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TWO-FREQUENCY VOLTAGE FLICKER ESTIMATION USING FUZZY LOGIC

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ABSTRACT

One of the crucial power quality problem is the voltage flicker. It is normally caused by rapidly occurring voltage fluctuations caused by sudden and large increases in the load current. This paper presents tracking technique of two voltage flicker signals occurring in electric power systems. A voltage flicker model consisting of two distinct flicker frequencies, amplitudes and phases is used for estimating the flicker signals. A discrete time linear dynamic state space model is adapted for Kalman filter to estimate the flicker parameters. Kalman filtering technique in conjunction with fuzzy rule-based logic are used to estimate the instantaneous voltage flicker magnitudes, frequencies and phases of the two flicker signals. The system and measurement covariance matrices are tuned up using a set of fuzzy logic rules to adjust their noise levels.

KEY WORDS

Power quality, Voltage flicker, Kalman Filter, Multiple flicker and Fuzzy logic.

1. Introduction

Electric power quality not only has great importance to electric distribution utilities but it also has become very crucial to many power users. Nowadays, modern electrical and electronic equipment are used in almost all amenities from governmental to commercial and educational institutions. Sensitive electrical and electronic equipment are exposed to a wide range of power quality problems. An extremely important power quality problem is the voltage flicker which is normally caused by rapidly occurring voltage fluctuations caused by sudden and large increases in the load current. Voltage flicker is generally caused by rapidly varying loads that has continuous variations in load current such as arc furnaces, welders, sawmills, and wood chippers. Equipment such as microprocessor based controls, and power electronics devices are sensitive to many types of electric disturbances. The effect of such disturbances are costly, it causes possible misoperation of control systems, incur production losses, lock up computers and loss of data.

Evident relation between voltage deviation and light response led to the following definition. Voltage flicker is defined as changes in the brightness of a lamp as perceived by the human eye. It is a measure of the human impression and feeling of comfort as the light fluctuates. Lamp flicker exceeding a particular level can become annoying and irritating the human eye. Voltage deviations on the order of a 0.5 percent could produce extremely annoying fluctuations in the output of lights, especially if the flicker frequency is 5-15 Hz values. The accepted level of voltage flicker that prevents population annoyance has been established many years ago. A flicker at the frequencies of a few Hz can be caused by common devices such as motor starting, and heaters in large capacity printers and photocopiers causing lights to dim and electrical and electronic devices such as computer equipments to lock up or restart and lose memory. Flicker mitigation equipment as well as many flicker testing equipment has been designed according to the IEEE 1453-2004 standard [1]and IEC 61000-4-15 standard [2], which define limits for the flicker voltage fluctuations . Both are intended to ensure that equipments connected to the same supply network do not cause annoyance to neighboring residential consumers. The magnitude of these voltage fluctuation depends on changes in the current consumed by the device causing the flicker. Most common voltage flicker sources are arc furnaces and arc wilders in steel fabrication plants which generally take large currents. It also may normally caused by variable loads on large motors, the switching of large heaters on and off, medical imaging machines such as MRI and X-Ray, and consumption of heavy currents by large amplifiers or lights.

A survey of flicker analysis and methods for electric arc furnace is presented in [3]. The maximum values of interharmonics to be allowed before they produce objectionable flicker are developed in [4]. In [5] a meter for voltage fluctuation are categorized, and the digital algorithms used to calculate voltage flicker are discussed and the use of fast Fourier transform to analyze the spectrum of voltage fluctuation signals is examined. An arc furnace model is developed in [6]. Fast Fourier transform (FFT) techniques are used to measure voltage flicker levels of stationary signals [7, 8]. Least absolute value (LAV) state estimation technique [9], the Kalman filtering technique (KF) [10] are also used for flicker estimation. The LAV technique assumes the flicker frequency is known in advanced; however, in practice, this assumption is not necessarily true. Due to the nonlinear nature of the flicker signal the KF technique does not provide an accurate adjustment of its model parameters and it suffers from heavy computational burden. Wavelets transform technique is also used to analyze voltage flicker [11, 12]. As in the case of KF, wavelets techniques suffer from the high computation and it also has a major difficulty of deciding on candidate wavelets. The Teager energy operator and Hilbert transform are both used to track voltage flicker in the presence of deviation of supply frequency [13]. However, the technique suffers of instability when the input voltage has high frequency components. A combined fuzzy-Kalman Filter approach to model flicker signal using extended state space model and rule-based fuzzy logic to tune the noise levels is developed in [14].

This paper estimates flicker consisting of two distinct sinusoidal signals that may occur due to different flicker sources hocked simultaneously to the system network. The proposed technique is an extension for the flicker tracking developed by the author in [14]. Basically, the two flicker signals are modeled as discrete time linear difference equation that has two distinct sinusoid flicker signals with two amplitudes, two frequencies and two phases as parameters. An extended discrete time state space model that extends the state vector with the system parameters as additional states is adapted for Kalman filter to estimate the parameters. Fuzzy rule-based logic is employed to tune up the system and measurement noise levels by adjusting their covariance matrices using flicker measurements. The model considers measurements as fuzzy values each belongs to a fuzzy set of values represented by triangular membership function.

2. Voltage Flicker Model

Voltage flicker appears as a modulation of the system waveform, similar to an amplitude modulated radio signal. Eq.(1) shows a system signal Eq.(2) modulated with a random flicker signal Eq.(3).

$$y(t)=(A_0+A_1\cos(\omega_1 t+\theta_1)+A_2\cos(\omega_2 t+\theta_2))\cos(\omega_0 t+\theta_0) \quad (1)$$

$$y_s(k)=A_0\cos(\omega_0 t+\theta_0) \quad (2)$$

$$y_f(k)=A_1\cos(\omega_1 t+\theta_1)+A_2\cos(\omega_2 t+\theta_2) \quad (3)$$

where A_0, ω_0, and θ_0 are a *constant* system parameters representing system amplitude, frequency and phase angle, respectively. A_i, ω_i, and θ_i , i=1,2, are the voltage flicker amplitudes, frequencies and phase angles, respectively. A typical one-frequency waveform is shown in Fig. 1. A two-frequency flicker signal is illustrated in Fig. 2 with

$$y(t)=2.0\ \cos(2\pi(50)t+\pi/6)\,[1+0.03\cos(2\pi(4)t+\pi/6)$$
$$+0.05\cos(2\pi(2.5)t+\pi/4)\,]$$

t is in msec. The two-frequency flicker signal in Fig. 2 shows more irregular waveform envelope than that in Fig. 1. due to the two distinct signals comprising the flicker voltage.

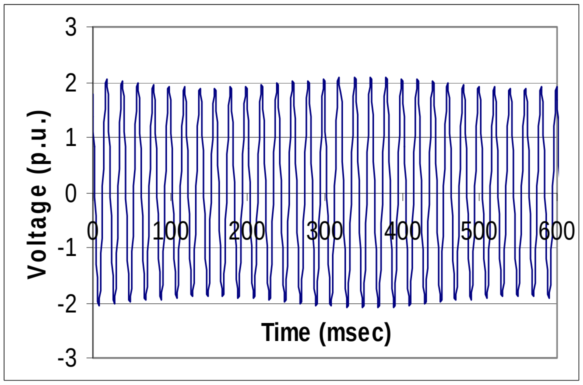

Figure 1. Typical Flicker Voltage Waveform *y(t)*

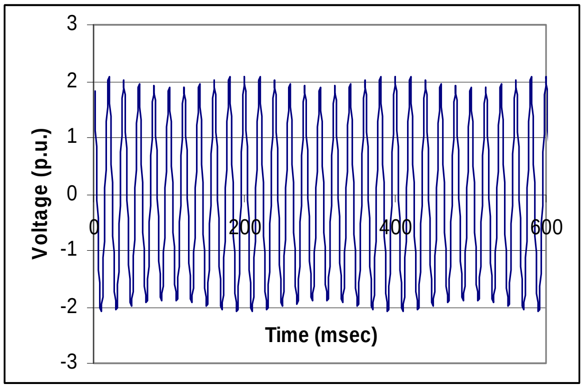

Figure 2. Two-Frequency Flicker Signal.

3. Parameter Estimation Using Kalman Filtering

Kalman Filter Algorithm is a well-established technique for estimating the parameters of stationary random processes. It is suitable for estimating stochastic processes producing optimal estimates in the presence of noise. It formulates the parameter estimation problem as state-space dynamic equations that include system as well as measurement uncorrelated Gaussian white noises. The estimates produced are optimized in the least square sense by minimizing error equations containing covariance matrices of both noises. Definitions of the basic filter and its adaptation for flicker estimation could be found in [14]. The state space dynamic system is used with the following definitions:

State transition matrix, A(k), defined in Eq.(7). The covariance error matrices, Q(k) and G(k), are diagonal positive semi-definite and positive definite matrices, respectively. They are adjusted using rule-based fuzzy logic described in Section 4.

The state vector, x(k), consists of seven variables described in Eq. (7). They are two system states and five flicker voltage parameters.

The output matrix C(k) is 1x7 time varying vector, described in Eq.(7). It relates the measurement flicker voltage to the system states.

4. Fuzzy Rule Based Inference

Electric voltage flicker depends on a collection of unpredictable operating and load conditions. When it occurs, it produces a nonlinear behavior on the system voltage and frequency manifested as the voltage flicker. Moreover, any parametric model that strives to track voltage flicker is affected by inevitable sudden load conditions that are modeled as sudden varying random noise. In this section, the state space flicker model parameters Eq. (7) are estimated using Kalman filter with white noises. However, fuzzy rule-based logic is used to tune the level of the flicker model noises Q(k) and G(k). No matter how much effort is applied to strive for an accurate flicker model there always exist un-modeled factors or uncertainties that affect the dynamics of the state model. Such factors are compensated by introducing system and measurement white noises, w(k) and v(k), respectively. However, these noises change in magnitude according to the variations in the power system conditions and load. Fuzzy logic is used to tune up noises levels by adjusting the covariance matrices Q(k) and G(k), respectively. The inputs of the fuzzy logic machine are the measurements: the flicker voltage yf(k) and its rate of change $\dot{y}_f(k)$. The outputs of the fuzzy machine are the diagonal elements of the covariance matrices Q(k) and G(k).

From the measurement equation of state model Eq.(7), $y_f(k)$ has direct relation with model states. Therefore, sudden noises states are compensated using the system error matrix *Q(k)*. The fuzzy rules for tuning q_{ii}, i= 1, 2, …, 13, according to $|y_f(k)|$ are summarized in Fig. 2.

If (|$y_f(k)$| is Small) then (q_{ii} is Small).
If (|$y_f(k)$| is Medium) then (q_{ii} is Medium).
If (|$y_f(k)$| is Large) then (q_{ii} is Large).

Figure 3. Inference fuzzy rules for Covariance *Q(k)* affected by magnitude of flicker voltage.

Table 1
Input-Output Fuzzy Logic Rules for g_{ii}.

		$\lvert\dot{y}_f(k)\rvert$		
		S	**M**	**L**
$\lvert y_f(k)\rvert$	**S**	VS	M	L
	M	S	L	L
	L	M	L	VL

Sudden peak level noise in measurement is compensated using the measurement covariance matrix *G(k)*. The fuzzy rules for tuning g_{ii}, i= 1, 2, … , 13, according to $|y_f(k)|$ and $|\dot{y}_f(k)|$ are illustrated in summarized in Table 1.

The above rules are formed and reflect our experimental experience of the voltage flicker waveforms and their noises. Typical voltage flicker envelope such as the one presented in Fig. 1 shows that there is a greater dependency of sudden noises on the rate of change of measured flicker waveform rather than on the changes in the flicker voltage itself. Accordingly, the fuzzy rules of Table 1 are established emphasizing $|y_f(k)|$ over $|\dot{y}_f(k)|$.

5. Simulation Results

To illustrate the proposed flicker model of Section 2 and the fuzzy ruled-based Kalman filter technique of Section 4 we use simulated flicker waveform Eq.(4) having 50 Hz system frequency, 240 volts amplitude, and π/4 radians phase angle. The fore mentioned parameters are known constant system parameters. The modulating flicker waveform is chosen to have two sinusoid signals: (10 volts, 5 Hz, π/6 ≈0.5236 radians) and (20 volts, 6 Hz, π/5 ≈0.6283 radians), respectively.

Kalman algorithm is used to estimate the three flicker signal parameters (A_1 , f_1, and φ_1) and (A_2 , f_2, and φ_2).

$$y_f(t) = 10\ \cos(2\pi(2.5)t + \pi/6)] + 20\cos(2\pi(6)t + \pi/5) \tag{4}$$

The state space model of Eq.7 is used to estimate the parameters. Starting with zero initial conditions, sample of the Kalman filter iterations is illustrated in Table 2. Fig. 3, 4, and 5 illustrate the convergence of the system states and parameters. After 6000 iterations, which corresponds to 30 seconds (T=0.005 sec), the estimated six flicker parameters (A_1 , f_1, and φ_1) and (A_2 , f_2, and φ_2) are computed using the definitions of Eq.(4) to be (9.99966, 5.03818, 0.52359) and (19.99933, 15.00046, 0.62832), respectively.

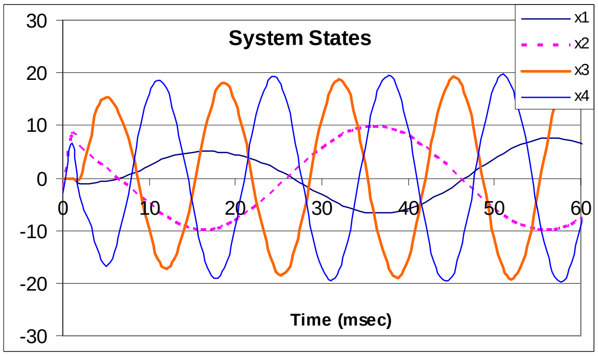

Figure 3. Convergence of System States

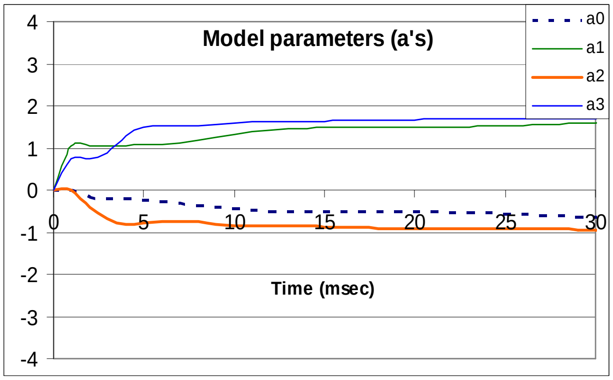

Figure 4. Convergence of Model Parameters (a's)

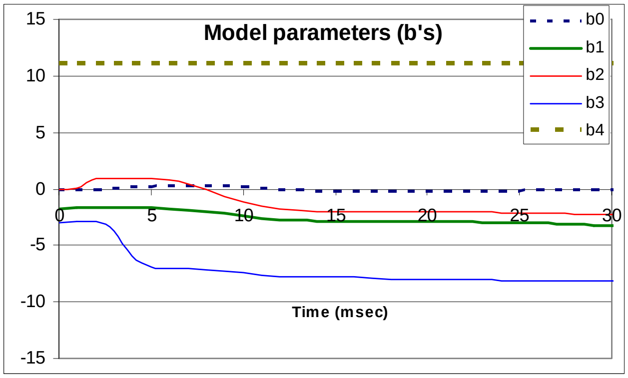

Figure 5. Convergence of Model Parameters (b's)

Table 2
Sample of the Kalman Filter Iterations for Parameter Estimation.

k	x1	x2	x3	x4	a0	a1	a2	a3	b0	b1	b2	b3	b4
0	0.000	-1.800	0.000	-2.960	0.000	0.000	0.000	0.000	0.000	-1.800	1.732	-2.960	2.427
1	0.000	1.505	0.000	1.607	0.000	0.968	1.180	-0.968	0.000	-1.241	1.732	-2.474	2.427
2	-0.062	1.196	0.000	-0.624	-0.458	0.947	1.093	-0.947	-0.027	-1.229	1.732	-2.404	2.427
3	-0.079	0.923	0.892	-1.603	-0.655	0.937	1.177	-0.937	0.004	-1.223	1.732	-2.472	2.427
4	-0.074	0.659	1.737	-2.398	-0.716	0.932	1.390	-0.932	0.024	-1.220	1.732	-2.644	2.427
5	-0.057	0.393	2.022	-2.769	-0.682	0.931	1.493	-0.931	0.041	-1.220	1.732	-2.728	2.427
6	-0.027	0.128	1.922	-2.285	-0.674	0.936	1.500	-0.936	0.055	-1.223	1.732	-2.733	2.427
7	0.016	-0.132	1.471	-1.200	-0.693	0.950	1.498	-0.950	0.065	-1.231	1.732	-2.732	2.427
8	0.075	-0.387	0.675	0.146	-0.728	0.977	1.509	-0.977	0.066	-1.246	1.732	-2.740	2.427
9	0.147	-0.643	-0.361	1.432	-0.768	1.016	1.534	-1.016	0.056	-1.269	1.732	-2.760	2.427
10	0.224	-0.905	-1.416	2.386	-0.803	1.065	1.567	-1.065	0.035	-1.297	1.732	-2.787	2.427
11	0.296	-1.168	-2.198	2.815	-0.822	1.114	1.596	-1.114	0.007	-1.325	1.732	-2.810	2.427
12	0.354	-1.417	-2.478	2.621	-0.826	1.156	1.610	-1.156	-0.022	-1.349	1.732	-2.821	2.427
13	0.396	-1.635	-2.204	1.834	-0.825	1.184	1.611	-1.184	-0.047	-1.366	1.732	-2.823	2.427
14	0.423	-1.806	-1.461	0.627	-0.829	1.201	1.612	-1.201	-0.064	-1.376	1.732	-2.823	2.427
15	0.439	-1.922	-0.394	-0.723	-0.840	1.210	1.617	-1.210	-0.074	-1.380	1.732	-2.828	2.427
16	0.447	-1.979	0.793	-1.912	-0.856	1.213	1.629	-1.213	-0.079	-1.382	1.732	-2.837	2.427
17	0.447	-1.979	1.845	-2.681	-0.870	1.214	1.644	-1.214	-0.080	-1.383	1.732	-2.849	2.427
18	0.440	-1.924	2.501	-2.862	-0.877	1.213	1.655	-1.213	-0.079	-1.382	1.732	-2.858	2.427
19	0.426	-1.819	2.600	-2.413	-0.878	1.213	1.659	-1.213	-0.076	-1.382	1.732	-2.862	2.427
20	0.405	-1.666	2.129	-1.429	-0.877	1.214	1.660	-1.214	-0.072	-1.383	1.732	-2.862	2.427

6. Conclusion

The paper presented a new technique for tracking two-frequency voltage flicker sinusoid signals. The voltage flicker signals are modeled as a discrete time linear dynamic system with flicker voltage parameters. An extended state space model is adapted for Kalman filter to estimate the parameters. Fuzzy rule-based logic is used to tune up the system and measurement noise levels by adjusting their covariance matrices using flicker voltage and its rate of change measurements. The simulation results show the convergence of the estimated parameters using Kalman filter iterations. The resulted estimated parameters values are very close to the original values.

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