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CLASSIFICATION OF POWER QUALITY DISTURBANCES USING HILBERT TRANSFORM

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Abstract: The quality of electric power and disturbances occurred in power signal has become a major issue among the electric power suppliers and customers. The power quality disturbances caused by large-scale grid connection of nonlinear loads and distributed generations seriously affect the safe and stable operation of precision computers and microprocessors in the power grid, and may cause serious security accidents and economic losses in some cases. Therefore, the accurate classification of power quality disturbances is of great significance for the power supply quality improvement. Most of the disturbances are non-stationary and transitory in nature hence it requires advanced tools and techniques for the analysis of PQ disturbances.

This project work presents an algorithm based on the Hilbert Transform for the classification of single multiple and multistage power quality disturbances. These power quality disturbances signals are generated using the simulation models and integral mathematical models of PQ disturbances using the MATLAB Environment. The single Power quality disturbances considered in this study are voltage sag, voltage swell, voltage interruption, the multiple power quality disturbances considered in the study are voltage sag with harmonics, voltage swell with harmonics, voltage interruption with harmonics and the multistage power quality disturbances considered in the study are multistage voltage sag, multistage voltage swell, multistage voltage sag with swell. These signals are processed using the Hilbert transform to obtain the power quality index curve and extract features from it. Multiple cases of power quality disturbances are created by varying the parameters and a dataset is created. A feature vector is created by processing the dataset signals using Hilbert transform in order to train and test the ANN classifier. The effectiveness of the proposed approach is obtained by calculating the efficiency of proposed algorithm. A thresholding based approach is also used to classify the single, multiple and multistage power quality disturbances.

Keywords:- Power Quality, ANN, Power Quality Disturbances, Wavelength Transform , Hilbert Transform etc.

I. INTRODUCTION

The quality of electric power has become an important issue for electric power utilities and its customers. Now-a-days, the equipment which are being used in electrical utilities, those are more sensitive to Power Quality. This equipment contains power electronic components which are sensitive to power quality disturbances. So, any type of disturbance occurs in the voltage current or frequency of the power signal that can also affect the customer's side which is called power quality problem. So, electrical utilities and customers both are aware of the power quality disturbances. In order to determine the sources and causes of power quality disturbances, we must be able to detect and classify the disturbances into different types. Degradation in quality of power is mainly caused by disturbances such as voltage swell, voltage sag, voltage interruption, voltage imbalance, notch, transients, and harmonic distortions and so on. These disturbances result in malfunctions, reduced life time, failure of electrical equipment and loss of important data. So, starting of large electric motor can be the reason of voltage sag. Energization of a large capacitor bank can also cause voltage swell. Electrical power with disturbances is called poor power quality. Electricity with a poor quality is dangerous and uneconomical at both utility and consumer end. There is a big need to focus on the quality of power being supplied to the loads. Power quality is the ability of a power grid to supply power to the consumers efficiently and it also expresses the ability of an equipment to consume the power being supplied to it. In technical terms, power quality is the measure, study and enhancement of sinusoidal waveform at the rated voltage and frequency. Power quality can have a big impact on the performance and cost of a power system. So, it is essential to make sure that the power being consumed by the system is of right quality and the system is compatible to function with the power delivered to it. Nowadays consumers have become well aware of power quality, that's why many governments have revised their policies to force electric utilities for making sure the power quality according to the designed standards. Also, the modern equipment is more sensitive to any changes in power quality. Manufacturers, utilities and consumers all are concerned about power quality and this concern is increasing day by day. In practical distribution network to improve power quality, such disturbances should be identified first before appropriate mitigation can be taken.

II. THE HILBERT TRANSFORM

The Hilbert Transform is one of the most important operators in the field of signal theory .Hilbert transform is named after David Hilbert (1862-1943).

The Hilbert transform of a function f(x) is defined by:

$$F(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{f(x)}{t-x} dx \qquad (4.1)$$

Theoretically, the integral is evaluated as a Cauchy principal value. Computationally one can write the Hilbert transform as the convolution:

$$F(t) = \frac{1}{\pi t} \cdot f(t) \qquad (4.2)$$

which by the convolution theorem of Fourier transforms, may be evaluated as the product of the transform of f(x) with -i*sign(x), where:

$$\operatorname{sgn}(x) = \begin{cases} -1 & x < 0 \\ 0 & x = 0 \\ 1 & x > 0 \end{cases} \qquad (4.3)$$

The Hilbert transform can be considered to be a filter which simply shifts phases of all frequency components of its input by $-\pi/2$ radians.

An "analytic" (complex time) signal Y(t) can be constructed from a real-valued input signal y(t):

$$Y(t) = y(t) + j\, h(t) \qquad (4.4)$$

where,

Y(t) is the analytic signal constructed from y(t) and its Hilbert transform

y(t) is the input signal

h(t) is the Hilbert Transform of the input signal

The real and imaginary parts can be expressed in polar coordinates as:

$$Y(t) = A(t) \exp[j\psi(t)] \qquad (4.5)$$

where,

A(t) is the "envelope" or amplitude of the analytic signal

ψ is the phase of the analytic signal (the derivative of ψ is called the "instantaneousfrequency")

These commands compute a signal´s "envelope" using the Hilbert Transform operation: Hilbert transform of a constant is zero. If you compute the Hilbert transform in more than one dimension and one of the dimensions does not vary (is a constant), the transform will be zero (or at least numerically close to zero).

Igor´s Hilbert Transform operation computes the Hilbert transformation of real or complex (single or double precision) data of 1-3 dimensions.

Basic properties of the Hilbert transform

(i) Linearity: H(a1x1(t) + a2x2(t)) = a1H(x1(t)) + a2H(x2(t))

(ii) Time shift: H (x (t − a)) = y (t − a)

(iii) Scaling: H(x(at)) = y(at), a > 0

(iv) Time reversal: H(x(−at)) = −y(−at), a > 0

(v) Derivative: H (x 0 (t)) = y 0 (t)

III. Artificial Neural network

Neural Networks are artificial networks used in Machine Learning that work in a similar fashion to the human nervous system. Many things are connected in various ways for a neural network to mimic and work like the human brain. Neural networks are basically used in computational models.

A neural network consists of three layers. The first layer is the input layer. It contains the input neurons that send information to the hidden layer. The hidden layer performs the computations on input data and transfers the output to the output layer. It includes weight, activation function, cost function.

The connection between neurons is known as weight, which is the numerical values. The weight between neurons determines the learning ability of the neural network. During the learning of artificial neural networks, weight between the neuron changes.

This research work develops an algorithm for the classification of power quality disturbances. The methodology use for the development of algorithm is describe as follows:

Step I:

The power quality disturbances signals are generated using the simulation models and integral mathematical models of PQ disturbances using the MATLAB Environment.

Step II:

The obtained voltage signal with PQ disturbances is processing through Hilbert Transform using following command of the MATLAB.

A=Hilbert (v)

Step III:

Output of Hilbert Transform yields power quality index curve values using the following command and plot the curve.

B=abs (A)

Step IV:

Collect the features F1, F2, F3 and F4 from the power quality index curve using the following relations.

F1=median (b)

F2=kurtosis (b)

F3=var (b)

F4=std (b)

Step V:

These features are given as input to the thresholding-basedalgorithm for classification purpose andPQ disturbances are classified effectively.

IV. GENERATION OF POWER QUALITY DISTURBANCES USING INTEGRAL MATHEMATICAL MODELS

The integral mathematical models of PQDs represented by parametric equations are used to generate the PQDs. By altering the values in parametric equations, the magnitude and period of the disturbances can be adjusted.In this research work, we have generated three PQDs namely voltage sag, voltage swell, and interruption by implementing the parametric equations based integral mathematical models using MATLAB programming. These amplitudes are regulated by the parameter A, while their durations are controlled by the time constants t1 and t2.The parametric equations for the PQDs are shown in Table 1.

Single Power Quality Disturbances

Table 1 :- Parametric equations of Single Power Quality Disturbances

PQDs	Equations	Parameters
Pure	x(t) = Asin(ωt)	A = 1(pu), ω = 2πf rad/s, f=50 Hz
Voltage sag	x(t) = A (1 −α (u (t − t1) −u (t − t2))) sin (ωt)	0.1 ≤ α ≤ 0.8, T ≤ (t2 −t1) ≤ 9T
Voltage swell	x(t) = A (1 +α (u (t − t1) −u (t − t2))) sin (ωt)	0.1 ≤ α ≤ 0.8, T ≤ (t2 −t1) ≤ 9T
Voltage interruption	x(t) = A (1 −α (u (t − t1) −u (t − t2))) sin (ωt)	0.9 ≤ α ≤ 1, T ≤ (t2 − t1) ≤ 9T
Harmonics	x(t) = α1sin(ωt) + α3sin(3ωt) +α5sin(5ωt) +α7sin(7ωt)	0.05 ≤ α3 , α5 , α7 ≤ 0.15, α1

The integral mathematical models of PQDs represented by parametric equations are implemented using MATLAB programming in order to generate the three PQDs. The amplitudes of the PQDs are regulated by the parameter A, while their durations are controlled by the time constants t1, t2 the maximum value of the instantaneous waveform under three phases for which the RMS value found to be 400 V. The voltage signal with a 50% sag for 0.4 seconds is shown in figure 1 which is generated at α=0.5, t1=0.3 and t2=0.7. The total duration of the waveform is 1 sec.

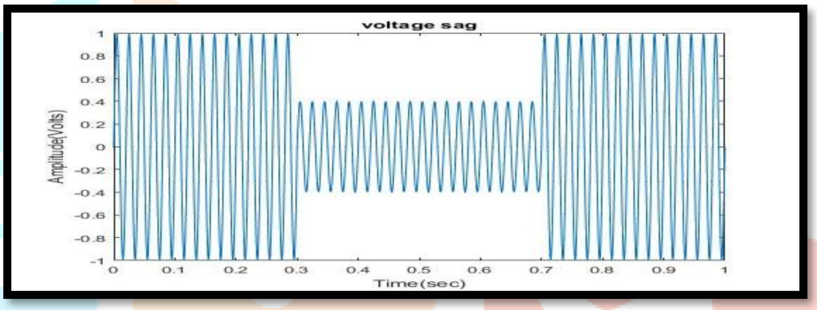

Figure 1:- Waveform for Voltage Sag

The voltage signal with swell for 0.4 seconds is shown in figure 2 which is generated by adjusting the parameters α=0.5, t1=0.3 and t2=0.7. The total duration of the waveform is 1 sec.

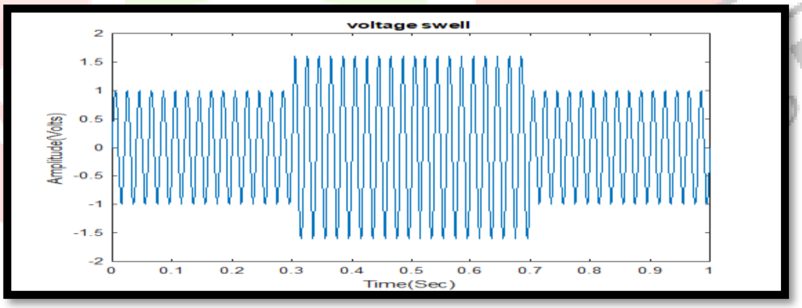

Figure 2:- Waveform for Voltage Swell

The voltage signal with an interruption for 0.4 seconds is shown in figure 3 which is generated by adjusting the parameters α=0.95, t1=0.3 and t2=0.7. The total duration of the waveform is 1 sec.

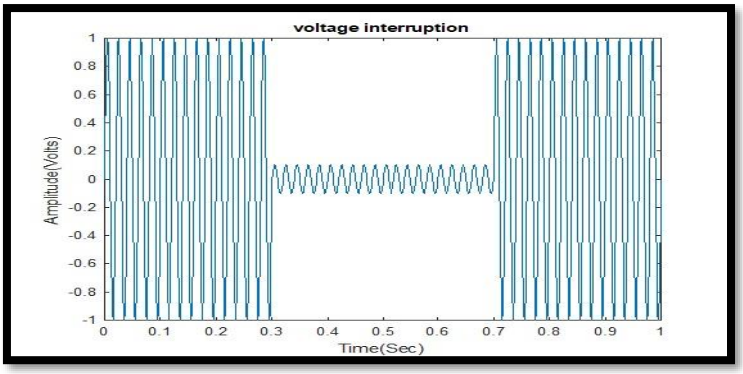

Figure 3:- Waveform for voltage interruption

Multiple Power Quality Disturbances

The superimposition of more than one type of PQ disturbances during the same period corresponds to multiple PQ disturbances e.g., voltage sag with harmonics, voltage swell with harmonics, interruption with harmonics etc. These disturbances are generated by the addition/multiplication of single-stage PQ disturbances. PQ variation such as harmonics which always exists in a power distribution network, when multiplied with single-stage PQ disturbances, produces multiple PQ disturbances. The multiple PQ disturbances have been simulated. The selection of parameter values of these disturbances has been performed as per table 2..

Table 2:- Parametric Equations of Multiple Power Quality Disturbances

PQDs	**Equations**	**Parameters**
Voltage sag harmonics	$x(t) = A(1 - \alpha(u(t-t1) - u(t-t2)))\ \sin(\omega t) * \alpha 1 \sin(\omega t) + \alpha 3 \sin(3\omega t) + \alpha 5 \sin(5\omega t) + \alpha 7 \sin(7\omega t)$	$0.1 \le \alpha \le 0.8,\ T \le (t2 - t1) \le 9T$
Voltage swell harmonics	$x(t) = A(1 + \alpha(u(t-t1) - u(t-t2)))\ \sin(\omega t) * \alpha 1 \sin(\omega t) + \alpha 3 \sin(3\omega t) + \alpha 5 \sin(5\omega t) + \alpha 7 \sin(7\omega t)$	$0.1 \le \alpha \le 0.8,\ T \le (t2 - t1) \le 9T$
Voltage interruption harmonics	$x(t) = A(1 - \alpha(u(t-t1) - u(t-t2)))\ \sin(\omega t) * \alpha 1 \sin(\omega t) + \alpha 3 \sin(3\omega t) + \alpha 5 \sin(5\omega t) + \alpha 7 \sin(7\omega t)$	$0.1 \le \alpha \le 0.8,\ T \le (t2 - t1) \le 9T$

Figure 4 shows the voltage signal with sag harmonics for time duration 0.4 sec generated by controlling the parameters of the parametric equation. t1=0.3 t2=0.7 a=0.5 a1=1 a3=0.06 a5=0.08 a7=0.1

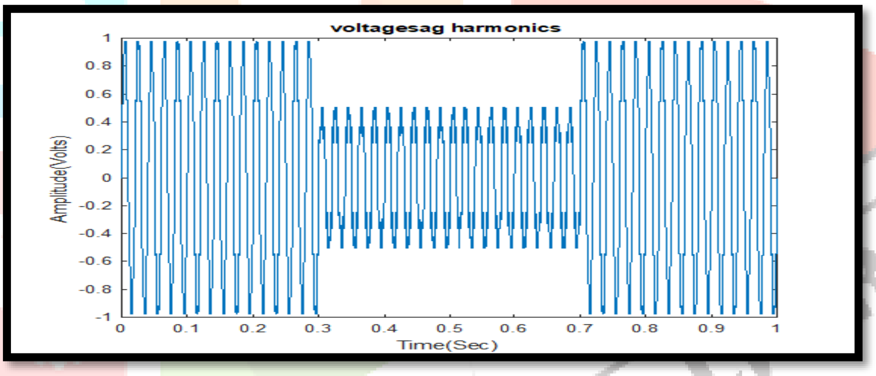

Figure 4:- Waveform for Voltage Sag Harmonics

Figure 5 shows the voltage signal with the swell and harmonics for time duration 0.4 sec generated by controlling the parameters of the parametric equation t1=0.3 t2=0.7 a=0.5 a1=1 a3=0.05 a5=0.07 a7=0.09

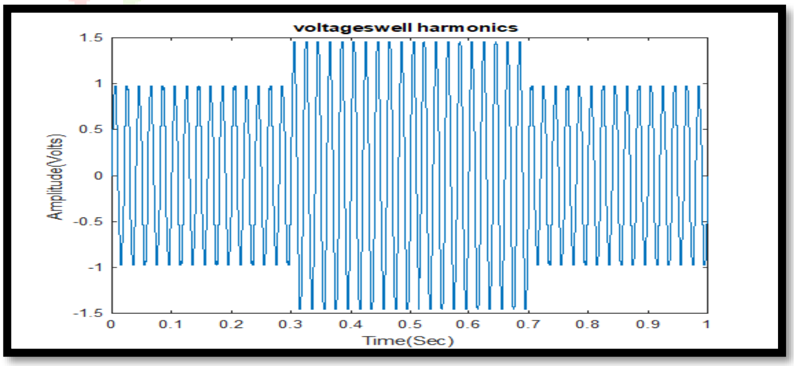

Figure 5:- Waveform for voltage swell harmonics

Figure 6 shows the voltage signal with interruption along with harmonics for time duration 0.4 sec generated by controlling the parameters of the parametric equation.
t1=0.3 t2=0.7 a=0.95 a1=1a3=0.09 a5=0.09 a7=0.09;

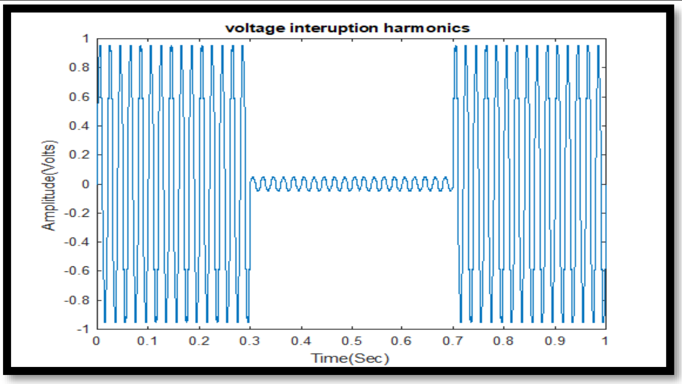

Figure 6:- Waveform for Voltage Interruption Harmonics

Multistage Power Quality Disturbances

Multi-stage PQ disturbances are defined as the single-stage PQ disturbance followed by some other PQ disturbance before the recovery of the former disturbance. The multistage PQ disturbances are voltage sag followed by sag, voltage swell followed by sag, voltage swell followed by voltage swell. It is formed using the addition of single-stage PQ disturbances. Several simulated multi-stage PQ disturbances (two stages) are shown in fig below. The parameters of these disturbances are selected as per table 3.

Table 3 :- Parametric Equations of Multistage Power Quality Disturbances

PQDs	**Equations**	**Parameters**
Multistage voltage sag	x(t) = A [(0.5 −α1(u(t − t1)− u(t − t2))+ (0.5 −α2(u(t − t2)− u(t2 − t3))] *sin (ωt)	0.9 ≤ α ≤ 1, T ≤ (t2 − t1) ≤ 9T
Multistage voltage swell	x(t) = A [(0.5 +α1(u(t − t1)− u(t − t2))+ (0.5 −α2(u(t − t2)− u(t − t3))] *sin (ωt)	0.1 ≤ α ≤ 0.8, T ≤ (t2 −t1) ≤ 9T
Multistage voltage sag with swell	x(t) = A [(0.5 −α1(u(t − t1)− u(t − t2))+ (0.5 −α2(u(t − t2)− u(t2 − t3))] *sin (ωt)	0.9 ≤ α ≤ 1, T ≤ (t2 − t1) ≤ 9T

Figure 7 shows the voltage signal with multistage sag for time duration 0.4 sec generated by controlling the parameters of the parametric equation.
t1=0.3 t2=0.7 t3=0.5 a1=0.8 a2=0.6

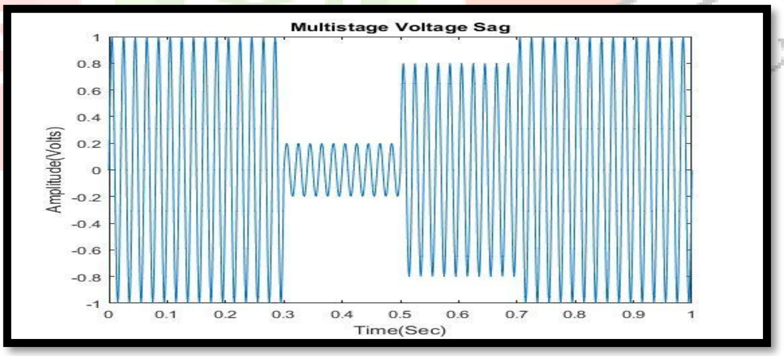

Figure 7:- Waveforms for Multistage Voltage Sag

Figure 8 shows the voltage signal with multistage swell for time duration 0.4 sec generated by controlling the parameters of the parametric equation.
t1=0.3 t2=0.7 t3=0.5 a1=0.5 a2=0.5

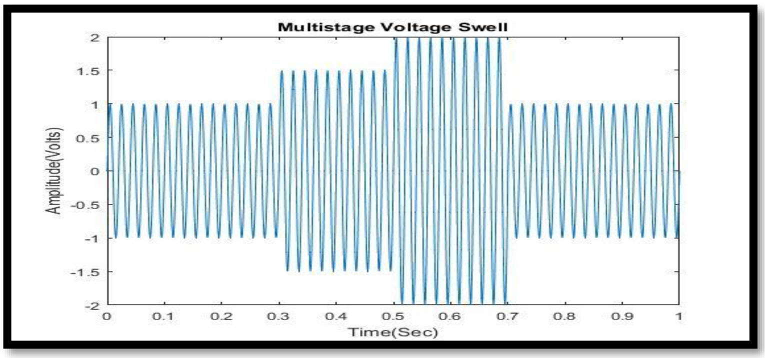

Figure 8:- Waveforms for Multistage Voltage Swell

Figure 9 shows the voltage signal with multistage sag and swell for time duration 0.4 sec generated by controlling the parameters of the parametric equation
t1=0.3 t2=0.5 t3=0.7 a1=0.5 a2=0.5

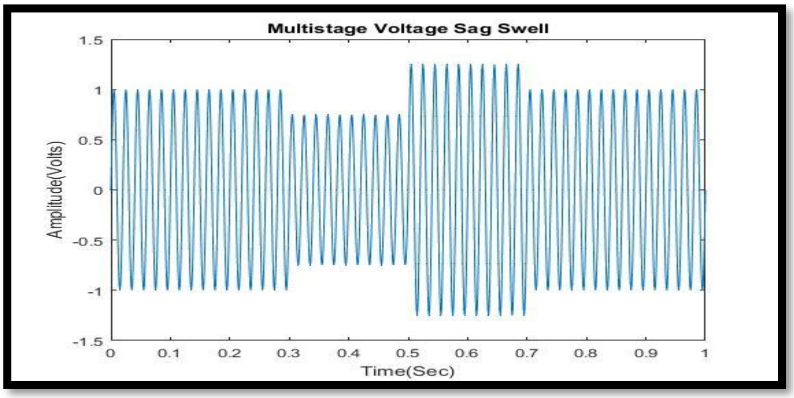

Figure 9 :- Waveform Multistage Voltage Sag Swell

V. RESULT AND DISCUSSION

HILBERT ANALYSIS

Power Quality Index Curve

The voltage signal with sag obtained by simulating the mathematical equations in MATLAB is processingthrough Hilbert transform. Power quality index curve is obtained by calculating absolute value of output of Hilbert transform. The waveform of signal with voltage sag and power quality index curve is shown in figure 10. This is observed from the given figure that values of the power quality index curve decrease at 0.3 s to 0.7s indicating the presence of voltage swells between time duration 0.3 to 0.7s.

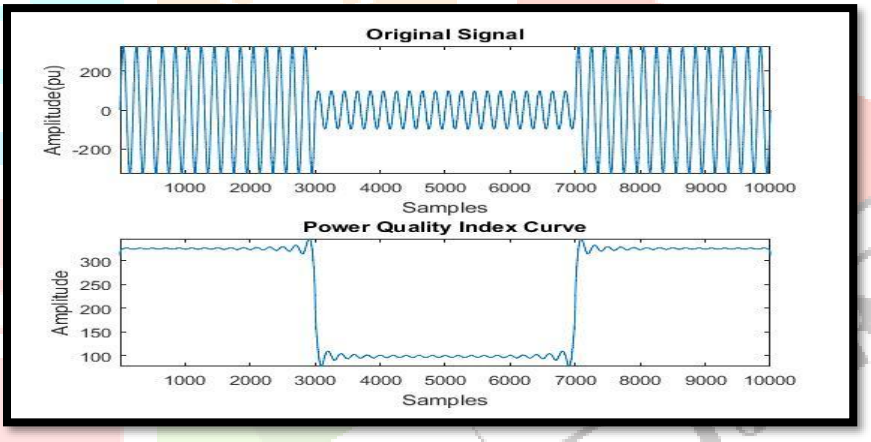

Figure 10:- Power Quality Index Curve For Voltage Sag

The signal with voltage swell obtained by simulating the mathematical relation is decomposed using the Hilbert Transform. The power quality index curve is obtained by calculating the absolute values of the output of the Hilbert transform. The waveforms of voltage signal with swell and proposed power quality index curve for the voltage swell are provided in figure 11. This is observed from the figure 11 the values of the power quality index curve increases at 0.3 s at 0.7 s indicating the presence of voltage swells between time duration 0.3 to 0.7s.

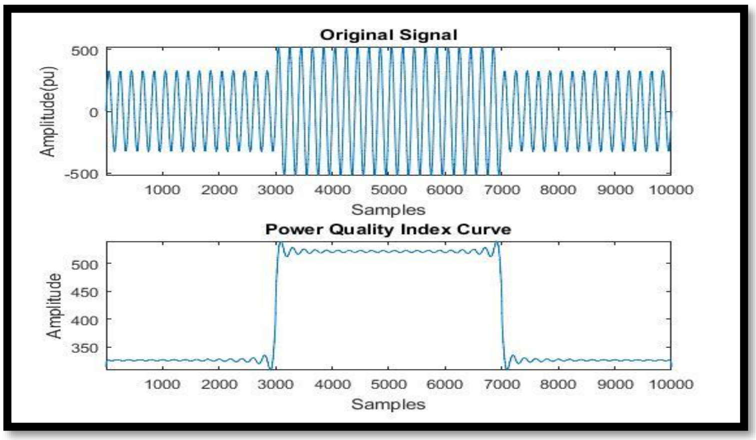

Figure 11:- Power Quality Index Curve For Voltage Swell

The signal with voltage interruption obtained by simulating the mathematical relation is processing through the Hilbert Transform. The power quality index curve is obtained by calculating the absolute values of the output of the Hilbert transform. The waveforms of voltage signal with interruption and proposed power quality index curve for the voltage interruption are provided in figure 12. This is observed from the figure 12 that the values of the power quality index curve increase at 0.3 s to 0.7 s indicating the presence of voltage interruption between time duration 0.3 to 0.7s.

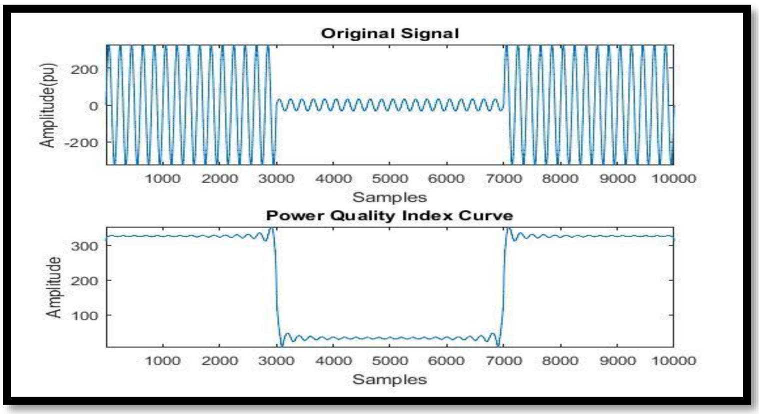

Figure 12:- Power Quality Index Curve For Voltageint

The signal with voltage sag along with harmonics obtained by simulating the mathematical equations in MATLAB is process through Hilbert transform. Power quality index curve is obtained by calculating absolute value of output of Hilbert transform. The waveform of signal with voltage sag with harmonics and power quality index curve is shown in figure 13. This is observed from the figure 13 that values of the power quality index curve decrease at 0.3 s to 0.7 s indicating the presence of voltage sag with harmonics between time duration 0.3 to 0.7 s.

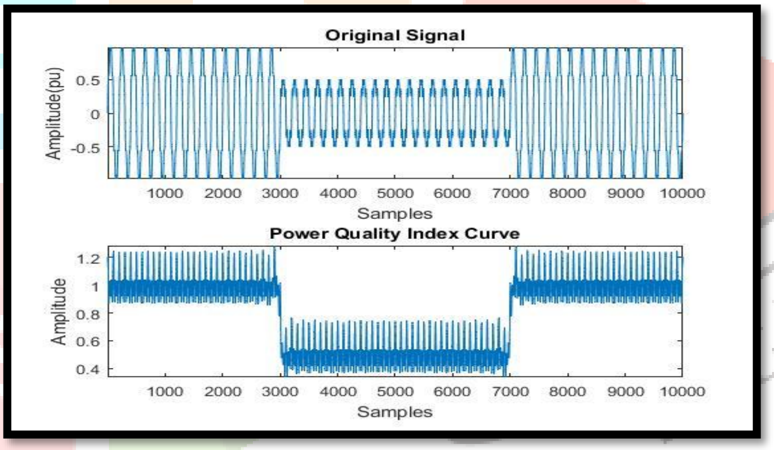

Figure 13:- Power Quality Index Curve For Voltage Sag With Harmonics

The signal with voltage swell along with harmonics obtained by simulating the mathematical equations in MATLAB is processing through Hilbert transform. Power quality index curve is obtained by calculating absolute value of output of Hilbert transform. The waveform of signal with voltage swell along with harmonics and power quality index curve is shown in figure 14. This is observed from the figure 14 that values of the power quality index curve increase at 0.3 s to 0.7s indicating the presence of voltage swell with harmonics between time duration 0.3 to 0.7s.

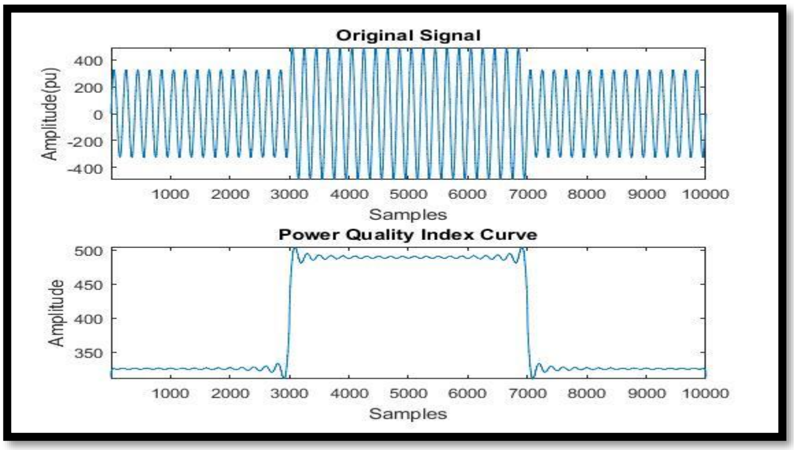

Figure 14:- Power Quality Index Curve For Voltage Swell With Harmonics

The signal with voltage Interruption with harmonics obtained by simulating the mathematical equations in MATLAB is processing through Hilbert transform. Power quality index curve is obtained by calculating absolute value of output of Hilbert transform. The waveform of signal with voltage Interruption along with harmonics and power quality index curve is shown in figure 15. This is observed from the figure 15 that values of the power quality index curve decrease at 0.3 s to 0.7 s indicating the presence of voltage interruption with harmonics between time duration 0.3 to 0.7s.

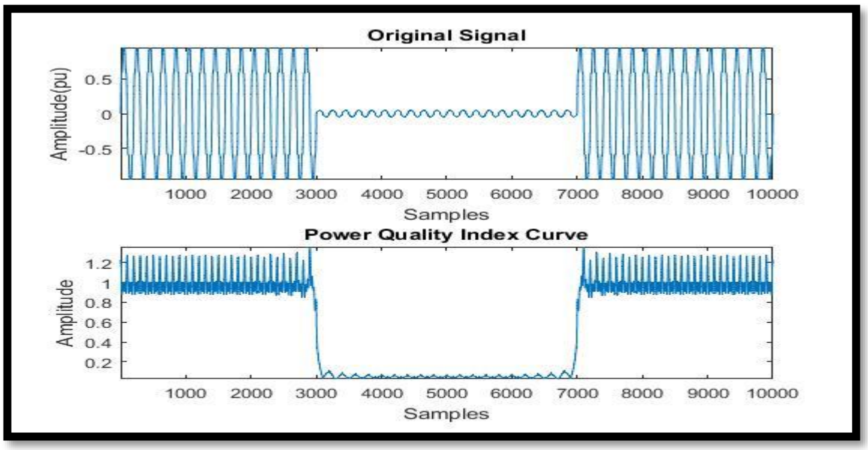

Figure 15:- Power Quality Index Curve For Voltage Interruption With Harmonics

The signal with multistage voltage sag obtained by simulating the mathematical equations in MATLAB is decompose using Hilbert transform. Power quality index curve is obtained by calculating absolute value of output of Hilbert transform. The waveform of signal with multistage voltage sag and power quality index curve is shown in figure 16. This is observed from the figure 16 that values of the power quality index curve decrease at 0.3s to 0.7s indicating the presence of multistage voltage sag between time duration 0.3 to 0.7s.

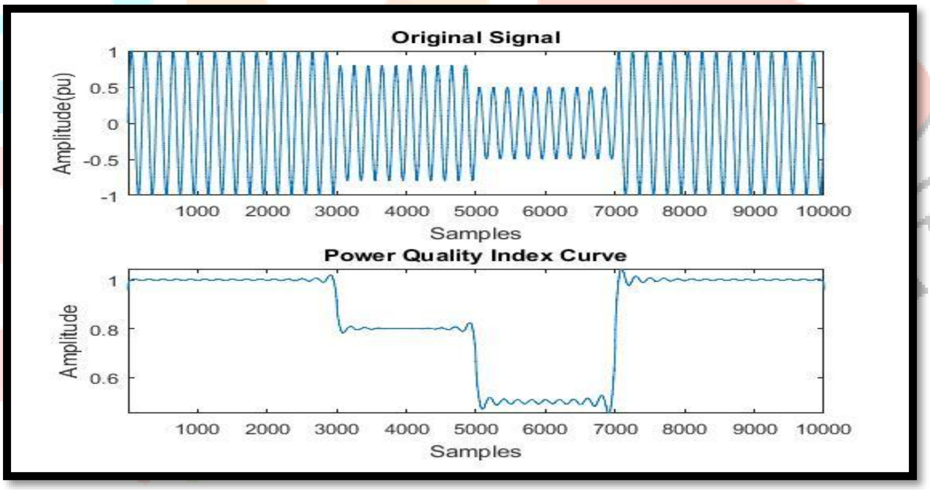

Figure 16:- Power Quality Index Curve For Multistage Sag

The signal with multistage voltage swell obtained by simulating the mathematical equations in MATLAB is decompose using Hilbert transform. Power quality index curve is obtained by calculating absolute value of output of Hilbert transform. The waveform of signal with multistage voltage swell and power quality index curve is shown in figure 17. This is observed from the figure 17 that values of the power quality index curve increase at 0.3s to 0.7s indicating the presence of multistage voltage swell between time duration 0.3 to 0.7s.

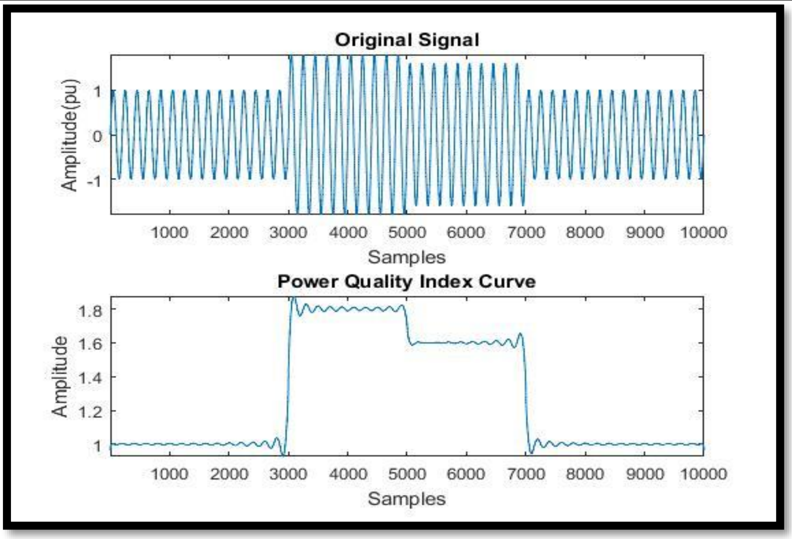

Figure 17:- Power Quality Index Curve For Multistage Voltage Swell

The signal with multistage voltage swell with sag obtained by simulating the mathematical equations in MATLAB is process through Hilbert Transform. Power quality index curve is obtained by calculating absolute value of output of Hilbert transform. The waveform of signal with multistage voltage swell and power quality index curve is shown in figure 18. This is observed from the figure 18 that values of the power quality index curve increase at 0.3s to 0.5 indicating the presence of voltage swell between time duration 0.3 to 0.7s. and decrease from 0.5 to 0.7s indicating the presence of voltage sag between time duration 0.3 to 0.7s.

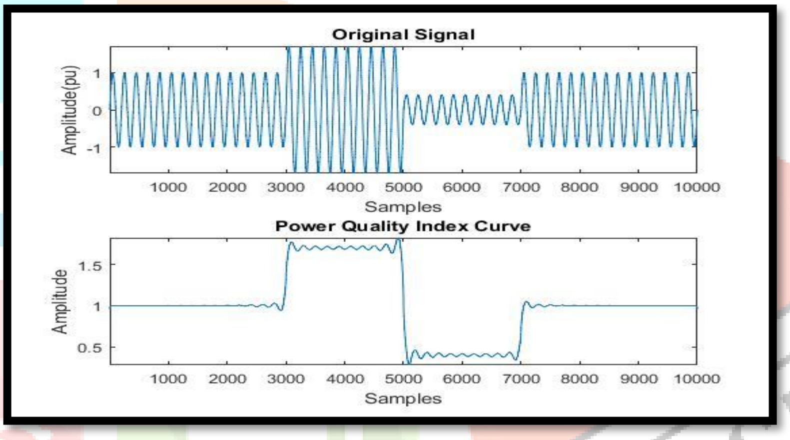

Figure 18:- Power Quality Index Curve For Multistage Voltage Sag Swell

FEATURES EXTRACTION

Features extracted from the absolute value of power quality index curve are given in table 4.

Table 4:- Features of Power Quality Disturbances

PQ Disturbances	F1	F2	F3	F4
Voltage Sag	9.953685	11.81264	1.170474	3.421219
Voltage Swell	10.03821	11.80576	8.62E-01	2.935442
Voltage Interruption	9.941036	11.81669	1.93E+00	4.388872
Voltage Sag Harmonics	9.941036	11.81669	1.93E+00	4.388872
Voltage Swell Harmonics	10.03296	11.80597	5.98E-01	2.44629
Voltage Interruption Harmonics	0.027945	12.73454	2.09E-05	0.014471
Multistage Voltage Sag Swell	0.03	25.62098	1.58E-05	0.012585
Multistage Voltage Sag	0.030604	24.5786	3.60E-06	0.005996
Multistage Voltage Swell	0.030811	13.94936	1.14E-05	0.010682

Classification of Power Quality Disturbances

Thresholding Based Algorithm

A] Classification of single stage Power Quality Disturbances

The values of features F1, F2, F3, F4 provided in the table 4. These features are given as input to the thresholding-based algorithm for the classification of the single stage power quality disturbances. The detailed classification of the power quality disturbances is provided in the figure 19. The classification is initialized using the feature F4.The first group consists of voltage interruption whereas the second group consists of the voltage sag, voltage swell.

B] Classification of Multiple Power Quality Disturbances

The values of features F1, F2, F3, F4 provided in the table 4. These features are given as input to the thresholding-based algorithm for the classification of the multiple power quality disturbances. The classification is initialized using the feature F1.First group consists of voltage swell with harmonics whereas the second group consists of the voltage sag with harmonics and voltage interruption with harmonics. The detailed classification of the power quality disturbances using the thresholding-based algorithmis provided in the figure 20.

C] Classification of Multistage Power Quality Disturbances

The values of features F1, F2, F3, F4 provided in the table 4. These features are given as input to the thresholding-based algorithm for the classification of the multistage power quality disturbances. The classification is initialized using the feature F2. First group consists of multistage voltage swell with sag whereas the second group consists of the multistage voltage sag and multistage voltage swell.T he detailed classification of the power quality disturbances using the thresholding-based algorithmis provided in the figure 21.

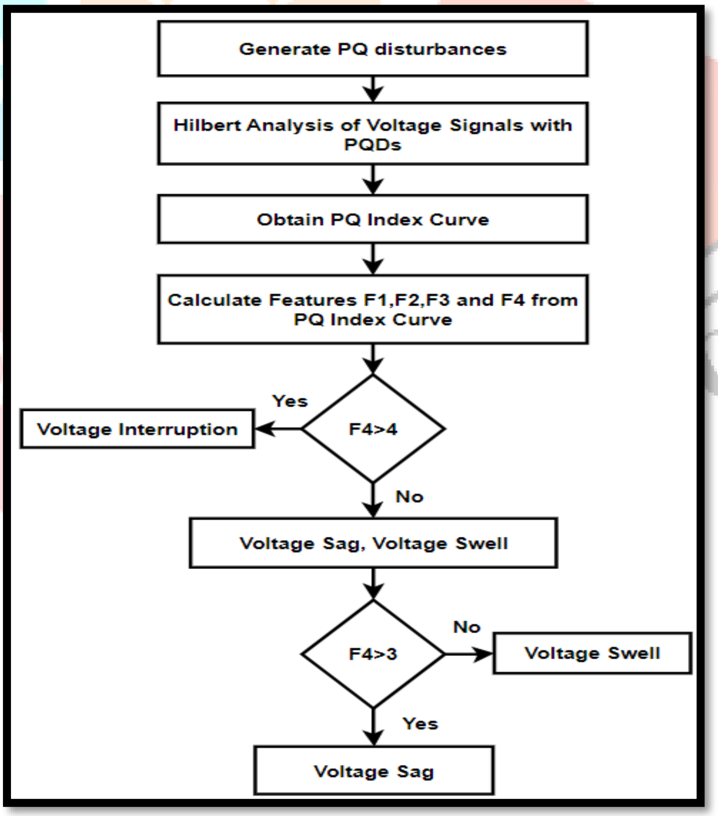

Figure 19 :- Classification of Single Stage Power Quality Disturbances using Thresholding BasedApproach

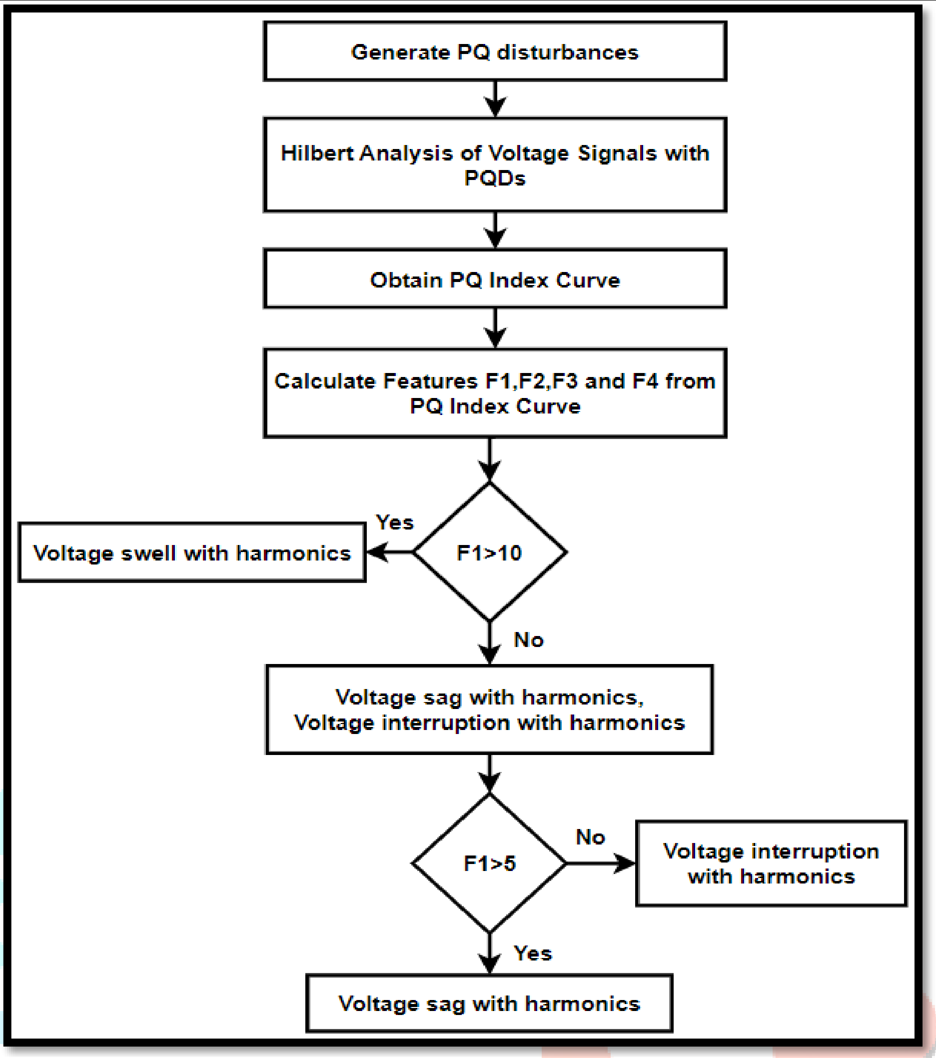

Figure 20:- Classification of Multiple Power Quality Disturbances

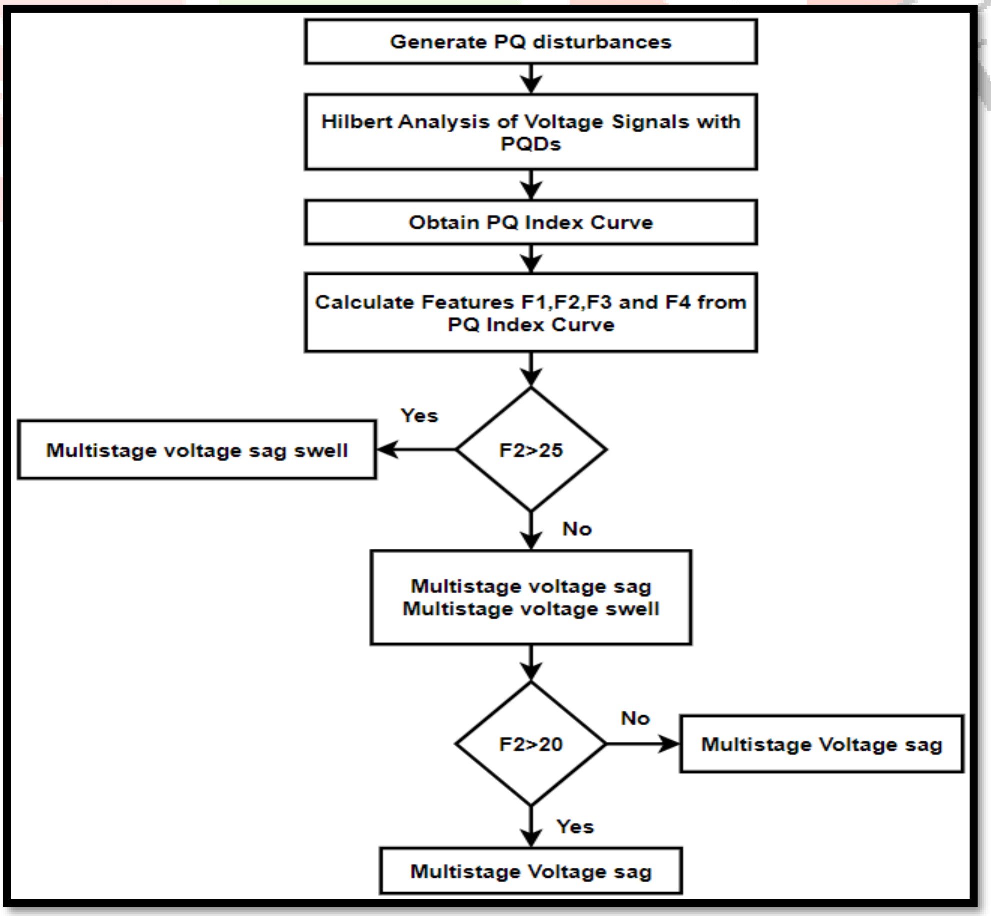

Figure 21:- Classification of Multistage Power Quality Disturbances

VI. CONCLUSION AND FUTURE SCOPE OF THE WORK

Conclusion

This project work presents an algorithm using Hilbert Transform and thresholding-based algorithm for classification of PQ disturbances. It has been concluded that the proposed the thresholding-basedalgorithms can effectively classify the single, multiple and multistage power quality disturbances. The features extracted from the Hilbert transform are very simple and yet very effective. They are found to be sufficient to accurately classify the single, multiple and multistage PQ disturbances with ease. Overall, the algorithms developed are less complex. The proposed technique has been found to be successful in classifying the various complex PQ disturbances. Compared to the wavelet transform and S-transform, the Hilbert transform can be quickly calculated, so that the proposed method is efficient, making the suggested method more efficient.

The proposed approach was validated using the synthetic data. The results reported in this report effectively demonstrate the ability of the proposed algorithm to correctly classify the PQDs. We can conclude from the analysis that the suggested methodology outperforms existing methods. The proposed approach was found to be much faster and simpler. The use of this technique on a broad scale could improve the power quality monitoring system and finally the quality of the power.

Future Scope

The work presented in this project work can be further extended

- To study more Power Quality Disturbances.
- To validate the algorithm using Realtime data.
- To study the effect of noise on detection and classification of Power Quality Disturbances. In the further research work, the effect of noise part will be included.
- The work should be extended towards developing mitigating algorithms for PQ disturbances.
- The behaviour of several other underlying causes of PQ disturbances should also be examined.

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