



REVIEW ON IMPLEMENTATION OF INTEGRAL MATHEMATICAL MODEL OF POWER QUALITY DISTURBANCES

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Abstract: Power quality disturbances lead to severe problems in industries and electrical grids. To mitigate PQ problems, the accurate detection and classification of the possible disturbances are essential. A large number of studies exist in this field. The first research step in these studies is to obtain several distorted signals to test the classification systems. In this regard, the most common trend is the generation of signals from mathematical models. In the literature, several models with significant differences are available. However, there is no integral model that considers all types of distortions.

In this dissertation work, an integral mathematical model of power quality disturbances will be developed based on the models available in the literature. The model will include new types of combined disturbances. Almost all types of power quality disturbances will be considered under study. Further, this integral mathematical model of various power quality disturbances will be implemented for the generation of power quality disturbances using MATLAB environment. By using this model various power quality disturbances will be generated in a fast and automatic way. This model aims to facilitate future studies, supporting researchers in the modelling stage.

Index Terms - Integral Mathematical Model, Power Quality

I. Introduction:

In recent years power quality has become a significant issue for both utilities and customers. This power quality issue is primarily due to increase in use of solid-state switching devices, nonlinear and power electronically switched loads, unbalanced power system, lighting controls, computer and data processing equipment's as well as industrial plants rectifiers and inverters. PQ events such as sag, swell, transients, harmonics and flicker are the most common types of disturbances that occur in a power line. Sophisticated equipment's connected to the power line are prone to these disturbances and are affected or get damaged due to disturbances that randomly occur for very short durations. Thus, it is required to estimate the presence of disturbance, and accurately classify the disturbances and also characterize the disturbances. In order to perform the tasks such as detection, classification and characterization, it is required to understand the basic properties of PQ events and their properties. This dissertation deals with modelling of power quality disturbances for power quality analysis.

II Aim and Objectives of work

The aim of this dissertation work is to implement the Integral Mathematical Models of various Power Quality Disturbances.

Objectives:

- To study the mathematical models of various power quality disturbances.
- To implement the integral mathematical models of various power quality disturbances using the MATLAB.
- To generate single & multiple synthetic power quality disturbances as per the definition and parameters outlined by IEEE-1159 and IEC61000 customary in MATLAB using the integral mathematical models.

III. Problem Definition

Nowadays Power Quality becomes an important issue. Both utilities and customers are concern about power quality. Due to increasing use of power electronic devices various power quality disturbances are arising. This PQDs may lead to malfunctioning of end user equipment's. Hence, it is important to have a detail analysis of these disturbances and mitigate them. To study the properties and characteristics of different PQDs one may need the PQD signals. These signals can be generated by different techniques such as simulating the power quality disturbances using simulation software or generating the PQD signals by implementing the standard integral mathematical models of various PQDs using the programming software and developing the GUI for the same. The PQD signals generated by using any of the way for the analysis of PQDs called as synthetic data. One may face problem to get the data or signal for analysis, so, he can use this synthetic data readily for his research which saves his time in developing the power quality monitoring algorithms which can detect and classify various PQDs. This research work mainly focuses on generation of various PQDs by implementing their integral mathematical models.

IV. Power Quality

Power quality is simply the interaction of electrical power with electrical equipment. If electrical equipment operates correctly and reliably without being damaged or stressed, we would say that the electrical power is of good quality. On the other hand, if the electrical equipment malfunctions, is unreliable, or is damaged during normal usage, we would suspect that the power quality is poor.

Power quality is a collection of various subjects in terms of voltage quality, current quality, supply quality and consumption quality. It can be defined as: 'Any power problem manifested in voltage, current, or frequency deviations that result in failure or malfunction of customer equipment'. Poor power quality is often the main reason of unexplained equipment trips or shutdowns; occasional equipment damage or component failure; erratic control of process performance; random lockups and data errors, power system component overheating

V. Power Quality Problem

A. The power quality problem causes the deterioration of performance of various sensitive electronic and electric equipment's. The good quality of power can be specified as

- The supply voltage should be within guaranteed tolerance of declared value.
- The wave shape should be pure sine wave within allowable limits for distortion.
- The voltage should be balanced in all three phases.
- Supply should be reliable i.e continuous availability without interruption.

B. Causes of poor power quality:

- Variations in voltage, magnitude and frequency
 - Variations in frequency can rise of out of system dynamics or harmonics injection.
- Consequently, the voltage or current waveforms of a power system ceases to be purely sinusoidal in nature but consist of harmonics and other noises.

VI. Power Quality Disturbances

- Transients are instantaneous high voltage increase in the range of nanoseconds.
- Interruption occurs when supply voltage or load current decrease to less than 0.1 pu for a period of time not exceeding 1 minute.
- Voltage sag happens when the RMS voltage decreases between 10 and 90 percent of nominal voltage for one-half cycle to one minute.
- Voltage swell is the increase in the RMS voltage level to 110% - 180% of nominal voltage for a period of time not exceeding 1 minute.
- Waveform distortion is the unexpected change in the waveforms of current and voltage as they pass through a device.

Table 1 shows the categorization of power quality disturbances based on time duration and voltage magnitude.

Table 1: Categorization of power quality disturbances

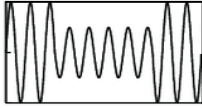
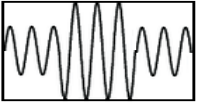


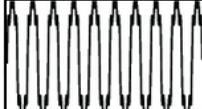
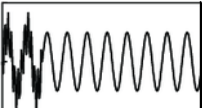
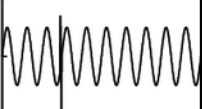
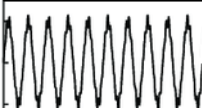
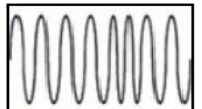
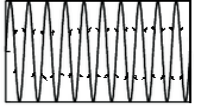
Power Quality Events		Time Duration	Voltage Magnitude
Short duration variation			
Sag	Instantaneous	0.5-30 cycle	0.1-0.9 pu
	Momentary	30 cycles-3 s.	0.1-0.9 pu
	Temporary	3 sec-1 min.	0.1-0.9 pu
Swell	Instantaneous	0.5-30 cycle	1.1-1.8 pu
	Momentary	30 cycles-3 s.	1.1-1.4 pu
	Temporary	3 sec-1 min.	1.1-1.2 pu
Interruption	Momentary	0.5 cycles-3 s.	<0.1 pu
	Temporary	3 sec-1 min.	<0.1 pu
Long duration variation			
Interruption (sustained)		>1 min.	0.0 pu
Under voltage (UV)		>1 min.	0.8-0.9 pu
Overvoltage (OV)		>1 min.	1.1-1.2 pu
Transients			
Impulsive	Nanosecond	<50 nsec.	
	Microsecond	50-1 msec.	
	Millisecond	>1 msec.	
Oscillatory	Low frequency	0.3-50 msec.	0-4 pu.
	Medium freq.	20 μ sec.	0-8 pu.
	High freq.	5 μ sec.	0-4 pu.
Waveform distortion			
DC offset		Steady state	0-0.1%
Harmonics		Steady state	0-20%
Inter harmonics		Steady state	0-2%
Notching		Steady state	

Noise	Steady state	0-1%
Voltage unbalance (VU)	Steady state	0.5-2%

A. Causes and Effects of Power Quality Disturbances

The power quality disturbances occurring frequently in power system. They may have adverse effect on power system equipment's. Table 2 shows the various power quality disturbances along with its causes and effects.

Table 2: Causes and effects of power quality disturbances

PQ Disturbances	Causes	Effects
 <p>Sag</p>	<ul style="list-style-type: none"> • Faults occurring in power system • Switching of large loads (ON) • Starting of large motors 	<ul style="list-style-type: none"> • Malfunction of sensitive equipment's like PCs, PLCs, ASDs, etc. • Tripping of contactors and relays • Loss of efficiency of electric machines
 <p>Swell</p>	<ul style="list-style-type: none"> • Faults occurring in power system • Switching of large loads (OFF) • Switching of capacitor banks 	<ul style="list-style-type: none"> • Data loss • Flickering of lighting • Failure or Damage of sensitive equipment
 <p>Short Interruption</p>	<ul style="list-style-type: none"> • Faults occurring in power system • Circuit breaker operation • Control circuit errors 	<ul style="list-style-type: none"> • Loss of information • Malfunction of data processing equipment. • Failure of sensitive equipment, such as ASDs, PCs, PLCs.
 <p>Long Interruption</p>	<ul style="list-style-type: none"> • Failure of electrical equipment's • Storms and objects striking lines • human error • Failure of protection devices 	<ul style="list-style-type: none"> • Failure of all equipment. • Malfunctioning in data processing devices.
 <p>Harmonics</p>	<ul style="list-style-type: none"> • Arc furnaces • Welding machines • Rectifiers • All non-linear loads • Data processing equipment • High efficiency lighting 	<ul style="list-style-type: none"> • Resonance • Neutral overload in 3-phase systems • Overheating of all cables and equipment • Loss of efficiency in electric machines • Interference with communication systems • Nuisance tripping of thermal protections
 <p>Oscillatory Transient</p>	<ul style="list-style-type: none"> • Switching events • Electrostatic discharge • Load switching • Capacitor bank switching 	<ul style="list-style-type: none"> • Insulation failure • Nuisance tripping of adaptable speed drives
 <p>Impulsive Transient</p>	<ul style="list-style-type: none"> • Lightning discharge • Sudden switching events 	<ul style="list-style-type: none"> • Degradation of dielectric • Instant dielectric breakdown in equipment's
 <p>Flicker</p>	<ul style="list-style-type: none"> • Intermittent loads • Motor starting • Arc furnaces 	<ul style="list-style-type: none"> • Flickering of lighting and screens • Damage of equipment's at load side
 <p>Frequency Variation</p>	<ul style="list-style-type: none"> • Heavy load. 	<ul style="list-style-type: none"> • Mainly affects the motors and sensitive devices
 <p>Notching</p>	<ul style="list-style-type: none"> • Intermittent voltage distortion initiated by the power electronic devices • Switching of heavy load • Transformers with bad regulation 	<ul style="list-style-type: none"> • Data loss • Failure or damage of sensitive devices

VII. Integral Mathematical Model of Power Quality Disturbances

A. Introduction

Verification of software reference models for PQ analysis requires PQ signals; which are generated using software programs. In order to represent the real time signals accurately, mathematical equations are used to generate PQ Synthetic signals. Synthetic signals generated need to have all the properties of a real-time signal and should match the real-time signal in all aspects. Performance of PQ analysis techniques is dependent of PQ signals; hence it is required that the synthetic signals which are generated using software programs are accurately modeled. Development of software programs to generate PQ disturbances are governed by standard definitions for events as given in Table is generated.

Sag and swell events are modeled using step functions defined for periods between t_1 and t_2 , amplitude of step function is used to control the intensity of voltages thus defining sag and swell. Time intervals t_1 and t_2 define the duration of sag and swell.

Harmonic signal consists of frequency components that are multiples of 1 KHz. In a PQ signal the disturbances in terms of harmonics will have more than three frequency components and are odd multiples of fundamental component. The odd harmonics also have voltage Variations and thus affect the fundamental signal. Parameters that define amplitudes of harmonic components given by $\alpha_1, \alpha_2, \alpha_3$ and α_4 have variations from 0.05 to 0.15 and the square sum of all components should not exceed unit magnitude. These parameters are used to control the harmonic variation in a pure sine wave signal.

In signal disturbances that create exponential variations within a short duration of time interval are transients. Parameters such as α, w and K control the variations in transients in a given pure sine wave as shown in table 1. Transients occur for a short time interval, controlled by t_1 and t_2 . During this time interval, the signal behaviors consist an exponential variation controlled by τ . Flicker is due to randomness in sag and swell affecting pure sine wave. Mathematical models for flicker are similar to sag and swell, but the duration of sag and swell is randomly added to the pure sine wave signal.

B. Integral Mathematical Model of PQDs

Table 3 shows the parametric equations of power quality disturbances obtained from the integral mathematical model. By varying the parameters from the equation, the duration of event and magnitude can be varied.

Table 3: Parametric equations of Power Quality Disturbances (PQDs)

PQDs	Equations	Parameters
Pure	$x(t) = A \sin(\omega t)$	$A = 1(pu), \omega = 2\pi f \text{ rad/s}, f = 50 \text{ Hz}$
Sag	$x(t) = A \left(1 - \alpha(u(t - t_1) - u(t - t_2))\right) \sin(\omega t)$	$0.1 \leq \alpha \leq 0.8, T \leq (t_2 - t_1) \leq 9T$
Swell	$x(t) = A \left(1 + \alpha(u(t - t_1) - u(t - t_2))\right) \sin(\omega t)$	$0.1 \leq \alpha \leq 0.8, T \leq (t_2 - t_1) \leq 9T$
Interruption	$x(t) = A \left(1 - \alpha(u(t - t_1) - u(t - t_2))\right) \sin(\omega t)$	$0.9 \leq \alpha \leq 1, T \leq (t_2 - t_1) \leq 9T$
Harmonics	$x(t) = \alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)$	$0.05 \leq \alpha_3, \alpha_5, \alpha_7 \leq 0.15, \alpha_1 = 1$
Flicker	$x(t) = (1 + \lambda \sin(\kappa \omega t)) \sin(\omega t)$	$0.1 \leq \lambda \leq 0.2, 5 \leq \kappa \leq 10$
Notch	$x(t) = \sin(\omega t) - \text{sign}(\sin(\omega t)) \sum_{n=0}^9 (K \times [u\{t - (t_1 - 0.02n)\} - u\{t - (t_2 - 0.02n)\}])$	$0.1 \leq K \leq 0.4, 0 \leq t_1, t_2 \leq 0.5T, 0.01T \leq t_2 - t_1 \leq 0.05T$
Spike	$x(t) = \sin(\omega t) + \text{sign}(\sin(\omega t)) \sum_{n=0}^9 (K \times [u\{t - (t_1 - 0.02n)\} - u\{t - (t_2 - 0.02n)\}])$	$0.1 \leq K \leq 0.4, 0 \leq t_1, t_2 \leq 0.5T, 0.01T \leq t_2 - t_1 \leq 0.05T$
Oscillatory Transient	$x(t) = \sin(\omega t) + \alpha_t \exp\left(-\frac{t - t_1}{\tau}\right) (u(t - t_1) - u(t - t_2)) \sin(2\pi f_n t)$	$0.1 \leq \alpha_t \leq 0.8, 0.5T \leq (t_2 - t_1) \leq 3T$ $8ms \leq \tau \leq 30ms, 300 \leq f_n \leq 900 \text{ Hz}$
Impulsive Transient	$x(t) = \sin(\omega t) + \alpha_t \exp\left(-\frac{t - t_1}{\tau}\right) (u(t - t_1) - u(t - t_2))$	$3 \leq \alpha_t \leq 4, 0.5T \leq (t_2 - t_1) \leq 3T$ $8ms \leq \tau \leq 30ms$
Sag Harmonics with	$x(t) = [A \left(1 - \alpha(u(t - t_1) - u(t - t_2))\right) \sin(\omega t)] \times [\alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)]$	$0.1 \leq \alpha \leq 0.8, T \leq (t_2 - t_1) \leq 9T$ $0.05 \leq \alpha_3, \alpha_5, \alpha_7 \leq 0.15, \alpha_1 = 1$
Swell Harmonics with	$x(t) = [A \left(1 + \alpha(u(t - t_1) - u(t - t_2))\right) \sin(\omega t)] \times [\alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)]$	$0.1 \leq \alpha \leq 0.8, T \leq (t_2 - t_1) \leq 9T$ $0.05 \leq \alpha_3, \alpha_5, \alpha_7 \leq 0.15, \alpha_1 = 1$
Interruption with Harmonics	$x(t) = [A \left(1 - \alpha(u(t - t_1) - u(t - t_2))\right) \sin(\omega t)] \times [\alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)]$	$0.9 \leq \alpha \leq 1, T \leq (t_2 - t_1) \leq 9T$ $0.05 \leq \alpha_3, \alpha_5, \alpha_7 \leq 0.15, \alpha_1 = 1$

In the above table we study integral mathematical model of PQDs are having following parameters

- Pure Sine Wave The plots obtained for the pure sine wave is considered as a reference for PQ disturbance detection. All curves were of constant amplitude except for amplitude frequency curve which showed one amplitude appeared at 50Hz.
- Voltage sag Voltage sag of (30%) and related ST plots are shown. The voltage sag can be recognized from the change in the amplitude of various curves such as, frequency contour, amplitude – time curve, and sum of absolute values curve F), (c), and (d), respectively. From which is the second derivative of the sum of absolute values curve we can easily localize the time of the disturbance between (0.06s – 0.14s).
- Voltage Swell Voltage swell of (30%) and related ST plots are shown in Fig. 3. The voltage swell can be recognized from the change in the amplitude of various curves such as, frequency contour, amplitude –time curve, and sum of absolute values curve respectively. Which is the second derivative of the sum of absolute values curve we can easily localize the time of the disturbance between (0.06s – 0.14s). Voltage sag of (30%) and related ST.
- Interruption Voltage Interruption of (8%) and related ST plots are shown. The voltage interruption can be recognized from the change in the amplitude of various curves such as, frequency contour, amplitude –time curve, and sum of absolute values curve respectively. Also some discontinuities in the frequency contour curve .
- Harmonics Harmonic and related ST plots are shown in Fig 5. It can be depicted from continuous ripples in frequency contour plot and sum of absolute values curve, respectively. A finite value of frequency between. the normalized frequencies 0.05 to 0.15 is another indication of the presence of Harmonics.
- Flicker Flicker is defined as a tiny movement of light, or an expression of emotion that comes and goes quickly. The flame of a candle that is bright and then weaker is an example of the flicker of the candle. When an evil person feels kindness just for a second, this is an example of a flicker of kindness.
- Notch It is a steady state phenomenon. Notch is a periodic supply voltage which is caused by power electronic devices like converters, rectifiers or universal bridges. This happens due to current commutation from one phase to another.
- Spike A voltage spike is a sudden increase in voltage that lasts for less than three nanoseconds. A sudden increase in voltage that lasts for three nanoseconds or more is called a voltage surge. They are harmful because they cause the wires in your electronic equipment to overheat.
- Oscillatory Transient A voltage spike is a sudden increase in voltage that lasts for less than three nanoseconds. A sudden increase in voltage that lasts for three nanoseconds or more is called a voltage surge. They are harmful because they cause the wires in your electronic equipment to overheat.
- Impulsive Transient An impulsive transient is a sudden, non–power frequency change in the steady state condition of voltage, current, or both that is unidirectional in polarity (primarily either positive or negative). Impulsive transients are normally characterized by their rise and decay times. Sag and swell events are modeled using step functions defined for periods between t_1 and t_2 , amplitude of step function is used to control the intensity of voltages thus defining sag and swell. Time intervals t_1 and t_2 define the duration of sag and swell. Harmonic signal consists of frequency components that are multiples of 1 KHz. In a PQ signal the disturbances in terms of harmonics will have more than three frequency components and are odd multiples of fundamental component. The odd harmonics also have voltage Variations and thus affect the fundamental signal. Parameters that define amplitudes of harmonic components given by $\alpha_1, \alpha_2, \alpha_3$ and α_4 have variations from 0.05 to 0.15 and the square sum of all components should not exceed unit magnitude. These parameters are used to control the harmonic variation in a pure sine wave signal. In signal disturbances that create exponential variations within a short duration of time interval are transients. Parameters such as α, w and K control the variations in transients in a given pure sine wave as shown in table 1. Transients occur for a short time interval, controlled by t_1 and t_2 . During this time interval, the signal behaviors consists an exponential variation controlled by τ . Flicker is due to randomness in sag and swell affecting pure sine wave. Mathematical models for flicker are similar to sag and swell, but the duration of sag and swell is randomly added to the pure sine wave signal.

VIII. System design

A. Block Diagram

Based on the discussions and numerical equations presented the software programs are developed for modeling power quality disturbances. Control parameters for variations in distortions or events are defined as user inputs. The known disturbances are introduced in the signal; graphical display helps in verifying the PQ events. Fig. 1 shows the block diagram for generation of power quality disturbances.

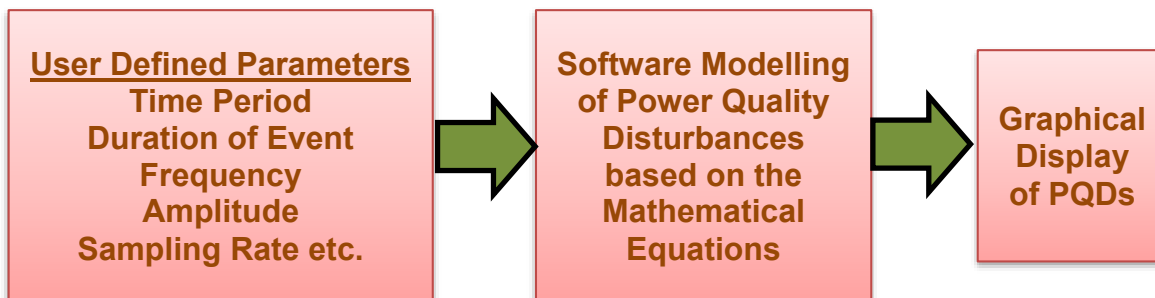


Figure 1: Block diagram for generation of power quality disturbances.

In order to validate the mathematical models that are used to generate PQ disturbances, it is required to verify the correctness of synthetically generated signal against real time signals. Hence it is required to generate and capture real time disturbances. Figure 5 shows the block diagram for the experimental set-up to acquire real time PQ disturbances for the analysis. Experimental set up consists of a power line connected to data acquisition system, loads such as resistive (lighting load or lamp), inductive load (induction motors) and both. Voltage variation across the power line is captured using the data acquisition system consisting of differential module. In order to check the correctness of the developed mathematical models and it is required to validate the generated synthetic signal against real-time signals. In this work, an experimental setup is developed to generate real-time signal

and disturbances are introduced by varying different loads. The data acquisition unit developed captures the signal along with the disturbances. The recorded signal is stored in a text file. The MATLAB model developed reads the text file and the contents are plotted. The software program developed based on mathematical model is used to generate similar kind (real-time) of signal by varying the input parameters to the software model. The output of both the software model and the real-time signal are compared and modifying the mathematical models minimizes the error between them. Various test cases are captured using the real-time experimental setup, which are used to verify the synthetic signal generated using software programs. The synthetic signal is validated against real-time signal and is used for PQ analysis. Figure 6 shows the experimental set up for PQ signal validation. Comparison or equivalence check is carried out to compare the similarities between real time PQ signal and synthetic PQ signal. Synthetically generated PQ signal is compared with the results of real time signals. In order to compare the signals Mean Square Error (MSE) [64] is computed between the real time signal and the synthetic signal as in equation $MSE = \frac{1}{Q} \sum_{k=1}^Q (t(k) - a(k))^2$ t(k) is the real time signal samples that are compared with a(k) which is the generated synthetic signal, Q is number of samples. The difference in samples values are squared and accumulated to compute MSE. Real time signals generated for various disturbances is compared with synthetic signal, the MSE is verified, MSE is well above threshold value of 2%, mathematical model presented in Table1 is modified to minimize the MSE well below the threshold.

B. Flow Chart for Generation of Power Quality Disturbances

The steps involved in the software program developed for the generation of power quality disturbances are represented in the form of flow chart shown in fig. 2

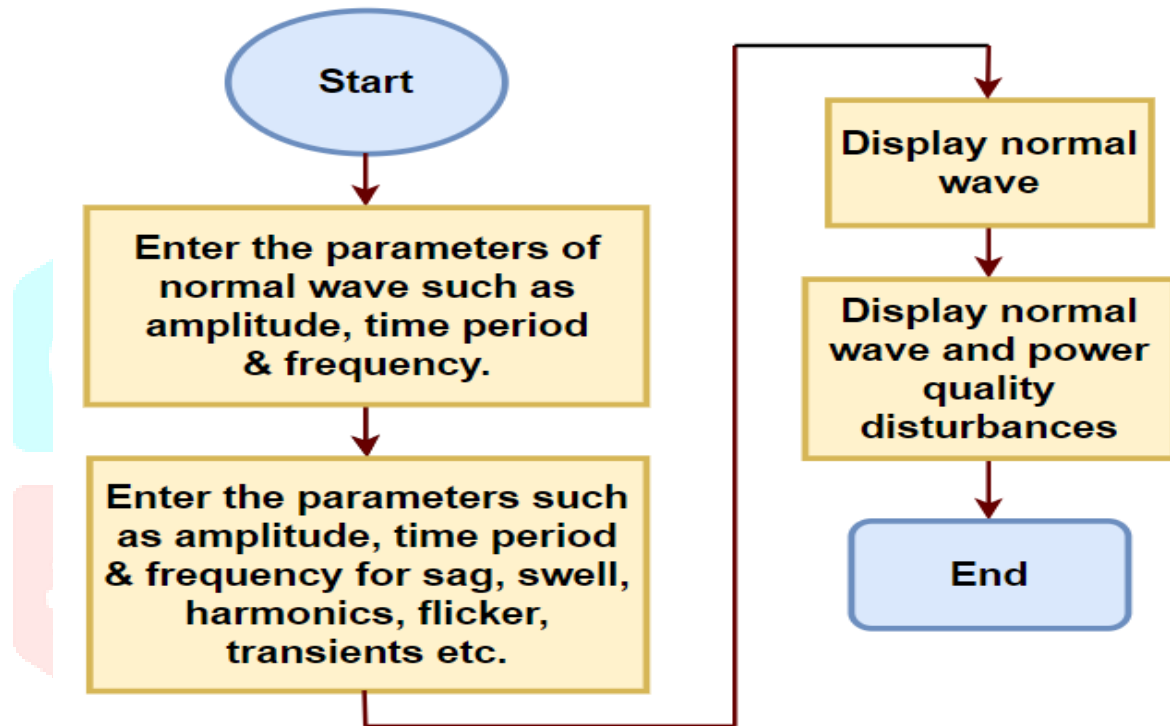


Figure.2: Flow Chart for generation of power quality disturbances.

for generating PQ disturbances using MATLAB Figure 2 shows flow chart for generating PQ disturbances. PQ signals are generated with 50 Hz with sampling frequency of 1KSPS. For various PQ signals 400,000 samples are generated. Before generation of the signals, the normal PQ signal is normalized hence the amplitude of the signal is 1p.u.(per unit) Illustrates a step wise flow chart from the point of power quality signal generation till obtaining the classification accuracy of tuned SVM classifier. To verify the proposed approach, single and multi-stage PQ disturbance signals are generated using MATLAB 2014A. For proper training of classifier, it is advantageous to use synthetic data as multiple variations of the same disturbance can be easily recreated artificially. The mathematical formulas are coded in MATLAB and a for loop is run for 100 iterations with change in the .

IX Conclusion

In this dissertation the implementation of integral mathematical models of eleven power quality disturbances in the form of parametric equation is done using the software program develop in MATLAB software. Total eleven power quality disturbances are generated namely voltage sag, voltage swell, voltage interruption, harmonics, impulsive transient, oscillatory transient, voltage flicker, voltage notch, noise, voltage sag with harmonics and voltage swell with harmonics.

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