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Improving Three Voltage Envelope Tracking Methods for Detecting Flicker Tones

Jalal Khodaparast, Ali Dastfan

Shahrood University of Technology

ABSTRACT

Envelope tracking is a necessary part of flicker meter, flicker sources detection, and flicker compensation. (In this paper three proposed method for tracking of all existing tones in voltage envelope is proposed) This study proposed three tracking methods of existing flicker tones in voltage envelope. (These) The methods are based on the d-q transformation to extract flicker tones which can be used to determine the sources of this event. (Three) The proposed methods include (a method) 1) based on the square method and the d-q transformation, (a method) 2) based on the half wave rectifier and the d-q transformation, and (finally, a method) 3) based on phase shifting method and the d-q transformation (are presented in this paper). The performances of the proposed method for flicker tones tracking are examined by simulation in MATLAB. Simulation results show that the all proposed methods can detect flicker tones correctly. In addition, according to simulation results, the second method shows the best results.
KEYWORDS: Flicker Tones, Inter-harmonic, Power Quality, Sub-harmonic, Voltage Envelope.

I. INTRODUCTION

With Proliferation of non-linear load like arc furnaces and spot welder, voltage flicker in the power network has become a major problem for both the electric consumers and utilities. Variations in power demand of these loads cause to fluctuating voltage drop across the impedance of a distribution network which results in flicker. Due to competition in power market, it is necessary to eliminate or reduce negative effects of flicker. In order to improve the voltage quality, it is important to correctly track the components of voltage fluctuations. Flicker defined as root mean square (RMS) voltage variation with low amplitude and with the frequency of 0.5 to 25 Hz [1]. The core of flicker analysis is tracking of the voltage envelope. The voltage signal that has one sinusoidal envelop, has one sub-harmonic and carrier frequency and one inter-harmonic in the frequency domain.

There are many methods for detection of voltage envelope. Square method (demodulation) is one of these techniques in which by using multiplying voltage signal to itself, frequency distances are increased and so flicker envelope is tracked by using filter chain [2]. Disadvantage of this method is its low accuracy as it generates additional low frequency components because square method is not linear [3]. The Fast Fourier Transformation (FFT) is another method which is used to detect the flicker tones included in voltage envelope [4]. However, the accuracy of the FFT is affected by the leakage effect [5]. In Phase Shifting method, main signal is fed to two phase shifter separately. One of them apply positive phase shifting and the other one apply the same value phase shifting but in negative sign. Then flicker envelope is separated by applying mathematical relationships [6]. However in this method there would be a small phase shift in flicker tones when main signal is fed to phase shifter so it decreases accuracy. Another technique is Hilbert Transform [7]. This transform is able to analyze the narrow-band signals, so this mathematical transform has been used for envelope tracking recently. However this method has a high mathematical burden, because impulse response of the filter corresponded to Hilbert Transformation is infinite and so it needs to know all the samples of a signal [6]. Wavelet Transform can separate a signal into different bandwidth and then reconstructs special bandwidth, so it is introduced as tool for envelope tracking [8]. But drawback of this technique is difficulty of interpretation of its returns results [9]. Kalman Filter is optimal recursive estimators which estimate the magnitude and frequency of voltage variation and is used to track flicker envelope [10]. However, its computational burden is high [5].

Detection of flicker sources is an important problem in compensation issue. Many methods have been presented in the literature for detection flicker source such as power flicker method [11] and Neural Network [12]. The problem of existence of several flicker sources has not been studied yet. In this case, if a neural network is used to detect the place of several flicker sources, all individual flicker tones are needed to separate.

d-q Transformation has been applied for detection and classification of power quality disturbances ([9], [13]) [9,13]. By using this method a three phase signal can be converted into a two dimensional frame (d-q) which direct axis (d) is at angle of 90^0 to quadrature axis (q) and this frame is rotating with angular velocity. By combining abc-0dq Transformation algorithm and 90^0 phase shift algorithm, a fast and accurate algorithm to recognize all voltage disturbances and faults characteristics have been presented in [9]. The utility input voltages are sensed and then converted to DC quantities in the d-q reference frame. Thus any disturbances at the utility input voltage will be reflected as disturbance in d-q values. Using these disturbed values, it is possible to detect the power quality events like sag, swell, flicker and so on ([9], [13]) [9, 13]. In this paper, a method is proposed for tracking of all flicker tones in voltage envelope using d-q transformation.

***Corresponding Author:** Jalal Khodaparast, Department of Electrical and Robotic Engineering, Shahrood University of Technology, Shahrood, 3619995161, Iran (e-mail: jalal_khodaparast@yahoo.com), Tel : 0098-273-3332240

II. D-Q TRANSFORMATION

The d-q Transformation is a transform that maps balanced three phase voltages to a synchronous rotating frame in order to extract a set of three-phase voltages with special frequency and to represent them as a DC component. The d-q Transformation is defined as follows [14]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = (2/3)\begin{bmatrix} \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = (2/3)\begin{bmatrix} \sin(\omega t) & \cos(\omega t) \\ \sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} v_d \\ v_q \end{bmatrix} \quad (2)$$

And also inverse of d-q transformation is defined as (2), where ω is d-q Transformation frequency, v_d and v_q are synchronous rotating frame parameters, v_a , v_b , and v_c are abc parameters coordinate system. If d-q Transformation frequency (ω) is equal to frequency of the phase voltage (ω_c), d-q synchronous rotating frame lock to abc synchronous rotating frame. Under this condition, relation between balanced three phase voltages as given in (3) and d-q synchronous rotating frame parameters have been defined as (4).

$$\begin{cases} v_a = V_c \cos(\omega_c t + \theta_c) \\ v_b = V_c \cos(\omega_c t + \theta_c - \frac{2\pi}{3}) \\ v_c = V_c \cos(\omega_c t + \theta_c + \frac{2\pi}{3}) \end{cases} \quad (3)$$

$$\begin{cases} v_d = -V_c \sin(\theta_c) \\ v_q = V_c \cos(\theta_c) \\ V_c = \sqrt{v_d^2 + v_q^2} \\ \theta_c = -\arctan(\frac{v_d}{v_q}) \end{cases} \quad (4)$$

where V_c, ω_c, θ_c are amplitude, frequency, phase angle of the phase voltage.

III. ENVELOPE SEPARATION

Several methods for tracking of flicker envelope have been presented in many literatures till now. In the proposed methods, d-q Transformation is used for envelope tracking in this paper. Previous methods include square, half wave rectifier and phase shifting are modified by using d-q transformation, which is defined in part II, to be able to track flicker tones separately. Assume three phase voltages that have N tone as (5).

$$\begin{cases} v_a = V_c\left(1 + \sum_{k=1}^{k=N} V_{mk}\cos(\omega_{mk} t + \theta_{mk})\right)\cos(\omega_c t + \theta_c) \\ v_b = V_c\left(1 + \sum_{k=1}^{k=N} V_{mk}\cos(\omega_{mk} t + \theta_{mk} - \frac{2\pi}{3})\right)\cos(\omega_c t + \theta_c - \frac{2\pi}{3}) \\ v_c = V_c\left(1 + \sum_{k=1}^{k=N} V_{mk}\cos(\omega_{mk} t + \theta_{mk} + \frac{2\pi}{3})\right)\cos(\omega_c t + \theta_c + \frac{2\pi}{3}) \end{cases} \quad (5)$$

So three are more than one flicker tone in voltage waveform and it needs to be separated all flicker tones individually. This purpose will obtain by improving previous methods. These methods are square, half wave rectifier and phase shifting.

A. Improvement of square method

In square demodulation by using multiplying voltage signal to itself, frequency distances are increased and so flicker envelope can be tracked by using filter chain. Improvement of square method is presented in this part and block diagram of this proposed algorithm is shown in Fig. 1.

Consider (6) as a voltage of phase ''a'' with N flicker tones in its voltage envelope then after squaring, (7) is obtained.

$$v_a = V_c\left(1 + \sum_{k=1}^{k=N} V_{mk}\cos(\omega_{mk} t + \theta_{mk})\right)\cos(\omega_c t + \theta_c) = V_c\left(1 + \sum_{k=1}^{k=N} v_{mk}\right)\cos(\omega_c t + \theta_c) \quad (6)$$

$$v_a^{'} = v_a^{\ 2} = V_c^{\ 2}\left(1+\sum_{k=1}^{k=N} v_{mk}\right)^2 \cos^2(\omega_c t+\theta_c) = V_c^{\ 2}\begin{bmatrix} 1+\sum_{k=1}^{k=N}\sum_{k^{'}=1}^{k^{'}=N}\frac{V_{mk}V_{mk^{'}}}{2}\cos\left((\omega_{mk}+\omega_{mk^{'}})t+\theta_{mk}+\theta_{mk^{'}}\right) \\ +\sum_{k=1}^{k=N}\sum_{k^{'}=1}^{k^{'}=N}\frac{V_{mk}V_{mk^{'}}}{2}\cos\left((\omega_{mk}-\omega_{mk^{'}})t+\theta_{mk}-\theta_{mk^{'}}\right) \\ +\sum_{k=1}^{k=N} 2V_{mk}\cos(\omega_{mk}t+\theta_{mk}) \end{bmatrix} \times\left(0.5+0.5\cos(2\omega_c t+2\theta_c)\right) \quad (7)$$

As is shown in (7), after squaring, many different frequencies are produced which flicker tones can be tracked by using the d-q transformation. Suppose that $\omega_{squ}(p)$,p=1,2,…P is available frequencies created after squaring (P is number of frequencies after squaring); if each of available frequencies created after squaring is equal to d-q transformation frequency, there will be DC voltage component at the output of transformation, but each of other frequencies rotate with frequency of (ω - $\omega_{squ}(p)$) which produces AC voltage component at the output of transformation. According to Fig. 1, outputs of the d-q transformation for tracking of the first tone are obtained as (8):

$$\begin{cases} v_{d1}{'} = -V_c^{\ 2}V_{m1}\sin(\theta_{m1}) + AC_{d1}(square) \\ v_{q1}{'} = V_c^{\ 2}V_{m1}\cos(\theta_{m1}) + AC_{q1}(square) \end{cases} \quad (8)$$

where $AC_{d1}(square)$ and $AC_{q1}(square)$ refer to alternating components after passing d-q transformation in square method. Then by using low-pass filter $v^{''}_{d1}$, $v^{''}_{q1}$ are:

$$\begin{cases} v_{d1}{''} = -V_c^{\ 2}V_{m1}\sin(\theta_{m1}) \\ v_{q1}{''} = V_c^{\ 2}V_{m1}\cos(\theta_{m1}) \end{cases} \quad (9)$$

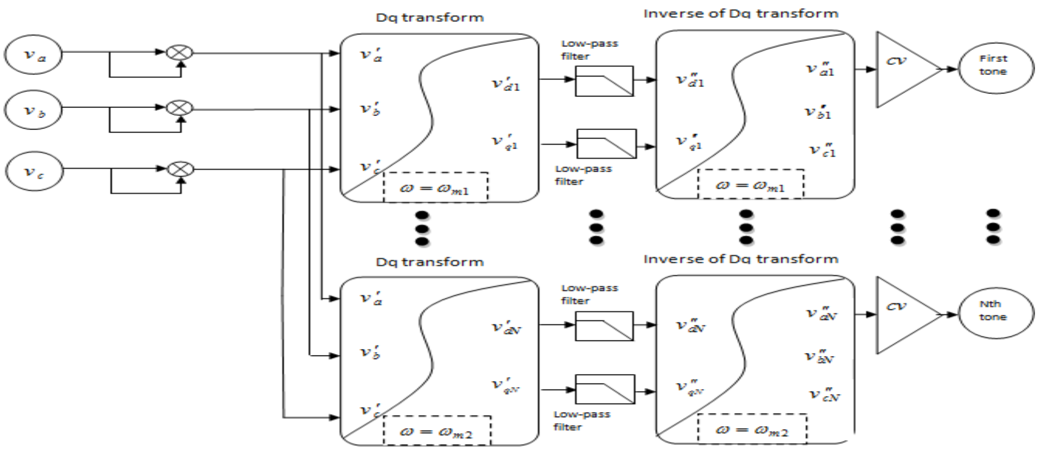

Fig. 1. Improvement of square method

Then by using inverse of d-q transformation, the first tone is given by

$$v_{a1}{''} = V_c^{\ 2}V_{m1}\cos(\omega_{m1}t+\theta_{m1}) \quad (10)$$

The correction value (cv) of $(1/V_c^{\ 2})$ has been applied to $v^{''}_{a1}$ and therefore the first tone is equal to:

$$v_{tone1} = \frac{v_{a1}{''}}{V_c^{\ 2}} = V_{m1}\cos(\omega_{m1}t+\theta_{m1}) \quad (11)$$

Similarly, the same procedure should be applied for other flicker tones which have been detected in previous section. But according to (12), this proposed algorithm cannot distinguish the following frequencies:

$$\left(\omega_{m1},\omega_{m2}\right) \neq \left(2\omega_{m1}, 2\omega_{m2}, \omega_{m1}+\omega_{m2}, \omega_{m1}-\omega_{m2}\right) \quad (12)$$

Because created components with different frequencies will overlay under these conditions and so d-q transformation cannot distinguish desired frequency correctly.

B. Improvement of half wave rectifier method

Half wave rectifier was another method which has been used for tracking flicker envelope. In half wave rectifier method, by feeding main voltage to a half wave rectifier block, flicker envelope is appeared independently. Then flicker envelope can be tracked by using filter chain. This method is improved by d-q transformation as fallow:

Consider (6) as a voltage of phase ''a'' with N flicker tones. After passing half wave rectifier, (13) is obtained as [3]:

$$v_a' = V_c\left(1+\sum_{k=1}^{k=N} v_{mk}\right)\cos(\omega_c t+\theta_c)|_{1/2waverect} = V_c\left(1+\sum_{k=1}^{k=N} v_{mk}\right)\times\begin{pmatrix}\frac{1}{\pi}+\frac{1}{2}\cos(w_c t+\theta_c)+\frac{1}{1.3}\cos(2w_c t+2\theta_c)- \\ \frac{1}{3.5}\cos(4w_c t+4\theta_c)+\frac{1}{5.7}\cos(6w_c t+6\theta_c)-...\end{pmatrix} \quad (13)$$

It can be seen that many different frequencies are produced which each frequency can be tracked by using d-q transformation.

Outputs of the d-q transformation for tracking of the first tone are obtained as (14):

$$\begin{cases} v_{d1}' = -\frac{V_c V_{m1}}{\pi}\sin(\theta_{m1}) + AC_{d1}(rectifier) \\ v_{q1}' = \frac{V_c V_{m1}}{\pi}\cos(\theta_{m1}) + AC_{q1}(rectifier) \end{cases} \quad (14)$$

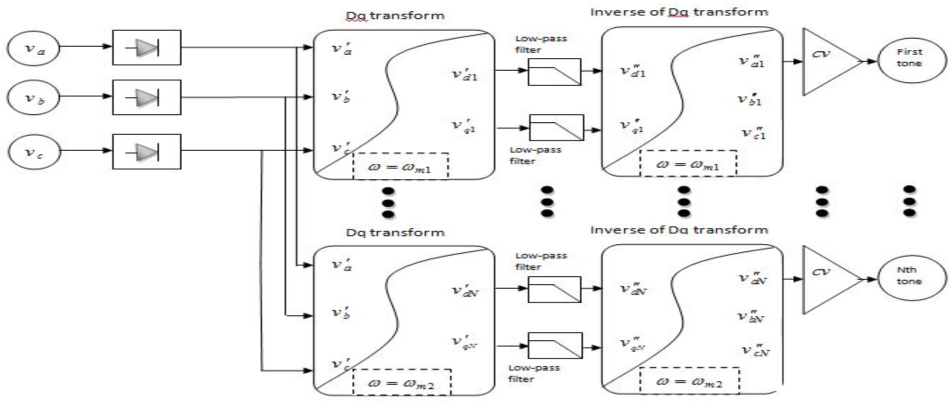

Fig. 2. Improvement of half wave rectifier method

where $AC_{d1}(rectifier)$ and $AC_{q1}(rectifier)$ refer to alternating components after passing dq transform in rectifier method. Then, by using low-pass filter v''_{d1}, v''_{q1} are:

$$\begin{cases} v_{d1}'' = -\frac{V_c V_{m1}}{\pi}\sin(\theta_{m1}) \\ v_{q1}'' = \frac{V_c V_{m1}}{\pi}\cos(\theta_{m1}) \end{cases} \quad (15)$$

Then by using inverse of d-q transformation, the first tone is given by

$$v_{a1}'' = \frac{V_c V_{m1}}{\pi}\cos(\omega_{m1}t + \theta_{m1}) \quad (16)$$

The correction value (*cv*) of (π/V_c) has been applied to v''_{a1} and therefore the first tone is equal to:

$$v_{tone1} = \frac{\pi v_{a1}''}{V_c} = V_{m1}\cos(\omega_{m1}t + \theta_{m1}) \quad (17)$$

Similarly, the same procedure should be applied for other flicker tones. The block diagram of this proposed algorithm is shown in Fig. 2.

C. Improvement of phase shifting method

Phase shifting method is the third method which is improved in this paper. In phase shifting method, first, main signal is fed to two phase shifter separately, one of them apply positive phase shift and the other one apply the same value phase shift but in negative sign. Then flicker envelope is separated by applying mathematical relationships. As mentioned in [6], consider transfer functions are shown in (18);

$$H^{+}(j\omega)=\frac{v_{a}^{+}}{v_{a}}=\frac{j\omega a^{+}\tau+1}{j\omega\tau+1}$$
$$H^{-}(j\omega)=\frac{v_{a}^{-}}{v_{a}}=\frac{j\omega a^{-}\tau+1}{j\omega\tau+1} \quad (18)$$

where τ is sample time and these transfer functions produce phase angles as (19);

$$\beta^{+}=\arctan(\omega a^{+}\tau)-\arctan(\omega\tau)$$
$$\beta^{-}=\arctan(\omega a^{-}\tau)-\arctan(\omega\tau) \quad (19)$$

Since the aim of these transfer function is eliminating fundamental frequency, (20) should be considered, and a^{+} and a^{-} are obtained according to (20).

$$\beta=\beta^{+}(\omega=\omega_c)=-\beta^{-}(\omega=\omega_c) \quad (20)$$

After passing transfer functions, (21) is obtained as

$$\begin{cases} v_a^{+}=V_c\left(1+v_1^{+}+v_2^{+}\right)\cos(\omega_c t+\theta_c+\beta) \\ v_a^{-}=V_c\left(1+v_1^{-}+v_2^{-}\right)\cos(\omega_c t+\theta_c-\beta) \end{cases}$$
$$\begin{cases} v_1^{+}=V_{m1}\cos(\omega_{m1}t+\theta_{m1}+\beta_1^{+}) \\ v_1^{-}=V_{m1}\cos(\omega_{m1}t+\theta_{m1}+\beta_1^{-}) \\ v_2^{+}=V_{m2}\cos(\omega_{m2}t+\theta_{m2}+\beta_2^{+}) \\ v_2^{-}=V_{m2}\cos(\omega_{m2}t+\theta_{m2}+\beta_2^{-}) \end{cases} \quad (21)$$

Also a^{+} and a^{-} should be determined such that this method creates the smallest phase shift in envelop tones.
Input of d-q transformation in this proposed algorithm is obtained as (22):

$$v_a^{'}=v_a^{2}-\left(v_a^{+}\times v_a^{-}\right)=\left(V_c\left(1+v_1+v_2\right)\right)^2\times\frac{1}{2}\sin^2(\beta) \quad (22)$$

$$v_a^{'}=V_c^{2}\times\frac{1}{2}\sin^2(\beta)\begin{bmatrix} 1+\sum_{k=1}^{k=N}\sum_{k^{'}=1}^{k^{'}=N}\frac{V_{mk}V_{mk^{'}}}{2}\cos\left((\omega_{mk}+\omega_{mk^{'}})t+\theta_{mk}+\theta_{mk^{'}}\right) \\ +\sum_{k=1}^{k=N}\sum_{k^{'}=1}^{k^{'}=N}\frac{V_{mk}V_{mk^{'}}}{2}\cos\left((\omega_{mk}-\omega_{mk^{'}})t+\theta_{mk}-\theta_{mk^{'}}\right) \\ +\sum_{k=1}^{k=N}2V_{mk}\cos(\omega_{mk}t+\theta_{mk}) \end{bmatrix}$$

Outputs of the d-q transformation for tracking of the first tone are obtained as (23):

$$\begin{cases} v_{d1}'=-V_c^{2}\sin^2(\beta)V_{m1}\sin(\theta_{m1})+AC_{d1}(shifting) \\ v_{q1}'=V_c^{2}\sin^2(\beta)V_{m1}\cos(\theta_{m1})+AC_{q1}(shifting) \end{cases} \quad (23)$$

where $AC_{d1}(shifting)$ and $AC_{q1}(shifting)$ refer to alternating components after passing d-q transformation in phase shifting method. Then, by using low-pass filter v''_{d1}, v''_{q1} are:

$$\begin{cases} v_{d1}''=-V_c^{2}\sin^2(\beta)V_{m1}\sin(\theta_{m1}) \\ v_{q1}''=V_c^{2}\sin^2(\beta)V_{m1}\cos(\theta_{m1}) \end{cases} \quad (24)$$

Then by using inverse of d-q transformation, the first tone is given by

$$v_{a1}''=\left(V_c^{2}\sin^2(\beta)\right)\times V_{m1}\cos(\omega_{m1}t+\theta_{m1}) \quad (25)$$

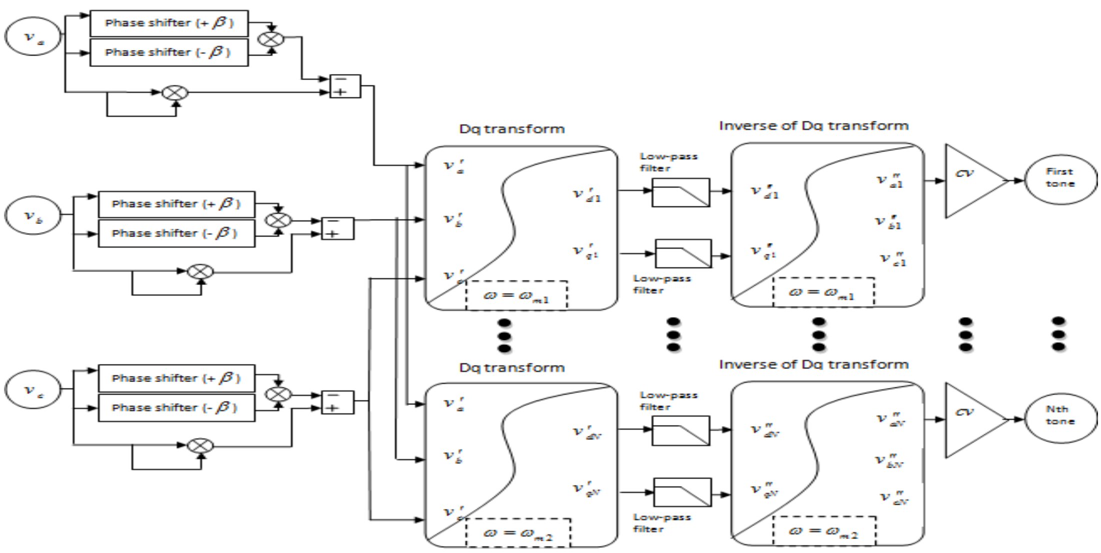

Fig.3 . Improvement of the phase shifting method

The correction value (*cv*) of $(1/V_c^2 \sin(\beta))$ has been applied to v''_{a1} and therefore the first tone is equal to:

$$v_{tone1} = \frac{v_{a1}''}{V_c^2 \sin^2(\beta)} = V_{m1}\cos(\omega_{m1}t + \theta_{m1}) \tag{26}$$

The block diagram of this proposed algorithm is shown in Fig. 3. But this proposed algorithm cannot distinguish the following frequencies:

$$(\omega_{m1}, \omega_{m2}) \neq (2\omega_{m1}, 2\omega_{m2}, \omega_{m1}+\omega_{m2}, \omega_{m1}-\omega_{m2}) \tag{27}$$

Because created components with different frequencies will overlay under these conditions and so d-q transformation cannot distinguish desired frequency correctly.

IV. SIMULATION RESULTS

First, artificial signals (generated in MATLAB) have been used to validate the proposed methods. Consider the case which has two flicker tones in the envelope defined as follows:

$$\begin{cases} v_a = 10\left(1+0.1\cos(2\pi 10t+\frac{\pi}{6})+0.05\cos(2\pi 7t+\frac{\pi}{12})\right)\cos(\omega_c t+\frac{\pi}{3}) \\ v_b = 10\left(1+0.1\cos(2\pi 10t+\frac{\pi}{6}-\frac{2\pi}{3})+0.05\cos(2\pi 7t+\frac{\pi}{12}-\frac{2\pi}{3})\right)\cos(\omega_c t+\frac{\pi}{3}-\frac{2\pi}{3}) \\ v_c = 10\left(1+0.1\cos(2\pi 10t+\frac{\pi}{6}+\frac{2\pi}{3})+0.05\cos(2\pi 7t+\frac{\pi}{12}+\frac{2\pi}{3})\right)\cos(\omega_c t+\frac{\pi}{3}+\frac{2\pi}{3}) \end{cases}$$

According to Fig. 5, there are two sub-harmonics with frequencies of 40 and 43 and two inter-harmonics with frequencies of 57 and 60. So frequencies of flicker tones are 7 Hz and 10 Hz (fundamental frequency is 50 Hz). After identifying of flicker tones frequencies, proposed methods is applied to analyzed signal for tracking of all flicker tones individually. Figs. 6 and 7 show the generated artificial tones, tracked tones and error of 10 and 7 Hz respectively based on proposed square method (error has been defined as difference between generated artificial tone and tracked tone).

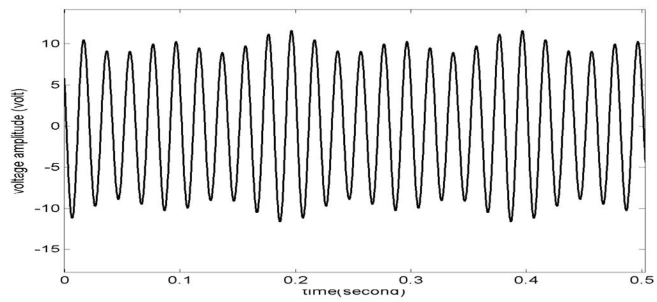

Fig. 4. Analyzed signal with 10 Hz and 7 Hz Tone frequencies

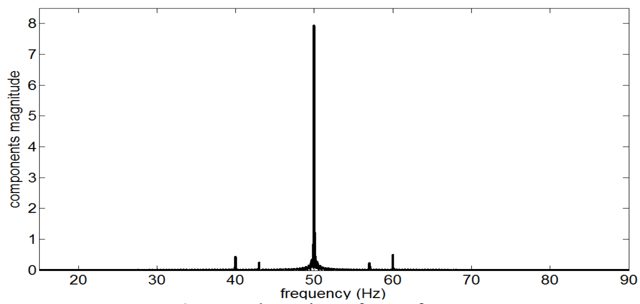

Fig. 5. detection of tone frequency

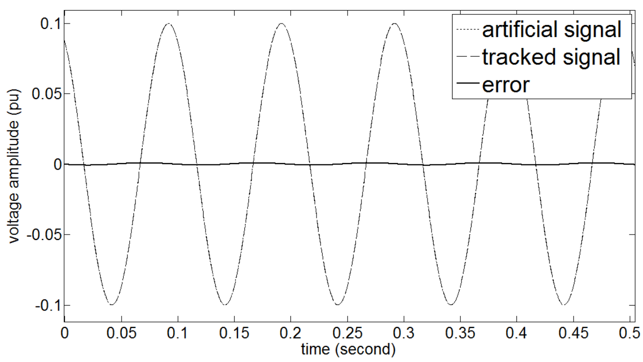

Fig. 6. Tone tracking by using proposed Square method (10Hz)

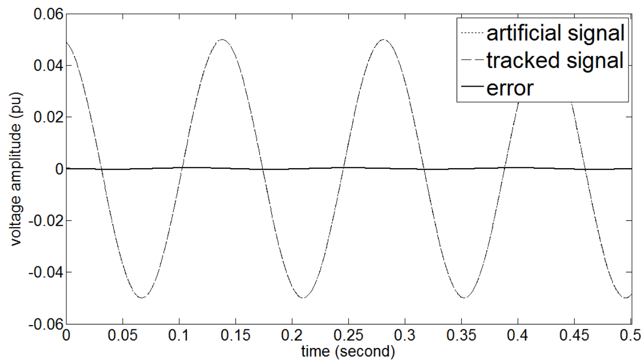

Fig. 7. Tone tracking by using proposed Square method (7 Hz)

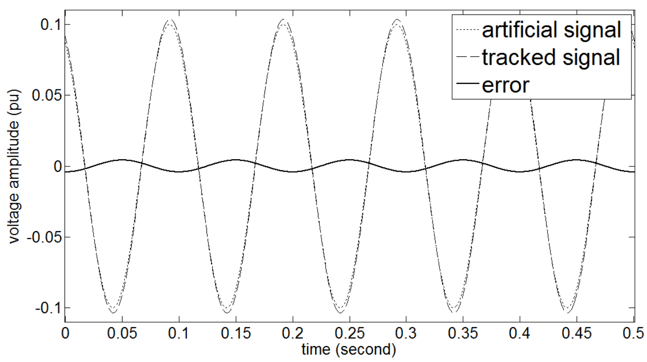

Fig. 8. Tone tracking by using proposed rectifier method (10 Hz)

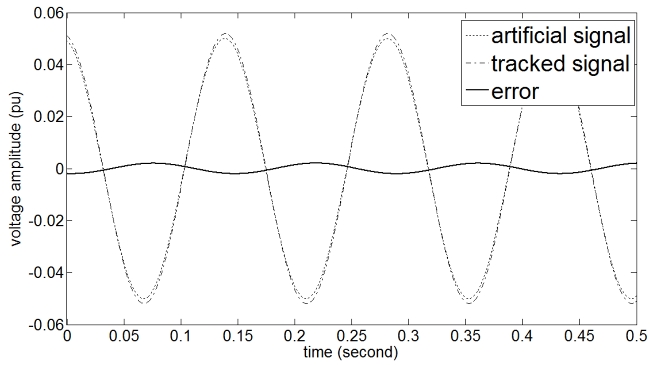

Fig. 9. Tone tracking by using proposed rectifier method (7 HZ)

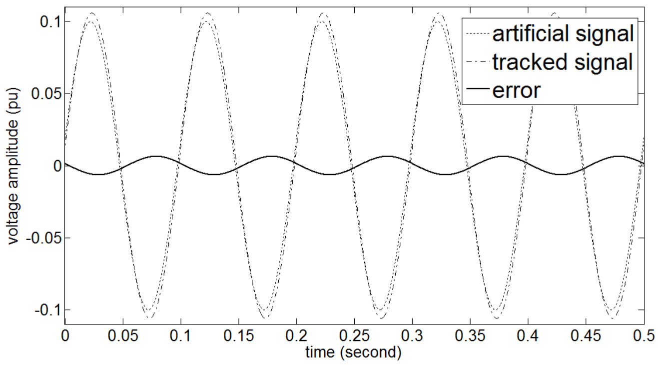

Fig. 10. Tone tracking by using proposed phase shifting method (10Hz)

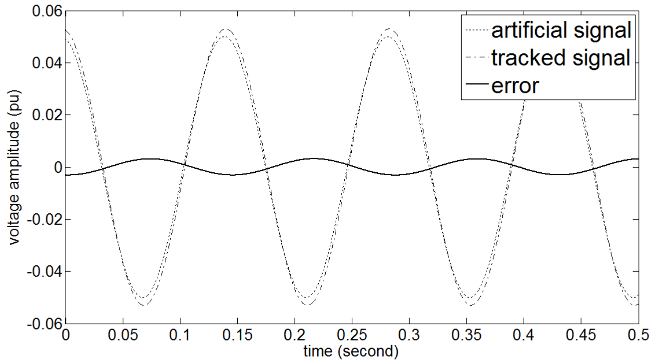

Fig. 11. Tone tracking by using proposed phase shifting method (7 Hz)

Figs. 8 and 9 show the generated artificial tones, tracked tones and error of 10 and 7 Hz respectively based on proposed rectifier method. Figs. 10 and 11 show the generated artificial tones, tracked tones and error of 10 and 7 Hz respectively based on proposed phase shifting method.

Test power system:

A 100-V, 50-Hz sinusoidal supply with internal impedance of Zs =1+j 6.28 Ω is connected to bus 1 of the system shown Fig. 12. The load connected to bus 2 is a spot welder (w) with envelop frequency 7 Hz and amplitude modulation 0.025 p.u. and the load connected to bus 4 is an spot welder with envelop frequency 10 Hz and amplitude modulation 0.03 p.u. which are modeled as variable resistor. Bus 3 feeds a Z_{load} =150+j78.5 Ω linear load. All line impedances are Z_s =2+j12.56 Ω [15]. Spot welders are one of the main loads which can produce flicker in the power network. There are some methods to simulate the spot welder. The performance of a spot welder can be simulated by variable resistor. The resistor *(R)* connected with an ideal switch which is controlled by pulse generator are treat as variable resistor.

this network is simulated in MATLAB. Tracking of flicker tone with frequency 10 Hz base on three proposed methods is shown in Fig. 14. Tracking of flicker tone with frequency 7 Hz base on three proposed methods is shown in Fig. 15.

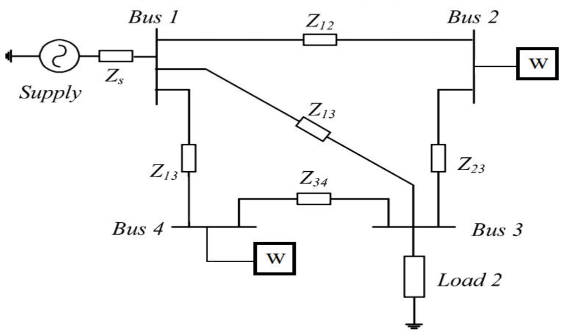

Fig. 12 . Test power system

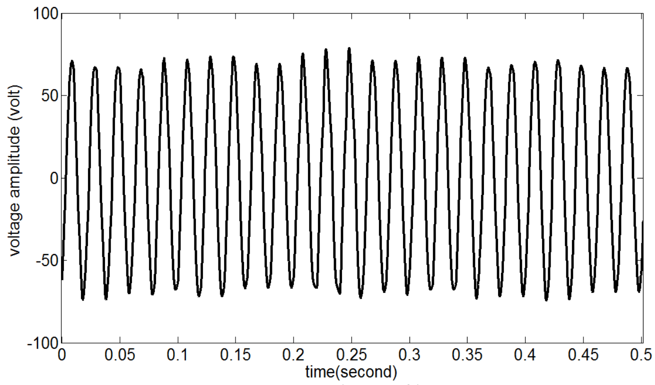

Fig. 13. Volatge of bus 1

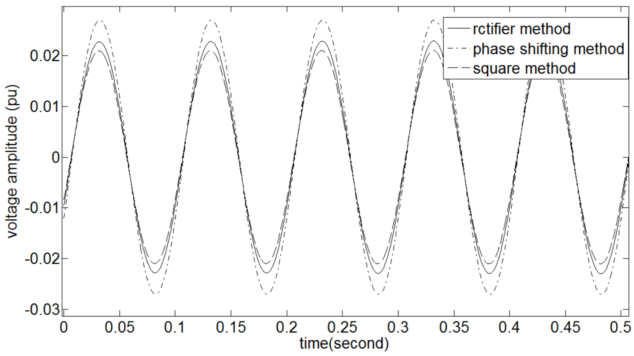

Fig. 14. Tone tracking (10 Hz) using three proposed methods

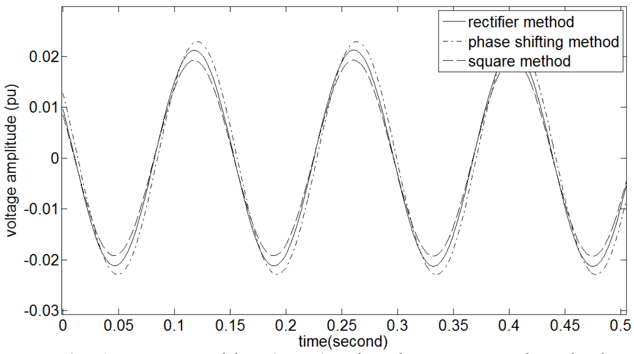

Fig. 15. Tone tracking (7 Hz) using three proposed methods

V. Conclusion

Identification of the flicker sources is the first step in the process to improve power quality. This paper proposed three methods based on d-q transformation for tracking all flicker tones (square, half wave rectifier, and phase shifting method). The proposed methods are capable of tracking more than one tone in voltage envelope. The performance of the d-q Transformation on tracking the flicker tones is examined with the signals generated by MATAB, as well as simulated flicker tones produced by flicker sources. Simulation has been carried out which results show accurate tracking of the proposed algorithm. Accuracy of all method is acceptable but the second method shows the best answer.

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