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Voltage Flicker Estimation and Mitigation Using Combined MUSIC-DVR Technique

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Abstract— This paper presents a technique based on the multiple signal classification (MUSIC) technique combined with the dynamic voltage restorer (DVR) scheme for voltage flicker estimation and mitigation. Different cases of voltage flicker distortion are investigated including low and high frequency bands. In the first phase, the MUSIC algorithm is applied for voltage flicker estimation, where the spectral components of the voltage signal are calculated by constructing the voltage flicker signal as a linear combination of sinusoids of different frequencies. Next, Hilbert transform (HT) is used to obtain the voltage envelope of the signal using the estimated spectral components of the voltage flicker waveform. Then, the voltage envelope is used to detect the level of voltage flicker. In the second phase, voltage flicker mitigation using the dynamic voltage restorer (DVR) scheme is employed by injecting the appropriate voltage signal to reduce unacceptable voltage fluctuations at the load side. The performance and effectiveness of the proposed method have been examined using MATLAB/SIMULINK simulation.

Keywords— Dynamic voltage restorer, Hilbert transform, Interharmonics, MUSIC, Signal processing, Simulation, Voltage flicker.

I. INTRODUCTION

Voltage flicker (VF) can be defined as small amplitude changes in voltage levels causing fluctuation in the illumination intensity of incandescent or fluorescent lamps. The illumination fluctuation is known as light flicker [1]. The voltage flicker phenomena can be divided into two categories, cyclic and stochastic. Cyclic flicker is caused by rapidly large fluctuating loads, which operate periodically in a weak power distribution system, such as arc furnaces, arc welders and reciprocating compressors and pumps. Stochastic flicker is produced by occasional load fluctuations such as starting of large motors or spot welders. Other common sources of flicker involve cycloconverters, variable frequency drives and static frequency converters [1]-[5]. These types of loads introduce interharmonics whose frequency components are not integer number of the supply fundamental frequency and can result in voltage waveform containing interharmonics [4]-[6]. Consequently, the effective (rms) and the peak values of the voltage waveform fluctuate. Tests found that the human eye is sensitive to light flicker occurring at frequencies between 0.5 and 25 Hz [4]. Therefore, voltage flicker is considered one of the major power quality problems.

The estimation and measurement of voltage flicker involve the derivation of the rms voltage variation and the frequency at which the variation occurs. The frequency may be a single frequency or a band of frequencies. The voltage flicker generated signal is a nonstationary signal with time-varying characteristics. Voltage flicker is usually expressed as the change in rms voltage (peak) divided by the average rms (peak) voltage. The relative change in rms or peak value is equivalent to the relative change in illumination intensity which can be perceived by human eye [5]-[8].

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Many studies, based on time and frequency domains, have been proposed to estimate the magnitude and frequency of the voltage flicker signal. The fast Fourier transform (FFT) has been used for voltage flicker estimation [9]. The FFT algorithm assumes that the voltage flicker signal is stationary and contains harmonic frequency components. However, this method suffers from the frequency resolution problem, which depends on the number of samples and sampling frequency. The major problems that make this method misleading are leakage effect, picket-fence effect and aliasing effect. Kalman filtering (KF) approach has also been used [10]. However, KF based technique requires a large mathematical burden. The least absolute value estimation (LAV) technique has been proposed for measurements of power system voltage and flicker levels [11]. Its performance, however, depends on a priori known as the flicker signal frequency components. Advanced signal processing techniques such as Wavelet transform (WT) have been proposed for voltage flicker estimation [12]. Although this technique has a good performance for analyzing nonstationary signals, it includes computational complexity as well as the difficulty of choosing the candidate wavelet. Voltage flicker parameters estimation using genetic algorithms (GA) has also been applied [13]. Flicker envelope tracking using adaptive linear neuron (ADALINE) and recursive least square (RLS) algorithms have been introduced [14]. The measurement of voltage flicker levels using particle swarm optimization (PSO) technique for power quality assessment was introduced [15]. The detection of voltage flicker envelope using high frequency resolution methods based on Prony analysis (PA) and estimation of signal parameters via rotational invariance (ESPRIT) techniques have been applied [16], [17]. The techniques decompose the distorted voltage flicker signal into its modal components. Both techniques proved to be reliable and efficient. Recently, the MUSIC technique has been proposed for parameter estimation of simulated stationary and nonstationary waveforms. The MUSIC technique is one of the most subspace based algorithm which was developed for estimating the parameters of complex sinusoids with additive white Gaussian noise [18]. The MUSIC method has many applications in areas such as communications, radar and sonar [19]. The MUSIC technique represents the distorted waveform as series of complex exponentials. In these techniques, the eigenvectors of the covariance matrix can be separated into two groups. The signal subspace that has the maximum valued eigenvectors represents the signal power, whereas the noise subspace that has the least minimum valued eigenvectors represents the noise power [20].

As far as harmonic mitigation is concerned, several types of custom power quality (CPQ) devices have been developed [21]. Compensation of the voltage flicker using DVR has been proposed for its small size and fast dynamic response for voltage disturbances [22]. P-pulse converter based static synchronous compensator (STATCOM) has also been investigated to compensate voltage flicker [23]-[25]. Voltage flicker mitigation using static VAR compensator (SVC) was also applied [26].

This paper presents a method for voltage flicker estimation and mitigation based on MUSIC technique combined with a DVR scheme [27]. Two cases of voltage flicker distortions including low, high and wide frequency bands are simulated using Matlab/Simulink software. In the first phase, the MUSIC algorithm is applied for voltage flicker parameter estimation, where the spectral components of the voltage signal including the frequency, amplitude and phase angle are calculated. The spectral components are obtained by constructing the voltage flicker signal as a linear combination of sinusoids of different frequencies. Next, Hilbert transform (HT) is used to obtain the voltage envelope of the signal using the estimated spectral components of the voltage flicker waveform. Then, the voltage envelope is used to detect the level of voltage flicker. In the second phase, a voltage flicker mitigation using the

DVR scheme is employed by injecting the appropriate voltage signal through the series injection transformer to maintain the magnitude of the load voltage at desired levels [27].
The paper is organized as follows. Section II provides the relation between interharmonics and voltage flicker. The mathematical analysis of MUSIC and HT are reviewed in section III. The basic structure of a DVR system is illustrated in Section IV. Simulation results are presented in section V. Finally, conclusions are summarized in section VI.

II. EFFECT OF INTERHARMONICS ON VOLTAGE FLICKER

Modern industrial power systems suffer from power quality problems caused by power system harmonics and interharmonics due to the proliferation of power electronics equipment and other loads with nonlinear characteristics [3]. Interharmonics have several impacts on the power system. One of these impacts is the fluctuation of the peak and rms values of the voltage waveform due to the asynchronous behavior of interharmonics relative to the fundamental and harmonic frequencies which cause visible light flickering [4]-[6]. Visible flicker can result when two or more closely spaced components of voltage spectrum beat at a lower frequency given by

$$f_{beat} = \left| f_i - f_k \right| \tag{1}$$

where f_k is the frequency of the harmonic that is closest to the interharmonic frequency f_i [4]. Each beat frequency equals the difference of the frequencies of individual components. Consequently, spectral components that are separated by less than approximately 35Hz have the potential to produce a perceptible flicker. Therefore detection of interharmonics for flicker estimation is highly desirable.
The voltage waveform during the time of flicker can be expressed as amplitude modulated (AM) waveform [16], [28]:

$$\begin{aligned} v(t) &= \left[A_o + \sum_{i=1}^{m} A_i \cos(\omega_{fi} t + \phi_{fi}) \right] \cos(\omega_o t + \phi_o) \\ &= A_o \cos(\omega_o t + \phi_o) + \sum_{i=1}^{m} \frac{A_i}{2} \cos\left[(\omega_o - \omega_{fi})t + (\phi_o - \phi_{fi})\right] + \\ &\sum_{i=1}^{m} \frac{A_i}{2} \cos\left[(\omega_o + \omega_{fi})t + (\phi_o + \phi_{fi})\right] \end{aligned} \tag{2}$$

Rewriting (2) as:

$$v(t) = A_o \cos(\omega_o t + \phi_o) + \sum_{i=1}^{m} A'_i \cos\left(\omega_{IH}^{-} t + \phi_{IH}^{-}\right) + \sum_{i=1}^{m} A'_i \cos\left(\omega_{IH}^{+} t + \phi_{IH}^{+}\right) \tag{3}$$

where,
A_o, ω_o and ϕ_o are the amplitude, frequency, and phase angle of the fundamental frequency component; A_i, ω_{fi} and ϕ_{fi} are the amplitude, frequency, and phase angle of the i^{th} interharmonic frequency component;

$A_i' = \dfrac{Ai}{2}$, $\omega_{IH}^{-} = (\omega_o - \omega_{fi})$, $\omega_{IH}^{+} = (\omega_o + \omega_{fi})$, $\phi_{IH}^{-} = (\phi_o - \phi_{fi})$, $\phi_{IH}^{+} = (\phi_o + \phi_{fi})$,

and m is the number of modal components.

In this problem, the fundamental frequency ω_o is known, whereas the other parameters A_o, A_i, ϕ_o, and ω_{fi}, and ϕ_{fi} are to be determined using MUSIC Technique.

III. Mathematical Analysis

A. Overview of MUSIC-Based Technique

For reader convenience, the algorithm of MUSIC technique is reviewed. The measured (simulated) data sequence of length N has m independent sinusoids signal corrupted by additive noise *w(n)* [20], [27]:

$$\begin{aligned} y(n) &= \sum_{i=1}^{P} a_i \cos(2\pi f_i n + \phi_i) + w(n) \\ &= \sum_{i=1}^{P} \overline{A}_i e^{j2\pi f_i n} + w(n) \end{aligned} \tag{4}$$

where

$\overline{A}_i = |A_i| e^{j\phi_i}$ is a complex amplitude, ϕ_i is the initial phase angle, f_i is the frequency in Hz, and P is the model order, where $P \geq m$.

The first step in MUSIC technique implementation is the estimation and Eigen analysis of the covariance matrix R_y from the data samples using (5) [29]:

$$\begin{aligned} R_y &= E\left[y(n)y(n)^H\right] \\ &= \frac{1}{M}\sum_{n=1}^{M} y(n)y(n)^H \end{aligned} \tag{5}$$

where $y(n) = \left[y(n), \cdots y(n+M-1)\right]^T$ is the matrix of a sinusoidal signal *y(n)*, M is the dimension of space spanned by *y(n)*, $E[\cdot]$ and $\{\cdot\}H$ are the expectation operator and the matrix complex conjugate transpose (Hermitian), respectively. The covariance matrix R_y can be written as:

$$\begin{aligned} R_y &= sDS^H + \sigma_w^2 I \\ &= R_S + R_W \end{aligned} \tag{6}$$

where D given in (7) is the diagonal matrix of the signal power of complex sinusoids $e^{j2\pi f_i}$, S given in (8) is a $M{\times}P$ matrix eigenvectors, R_S consists of signal frequencies, σ_w^2 is the noise variance and I is the identity matrix.

$$D = \begin{bmatrix} |A_1|^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & |A_P|^2 \end{bmatrix} \tag{7}$$

$$S = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ e^{j2\pi f_1} & e^{j2\pi f_2} & \cdots & e^{j2\pi f_P} \\ e^{j2\pi f_1 2} & e^{j2\pi f_2 2} & \cdots & e^{j2\pi f_P 2} \\ \vdots & & & \\ e^{j2\pi f_1 (M-1)} & e^{j2\pi f_2 (M-1)} & \cdots & e^{j2\pi f_P (M-1)} \end{bmatrix} \tag{8}$$

The Eigen values are arranged in decreasing order (i.e. $\mu_1 \geq \mu_2 \geq, \ldots, \mu_M$) and the corresponding eigenvectors are $U_1, U_2, \ldots, U_P$. The MUSIC spectrum is defined as [29]:

$$\begin{aligned} P_{music}(f) &= \frac{1}{\sum_{i=P+1}^{M} \left| e_i^H U_i \right|^2} \\ &= \frac{1}{e_i^H(f) U_i U_i^H e_i(f)} \end{aligned} \tag{9}$$

The frequencies of (4) are then estimated like the locations of the P largest peaks in (9). Instead of searching for the peaks, the Root-MUSIC assumes that the demodulator in (9) can be written in z-transform on unit circle as [30]:

$$q(z) = z^{-(M-1)} \left[z^{(M-1)}, z, \cdots, 1 \right] U U^H \left[1, z, \cdots, z^{(M-1)} \right]^T \tag{10}$$

where $z_i = e^{j2\pi f_i}$. By calculating the roots of the polynomial, the frequencies corresponding to different signal components in (4) are then obtained in the form:

$$f_i = \frac{1}{2\pi} angle(z_i), \qquad i = 1, 2, \cdots P \tag{11}$$

Once the frequencies are estimated, the amplitudes and phase angles can be calculated using the following matrix:

$$\begin{bmatrix} y(0) \\ y(1) \\ y(2) \\ \vdots \\ y(N-1) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ e^{j2\pi f_1} & e^{j2\pi f_2} & \cdots & e^{j2\pi f_P} \\ e^{j2\pi f_1 2} & e^{j2\pi f_2 2} & \cdots & e^{j2\pi f_P 2} \\ \vdots & \vdots & \vdots & \vdots \\ e^{j2\pi f_1 (N-1)} & e^{j2\pi f_2 (N-1)} & \cdots & e^{j2\pi f_P (N-1)} \end{bmatrix} \begin{bmatrix} A_1 e^{j2\pi\phi_1} \\ A_2 e^{j2\pi\phi 2} \\ A_3 e^{j2\pi\phi_3} \\ \vdots \\ A_P e^{j2\pi\phi_P} \end{bmatrix} \tag{12}$$

This matrix can be expressed in vector notation as:

$$Y = S.H \tag{13}$$

The unknown vector H can be computed using the least squares technique as:

$$H = \left(S^H S\right)^{-1} S^T Y \tag{14}$$

Then, the amplitudes and the initial phase angles are calculated as:

$$A_i = 2|h_i| \tag{15}$$

$$\phi_i = angle(h_i) \tag{16}$$

For real valued signals, the frequencies obtained by MUSIC method appear in pairs of frequencies of opposite signs. The order of the model P is, therefore, set equal to twice the number of frequencies expected in the signal. The degree of the fitness of the estimated voltage flicker signal using MUSIC technique to the measured (simulated) voltage flicker signal can be assessed in terms of the signal-to-noise ratio (SNR) as [31]:

$$SNR = 20\log\frac{\|y(n)\|}{\|y(n)-\hat{y}(n)\|} \tag{17}$$

where $\|y(n)\|$ is the second norm of the measured signal and $\|y(n)-\hat{y}(n)\|$ is the norm of the error signal between the measured and estimated signal. For perfect fitting, the number of samples N and the number of modes P are varied until the $SNR \geq$ 40dB [16].

B. Hilbert Transform

The HT is commonly used to detect the envelope of the fundamental frequency component [16], [32]. An analytic discrete signal $y(n)$ for the real valued signal $x(n)$ with Fourier transform $X(\omega)$ can be defined as:

$$y(n) = x(n) + jx_H(n) \tag{18}$$

where $x_H(n)$ is the HT of $x(n)$, which can be calculated numerically by inverting the Fourier transform of $X_H(\omega)$ given by:

$$X_H(\omega) = \frac{-j\omega X(\omega)}{|\omega|} \tag{19}$$

For a pure sinusoidal signal, HT can be found easily. If $x(t)=cos(\omega t)$, then $x_H(t)= sin(\omega t)$. Accordingly, the envelope of $x(n)$ can be obtained by calculating the modulus $|y(n)|$ of the analytic signal $y(n)$. This can be written mathematically as:

$$|y(n)| = \sqrt{x(n)^2 + x_H(n)^2} \tag{20}$$

IV. BASIC STRUCTURE OF DVR SCHEME

The main function of the DVR is to inject a controlled voltage in series with the distribution system through an injection transformer when the disturbance is detected [33]. Normally, it is installed at feeders supplying critical or sensitive loads such as hospitals or computer centers. Following the voltage variation, the voltage is kept at a certain desired level. The basic structure of the DVR is shown in Fig. 1. The DVR scheme consists of the injection transformer, filter unit, PWM inverter, energy storage device and control system that is used to mitigate voltage flicker in the power distribution system [34], [35].

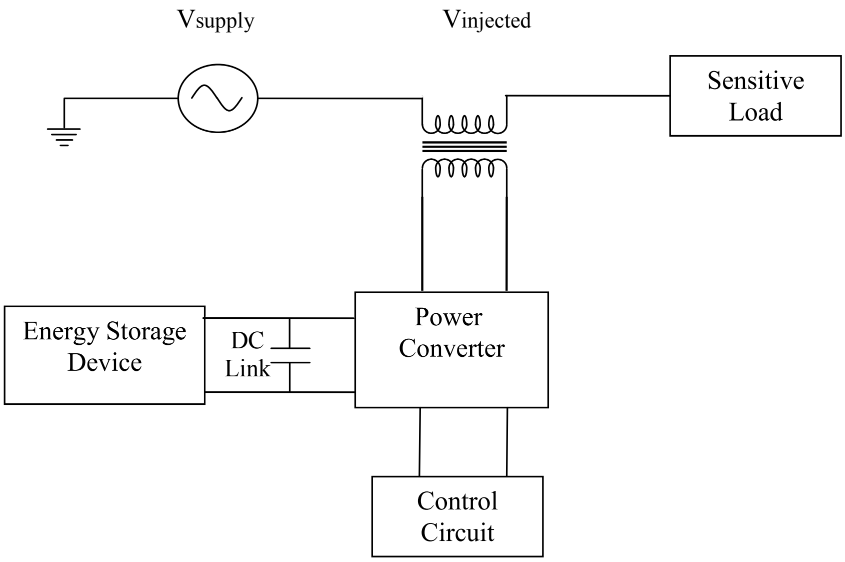

Fig. 1. Basic structure of the DVR scheme

The sequence operation of DVR system is started when the voltage flicker is detected. The controller input is an error signal obtained from the comparison of the reference signal and the value of RMS of the load voltage measurement as shown in Fig. 2. The reference signal represents the nominal value of the system voltage.

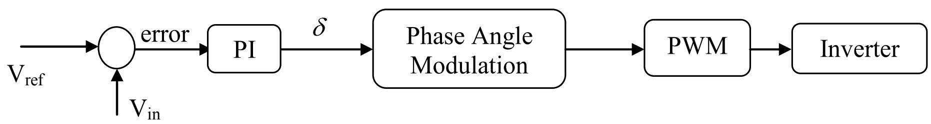

Fig. 2. DVR control unit

Such an error signal is processed by a proportional-integral (PI) controller; and the output has the form of an angle δ that is applied to the phase angle modulator. This modulator generates the sinusoidal signals which are mutually displaced by 120^o. The control signal is fed into the pulse width modulation (PWM) to generate the gate pulses which the inverter requires. In this work, the parameters of the PI controller were chosen arbitrarily by trial and error, and set at K_p= 0.5 and K_i= 150. A well-tuned PI controller should respond quickly to the changes in the error deviation to derive the error to zero, and the load RMS voltage is brought back to the reference voltage [36]. However, to achieve this goal the parameters of the PI controller should be tuned accurately using the optimization technique, which is beyond the scope of this paper. A flow chart showing the stages of the proposed combined MUSIC-DVR technique for voltage flicker estimation and mitigation is depicted in Fig. 3.

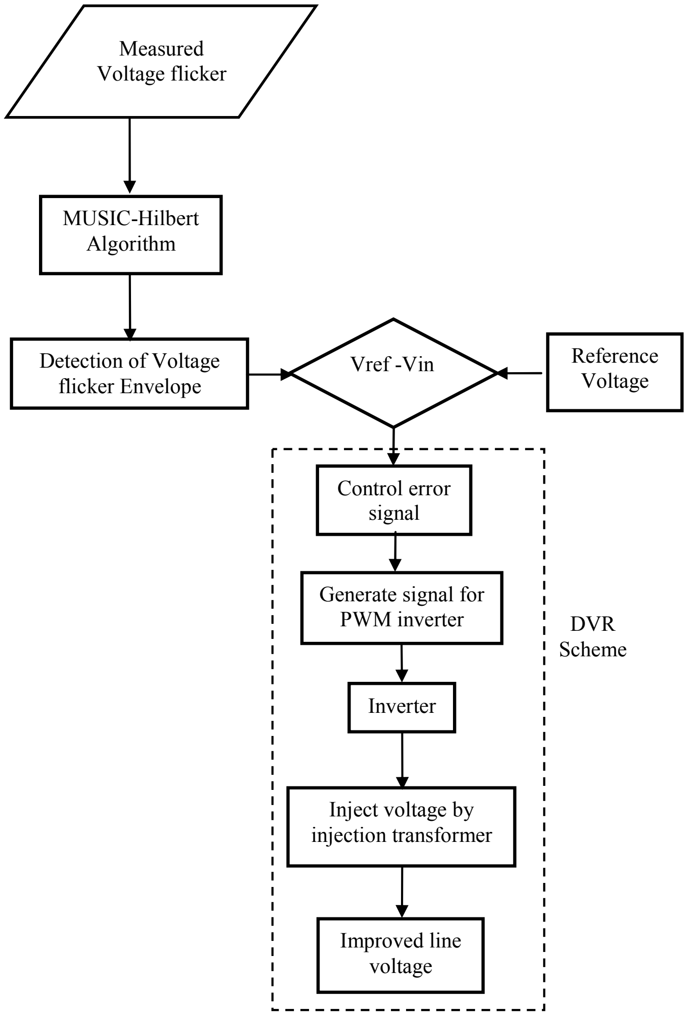

Fig. 3. Flow chart of voltage flicker estimation and mitigation

V. SIMULATION RESULTS

The performance of the proposed combined MUSIC-DVR technique for voltage flicker estimation and mitigation has been simulated for two cases of low and high band interharmonic frequencies.

A. Case 1: Single Low Frequency Band (LFB) Interharmonics

In case 1, the amplitude modulation of a synthetic voltage flicker signal *v(t)* caused by single LFB interharmonics is investigated [16], [36]:

$$\begin{aligned} v(t) &= \left[1 + 0.2\cos(2\pi 10t)\right]\cos(2\pi 50t) \\ &= 1.\cos(2\pi 50) + 0.1\cos(2\pi 40) + 0.1\cos(2\pi 60) \end{aligned} \tag{21}$$

The voltage waveform is sampled at a sampling frequency of 1000Hz over a window size of five 50-Hz cycles giving a total number of samples *N* equal 100 samples. Fig. 4 shows the voltage flicker signal caused by two LFB interharmonics superimposed into the 50-Hz voltage signal.

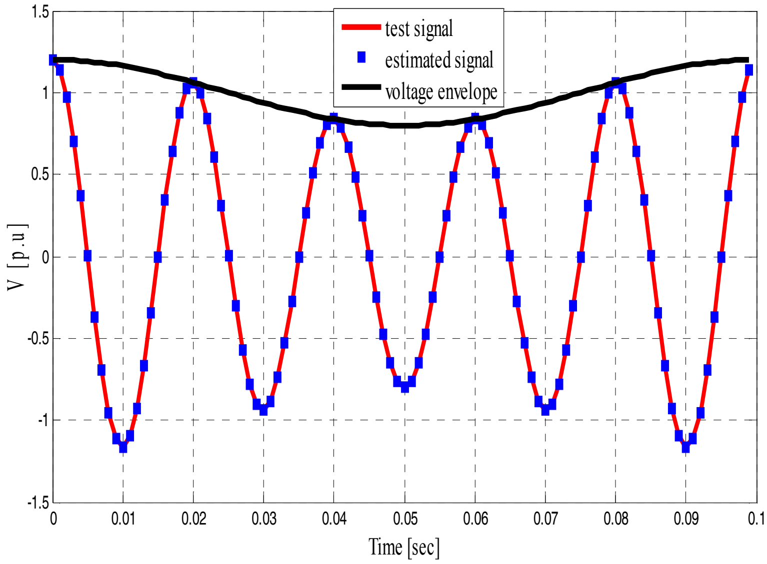

Fig. 4. LFB voltage flicker signal

The voltage signal is decomposed into its frequency components using MUSIC technique. The magnitudes, frequencies and phase angles of frequency components are given in Table 1.

TABLE 1
MUSIC ESTIMATION OF SINGLE LFB VOLTAGE FLICKER SIGNAL

Frequency Component	Frequency (Hz)	Amplitude (pu-V)	Phase Angle (Deg)
f_o	50	1.0	0
f_{IH-}	40	0.1	0
f_{IH+}	60	0.1	0

The MUSIC technique shows two interharmonics of 40 and 60Hz with amplitude of 0.1 pu-V. The signal is reconstructed as the linear sum of its frequency components and compared with the original signal (test signal) as shown in Fig. 4. The number of modes *P* is set to six and the dimension of space *M* is set to *N*(4/5). An exact fit was obtained with SNR of 112. Fig. 4 also shows the envelope of the voltage flicker signal. Based on Fig. 4, the voltage fluctuates with flicker frequency of 10Hz.

In this paper, the voltage flicker was simulated by a programmable voltage source applied to a one feeder distribution system as shown in Fig. 5 for a window size of 10, 50-Hz cycles using amplitude with modulation index of 0.2 and flicker frequency of 10Hz. To reduce the flicker severity, a DVR scheme is installed at the 11kV side where the sensitive load is connected. The corresponding system parameters are given in Table A1 in the Appendix [27].

Simulations of the instantaneous and RMS value of the fluctuated load voltage without DVR compensation are demonstrated in Fig. 6 and 7, respectively.

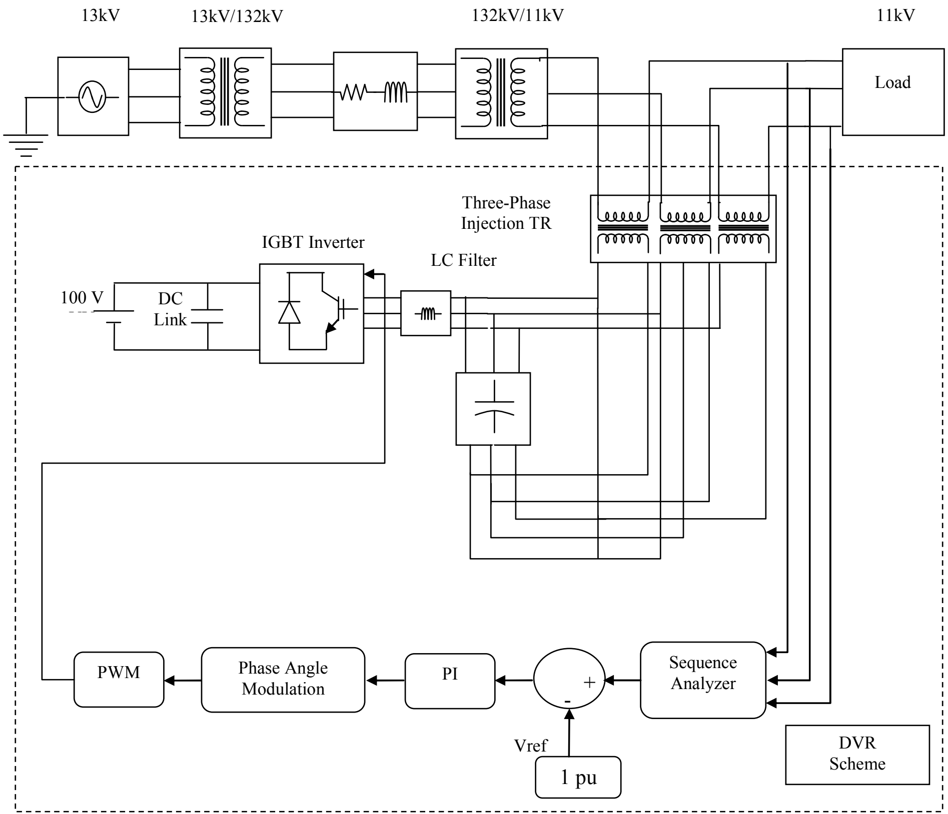

Fig. 5. Distribution feeder system under study with DVR scheme

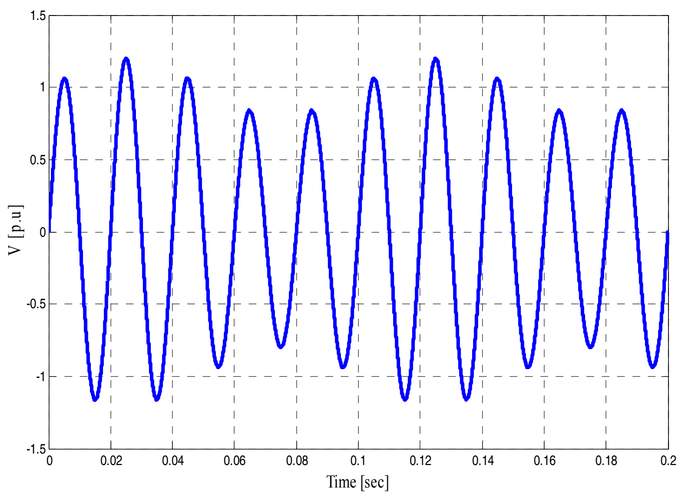

Fig. 6. Fluctuated load voltage without DVR

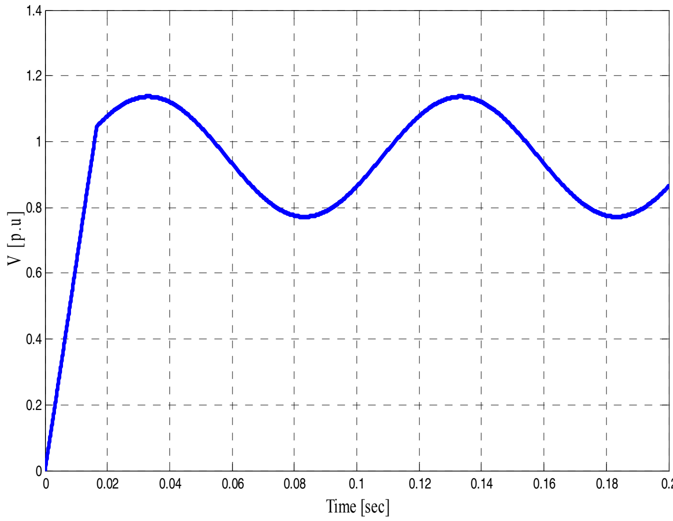

Fig. 7. RMS value variation of the fluctuated load voltage without DVR

Fig. 6 shows the instantaneous voltage fluctuation of phase *a* at the 11kV busbar of the sensitive load without DVR compensation. Fig. 7 displays the variation of the per unit RMS value of the load voltage over 10 cycles. It shows that the flicker level is 36% with flicker frequency of 10Hz.

Simulation results of the compensated system are displayed in Fig. 8 and 9. Fig. 8 shows the waveform of the load voltage, whereas Fig. 9 shows the corresponding RMS value. It can be seen that the DVR scheme has successfully reduced the flicker level to 9%.

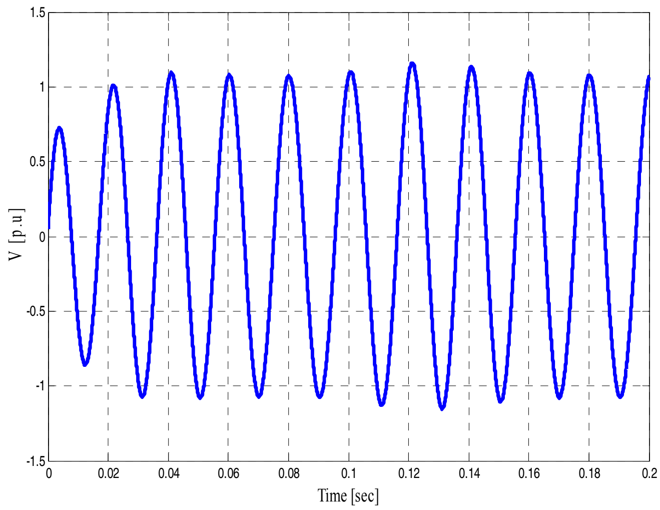

Fig. 8. Compensated load voltage waveform with DVR

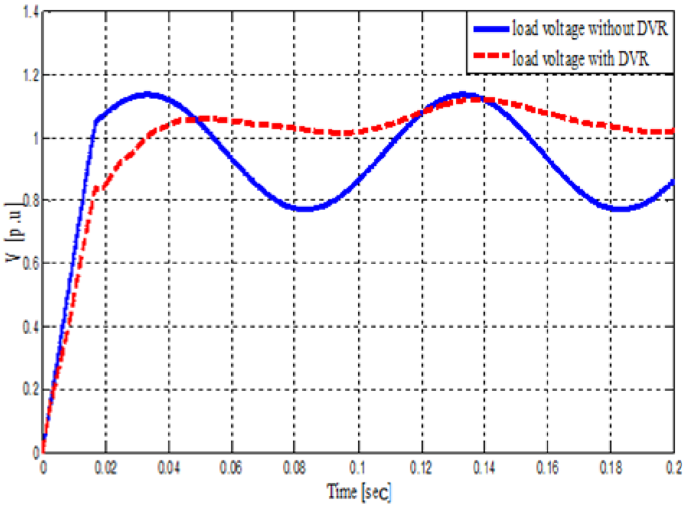

Fig. 9. RMS value variation of the compensated load voltage with DVR

B. Case 2: Single High Frequency Band (HFB) Interharmonics

This case study presents a case of apparent voltage flicker caused by a third harmonic component with a beat frequency of 5Hz. The voltage waveform is synthesized as [16], [36]:

$$\begin{aligned} v(t) &= 1.\sin(2\pi 50t) + 0.3\sin(2\pi 155t) \\ &= 1.\sin(2\pi 50t) + 0.3\sin(2\pi 5t)\cos(2\pi 150t) + 0.3\cos(2\pi 5t)\sin(2\pi 150t) \end{aligned} \tag{22}$$

The voltage waveform is sampled at a sampling frequency of 1000Hz over a window size of five. 50-Hz cycles give a total number of samples N equal 100 samples. Fig. 10 shows a voltage flicker signal caused by a HFB interharmonics superimposed into the 50-Hz voltage signal. The variation of the RMS value of the fluctuated voltage signal over 10 cycles is depicted in Fig. 11. Fig. 10 and 11 show that the flicker level is 6% with a flicker frequency of 105Hz. The voltage signal is decomposed into its frequency components using MUSIC technique. The parameters are set at P= 4 and M= N0.8. The magnitudes, frequencies and phase angles of the frequency components are presented in Table 2.

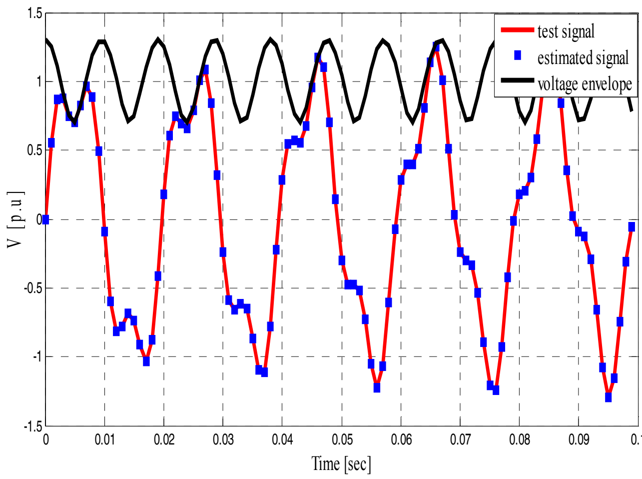

Fig. 10. HFB voltage flicker signal

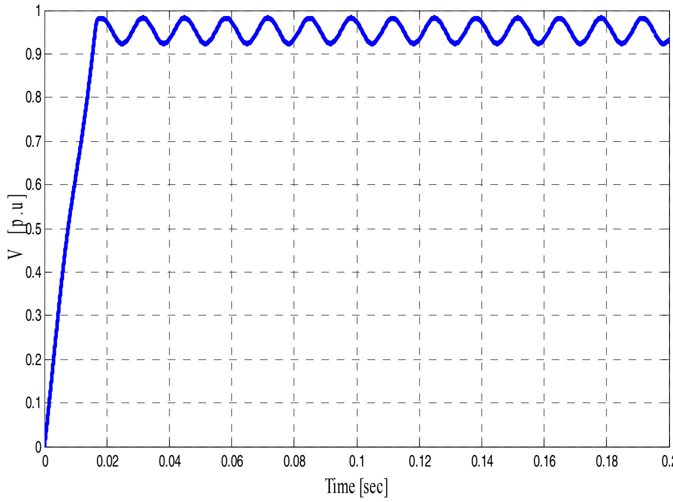

Fig. 11. RMS value variation of the fluctuated load voltage without DVR

TABLE 2
MUSIC ESTIMATION OF SINGLE HFB VOLTAGE FLICKER SIGNAL

Frequency Component	Frequency (Hz)	Amplitude (pu-V)	Phase Angle (Deg)
f_o	50	1.0	90
f_{IH}	155	0.3	-90

The MUSIC technique shows high frequency interharmonics of 155Hz with amplitude of 0.3puV. The signal is reconstructed as linear sum of its frequency components and compared with the original signal as shown in Fig. 10. The exact estimation of the magnitudes, frequencies, and phase angles is obtained. Likewise, the exact fitness of the predicted signal to the original signal can also be observed in Fig. 10 with SNR of 142. Fig. 10 shows that the envelope of the voltage signal is cyclic due to the presence of the third harmonic.

The effectiveness of the DVR scheme on mitigating the voltage flicker caused by a single HFB interharmonic has been examined. The voltage flicker was simulated by a programmable voltage source for a window size of 10 cycles. Fig. 12 and 13 show the simulation result of the compensated load voltage waveform and the corresponding RMS value. Fig. 13 shows that the DVR scheme has successfully reduced the flicker level to 2%.

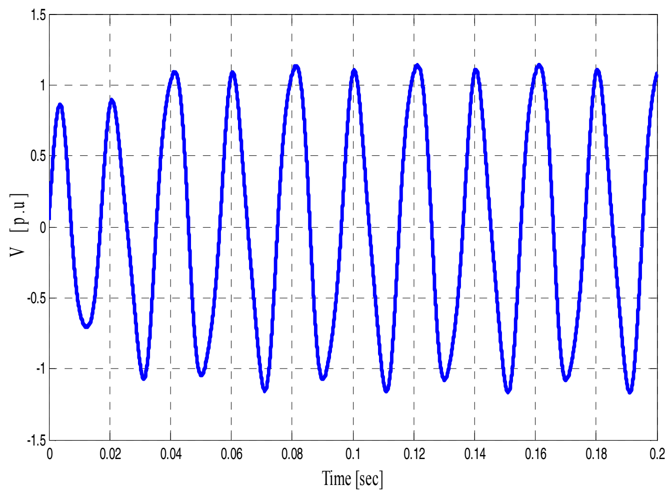

Fig. 12. Compensated load voltage waveform with DVR

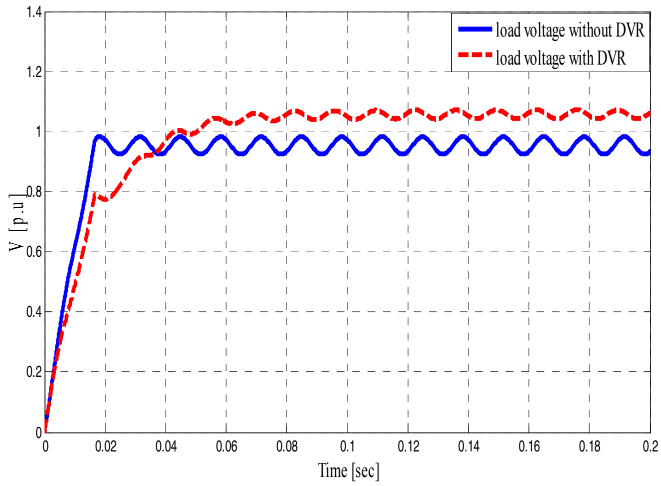

Fig. 13. RMS value variation of the compensated load voltage with DVR

VI. CONCLUSION

This paper presents a two-phase approach for voltage flicker estimation and mitigation using a combined signal processing technique and custom power quality scheme. In phase one, a high resolution method using MUSIC technique for an accurate estimation of the voltage flicker level was applied to extract the magnitudes, frequencies and phase angles of the interharmonic components of the distorted voltage signal. Furthermore, the voltage envelope of the voltage flicker distorted waveform was constructed using Hilbert transform. Two cases of voltage flicker distortion including low and high frequency bands were investigated. The simulation results show that MUSIC is very effective on the accurate estimation of interharmonics. In phase two, the mitigation of the voltage flicker was accomplished using the DVR scheme. The DVR scheme is simulated on a power distribution system using Matlab/Simulink software. The performance of the DVR was examined under the two cases of voltage fluctuation. Simulation results show a successful operation of the DVR in reducing the voltage flicker levels in case of both the low and high frequency bands.

APPENDIX

TABLE A1
SYSTEM PARAMETERS

System Quantities	Value
Three phase programmable voltage source	13KV, 50Hz
Three phase two winding transformer (1)	100MVA, 50Hz, 13/132kV
Three phase two winding transformer (2)	100MVA, 50Hz, 132/11kV
Three phase RLC load (1)	11kV, 50Hz, 1000W, 1000VAR (inductive)
Filter Inductance	0.5mH
Filter Capacitance	1μF
Universal Bridge	IGBT/Diode, 3 arm, 6 pulse
Transmission line	0.001Ω, 5mH
PI Controller	K_p= 0.5, K_i= 150, Sampling time= 50μs
DC Voltage Source	100V
PWM	Carrier Freq.= 1080Hz, Sampl. time= 50μs
DC Link	200μF

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