

Data Compression of Power Quality Events Using the Slantlet Transform

G. Panda, P. K. Dash, A. K. Pradhan, and S. K. Meher

Abstract—The slantlet transform (SLT) is an orthogonal discrete wavelet transform (DWT) with two zero moments and with improved time localization. It also retains the basic characteristic of the usual filterbank such as octave band characteristic, a scale dilation factor of two and efficient implementation. However, the SLT is based on the principle of designing different filters for different scales unlike iterated filterbank approaches for the DWT. In this paper a novel approach for power quality data compression using the SLT is presented and its performance in terms of compression ratio (CR), percentage of energy retained and mean square error present in the reconstructed signals is assessed. Varieties of power quality events, which include voltage sag, swell, momentary interruption, harmonics, transient oscillation and voltage flicker are used to test the performance of the new approach. Computer simulation results indicate that the SLT offers superior compression performance compared to the conventional discrete cosine transform (DCT) and the DWT based approaches.

Index Terms—Discrete wavelet transform (DWT), power quality waveform analysis, slantlet transform.

I. INTRODUCTION

POWER QUALITY (PQ) events can be referred to any electrical disturbances, which adversely affect customer load or power system equipment. Typical PQ issues include short-term events such as voltage sags or dips lasting a few cycles to a few seconds caused by faults on nearby feeders, large loads switch on, subcycle transients caused by switching power factor corrections capacitors and lightning strikes, etc. Harmonics and flickers also fall into the category of PQ though these items occur over much longer intervals. Such signal disturbances severely affect the performance of the automated equipment, programmable logic controllers, computers, etc. Presently many utilities, therefore, utilize dedicated PQ monitoring devices on light/medium voltage station to record these events, typically for post event analysis or communication with distant control devices. Further, there are some indications that information about the PQ itself will become a valuable commodity after deregulation subject to negotiations, pricing, ownership, etc [1]. Such information in the form of oscillographic waves are captured at a high sampling rate (to include high frequency components) and the data are stored in a memory device. The volume of the current

and voltage data of all phases for such events is quite high. For example, for only 100 such events, with 128 samples per cycle and data length of four cycles only will require 3686 Kb (100 events \times 128 samples per cycle \times 4 cycles \times 7 channels \times 2 bytes). Thus, it is evident that the PQ study requires large amounts of data. Therefore, for storing, transmitting and interpretation purpose compression operation for such data is essential. A compression technique involves a transform to extract for feature information contained in the data and a logic for removal of redundancy present in the extracted features. The discrete cosine transform (DCT) is conventionally used for data compression because of its orthogonal property [2]. In the recent past the discrete wavelet transform (DWT) has emerged as a potential tool for analysis [3], [4], denoising [5] and compression [6], [7] of different signals because it provides relatively efficient representation of piecewise smooth signals [8], [9]. The degree to which a wavelet basis can yield sparse representation of different signals depends on the time-localization and smoothness property of the basis function. The DWT is usually carried out by filterbank iteration, but for a fixed number of zero moment it does not yield a discrete time basis that is optimal with respect to time-localization. A fundamental trade off exists between time-localization and smoothness characteristics. The slantlet transform (SLT) [10] has been developed by employing the lengths of the discrete time basis function and their moments as the vehicles in such a way that both time-localization and smoothness properties are achieved. It is an orthogonal DWT with two zero moments and possesses improved time-localization properties. In this paper, we use the SLT as a tool in devising an efficient method for compression of different PQ events.

The organization of the paper proceeds as follows. In Section II, the SLT is introduced and its properties and features are outlined. A novel approach of data compression and reconstruction using the SLT is discussed in Section III. In Section IV, compression and reconstruction of different PQ events are simulated and the test results obtained are analyzed and interpreted. The corresponding results are also obtained by using the DCT as well as DWT based compression and the results are compared. Finally conclusions have been made in Section V.

II. SLANTLET TRANSFORM

The SLT uses a special case of a class of bases described by Alpert [11], the construction of which relies on Gram–Schmidt orthogonalization. The SLT is based on a filterbank structure where different filters are used for each scale. Let us consider a usual two-scale iterated DWT filterbank shown in Fig. 1(a) and its equivalent form [Fig. 1(b)]. The SLT filterbank employs the

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structure of the equivalent form shown in Fig. 1(b) but it is occupied by different filters that are not products. With this extra degree of freedom obtained by giving up the product form, filters of shorter length are designed satisfying orthogonality and zero moment conditions. For two-channel case the Daubechies filter [12] is the shortest filter which makes the filterbank orthogonal and has K zero moments. For $K = 2$ zero moments the iterated filters of Fig. 1(b) are of lengths 10 and 4 but the SLT filterbank with $K = 2$ zero moments shown in Fig. 2 has filter lengths 8 and 4. Thus the two-scale SLT filterbank has a filter length which is two samples less than that of a two-scale iterated Daubechies-2 filterbank. This difference grows with the number of stages. Some characteristic features of the SLT filterbank are orthogonal, having two zero moments and has octave-band characteristic. Each filterbank has a scale dilation factor of two and provides a multiresolution decomposition. The slantlet filters are piecewise linear. Even though there is no tree structure for SLT it can be efficiently implemented like an iterated DWT filterbank [10]. Therefore, computational complexities of the SLT is of the same order as that of the DWT. The filter coefficients used in the SLT filterbank as derived in [10] are given by

$$\begin{aligned}
 E_0(z) &= \left(-\frac{\sqrt{10}}{20} - \frac{\sqrt{2}}{4} \right) + \left(\frac{3\sqrt{10}}{20} + \frac{\sqrt{2}}{4} \right) z^{-1} \\
 &\quad + \left(-\frac{3\sqrt{10}}{20} + \frac{\sqrt{2}}{4} \right) z^{-2} + \left(\frac{\sqrt{10}}{20} - \frac{\sqrt{2}}{4} \right) z^{-3} \\
 E_1(z) &= \left(\frac{7\sqrt{5}}{80} - \frac{3\sqrt{55}}{80} \right) + \left(-\frac{\sqrt{5}}{80} - \frac{\sqrt{55}}{80} \right) z^{-1} \\
 &\quad + \left(-\frac{9\sqrt{5}}{80} + \frac{\sqrt{55}}{80} \right) z^{-2} + \left(-\frac{17\sqrt{5}}{80} + \frac{3\sqrt{55}}{80} \right) z^{-3} \\
 &\quad + \left(\frac{17\sqrt{5}}{80} + \frac{3\sqrt{55}}{80} \right) z^{-4} + \left(\frac{9\sqrt{5}}{80} + \frac{\sqrt{55}}{80} \right) z^{-5} \\
 &\quad + \left(\frac{\sqrt{5}}{80} - \frac{\sqrt{55}}{80} \right) z^{-6} + \left(-\frac{7\sqrt{5}}{80} - \frac{3\sqrt{55}}{80} \right) z^{-7} \\
 E_2(z) &= \left(\frac{1}{16} + \frac{\sqrt{11}}{16} \right) + \left(\frac{3}{16} + \frac{\sqrt{11}}{16} \right) z^{-1} \\
 &\quad + \left(\frac{5}{16} + \frac{\sqrt{11}}{16} \right) z^{-2} + \left(\frac{7}{16} + \frac{\sqrt{11}}{16} \right) z^{-3} \\
 &\quad + \left(\frac{7}{16} - \frac{\sqrt{11}}{16} \right) z^{-4} + \left(\frac{5}{16} - \frac{\sqrt{11}}{16} \right) z^{-5} \\
 &\quad + \left(\frac{3}{16} - \frac{\sqrt{11}}{16} \right) z^{-6} + \left(\frac{1}{16} - \frac{\sqrt{11}}{16} \right) z^{-7} \\
 E_3(z) &= z^{-3} E_2 \left(\frac{1}{z} \right).
 \end{aligned}$$

III. SLT BASED DATA COMPRESSION AND RECONSTRUCTION

A scheme of data compression and reconstruction using a two-scale SLT filterbank is shown in Fig. 3. It involves three distinct steps.

- 1) Transformation of input signal using the SLT.
- 2) Thresholding of transformed coefficients.

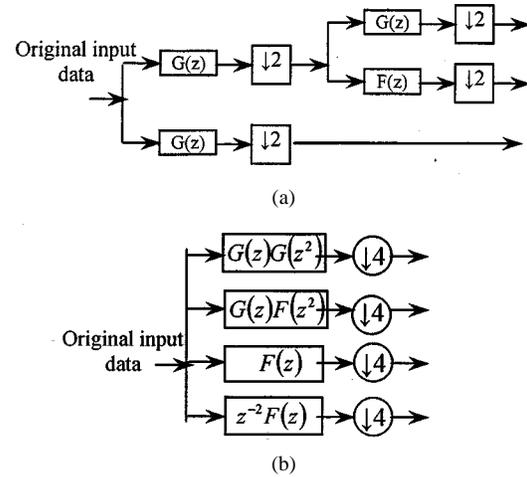


Fig. 1. Two-scale iterated filterbank and its equivalent form using the DWT.

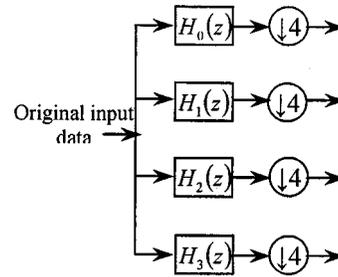


Fig. 2. Two-scale filterbank structure using the SLT.

- 3) Reconstruction of the signal from the thresholded coefficients using the inverse SLT.

The first two steps constitute compression operation where as the last step performs the reconstruction operation. The filter coefficients used in the analysis part are given in Section II. The PQ disturbance signal is fed to the two-scale SLT filterbank, where the outputs are down sampled by a factor four. The transformed coefficients of the SLT are $H_1(z)$, $H_2(z)$, $H_3(z)$, and $H_4(z)$. The SLT retains most of its input signal energy in some selective coefficients and the magnitudes of the remaining coefficients are insignificant. Thus by judiciously fixing the threshold level a number of SLT coefficients are discarded by setting them to zero. Keeping the quality of signal reconstruction in view the threshold level is fixed. The remaining thresholded coefficients represent the PQ disturbance signal in the compressed form. The percentage of energy retained used as a performance index for compression is defined as

$$\left[\frac{\text{(Vector norm of the retained SLT coefficients after thresholding)}}{\text{Vector norm of the original SLT coefficients}} \right] \times 100.$$

The retained coefficients are encoded to binary form for storing and transmission purpose. From the compressed data the original PQ events can be reconstructed by using the two-scale SLT synthesis filterbank whose transformed coefficients are $H'_0(z)$, $H'_1(z)$, $H'_2(z)$ and $H'_3(z)$ (Fig. 3). The synthesis filter coefficients are obtained by time reversal of the corresponding analysis filters. In the reconstruction process the

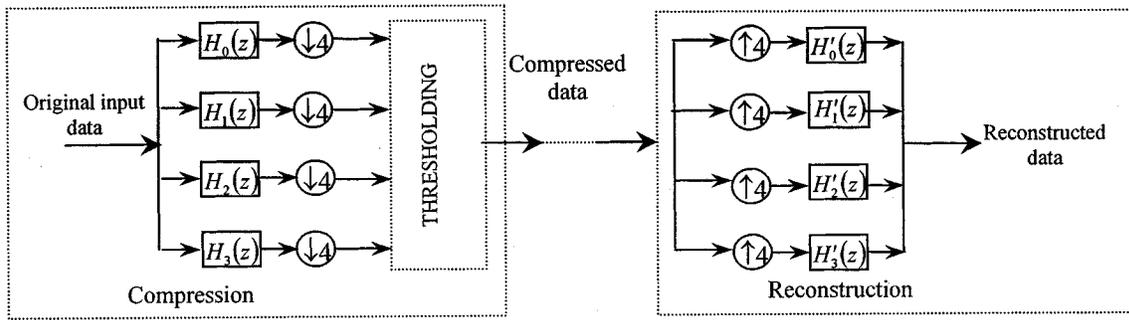


Fig. 3. Two-scale SLT based data compression/reconstruction scheme.

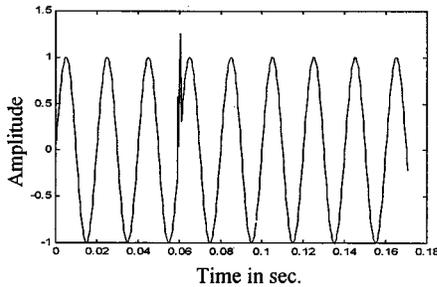


Fig. 4. A 50 Hz fundamental signal with an impulse.

compressed data are first upsampled by a factor four and then convolved with the synthesis filter coefficients of each channel. These synthesized data are then added together to reconstruct the original PQ signal for the purpose of further analysis and interpretation. To assess the quality of compression the mean square error (MSE) in decibels is used as the performance index and is defined as

$$\text{MSE (dB)} = 10 \left[\log_{10} \left(\frac{1}{N} \sum_{i=1}^N \|x(i) - \hat{x}(i)\|^2 \right) \right] \quad (9)$$

where $x(i)$ is the original signal and $\hat{x}(i)$ is the reconstructed signal. In the proposed scheme we have chosen a two-level SLT filterbank considering both the complexity of computation and the quality of compression.

IV. TEST RESULTS

To demonstrate the data compression capability of the new approach a disturbance signal containing an impulse at 0.001 s is considered (Fig. 4). The signal is decomposed by the SLT into two levels and the corresponding filter outputs are shown in Fig. 5. It is evident from these figures that each filter output contains the information of different frequency components of the disturbance signal and can accurately localize the disturbance point. Subsequently threshold value is selected based on the maximum absolute value of the transformed coefficients and then the discarding operation takes place. In the next stage the retained transform coefficients are utilized to accurately reconstruct the original signal and is shown in Fig. 6. This figure depicts that the disturbance signal is successfully retrieved from the transformed coefficients. The ratio between the number of original signal data to the number of data retained after the thresholding is termed as the compression ratio (CR) and in the present case CR = 10 is considered. Keeping a lower CR that

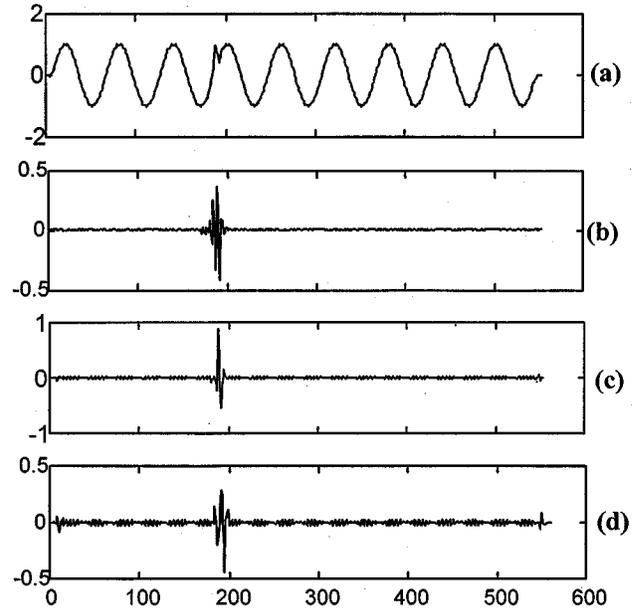


Fig. 5. SLT filter bank output. (a) First filter o/p. (b) Second filter o/p. (c) Third filter o/p. (d) Fourth filter o/p.

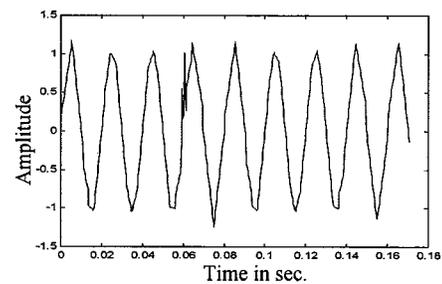


Fig. 6. A 50 Hz fundamental signal with an impulse reconstructed using the SLT at CR = 10.

is at CR = 5, the signal is again reconstructed and is observed to be better than at CR = 10 (Fig. 7). It is obvious from the above discussion that with higher CR value less data are retained after thresholding stage and hence accuracy is sacrificed in reconstructing the signal. However, high CR value is preferred from data communication and storage point of view. Further, in case of the SLT we have considered signal decomposition up to second level with an objective to reduce the computation burden. In practical application, a compromise is made between the diverging factors.

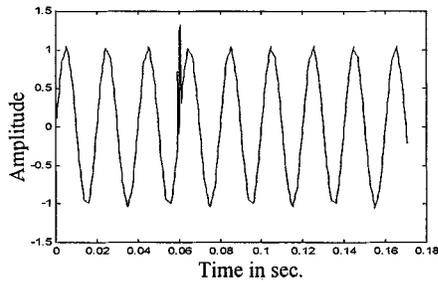


Fig. 7. A 50 Hz fundamental signal with an impulse reconstructed using the SLT at CR = 5.

TABLE I
PERCENTAGE OF ENERGY RETAINED AND THE MSE IN dB OBTAINED USING THE DCT, DWT AND SLT BASED COMPRESSION/EXPANSION TECHNIQUES FOR ALL THE SIGNALS AT CR = 10

Signal	Energy Retained (%)			MSE (dB)		
	DCT	DWT	SLT	DCT	DWT	SLT
Impulse	88.01	91.13	94.01	-10.67	-13.56	-16.98
Sag	87.81	90.01	93.20	-10.08	-13.04	-17.54
Swell	89.46	91.01	94.44	-11.88	-13.77	-17.95
Harmonics	87.69	90.89	93.14	-11.04	-13.31	-17.68
Momentary Interruption	90.44	91.10	94.11	-12.27	-15.89	-18.79
Oscillatory transient	91.63	90.88	95.04	-12.98	-14.45	-19.07
Voltage Flicker	90.75	91.34	95.18	-10.76	-14.74	-19.78

The proposed data compression technique is applied to many PQ issues such as: sag, swell, harmonics, interruption, oscillatory transient and flicker. All the data are generated using the MATLAB code at a sampling rate of 3 kHz. To demonstrate the efficacy of the proposed technique some test cases are presented below. For all simulation study a pure sinusoidal signal of 50 Hz and 1 p.u. amplitude is considered. To compare the performance of the new approach with the standard DCT and the DWT based approaches, we consider the same signal (Fig. 4) for all the three cases. Percentage of energy retained and the MSE in decibels as defined earlier are calculated for different types of power system signals at CR = 10 and are listed in Table I. It is evident from this table that at CR = 10, the energy retained by the SLT approach is 94.01% as compared to 88.01% and 91.13% by the DCT and DWT approaches, respectively. Similarly the corresponding MSE for the SLT approach is -16.98 dB and that for the DCT and the DWT is -10.67 dB and -13.56 dB, respectively. This clearly demonstrates better compression capability of the new technique.

A. Voltage Sag

A voltage sag is a sudden reduction (10–90%) in the voltage magnitude, lasting for 0.5 cycle to several seconds. A sag may be caused by switching operation associated with temporary disconnection of supply, flow of heavy current associated with the starting of large motor load or the flow of fault currents. The effect of voltage sag on equipment depends on both the magnitude and its duration. To evaluate the performance of the SLT approach a 20% sag case of 3.5 cycles of duration signal is considered. The original and the reconstructed signal obtained through simulation at a CR = 10 is shown in Fig. 8, which depicts the accuracy of the approach at reduced data size also. By varying the

threshold value the CR is changed and the corresponding percentage of energy retained in the reconstructed signal is evaluated using all three methods. Fig. 9 shows the performance graph of three methods and it is clear that for CR > 5 the slantlet approach provides higher energy retaining capacity compared to that of other two. For the same sag case the mean square error (MSE), is also calculated for the reconstructed signal for different values of CR. The curves in Fig. 10 show that for CR value above six the new approach is more accurate in reconstructing the signal as compared to the DCT or the DWT. In Table I, for the sag waveform at CR = 10, the percentage of energy retained as obtained in DCT, DWT and SLT approaches are 87.81%, 90.01% and 93.20%, respectively. Further the MSE level for SLT is -17.54 dB as compared to -10.08 dB and -13.04 dB for DCT and DWT, respectively. This information clearly indicates better accuracy of reconstruction of the SLT over each of the DCT and DWT.

B. Voltage Swell

When the voltage signal increases by 10%–90% it is known as voltage swell. They often appear on the sound phases of a power system where a phase-to-ground fault occurs or when heavy motor loads are switched off. Swell may stress the delicate equipment components to premature failure. Fig. 11 depicts the waveform of a voltage swell (80%) lasting for three cycles. The corresponding data are used for the decomposition and reconstruction of the disturbance signal using all the three approaches as mentioned earlier. Similar to the sag case at different CR values the reconstructed signals by the SLT show higher accuracy both in terms of energy retained and MSE as compared to that of DCT and DWT. For example, at CR = 10, the percentage of energy retained as obtained by the DCT and DWT approaches are 89.46 and 91.01, respectively, as compared to 95.44 by the new approach (Table I). Further, the MSE for the waveform in case of SLT is as low as -17.95 dB as compared to -11.88 dB and -13.77 dB for the DCT and DWT, respectively. In the case of voltage swell also superior performance of the SLT is observed.

C. Harmonically Distorted Signal

With the introduction of more power electronic equipment in distribution system, the power quality is further degraded as they produce significant amount of different harmonics. Such harmonic pollution in voltage signal leads to poor performance of converter circuit. A 1 p.u. fundamental voltage signal (50 Hz) distorted by 30% third harmonic and 10% fifth harmonic as shown in Fig. 12 is considered to evaluate the performance of the SLT based compression technique. AT CR = 10, the SLT reconstructs the signal with 93.14% of energy as compared to 87.69% and 90.89% by the DCT and DWT, respectively. Further, for the same waveform and CR value the MSE index for the SLT is -17.68 dB as compared to -11.04 dB and -13.31 dB obtained by the DCT and DWT, respectively.

D. Momentary Interruption

Interruptions can be considered as voltage sags with 100% amplitude and are mainly due to short circuit faults being

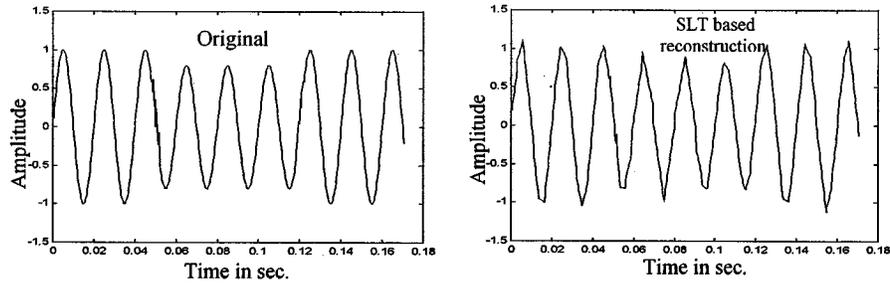


Fig. 8. Original and the reconstructed sag signal at CR = 10.

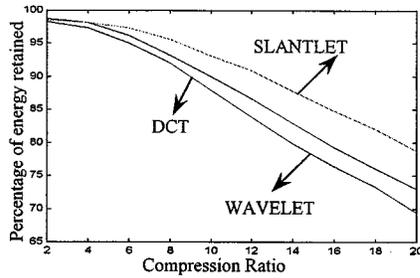


Fig. 9. Percentage of energy retained in the reconstruction of sag signal.

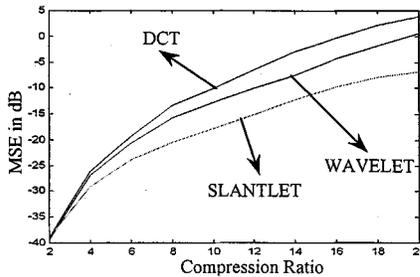


Fig. 10. MSE in dB obtained in the reconstruction of sag signal.

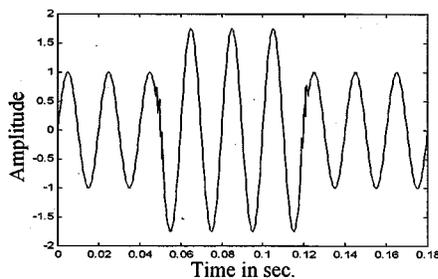


Fig. 11. A 50 Hz signal with SWELL.

cleared by the protection. Supply interruption for few cycles will greatly influence the performance of glass and computer industries. For evaluating the performance of the SLT based compression technique a voltage signal interrupted for three cycles is shown in Fig. 13. The SLT reconstructs the signal with 94.11% of energy (90.44% and 91.10% for the DCT and DWT, respectively). Similarly the MSE for the SLT is -18.79 dB as compared to -12.27 dB and -15.89 dB for the DCT and DWT, respectively. This simulation study is extended to other CR values and it is, general, found that the SLT is a better candidate for data compression of such signals.

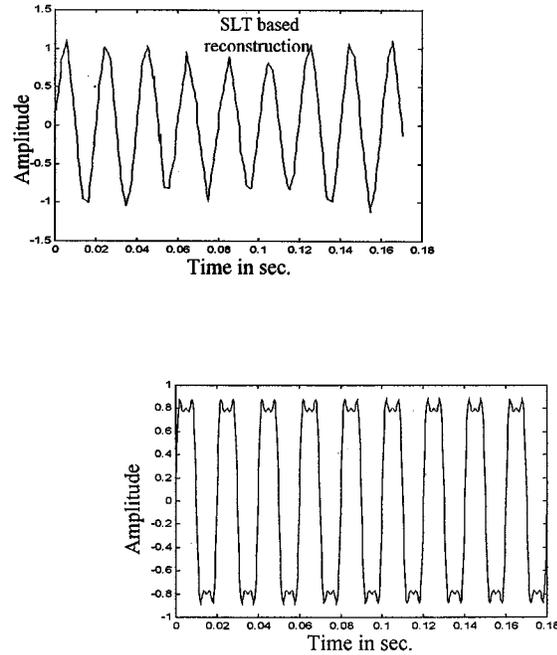


Fig. 12. A 50 Hz signal with third and fifth harmonics.

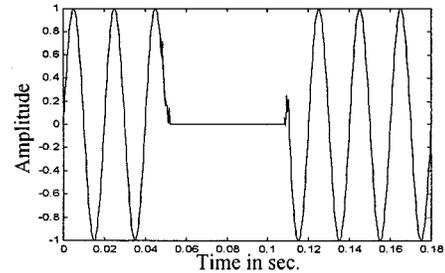


Fig. 13. A 50 Hz signal with momentary interruption.

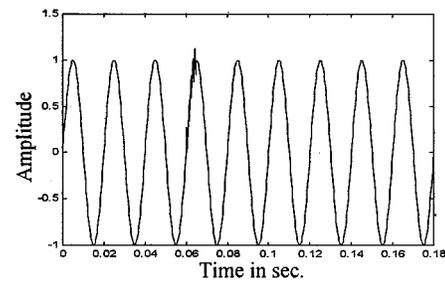


Fig. 14. A 50 Hz signal with oscillatory transient.

E. Oscillatory Transient

Transient disturbances are shorter than the sags and swells. A transient disturbance waveform may have oscillatory characteristic and such signals are found during capacitor bank switching. An oscillatory transient signal is shown in Fig. 14, which persists for 5 ms only. As mentioned in Table I for CR = 10 the percentage of energy retained by DCT, DWT and SLT approaches are 91.63%, 90.88%, 95.04%, respectively. Further the MSE for SLT is -19.07 dB as compared to -12.98 dB and -14.45 dB obtained by the DCT and DWT approaches, respectively. In this type of signal also the SLT outperforms the other two.

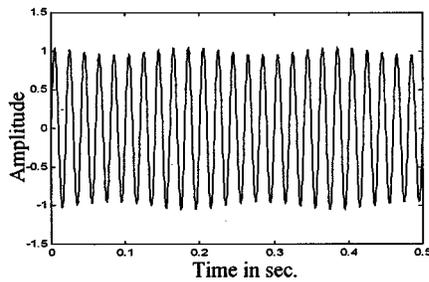


Fig. 15. A 50 Hz signal with voltage flicker.

F. Voltage Flicker

Voltage flicker refers to slow (0.5–30 Hz) modulation of the voltage magnitude. Cyclic and acyclic loads with temporal variation or sudden starting of large induction motors can cause voltage flicker. The amplitude of a sinusoidal voltage signal (1 p.u., 50 Hz) is modulated by a low frequency component of 0.05 p.u., 5 Hz and is shown in Fig. 15. At CR = 10 the reconstructed signal by SLT possess 95.18% of energy as compared to 90.75% by the DCT and 91.34% by DWT. Again, the MSE index for SLT is -19.78 dB and that for the DCT and DWT are -10.76 dB and -14.74 dB, respectively. This result clearly shows the superiority of the SLT approach to compress the flicker signal.

V. CONCLUSION

In this paper, the SLT has been applied for compression of data pertaining to the PQ events. The SLT is an orthogonal DWT and provides improved time localization than the DCT and DWT. The compression performance of the new approach is assessed through computer simulation and the results are compared with the DCT and the DWT approaches. Considering various compression parameters such as the percentage of energy retained and the MSE in decibels of different PQ signals, it is, in general, observed that the accuracy of the reconstruction of the proposed SLT method is better than that the DCT and DWT. Exhaustive computer simulation results on different PQ signals indicate this trend. Thus it is, in general, concluded that the SLT based compression technique yields better performance compared to both the DCT and DWT.

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