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Power Quality Event Classification Using Short Time Fourier Transform, Wavelet Transform And Hilbert Transform.

Nipun Dahiya
Department of Electronics and Communicaiton Engineering
Jss Academy of Techical Education
Noida,India

Harsh Narayan Singh Yadav
Department of Electronics and Communicaiton Engineering
Jss Academy of Techical Education
Noida,India

Manav Rishi Yadav
Department of Electronics and Communicaiton Engineering
Jss Academy of Techical Education
Noida,India

***Abstract*—This paper evaluates and compares various power quality event classification techniques. We have tested 4 feature extraction techniques along with 3 classification techniques. Feature extraction techniques used are STFT, Wavelet transform (WT), Multi-level wavelet decomposition and Hilbert Huang transform. Classification techniques used are KNN, ANN and Random Forest. All the techniques are trained and tested in 80:20 ratio on the dataset of 162 signals that we have generated. There are a total of 12 methods that are being compared, dataset generation and feature extraction is done in MATLAB while classification is done in python.**

Keywords—Short time Fourier transform (STFT), K Nearest Neighbor (KNN), Artificial Neural Network (ANN), Wavelet Transform (WT).

I. INTRODUCTION

Demand of today's appliances is of quality power, as a result the need of accurately classifying power quality events is of upmost importance. Accurate classification of power quality events is the first step in delivering of quality power to industries and homes. After the power quality event has been successfully classified proper mitigation techniques can then be applied. Quality power results in longer life span of appliances, better efficiency, cost saving in terms of energy bills, less breakdowns and malfunctioning of the equipment.

Power quality events include voltage sags, voltage swells, harmonics, interruptions, flickers and frequency variations. Voltage sag refers to the sudden drop of voltage levels of the signal, Voltage swell refers to the sudden increase of the voltage levels of the signals, interruption refers to the complete loss of power of the signal, flicker refers to the voltage fluctuations that occur in rapid succession It is because of repetitive and random variations in voltage between 0.9 and 1.1 per unit. [1]

This topic has been subject to alot of research in the past decade and a lot of signal processing techniques have been used in the past. Fourier transform converts a time domain signal to frequency domain signal, this technique trades all the timing information for the frequency information, as a result Fourier transform is only applicable to stationary signals, power quality events are mostly of non-stationary nature hence Fourier transform's performance is not practically viable. Techniques that contain both timing as well as frequency information are of particular interest in this problem these techniques include wavelet transform, S-transform, Short time Fourier transform (STFT), Hilbert Huang transform, Kalman filters etc. Short time Fourier transform (STFT) tries to overcome the short coming of the basic Fourier transform by dividing the signal into fixed time windows,[2] Fourier transform is then performed within these time windows extracting both timing and frequency information of the signal. Major disadvantage of the STFT is the fixed sized windows that is has, because of these fixed sized windows the techniques perform poorly for non-stationary signals in which there are abrupt frequency and amplitude changes. Wavelet transform is a better suited technique for power quality event classification in this the signal is multiplied by a wavelet signal and the resulting signal is then taken further for feature extraction, wavelet signals are time limited wave like oscillations with zero mean and finite energy. Wavelets can be scaled and translated to better fit the original signal. FFT and STFT breaks down the signal into sine waves of varying frequencies similarly wavelet transform breaks down the original signal into scaled and time shifted version of the mother wavelet. Wavelet transform provides better performance for non-stationary signals than the FFT and STFT. Graphical representation of the wavelet transform is called as a scalogram, it is given as |CWT| plotted vs both the domains time and frequency, where CWT stands for continuous wavelet transform and |CWT| represents its absolute value.[3]

Another technique called Hilbert Huang transform (HHT) has gotten some attention for its applications in power quality event classification. HHT refers to the combination of Empirical mode decomposition (EMD) and Hilbert spectrum.

In this paper WT, STFT, Multi-level wavelet decomposition (MLWD) and HHT techniques are used for signal processing and feature extraction, features thus extracted are then sent to classification algorithms for classification, with all the 4 feature extraction techniques we have used KNN, ANN and Random Forest as classification technique and have compared the accuracy obtained by them. In our work we have attained maximum accuracy of 99.7%.

II. Power quality event generation.

Power quality events are generated using the parametric equations given in [3]. Events are generated in MATLAB R2022.

Power supply is India has a frequency of 50 HZ and a voltage od 220V. Signals generated for both training and testing satisfy the conditions laid out in the table 1.

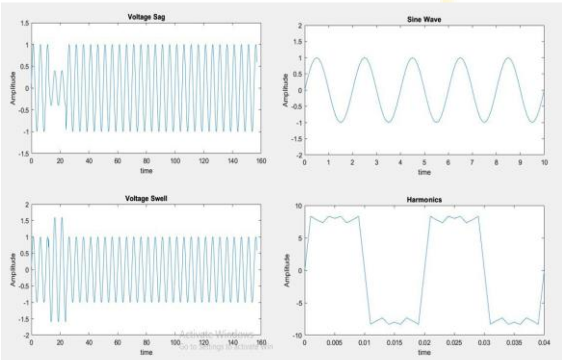

Figure 1. Power quality events generated in MATLAB

In order to generate 162 signals, we have taken the basic signals and have made changes to these basic signals to generate various other signals. We have varied amplitudes, duration of the signals and have also introduces frequency changes upto 3 % as deemed acceptable by the Indian Electricity Rules 1956.

Apart from this we have also tried to generalize the power quality events by introducing signals of different frequencies.

For sag and swell signals the amplitude can vary from 10% to 90% of the original values, we have taken various sag and swell signals covering all these variations into our dataset.

III. Wavelet transform

Wavelet transform is a mathematical tool that is used for signal processing and signal analysis. While in Fourier transform and in Short time fourier transform we decompose a signal into sin waves of specific frequencies, wavelet analysis/tranform is based on decomposing signals into sifted and scaled versions of a wavelet.[4]

A wavelet is a wave like oscillation that is localized in time, examples of wavelets are morse wavelet, Haar wavelet, Daubechies wavelet, Symlets, Meyer wavelets etc.

For the continuous time wavelet transform for a given signal x(t) and mother wavelet ψ(t) we have the following definition mathematically [5]:

$$\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} s(t)\psi^{*}\frac{(t-b)}{a}dt$$

Similarly for the discrete time case we have the following the definition:

$$\int_{-\infty}^{+\infty} x(t)\psi_{m,n}(t)dt$$

We have taken wavelet transform of the power quality events in MATLAB R2022b.

And the output is feed into classification algorithms namely KNN, ANN and the Random Forest in python 3.0.

Another feature extraction technique that we have employed using the wavelet transform is the Multi-level Wavelet decomposition (MLWD) technique. Wavelet decomposition or wavelet transform is calculated at each level of decomposition, we have taken a total of 7 levels of decomposition, this decomposition is also performed in the MATLAB R2022b.

IV. STFT

STFT is a modified version of the Fourier transform. The modification is done as an attempt to overcome the disadvantages present in FFT. In STFT we perform Fourier transform for a period of time, allowing us to retain both frequency and time components. In practice the procedure for computing STFT is to divide a longer signal into smaller equal sized segments and then perform Fourier Transform on each of those segments.

One can then plot the changing spectra as a function of time in the plot called as a spectrogram. For the continuous time case, the signal is multiplied by a windowing function and the Fourier Transform of the resulting signal is taken.

$$\int_{-\infty}^{+\infty} x(t)w(t-\tau)e^{-iwt}\,dt$$

Where w(τ) is the windowing function, x(t) is the original signal.

In the discrete time case, the signal is broken down in to frames, each of these frames are then Fourier transformed, mathematically we have:

$$\sum_{n=-\infty}^{+\infty} x[n]w[n-m]e^{-iwn}$$

Where x[n] is the original signal and w[n] is the window signal.

We have taken power quality events and then and performed STFT on them, STFT is performed in matlab R2023b.

V. Hilbert – Huang Transform

Hilbert Huang Transform is also a mathematical technique of decomposing a signal. It is the combination of the empirical mode decomposition (EMD) and Hilbert transform (HT). HHT uses the EMD method to decompose a signal into intrinsic mode functions (IMF) with a trend and applies the HT to the IMFs to the Hilbert Huang Transform.

A. Empirical Mode Decomposition

EMD is a technique of breaking a down a signal into physically meaningfull components called as intrinsic mode functions (IMF). IMFs of the signal taken together are sufficient in completely describing the signal. IMFs must satisfy the following conditions:

1) In the whole dataset, the number of extremas and the number of zero crossing must at most differ by 1 .

2) At any point, the mean value of the envelope defined by local maxima and the envelope defined by the local minima is zero. [6]

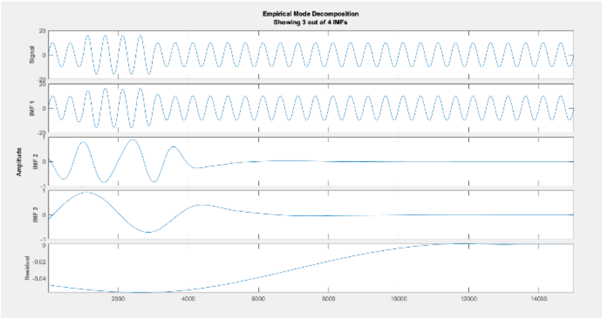

Fig. 2. EMD of a voltage swell signal

B. Hilbert Transform (HT)

HT of a signal u is defined as the convolution of the signal u(t) with the function h(t) = $\frac{1}{\pi t}$, where the function h(t) is called as the Cauchy kernel. It is defined using the Cauchy principal value (p.v.), HT of signal u(t) is given mathematically as:

$$H(u)(t) = \frac{1}{\pi}\, p.v. \frac{u(\tau)}{t-\tau} d\tau$$

Above equation is nothing but the convolution of u with the tempered distribution p.v. $\frac{1}{\pi}$.

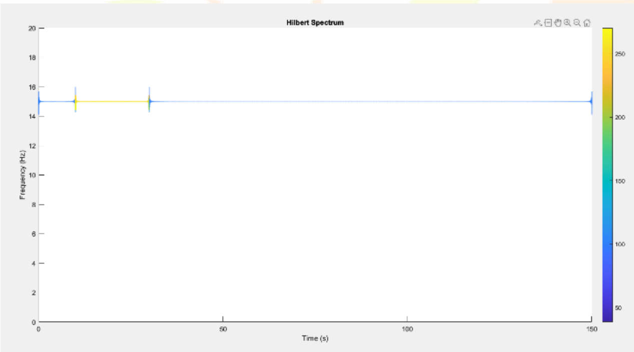

Fig. 3. Example of Hilbert spectrum of voltage swell signal.

Alternatively, If we change the variables we have the following description:

$$H(u)(t) = \frac{2}{\pi} \lim_{\xi \to \infty} \int_{\xi}^{+\infty} \frac{u(t-\tau)-u(t+\tau)}{2\tau} d\tau$$

The frequency time distribution of signal amplitude or energy in Hilbert spectrum analysis is called as the Hilbert spectrum, it helps in visual identification of localized features.

In our work we have first taken EMD of the power quality events and then have performed Hilbert transform on the result of the EMD. This is performed on MATLAB R2022b.

After calculating the Hilbert transform, we have then extracted the following features from the final result: Mean, Median, Entropy, Energy, Variance, Standard deviation and kurtosis. These features are summarized in the table below:

TABLE 1: FEATURES USED IN HHT

Features	Functions
Mean	$\frac{1}{n}\sum_{i=1}^{n} Xi$
Max	$MAX_{1\ldots n}(X_n)$
Entropy	$-\sum p(x) log p(x)$
Energy	$\sum_{n=1}^{m}(X_1^2 + X_2^2 + \cdots .. + X_m^2)$
Variance	$\frac{\Sigma(x-\dot{x})^2}{n-1}$
Kurtosis	$\frac{n(n+1)}{(n-1)(n-2)(n-3)} \Sigma \frac{(x_j - \dot{x})^4}{s} \quad \frac{3(n-1)^2}{(n-2)(n-3)}$
Standard Deviation	$\sqrt{Variance}$
Min	$MIN_{1\ldots n}(Xn)$

VI. Results

This section presents the results of our work, in this we have tested and compared a total of 12 methods for power quality event classification.
Power quality events that we have considered are:

1) *Normal signal*
2) *Voltage Sag*
3) *Voltage Swell*
4) *Harmonics*
5) *Interruption*

We have taken a total of 18 Normal signals, 41 Voltage sag signals, 56 Voltage swell signals, 35 Harmonic signals and 12 Interruption signals, making it a total of 162 signals.

The dataset is split in 50:50 ratio for training and testing respectively. Performance of STFT, WT, HHT and MLWD are summarized in TABLE 2,3,4,5 respectively.

The overall performance considering all the power quality events of all the methods that we have used is given in table 2.

TABLE 2: STFT PERFORMANCE

PQ Event	Classification Technique		
	KNN	ANN	Random Forest
Normal	97.48%	81%	97.577%
Sag	84.76%	77.4%	91.09%
Swell	90.06%	84.66%	94.14%
Harmonics	92.42%	81.16%	95.38
Interruption	65.89%	73.49%	71.77%

TABLE 3: WT PERFORMANCE

PQ Event	Classification Technique		
	KNN	ANN	Random Forest
Normal	99.81%	99%	100%
Sag	99.33%	21.55%	57%
Swell	99.62%	42%	43%
Harmonics	99.83%	21%	42%
Interruption	74.18%	17%	19%

TABLE 4: HHT PERFORMANCE

PQ Event	Classification Technique		
	KNN	ANN	Random Forest
Normal	62.95%	62.08%	84.33%
Sag	69.3%	62.85%	89.51%
Swell	79.96%	62.09%	93.10%
Harmonics	90.97%	62.57%	99.4%
Interruption	56.18%	58.05%	86.63%

TABLE 5: MLWD PERFORMACE

PQ Event	Classification Technique		
	KNN	ANN	Random Forest
Normal	87.47%	78.35%	90.16%
Sag	92.79%	78.08%	93.3%
Swell	97.83%	78.6%	98.8%
Harmonics	99.2%	78.73%	99.97%
Interruption	78.27%	78.4%	65.3%

TABLE 6: OVERALL PERFORMANCE

PQ Events	Classification Technique		
	KNN	ANN	Random Forest
STFT	92.19%	81.3%	92.25%
WT	99.71%	51.5%	57.18%
MLWD	90.65%	80.16%	93.06%
HHT	70.18%	62.3%	84.05%

VII. CONCLUSION AND FUTURE SCOPE

In the study it was found that the combination of Wavelet Transform with KNN yields the best performance with an accuracy of about 99.7%, followed by this comes the Multi-Level Wavelet Decomposition with Random Forest at about 93%. As expected, WT and MLWD perform better than STFT as STFT suffers from fixed window problem that limits its capabilities of detecting non-stationary changes to a signal. The next highest performance is given by STFT with Random Forest classifier. For STFT there is only marginal improvements in Random Forest and KNN.

The poorest overall performer out of the 3-feature extraction technique was the HHT. Maximum accuracy achieved through HHT was with Random Forest at about 84%. In HHT we had taken 8 features as explained before, HHT as a feature extraction technique has a lot of potential and can yield a much higher accuracy if classifiers other than KNN, ANN and Random Forest are used. Advanced classifiers like the LVQ (Learning vector quantization), Binary Tree neural networks or the more basic ones like the Support Vector Machines (SVM) can be used with HHT to yield results that can be comparable to the best results obtained here.

Other than using different classifiers, different features can also be used with the HHT to get better performance, features like skewness and mode can also be used with the HHT along with the features that we have used.

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