Identification of Flicker Source Using Continuous Wavelet Transform

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Abstract— **In this paper, a method based on continuous wavelet transform is suggested for calculation of flicker power. The flicker power can be utilized to identify the flicker direction to a flicker source with respect to a monitoring point. In our proposed method, using continuous Gaussian wavelet transform, pure flicker waveforms are extracted from the measured voltage and current signals. The flicker power can then be calculated. The direction to a flicker source is obtained from the sign of this flicker power. The proposed algorithm is tested using IEEE 13 Node Test Feeder. The simulation results validate the effectiveness of the proposed method.**

Keywords- Power quality; Flicker direction; Flicker power; Continuous wavelet transform.

I. INTRODUCTION

Voltage flicker is created due to fast load variations in power systems. Motors, electric welders, rolling mills, electric arc furnaces and wind turbines are the main resources of the flicker [1]-[3]. Random variations of these loads results in a waveform with irregular envelop. The frequency of the flicker waveform is lower than system frequency (between 0.5 to 35 Hz) and its amplitude fluctuates between 90 to 110 percent of nominal voltage [4]. These voltage changes may result in light fluctuations and noise in television broadcasting and some effects on ICU and CCU systems [5]. The voltage flicker may exist in any power grid. The measured flicker level at the point of common coupling (PCC) is sum of the flicker level from the different sources. In costly mitigation processes, it is essential to trace the dominant flicker source. Many techniques have been applied to determine flicker contributions at the PCC. In [6], the low frequency variations of the PCC voltage and the load current are represented by the complex phasors. The phasor of the load current are then decomposed into a conforming current phasor which is in phase with the voltage phasor and a non-conforming current phasor represents the rest of the load current. If the network is assumed linear, the flickers related to the conforming and non-conforming currents are originated from the network side and the load side, respectively. One possible disadvantage with this method is that it requires a phase sensitive measurement, which is quite difficult to obtain with high accuracy. Flicker direction in [7] and [8] is determined by calculating flicker power and its sign. There are some deficiencies in this method which can lead to improper results, e.g. the method uses square [7] and envelope detectors [8] for demodulation process. These demodulation methods are non-linear operations and produce unwanted signal components within the flicker frequency range and consequently the flicker power cannot be calculated accurately.

In this paper, a new method is proposed to solve the above problems. The method uses the wavelet transform which is an appropriate tool to analyze non-stationary signals and power quality disturbance analysis [9], [10]. Gaussian Continuous Wavelet Transform (CWT) will be used to determine amplitude and frequency of voltage and current flicker waveforms. These values will then be utilized to calculate flicker power and to identify the flicker source. Some useful features of the proposed method are listed below:

- It does not produce unwanted signal components within the flicker frequency rang.
- The computational burden is reduced.
- The method can deal both frequency and time domain information simultaneously and with proper resolution.
- If the measured signal contains several flicker waves with different frequencies, amplitude and frequency of each wave can easily determine separately.
- Besides determining flicker direction, knowing the flicker sensitivity coefficients, the method owns the potential of being extended to calculate severity of the flicker (ΔV_{10}) and compare it to the standard values.

The paper is organized as follows: section II outlines the wavelet transform, section III presents wavelet demodulation procedure, section IV demonstrates the flicker direction determination approach, section V shows the simulation results and section VI draws the conclusions.

II. WAVELET TRANSFORM

With the advent of wavelet transform, this technology is being comprehensively applied in electrical power engineering. This emerging technology does not have the drawbacks of Fast Fourier Transform (FFT) where a window is used uniformly for spreaded frequencies. The wavelet transform presents a multi-resolution analysis and uses short windows at high frequencies and long windows at low frequencies to more closely monitor the characteristic of non-stationary signals such as voltage flicker generated signals. Given $x(t)$ as a time variable signal, the continuous wavelet transform is derived as (1) [11]:

$$CWT(\tau, a) = |a|^{-\frac{1}{2}} \int_{-\infty}^{+\infty} x(t)\,\Gamma^{*}\left(\frac{t-\tau}{a}\right)dt \qquad (1)$$

where τ and a are the translating and the scaling parameters, respectively. Also, $\Gamma(t)$ is the wavelet function and $\Gamma^*(t)$ is the complex conjugate of $\Gamma(t)$. Wavelet functions should have limited energy and hence the function of $\Gamma(.)$ should satisfy the requirements of (2) [11]:

$$\int_{-\infty}^{+\infty} \Gamma(t)dt = 0 \tag{2}$$

Various wavelet functions such as Symlet, Morlet and Daubechies have been proposed to analyze different power system phenomena. The selection of the wavelet function should be performed based on its application and the features of the signal which will be processed. In this paper, Gaussian wavelet was selected as the wavelet basis function for flicker study. Gaussian wavelet has exponential form and is symmetric around zero and more important satisfies (2) such that the orthogonality can be guaranteed. Moreover, the Gaussian wavelet transform is more convenient in analyzing various frequency components of a signal [12]. The formulation of this function is given as below [1]:

$$\Gamma(t) = \exp(j2\pi F_0 t - 0.5t^2) \tag{3}$$

where F_0 is the wavelet function frequency. F_0 is determined based on the requirements and it is assumed *25π* in this paper.

III. WAVELET DEMODULATION PROCEDURE

The behavior of the voltage flicker can be cyclic, stochastic or chaotic. Nevertheless, in a short period, the voltage flicker can be approached by an amplitude modulation formula where the modulating signal is a sinusoid of random frequency and random magnitude [13]. With this assumption, a voltage flicker signal can thus be represented by (4):

$$\begin{aligned} v(t) &= \sqrt{2}V_{rms}\left[1 + \sum k_n \sin(2\pi f_n t + \varphi_n)\right]\times \\ \sin(2\pi f t + \varphi) &= \sqrt{2}\,V_{\mathrm{rms}} \sin(2\pi f t + \varphi) \\ &+ \sum \frac{k_n V_{rms}}{\sqrt{2}} \cos\left[2\pi(f - f_n)t + \phi_n^-\right] \\ &- \sum \frac{k_n \mathrm{V}_{\mathrm{rms}}}{\sqrt{2}} \cos\left[2\pi(f + f_n)t + \varphi_n^+\right] \end{aligned} \tag{4}$$

where f is the fundamental frequency, f_n is the flicker frequency, k_n is the magnitude of voltage flicker at the frequency f_n (modulating depth) and φ and φ_n are the phase angles of frequencies f and f_n, respectively. Given a signal sampled at the interval T_s for the duration of T_{ds}, the number of samples will be $N_{ds} = {}^{T_{ds}}\!/\!_{T_s}$ and the sampling frequency is $f_s = {}^{1}\!/\!_{T_s}$. As the wavelet function and the signal are sampled with the same frequency f_s, then the duration will be T_{dw} ($T_{dw} = N_{dw}.T_s$) where the total number of the wavelet function samples is N_{dw}. With these parameters, the discrete version of the wavelet transform can be expressed as follow [1]:

$$CWT(a, T_s) = T_s . \sum_{n=1}^{N_a} v(n.T_s).\Gamma^*\left[\frac{nT_s}{a} - \frac{N_{dw}.T_s}{2}\right] \tag{5}$$

where $v(nT_s)$ is the sampled version of $v(t)$, $\Gamma(nT_s)$ is the sampled signal of the wavelet function and $N_a = N_{dw}.a$. In the study, T_{ds} and T_{dw} are selected to be 2π. In order to assess the flicker components, the system frequency should first be determined. For doing this, the first step is to calculate a_k values through (6), where k is an integer value between 1 to ${}^{(f_h - f_l)}\!/\!_{f_{ru}}$. f_h and f_l indicate the maximum and minimum of the system frequency respectively, and f_{ru} is the frequency resolution [1]. In the study, if $f_{ru} = 0.01Hz$, $f_h = 60.5Hz$ and $f_l = 59.5Hz$, the value of k starts from 1 to 100.

$$a_k = \frac{F_0}{f_l + kf_{ru}} \tag{6}$$

Having a_k values, CWT can be calculated for each a_k and then A_k values are computed using (7) [1]:

$$A_k = \frac{(a_k)^{\frac{1}{2}}\left|CWT(a_k)\right|}{T_{dw}} \tag{7}$$

After all A_k are calculated, for the maximum A_k, its corresponding frequency will be the system frequency.

Knowing the system frequency, the amplitude and phase angle of this frequency component can be computed by comparing the original signal *CWT* with the *CWT* of a hypothetical signal. The hypothetical signal is a wave with the system frequency and a zero phase angle. After the amplitude and the frequency of the base component of the original signal are determined, the base component wave can be subtracted from the original signal and then the pure flicker wave is computed. The values of a_k for the pure flicker wave are computed using (8) [1]:

$$a_k = \frac{F_0}{f + k_f f_{rf}} \tag{8}$$

where f_{rf} is the flicker frequency resolution and k_f is an integer varies from 0 to ${}^{30}\!/\!_{f_{rf}}$. As *CWT* is calculated for these a_k values, there is a lobe at the frequency component of the flicker wave. Flicker frequency can be determined based on this lobe. If flicker wave contains multiple frequencies, the lobes are created at each frequency. After the flicker frequencies are obtained, the flicker frequency components amplitudes and phase angles are ready to be computed. For doing this, the *CWT* coefficients for a hypothetical wave with predetermined flicker frequency and amplitude equal to the system frequency component amplitude and a zero phase angle should first be computed. Dividing the CWT coefficients of the extracted flicker wave by the CWT of the hypothetical wave results the per unit values of the flicker frequencies amplitude as well as the flicker frequencies phase angles. The computed phase angle is φ_n^- in (4). This procedure can be repeated using a_k values of (9) and values of φ_n^+ is also determined.

$$a_k = \frac{F_0}{f - k_f f_{rf}} \tag{9}$$

Now, the amplitudes and the phase angles as well as the frequencies of the flicker components are obtained and the voltage envelop (voltage fluctuations) can then be completely determined. Similar process can be applied to the measurement current signal at the monitoring point in order to specify the current envelope. Flicker power can be calculated according to these envelops.

IV. FLICKER DIRECTION DETERMINATION

Consider the network shown in Fig.1. If the flicker source is placed at node 1 (Downstream of the monitoring point M), the voltages drops on z_s and z_t increase while flicker load current increases and also decrease while flicker load current decreases. Hence the voltage and current envelops are in opposite phase.

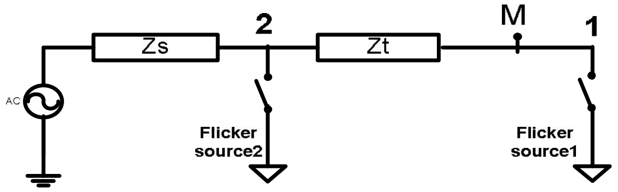

Fig.1 – a network with flicker source

Now, if the flicker source is located at node 2 (Upstream of the monitoring point M), the monitoring point current increases when node 2 voltage increases and decreases when that voltage decreases. Consequently, voltage and current envelops are in phase. Assume that $m_u(t)$ and $m_i(t)$ are voltage and current envelopes respectively, the flicker power can be computed using (10) [8]:

$$P_{FL} = \frac{1}{T}\int_0^T m_u(t).m_i(t)dt \tag{10}$$

The flicker source is placed upstream in proportion to monitoring point, if the sign of the flicker power is positive, and it is located downstream with respect to the monitoring point if the flicker power sign is negative. More details are presented in [7] and [8].

V. SIMULATION RESULTS

To validate the feasibility of the proposed method, a flicker source is located at node 632 of IEEE 13 Bus Test Network and voltage and current waves are analyzed in two monitoring points. The monitoring points are node 632 and 645 as shown in Fig.2. The flicker source is a fluctuating load. The proposed method has been implemented in MATLAB environment.

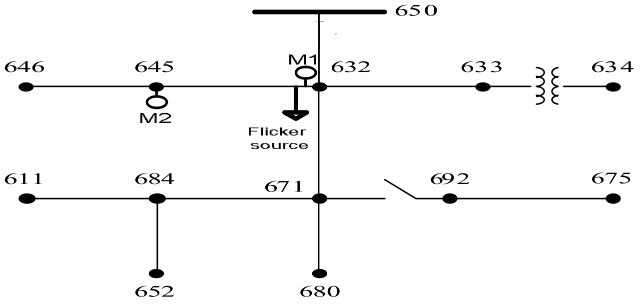

Fig.2 – 13 node test feeder

A. Monitoring Point M1

Typical voltage and current waveforms at point M1(with 14Hz flicker) are shown in Fig.3 and Fig.4, respectively. It is clear that voltage and current envelops are in opposite phase. The system frequency, amplitude and phase angle was obtained from the measured signal by the proposed method. CWT coefficients for the pure voltage flicker wave are shown in Fig.5a. Fig.5b shows the CWT coefficients for a hypothetical 14Hz flicker wave with magnitude equal to the system voltage and a zero phase angle. The result of dividing CWT of the pure flicker wave (Fig.5a) by the CWT of the hypothetical wave (Fig.5b) is the flicker amplitude in per unit. The similar process can be applied to the current wave. Fig.6a and Fig.6b show the results. After calculating the voltage and current envelopes, the flicker power can be determined from the expression (10). The results for some cases are presented in Table I. As it is seen, the flicker power is negative and shows that the flicker source has been located downstream with respect to the monitoring point *M1*.

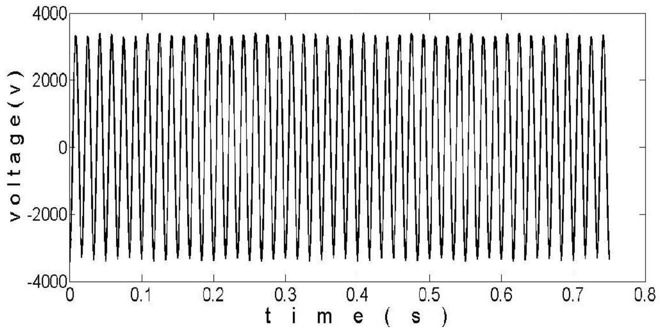

Fig.3- voltage waveform in M1

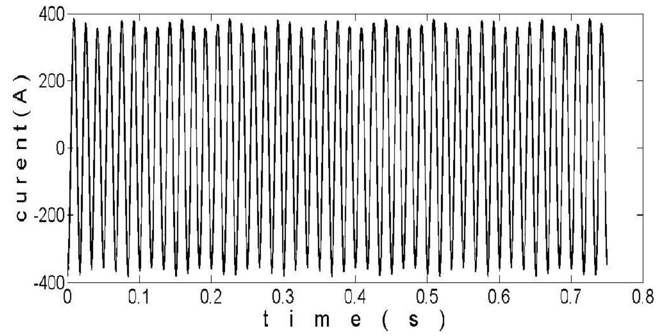

Fig.4- current waveform in M1

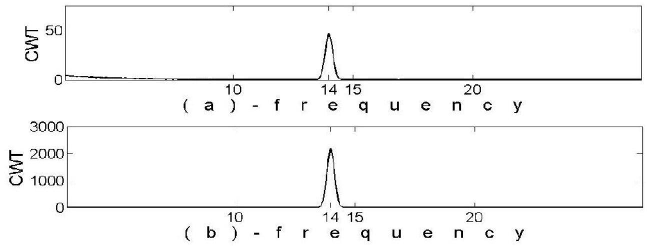

Fig.5- CWT coefficients for M1 voltage

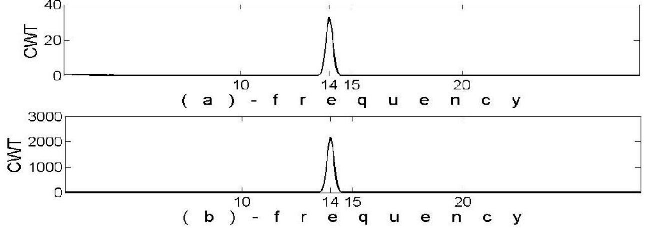

Fig.6- CWT coefficients for M1 current

TABLE I- Results in monitoring point M1

f_{system}	v_{system}	$v_{flicker}$	i_{system}	$i_{flicker}$	$f_{flicker}$	$power_{flicker}$
59.58	3435.11	52.1	371.25	12.07	10	-375.8
60.1	3350.51	50.5	386.65	20.35	14	-903.18
60.4	3437.18	62.11	320.13	14.22	7	-208.27

B. Monitoring Point M2

In this case, the monitoring point is located at M2. Voltage and current waveforms are shown in Fig.7 and Fig.8, respectively. As it can be seen, voltage and current envelops are in phase. Fig.9 and Fig.10 are CWT coefficients for the voltage and current waveforms at monitoring point, respectively. As seen, a lobe is created at 14Hz again. Table II shows the results for some cases. The flicker power is positive which shows that the flicker source has been placed upstream with respect to the monitoring point.

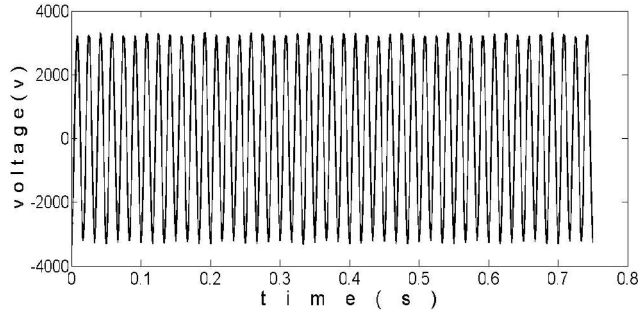

Fig.7- voltage waveform in M2

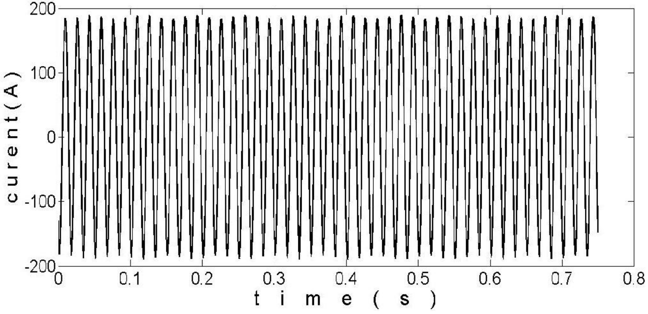

Fig.8-current waveform in M2

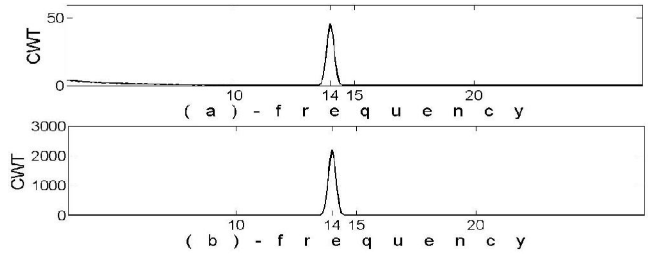

Fig.9 - CWT coefficients for M2 voltage

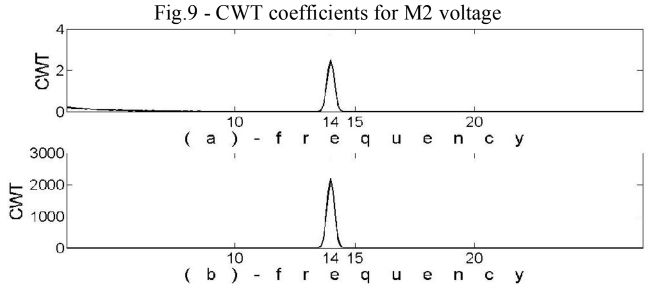

Fig.10 - CWT coefficients for M2 current

TABLE II -Results in monitoring point M2

f_{system}	v_{system}	$v_{flicker}$	i_{system}	$i_{flicker}$	$f_{flicker}$	$power_{flicker}$
59.85	3260.11	40.31	142.32	4.21	11	101.65
60	3374.51	33.53	143.85	5.11	18	142.54
60.32	3387.8	50.31	148.27	5.21	5	85.81

VI. CONCLUSIONS

In this paper pure flicker wave was extracted from the monitored signal using Gaussian wavelet transform and the flicker frequency and amplitude were defined. Then, the flicker power was computed and direction to a flicker source was traced using the flicker power sign. If the flicker power sign is negative, the flicker source is located downstream with respect to the monitoring point and if the power sign is positive, the flicker source is placed upstream. The Proposed method was tested on IEEE 13Node Test Feeder. Simulation results show that the suggested approach is a suitable and more applicable method to determine the flicker source direction.

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