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Welch-Windowed Finite Impulse Response Filter for Electrocardiographic Signal Processing

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***Abstract*— Electrical signal (electrocardiogram ECG) that is produced in the heart can be detected and studied. It reveals the functionality of the heart. Like other bio-electrical signals, ECG is a non-stationary signal. ECG of a patient is obtained and compared with known ECG pattern, then the illness the patient suffers will be diagnosed and proper treatment commences. This may not be achieved if information the ECG carries is compromised with some other signals that may be recorded when ECG was being recorded. It is very essential that all artifacts that corrupted the ECG are removed before the signal gets to the physicians. 50Hz power line interference (PLI) and baseline wander (BW) are some of the noises that effect ECG. In this work, a Finite Impulse Response (FIR) filter using Welch Window is designed to remove 50Hz PLI and BW from a contaminated 7-cycle ECG signal. MATLAB periodogram is used to demonstrate the effectiveness of the filter.**

***Index Terms*— Electrocardiographic signal, Power line interference, FIR filter, Digital filter, Welch window, Noise removal.**

I. Introduction

At the state of rest, the cells of the heart muscles have slightly unequally concentration of ions across the cell membranes. This state is called polarization. Sodium ions tend to dwell outside the cell membrane, making the outer part of the muscle cell to be relatively positively charged compared to the inside. When the muscles of the heart are simulated, sodium ions are forced into the inner part of the cell membrane to cause a situation of change of potential difference in the cells. This is referred to as depolarization. However, these processes of polarization and depolarization occur continually in a rhythmic pattern resulting to an electrical signal from the heart transmitted and detected on the skin. This is called the electrocardiogram (ECG or EKG). Interestingly, since the polarization-depolarization process is rhythmical, the overall electrical signal discharged occurs in a particular pattern. The pattern referred to as the PQRST wave form. The PQRST wave form reveals a lot to the clinicians about the state of wellness of the heart of a patient by means of signal strength and wave timing. With the ECG of a patient, the physicians will be able to diagnose heart attack, heart chamber enlargement, and poor blood flow (Ischemia) and other cardiovascular illnesses. ECG of a subject is obtained by placing ECG electrodes on the chest and other parts of the patient's body. During the process, other electrical signals around might be recorded with the ECG. Signals like Electromyogram (EMG), Power line Interference (PLI) and Baseline wander (BW) might constitute the ECG noise. EMG is a high frequency signal generated by the muscular system. It is as high as 500Hz [1]. PLI is noise produced due to the coupling effect of electrical components of the ECG device. It is either 50Hz or 60Hz depending on the equipment power source. BW is a low range frequency electrical signal. It ranges between 0.1Hz to 0.5Hz [2]. BW comes about as a result of variations in electrode-skin impedance as well as patient's movement and patient's breathing process [2]. That it can further be described as a low frequency fluctuation that occurs due to the rhythmic depolarization and re-polarization activity in the respiratory process of the patient. Meanwhile, the frequency range of ECG signal is between from 0.5Hz to 100Hz [2].

These are unwanted signals that corrupt recorded ECG. If these unwanted signals are not removed from ECG, interpretation of recorded ECG will be inaccurate and wrong diagnoses and treatment will be inevitable. Digital filters are very useful in presenting clean ECG. Finite impulse response (FIR) filter method among other methods have been applied and found effective in ECG signal processing.

In FIR filter modeling, windows are of great importance to implement the filter. Many researchers have used different windows for this purpose. Some researchers applied low pass, high pass and notch filters modeled with Kaiser Windowed-FIR filter on ECG [3]. They concluded that Kaiser Window was found very effective in designing FIR digital for PLI reduction from ECG. A Modified Triangular Window FIR filter was modeled and proposed for the removal of 50Hz PLI ECG [4]. They researchers juxtaposed the results obtained from the Modified Triangular Window FIR filter and the ones from Triangular Window FIR filter, and concluded that the proposed filter was effective in de-noising ECG of 50Hz PLI. Design and implementation of digital FIR notch filter using Blackman window for reduction of 50Hz PLI on ECG signal was successfully demonstrated by some researchers [5]. Using MATLAB Periodogram plot, the researchers displayed the ability of Blackman-windowed FIR filter in ECG signal improvement. It was also shown that the Parzen Window can also be used to implement FIR filter in ECG signal improvement [6]. Filter order of 187 was found most appropriate for implementing FIR filter for ECG signal 50Hz PLI noise removal. The researcher used MATLAB generated phase response diagrams to show the linearity of the window. Other important properties of the window shown include; time domain response, frequency response, magnitude response and impulse response. The Sine Window is not left out in the litany of windows used in implementing FIR filter for ECG artifact reduction. In their work on ECG improvement using Sine Window [7], a filter order of 100 successfully implemented FIR Sine Windowed filter for 50Hz PLI reduction. The Nuttall and Hanning

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Windows in [8] and [9] respectively implemented a stopband filter for 50Hz interference removal from ECG signal. Once more MATLAB periodogram plot confirms the effective reduction of the 50Hz PLI from the desired ECG signal.

Furthermore, some researchers chose to do windowed FIR filters with multiple windows to compare the effectiveness of each of the windows in ECG signal 50Hz PLI noise filtration a multiple windows of six namely Rectangular, Kaiser, Hanning, Hamming, Blackman and Bartlett were used in the process. Many other windows have not reviewed here been used in ECG enhancement yet one modeled with Welch Window cannot be found. Therefore the researcher investigates on the functionality of the Welch Window in FIR filter modeling for the purpose of enhancing ECG by reduction of 50Hz PLI.

II. The Welch Windowed

The aim of this work is to show that the Welch Window will make a very good window in the design of digital FIR filter. The Welch Window can be mathematically expressed as shown in (1).

$$W(n) = 1 - \left(\frac{n - \frac{N-1}{2}}{\frac{N-1}{2}} \right)^2 \quad (1)$$

Where N is filter length, n is number of samples.

Welch window like most windows has a zero-origin and zero-terminus bell shape. This means that in the time domain plot (see fig 1), the amplitude of the window originates from zero, rises to maximum and in a symmetrical form falls to zero. In fig 1, a MATLAB “wintool” plot of Welch Window is shown for window length of 10 samples. Also from fig 1, it can be seen that the window has two amplitude values in the time domain plot. Table 1 clearly shows the two amplitude values at samples 5 and 6. However, the Welch Window is a non-one maximum amplitude window. More so, the window is an even-length symmetrical window. Trying to make the window odd length will give it a negative value terminus. The frequency domain plot of the window is also displayed in fig 1.

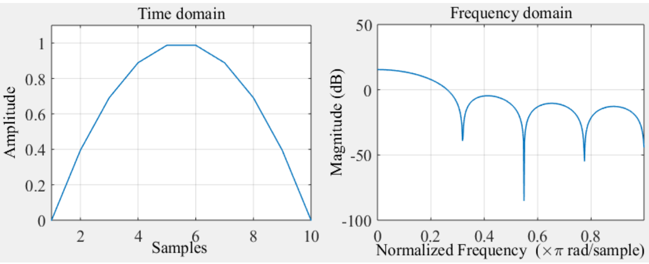

Fig 1 Time domain and Frequency domain of Welch Window for window length = 10 samples

Table 1; Amplitudes and corresponding sample values for 10 window length Welch Window

Samples	1	2	3	4	5
Amp	0	0.3951	0.6914	0.8889	0.9877

Samples	6	7	8	9	10
Amp	0.9877	0.8889	0.6914	0.3951	0

III. Welch-Windowed Filter Concept

Digital FIR filters are designed by limiting the infinite sequence of desired unit sample response $h_d(n)$ with defined boundaries of a window. The process is called windowing and it is achieved by multiplying the desired unit sample response $h_d(n)$ with the function of a window of a known window length. This means that (1) multiplied by (2), yields the desired response h(n) of windowed FIR filter as shown in (3).

$$h_d(n) = \frac{1}{2\pi}\left[\int_{-\pi}^{\pi} H(e^{j\omega}).e^{j\omega n}\, d\omega\right] \quad \text{(for 1 and 0)} \quad (2)$$

$$h(n) = h_d(n) * W_n \quad (3)$$

Where $H(e^{j\omega})$ is the desired frequency response. Importantly, in FIR filter modeling, proper filter order is requested to be used as it helps to achieve the desired transition width needed for maximum impulse response operation [1]. The filter order (L) used in this design is 97 corresponding to Welch Window length (N) of 98 samples. In (4), the relationship between filter order and window length is stated.

$$L = N-1 \quad (4)$$

The noises that are targeted for removal are BW 0Hz to 0.4Hz and PLI 50Hz. But ECG signal occurs within 0.5Hz to 100Hz [2]. Hence, while BW occurs outside ECG range yet PLI exits within the same frequency range with ECG. Therefore, a highpass filter with passband frequency of 0.5Hz is required for BW removal. A notch (stopband) filter of lower cutoff frequency 45Hz and upper cutoff frequency 55Hz is needed for 50Hz PLI removal.

One of the properties of a window based FIR filter is its linearity. If a filter has a good linearity feature, it implies that the filter is stable. An important plot that reveals the linearity and by extension, the stability of the filter is the unwrapped phase response plot shown in fig 2. Fig 3 and fig 4 show the Magnitude response plot and Impulse response plot of Welch-Window FIR filter.

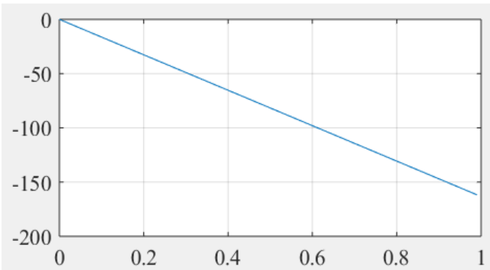

Fig 2 Unwrapped Phase response plot of Welch Window

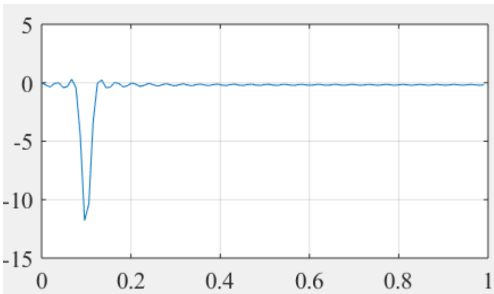

Fig 3 Magnitude response plot of Welch Window

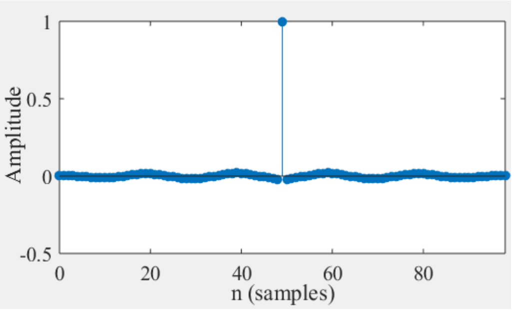

Fig 4 Impulse response plot of Welch Window

IV. Noise Reduction

The proposed Welch-windowed FIR filter is modeled and simulated with MATLAB R2015a application. A 7-cycle ECG signal is generated in MATLAB application environment as well as a 1.0mV magnitude 50Hz PLI and 0.1mV 0.5Hz BW. Fig 5 and fig 6 show 7-cycle ECG signal and PLI respectively. A simulation of ECG signal corrupted with 50Hz PLI and BW is executed in the same MATLAB environment. This is shown in fig 7. When the corrupted ECG signal is made to pass through a highpass FIR filter modeled with Welch Window, a signal akin to the corrupted ECG is obtained. This signal is ECG plus PLI minus BW as shown in fig 8. A delay is observed in the early part of the signal plot. Furthermore, when the ECG plus PLI signal passes through the Welch-window stopband FIR filter, another signal appears (see fig 8). Now this signal looks very much like the ECG signal of fig 5. Hence this shows that the proposed Welch-windowed FIR filter has effectively performed BW and PLI attenuation from the ECG. It can clearly be seen that the unwanted 50Hz sine wave and low frequencies are removed leaving the filtered ECG signal with most of the known properties of ECG signal. Although fig 9 shows some distortion is noticed at the early part of the filter ECG plot. Though effort was made to remove the distortion, yet it was noticed that the quality of the filtered signal was been compromised. However, the researchers prefer to accommodate little distortion to rather than compromising with integrity of the filtered ECG signal.

The parameters and elements used to implement the filter and signal simulations include the following;

- Window length; 98
- Filter order; 97
- Sampling frequency; 1000Hz
- Filter type 1; Stopband filter
- Filter type 2; Highpass filter
- Stopband filter lower limit frequency f_1; 45Hz
- Stopband filter upper limit frequency f_2; 55Hz

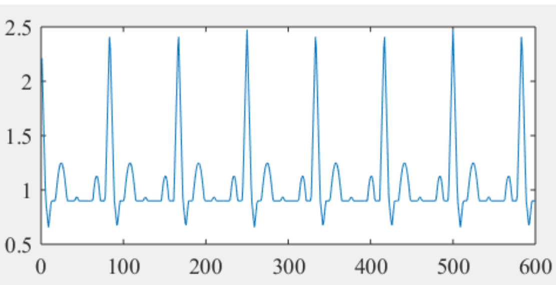
Fig 5 Multi-cycle ECG signal

- Highpass filter passband limit frequency f_3; 0.5Hz
- PLI magnitude = 1.0

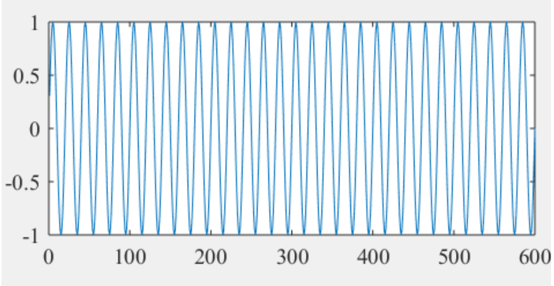
Fig 6 1.0mV magnitude 50Hz PLI

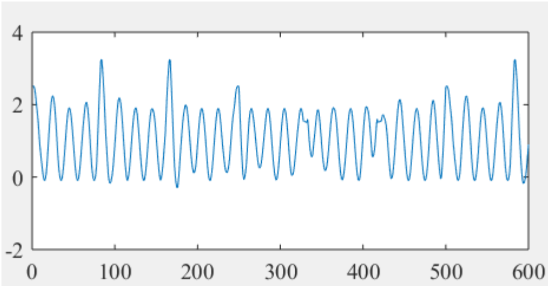
Fig 7 ECG signal corrupted 50Hz PLI

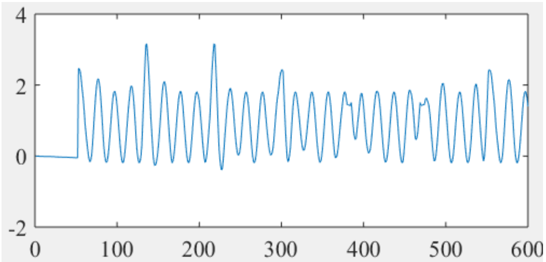
Fig 8 Filtered ECG signal after BW is removed

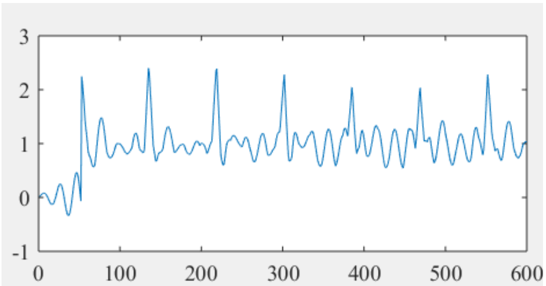
Fig 9 Filtered ECG signal after PLI is removed

V. Result Analysis

MATLAB offers a lot of tools for the processing and analysis of Digital signal processing (DSP). Deeper investigation into ECG signal enhancement using the proposed Welch-windowed FIR filter can be carried out with the aid of MATLAB's periodogram plots of magnitude response estimate (MRE) and power spectral density estimate (PSDE). Corresponding diagrams are used to elaborate results obtained from the signal enhancement process.

A. Magnitude Response Estimate

FIR filters can be processed and analyzed with a number of MATLAB periodogram. One of such periodograms is the MRE. It is invoked by Filter Visualization Tool (fvtool) command. MRE weighs the spectral power of a signal at a particular normalized frequency. It is expressed in decibel (dB). All the signals in this work are examined with MRE and displayed in fig 10, fig 11, fig 12 and fig 13. Periodogram of MRE for ECG and 50Hz PLI are displayed in fig 10 and fig 11 respectively. Analysis on the performance of the proposed filters will be based on the magnitude (dB) of each signal corresponding to normalized frequency value of 0.1π rad/sample. In fig 10 signal power of ECG at 0.1π rad/sample is 35.938dB. PLI spectral power at the same 0.1π rad/sample is 49.362dB in fig 11. When ECG, PLI and BW are combined together to form a contaminated ECG, it can be observed that the spectral strength of the signal at normalized frequency of 0.1π rad/sample becomes 49.535dB, fig 12.

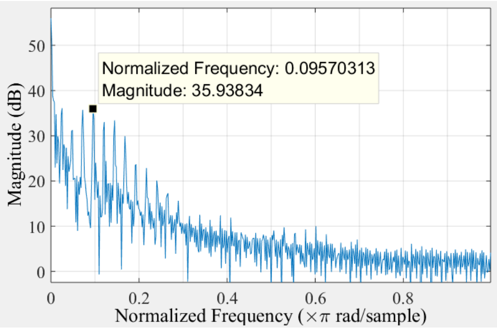

Fig 10 Periodogram of ECG signal

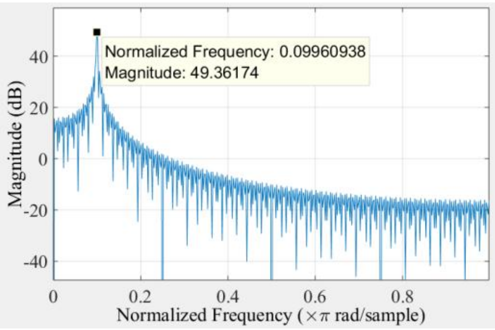

Fig 11 Periodogram of 50Hz PLI

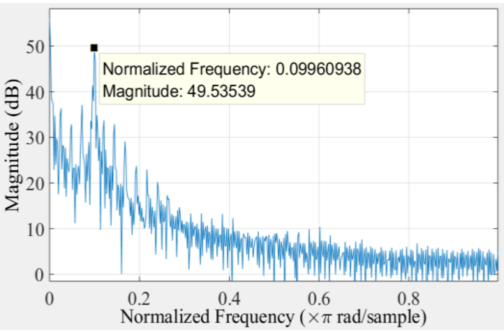

Fig 12 Periodogram of ECG signal plus PLI plus BW

Fig 13 and fig 14 display the output of highpass filter and stopband filter respectively. From fig 13 it can be noticed that after BW has been filtered out from the ECG plus PLI plus BW signal leaving only the ECG plus PLI signal, spectral power of the signal at the same 0.1π rad/sample is 48.8087dB. However, the output signal strength from the stopband filter drops to 36,2094dB at 0.1π rad/sample when PLI is removed from the ECG plus PLI signal, as can be seen in fig 14. This is the filtered ECG signal.

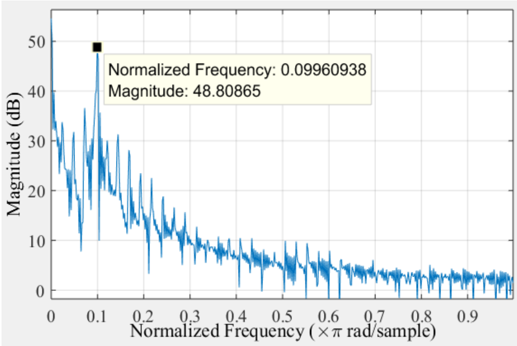

Fig 13 Periodogram of filtered ECG signal after the removal of BW

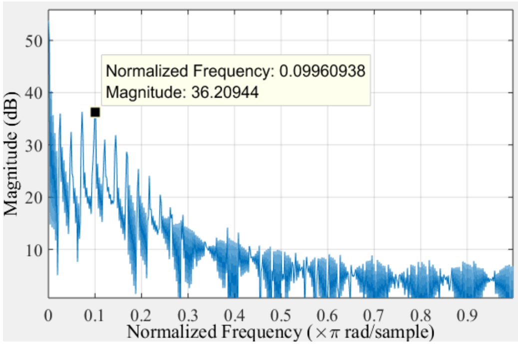

Fig 14 Periodogram of filtered ECG signal after the removal of PLI

However, it has been stated that effective filter order is essential for most effective filter design. [1]. It has also been stated earlier that filter order (L) used in this design is 97 corresponding to Welch Window length (N) of 98 samples. Moreover, different filter orders were tried in this work and the researcher eventually found that the filter order that yields the best results is L = 97. This value of filter order produces filtered ECG whose spectral periodogram magnitude value is closest to the magnitude of the spectral periodogram value of the ECG before contamination. Table 2 summarized the results obtained with divers filter orders and their corresponding window length as well as corresponding MRE values of filtered ECG at normalized frequency value of 0.1π rad/sample. From the table, we can see that the filter order of 97 makes MRE of filtered ECG nearest to MRE of original ECG.

Table 2; Filter order with corresponding window length and Magnitude Response Estimate values of filtered ECG

Filter Order	Window length	Magnitude Response Estimate (dB)
91	92	38.3562
93	94	37.6831
95	96	37.1308
97	98	36.2094
99	100	35.4078
101	102	35.0072
103	104	34.8069
105	106	34.6450
107	108	34.5150
109	110	34.3159

B. Power Spectral Density Estimate

Power Spectral Density Estimate (PSDE) is another analytical tool employed in this work to analyze the effectiveness of the proposed FIR digital filter modeled with the Welch Window for the purpose of ECG signal processing. PSDE is applied using the MATLAB's "pxx" command. It displays graphics of estimated power density of a signal. Analysis is made on various stages of this work with various plots of the PSDE. In fig 15 is displayed the PSDE of ECG signal. The position of the spike representing the signal can clearly be seen of having power density of about 22dB. Fig 16 and fig 17 show PSDE of PLI and BW respectively with power densities of about 7.5dB and 0.11 in that order.

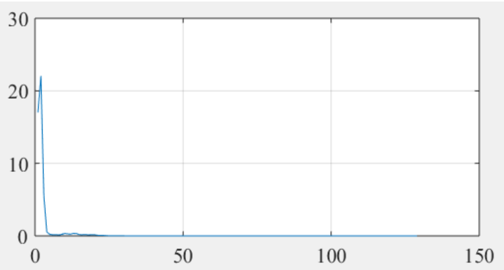

Fig 15 PSDE of ECG signal

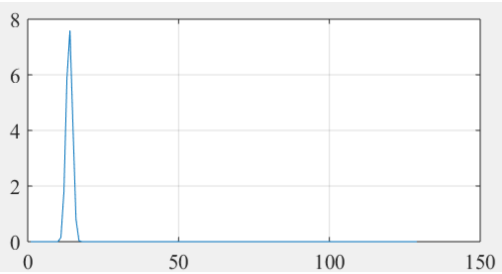

Fig 16 PSDE of PLI noise signal

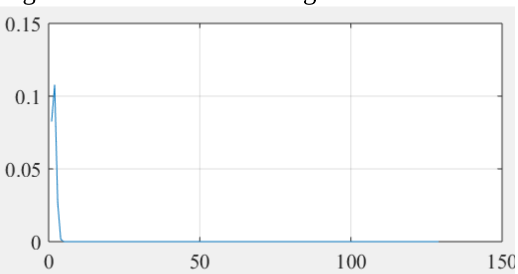

Fig 17 PSDE of BW signal

Although the spikes of fig 15 and fig 17 seem to have appeared on the same range on the x-axis, yet the magnitude values of each of the plots show the difference between them. The position of the PLI in fig 16 shall also be noted. When the ECG, PLI and BW signals are mixed together to form contaminated ECG, a plot representing the resultant signal is shown in fig 18. The two spikes that are shown in fig 18 evidently highlight the presence of the three signals. The increased magnitude of about 25dB of the first spike indicates that both ECG and BW signals are represented. The second spike is representing PLI. When firstly the highpass filter of proposed filter is applied on the contaminated ECG, to remove BW the resultant signal, (fig 19) can be seen to have resemblance with fig 18. We can see that in fig 15 and fig 17 ECG and BW appear in the same range. But now in fig 19 that BW is removed, the only difference between fig 18 and fig 19 now is that the power density value of the first spike has reduced to 19dB while that of PLI still has the same as magnitude with PLI in fig 18.

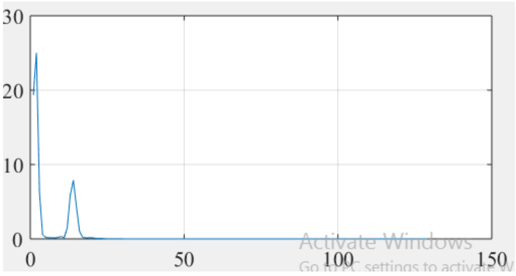

Fig 18 PSDE of contaminated ECG signal

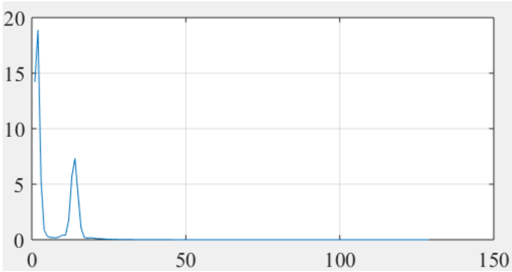

Fig 19 PSDE of contaminated ECG plus PLI after BW is removed

However, applying the stopband section of the proposed filter on the now ECG plus PLI corrupted signal with the sole aim of removing the 50HZ PLI will produce a graphical plot shown in fig 20. This is the filtered and noise free ECG signal. This shows the removal of PLI from the ECG signal. The filtered ECG in fig 20 has spectral density of about 16dB less than the spectral power density of the ECG before contamination. This can be attributed to the ECG signal loss between 45Hz and 55Hz of the lower cutoff and upper cutoff frequencies of the notch filter.

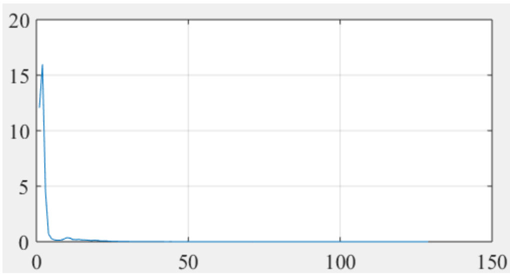

Fig 20 PSDE of noise free ECG signal

VI. CONCLUSION

The proposed FIR digital filter modeled with the Welch Window has been shown to have manifested effective and efficient noise reduction ability in ECG signal enhancement. The filter was modeled in two segments firstly, the highpass segment for low frequency BW removal and secondly the notch filter segment to remove 50Hz PLI. With the graphical evidences shown above, it can be concluded that Welch Window is effective in modeling of digital FIR filters. More so, the filter has good linearity property and thus makes a very stable FIR filter. Lower cutoff frequency and upper cutoff frequency used in this filter modeling is 45Hz and 55Hz respectively. This is contrary to the normally used 40Hz and

50Hz and is so chosen to reduce loss of ECG signal that may occur within the frequency range.

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