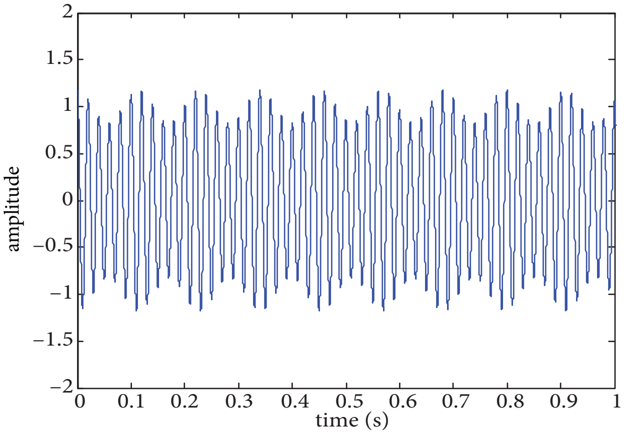

Figure 2. Voltage signal with a single flicker frequency.

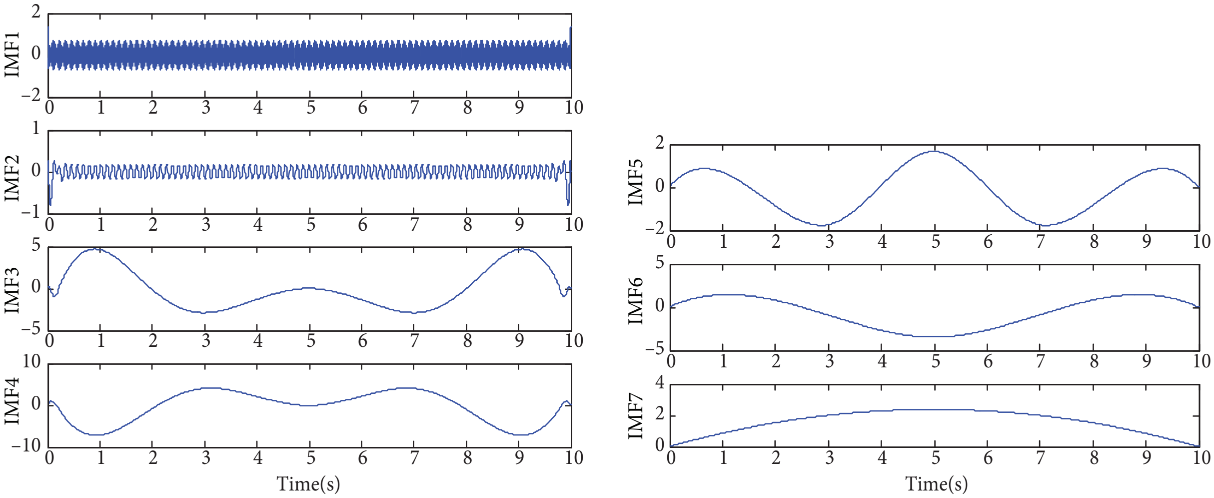

Figure 3. IMF components obtained from EMD.

Secondly, the voltage signals with single frequency flickers are measured using EMD and SD methods. The chosen flicker frequency f, voltage fluctuation, and the IFL values obtained from EMD and SD methods are compared in Table 1. As defined in [3], if IFL values are within the ±5% limits of a unit output of perceptibility, the desired accuracy is obtained. Furthermore, it can be observed that the Pst error percentage values obtained by EMD never exceed those obtained from SD. Consequently, we conclude that EMD method gives more accurate results than SD. These Pst error values are comparatively provided for EMD and SD methods in Figure 6. It can be seen that the Pst error obtained from the EMD method takes values lower than 2% for all flicker frequencies, whereas the Pst error reaches 4.5% for the SD method. The IEC 61000-4-15 standard requires an acceptable error lower than 5%, which is already satisfied by SD. However, for a more accurate analysis, these results show that even a lower Pst error can be easily achieved using the proposed method. The proposed EMD method pushes the envelope-resolving limit to within 1% of 50 Hz, which is far beyond the IEC standards.

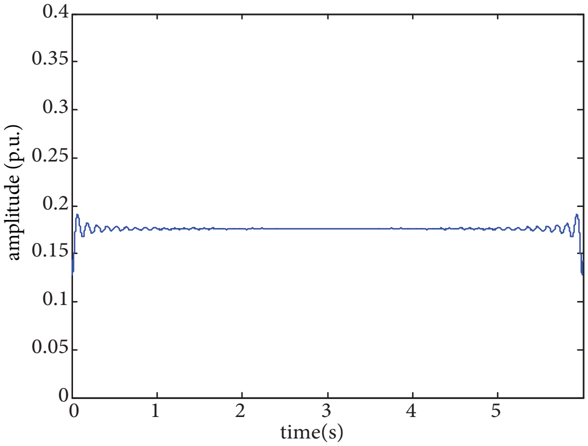

Figure 4. Flicker amplitude signal.

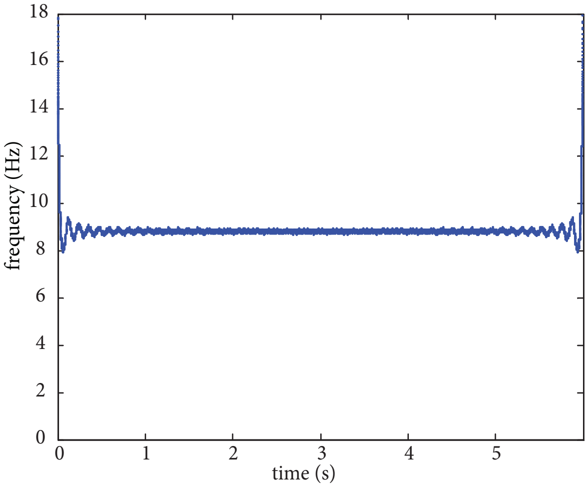

Figure 5. Flicker frequency signal.

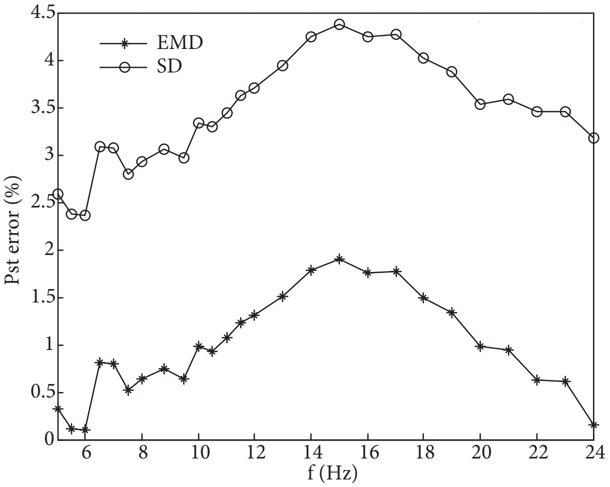

Figure 6. Comparison of Pst error for EMD and SD methods.

4.2. Voltage signal with harmonic component

This section provides a numerical example of a flicker case, which is analyzed under an additive harmonic component. The harmonic component is expected to confuse the numerical value of the flicker amount. For our experiments, the voltage expression is modulated by single flicker frequency and contains a fifth harmonic component as shown in Eq. (11):

$$u(t) = A_0[1 + m\cos(2\pi f_1 t + \varphi_1)]\cos(2\pi f_0 t + \phi_0) + A_5\cos(2\pi f_5 t + \phi_0) \tag{11}$$

Simulations are done by adjusting the values as $A_0 = 1$ V, $m = 0.000884(d = 0.25\%)$, $f_1 = 8.8$ Hz, $\phi_1 = 0$, $f_0 = 50$ Hz, $\phi_0 = 0$, and $A_5 = 0.02$, $f_5 = 250$ Hz.

The applied and measured numerical values of flicker amplitude and frequency are given in Table 2. The percentages of the error are also provided in that table. Here, HT is applied to IMF components and so flicker frequency and amplitude values are evaluated and compared to the constructed true values. The error in amplitude is just 1.36% as compared to the applied value. The frequency error is even smaller at a rate of 0.052598% when compared to the applied frequency value. Combining these values, the Pst error is calculated as 1.6073%.

Table 2. Amplitude and frequency of flicker signal obtained from EMD methods.

Parameter	f (Hz)	m (p.u.)	Pst
Setting value	8.800000	0.000884	0.7092
Measurement value	8.795374	0.000896	0.7208
Error (%)	0.052598	1.361176	1.6073

Despite the confusing effect of harmonics within the line voltage, the flicker component is observed to be very accurately extracted by the proposed EMD method.

4.3. Homogeneity of the suggested algorithm

The IEC 61000-4-15 standard requires a Flickermeter response that has a homogeneous feature. For example, when the d value is two times higher, flicker severity Pst should be two times higher [3]. The homogeneity of the suggested algorithm is controlled by applying the two times or half times of the m value corresponding to flicker frequency given in Table 1 and the results are given in Table 3.

Table 3. Homogeneity test results of EMD methods.

Flicker frequency (Hz)	m (%)	Pst	Pst error (%)
4	0.001768	0.7112	-
	2 × 0.001768	1.4224	0.000
	0.5 × 0.001768	0.3556	0.000
6	0.001160	0.7137	-
	2 × 0.001160	1.4273	0.007
	0.5 × 0.001160	0.3568	0.000
8	0.000905	0.7099	-
	2 × 0.000905	1.4197	0.007
	0.5 × 0.000905	0.3549	0.000
10	0.000919	0.7074	-
	2 × 0.000919	1.4148	0.000
	0.5 × 0.000919	0.3537	0.000
12	0.001103	0.7052	-
	2 × 0.001103	1.4104	0.000
	0.5 × 0.001103	0.3526	0.000
14	0.001372	0.7018	-
	2 × 0.001372	1.4037	0.007
	0.5 × 0.001372	0.3509	0.000
16	0.001697	0.7020	-
	2 × 0.001697	1.4041	0.007
	0.5 × 0.001697	0.3510	0.000
20	0.002475	0.7075	-
	2 × 0.002475	1.4049	0.007
	0.5 × 0.002475	0.3537	0.000

If the suggested algorithm has a homogeneous feature, when the two times and half times of the m value are applied respectively, the Pst value is expected to be two times and half times. As given in Table 3, it is observed that the suggested approach can calculate the Pst value with minor error. The error in this Table is defined as the percentage difference between the value obtained by calculating the two times/half times of Pst and the Pst value obtained by the suggested method when the m value is two times higher and half times lower.

5. Results

In this article, first EMD is used for removing a voltage flicker and then the short-term flicker severity Pst is calculated by a statistical evaluation of the voltage flicker amplitude. EMD is a novel technique that is capable of splitting signal components with different spectral characteristics. The simulation results indicate that this method has pronounced advantages over the existing methods. The advantages are listed below:

1. The method is able to determine frequency and amplitude parameters of the flicker, IFL, and short-term flicker severity Pst extremely accurately within the parametric range of interest.
2. The method is capable of isolating separate flicker components, which gives a great advantage to quantification, unlike the classical square demodulation strategy.
3. Even in cases with normal voltage carrying harmonics, the flicker component could be extracted and accurately measured.
4. Naturally, once the amplitude and frequencies are accurately measured, the short-term flicker severity (P_{st}) is calculated easily and accurately.
5. The proposed Flickermeter algorithm has a homogeneous feature.

References

[1] IEC 61000-3-3-1994. Electromagnetic compatibility (EMC). Part 3: Section 3: Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current max.16A.

[2] Gunther EW. Interharmonics in power systems. In: IEEE 2001 Power Engineering Society Summer Meeting Conference; 15–19 July 2001; Vancouver, BC, Canada: IEEE. pp. 813–817.

[3] IEC 61000-4-15-1997. Electromagnetic compatibility (EMC). Part 4: Testing and measurement techniques. Section 15: Flickermeter-functional and design specifications.

[4] IEEE 1453-2004. Recommended practice for measurement and limits of voltage fluctuations and associated light flicker on AC power systems.

[5] Keppler T, Watson N, Arrillaga J. Computation of the short-term flicker severity index. IEEE T Power Deliver 2000; 15: 1110–1115.

[6] Özgönenel O, Terzi ÜK, Khan A. A hybrid approach for power quality monitoring. Turk J Elect Eng & Comp Sci 2012; 20: 854–869.

[7] Yalcin T, Ozgonenel O, Kurt U. Multi-class power quality disturbances classification by using ensemble empirical mode decomposition based SVM. In: IEEE 2011 Electrical and Electronics Engineering; 1–4 December 2011; Bursa, Turkey: IEEE. pp. I-122–I-126.

[8] Ozgonenel O, Yalcin T, Guney I, Kurt U. A new classification for power quality events in distribution system. Electr Pow Syst Res; 95: 192–199.

[9] Yalcin T, Ozgonenel O, Kurt U. Feature vector extraction by using empirical mode decomposition for power quality disturbances. In: IEEE 2011 Environment and Electrical Engineering; 8–11 May 2011; Rome, Italy: IEEE. pp. 1–4.

[10] Wang T, Zhang M, Yu Q, Zhang H. Comparing the applications of EMD and EEMD on time frequency analysis of seismic signal. J Appl Geophys 2012; 83: 29–34.

[11] Chen MT. Digital algorithms for measurement of voltage flicker. IEE P Gener Transm D 1997; 144: 175–180.

[12] Srinivasan K. Digital measurement of voltage flicker. IEEE T Power Deliver 1991; 6: 1593–1598.

[13] Toivonen L, Mörsky J. Digital multirate algorithms for measurement voltage, current, power and flicker. IEEE T Power Deliver 1995; 10: 116–126.

[14] Zhang R, Xu JF. The application of wavelet in the short-term flicker severity calculation. In: IEEE 2008 Information Science and Engineering Symposium; 20–22 December 2008; Shanghai, Chine: IEEE. pp. 511–514.

[15] Keppler T, Watson NR, Chen S, Arrillaga J. Digital Flickermeter realisation in the time and frequency domains. In: Proc of Australasian Universities Power Engineering Conference; 23–26 September 2001; Perth, Australia: AUPEC. pp. 1–6.

[16] Hong S, Yi W. Detection of voltage flicker based on mathematical morphology filter and Teager energy operator. In: IEEE 2006 Power System Technology; 22–26 October 2006; Chongqing: IEEE. pp. 1185–1190.

[17] Chen Q, Jia X, Zhou C. Analysis on measuring performance of three flicker detecting methods. In: IEEE 2009 Power Engineering Society General Meeting; 26–30 July 2009; Calgary, AB, Canada: IEEE. pp. 1–7.

[18] Abdel-Galil TK, El-Saadany EF, Salama MA. Online tracking of voltage flicker utilizing energy operator and Hilbert transform. IEEE T Power Deliver 2004; 19: 861–867.

[19] Tong W, Yuan S, Li Z, Song X. Detection of voltage flicker based on Hilbert transform and wavelet denoising. In: IEEE 2008 Electric Utility Deregulation and Restructuring and Power Technologies; 6–9 April 2008; Nanjing, China: IEEE. pp. 2286–2289.

[20] Wei X, Xu Y, Xiao X. Parameter estimation of voltage flicker based on Hilbert transform and Pisarenko harmonic decomposition. In: IEEE 2009 Energy and Environment Technology; 16–18 October 2009; Guilin, Guangxi, China: IEEE. pp. 189–192.

[21] Huang NE, Shen Z, Long SR, Wu MC, Shih HH, Zheng Q, Yen NC, Tung CC, Liu HH. The empirical mode decomposition and the Hilbert spectrum for nonlinear and nonstationary time series analysis. P Roy Soc Lond A Mat 1998; 454: 903–905.

[22] Rilling G, Flandrin P, Gonvalves P. On empirical mode decomposition and its algorithms. In: IEEE 2003 Workshop on Nonlinear Signal and Image Processing; June 2003; Grado, Italy: IEEE. pp. 1–5.

[23] Yang C, Dong S, Tong Z, Wan Y. Analysis and research of the transient composite disturbance signal of power system based on HHT. In: IEEE 2008 Intelligent Information Technology Application Workshops; 21–22 December 2008; Shanghai, China: IEEE. pp. 1029–1032.

[24] Yu J, Yang L. Analysis of harmonic and inter-harmonic based on Hilbert Huang transform. In: IEEE 2009 Computational Intelligence and Software Engineering; 11–13 December 2009; Wuhan, China: IEEE. pp. 1–4.

[25] Baykut S, Akgül T, Ergintav S. EMD based analysis and denoising of GPS data. In: IEEE 2009 Signal Processing and Communications Applications Conference; 9–11 April 2009; Antalya, Turkey: IEEE. pp. 644–647.

[26] Jia X, Chen Q. A method of tracking voltage flicker envelope real-time. In: IEEE 2009 Power & Energy Society General Meeting; 26–30 July 2009; Calgary, AB, Canada: IEEE. pp. 1–6.