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INTEGRAL MATHEMATICAL MODEL BASED GENERATION OF SINGLE AND MULTIPLE POWER QUALITY DISTURBANCES

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Abstract:
In order to meet the increased demand for power, renewable energy generation is being used more and more frequently today. For the grid integration of this generation, power electronic converters are required. These power electronic converters, switching activities, non-linear loads, and network issues are the primary sources of Power Quality Disturbances (PQDs). These PQDs cause significant damage to the end-equipment. user's Power Quality (PQ) thus becomes the main area of concern for both utilities and clients. In order to address the PQ issue, we need an accurate PQ monitoring system that can recognise and classify PQDs. Numerous studies are being conducted in this area.
The first step in this project is to gather some synthetic data to test and train the detection and classification algorithms. It is now common to use integral mathematical models, which are stated as parametric equations, to construct single and many PQDs. In this study, integral mathematical models of single and multiple PQDs—including voltage sag with harmonics—are produced using MATLAB programming. These models include voltage sag, swell, interruption, harmonics, voltage flicker, voltage notch, and impulsive, oscillatory, and voltage notch. This will provide a rapid and automatic method to generate PQDs for the researcher working in this subject.
Keywords: Power Quality; Power Quality Disturbances, Power Quality Monitoring, Detection and Classification.

Introduction
In the current scientific and technical era, the idea of power quality has gained increased significance.
Both utilities and customers are currently concerned about power quality. The biggest contributor to power quality issues is the expanding usage of non-linear loads, power electronic load/converters, solid-state devices, unbalanced loads, computer systems, and data processing units [1]. Disruptions to power quality are mostly brought on by the installation of distributed generating systems using power electronic converters and renewable energy sources [2]. Power quality disturbances, such as voltage sag, voltage swell, interruption, harmonics, transients, and flicker, are the most frequent disturbances in power systems [3]. Modern equipment that is connected to the power system may be impacted by or damaged by power quality disruptions that occur in the system for any reason [5]. It is crucial to accurately classify and diagnose power quality disruptions when they happen. For the purpose of detection, classification, and characterisation, understanding the attributes and characteristics of power quality disruptions is essential. Eleven power quality disturbances are produced in this study using mathematical models for power quality analysis.

Power Quality
Power quality is defined in a number of ways. Varied international standard organisations have different definitions of the term "power quality." It is described as the idea of grounding and powering electronic equipment in a way that is appropriate for the equipment's operation and compatible with the supply system and other connected equipment by IEEE. The ability of a device, piece of equipment, or system to perform properly in its electromagnetic environment without causing intolerable electromagnetic disturbances to anything in that environment is what the IEC defines as electromagnetic compatibility. Customer equipment malfunctions may be brought on by power quality problems. It might result in the production process being interrupted, causing the product to be harmed and the manufacture to be hindered, which would result in financial loss. The supply quality needs to be good for the electric and electronic equipment to operate properly. Good power quality has the following qualities.

- The supply voltage should be rated or within the tolerance limit.
- The three-phase voltage should be balance.
- The supply frequency should be rated or within the tolerance limit.
- The nature of the alternating wave should be purely sinusoidal within the allowable distortion limits.

The most common types of power quality disturbances are discussed below

- **Voltage sag** is the reduction in the RMS value of the voltage between 10% to 90% of nominal voltage for a period less than one minute.
- **Voltage swell** occurs when the RMS value of voltage increases to 110% - 180% of nominal voltage for a period not exceeding one minute.
- **Interruption** is the decrease in the value of supply voltage below 0.1 pu for a period less than one minute.
- **Harmonics** is the signal in which the frequency of a signal is multiple of the fundamental frequency.
- **Transients** are the instantaneous rise in the voltage value for a very short duration.
- **Waveform distortion** is the unpredicted change in the value of current and voltage waveforms when they are applied to any device.

Table 1 shows the categorization of power quality disturbances in different groups along with the time duration and variation in 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
Undervoltage (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 µsec.	0-8 pu.
	High freq.	5 µsec.	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%

Integral Mathematical Models of Power Quality Disturbances

The integral mathematical models of PQDs are represented by a set of parametric equations using different mathematical functions in order to generate the required power quality disturbance. The magnitude and duration of the disturbances are controlled by controlling the parameters of parametric equations. These mathematical models are used to generate the synthetic power quality signals. This will help to represent the real-time power quality signals accurately. The generated synthetic power quality signals will have the same characteristics as the real-time power quality signals have in all standpoints [2]. The performance of the power quality disturbance detection and classification algorithm is dependent on PQ signals. Hence, it is necessary to accurately model and implement the software program for the generation of synthetic power quality signals.

In the integral mathematical models of PQDs, the representation of voltage sag, voltage swell, and interruption events is done using the step function. The amplitudes of these events are controlled by the parameter A and the duration is controlled by t1 and t2 [2]. Harmonic event is represented by the algebraic sum of sine functions of different frequencies and the parameters α1, α2, α3, and α4 are varied from 0.05 to 0.15 in order to control the harmonic [9]. The transients are represented by the exponential function where the parameters α, w, and K controls the transients in a sinusoidal wave. Flicker is represented by randomizing the sine wave.

Table 2 shows the parametric equations of power quality disturbances obtained from the integral mathematical model. By varying the parameters of the equation, the duration of the event and magnitude can be varied.

Table 2: Parametric equations of Power Quality Disturbances (PQDs)

PQDs	*Equations*	*Parameters*
Pure	$x(t) = A\sin(\omega t)$	$A = 1(pu), \omega = 2\pi f\ rad/s, f = 50\ Hz$
Voltage Sag	$x(t) = A\left(1 - \alpha\left(u(t-t1) - u(t-t2)\right)\right)\sin(\omega t)$	$0.1 \le \alpha \le 0.8, T \le (t2 - t1) \le 9T$
Voltage Swell	$x(t) = A\left(1 + \alpha\left(u(t-t1) - u(t-t2)\right)\right)\sin(\omega t)$	$0.1 \le \alpha \le 0.8, T \le (t2 - t1) \le 9T$
Interruption	$x(t) = A\left(1 - \alpha\left(u(t-t1) - u(t-t2)\right)\right)\sin(\omega t)$	$0.9 \le \alpha \le 1, T \le (t2 - t1) \le 9T$
Harmonics	$x(t) = \alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)$	$0.05 \le \alpha_3, \alpha_5, \alpha_7 \le 0.15, \alpha_1 = 1$
Voltage Flicker	$x(t) = (1 + \lambda \sin(\kappa\omega t))\sin(\omega t)$	$0.1 \le \lambda \le 0.2, 5 \le \kappa \le 10$
Voltage Notch	$x(t) = \sin(\omega t) - sign(\sin(\omega t)) \sum_{n=0}^{9} (K \times [u\{t - (t1 - 0.02n)\} - u\{t - (t2 - 0.02n)\}])$	$0.1 \le K \le 0.4, 0 \le t1, t2 \le 0.5T,$ $0.01T \le t2 - t1 \le 0.05T$
Oscillatory Transient	$x(t) = \sin(\omega t) + \alpha_t \exp(-\frac{t - t1}{\tau})(u(t - t1) - u(t - t2))\sin(2\pi f_n t)$	$0.1 \le \alpha_t \le 0.8, 0.5T \le (t2 - t1) \le 3T$ $8ms \le \tau \le 30ms, 300 \le f_n \le 900\ Hz$
Impulsive Transient	$x(t) = \sin(\omega t) + \alpha_t \exp(-\frac{t - t1}{\tau})(u(t - t1) - u(t - t2))$	$3 \le \alpha_t \le 4, 0.5T \le (t2 - t1) \le 3T$ $8ms \le \tau \le 30ms$
Sag with Harmonics	$x(t) = [A\left(1 - \alpha\left(u(t-t1) - u(t-t2)\right)\right)\sin(\omega t)]\text{x}[\alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)]$	$0.1 \le \alpha \le 0.8, T \le (t2 - t1) \le 9T$ $0.05 \le \alpha_3, \alpha_5, \alpha_7 \le 0.15, \alpha_1 = 1$
Swell with Harmonics	$x(t) = [A\left(1 + \alpha\left(u(t-t1) - u(t-t2)\right)\right)\sin(\omega t)]\text{x}[\alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)]$	$0.1 \le \alpha \le 0.8, T \le (t2 - t1) \le 9T$ $0.05 \le \alpha_3, \alpha_5, \alpha_7 \le 0.15, \alpha_1 = 1$
Interruption with Harmonics	$x(t) = [A\left(1 - \alpha\left(u(t-t1) - u(t-t2)\right)\right)\sin(\omega t)]\text{x}[\alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)]$	$0.9 \le \alpha \le 1, T \le (t2 - t1) \le 9T$ $0.05 \le \alpha_3, \alpha_5, \alpha_7 \le 0.15, \alpha_1 = 1$

Flow Chart for Generation of Power Quality Disturbances

The steps involved in the software program developed in MATLAB for the generation of power quality disturbances using the integral mathematical models are represented in the form of flow chart shown in figure1.

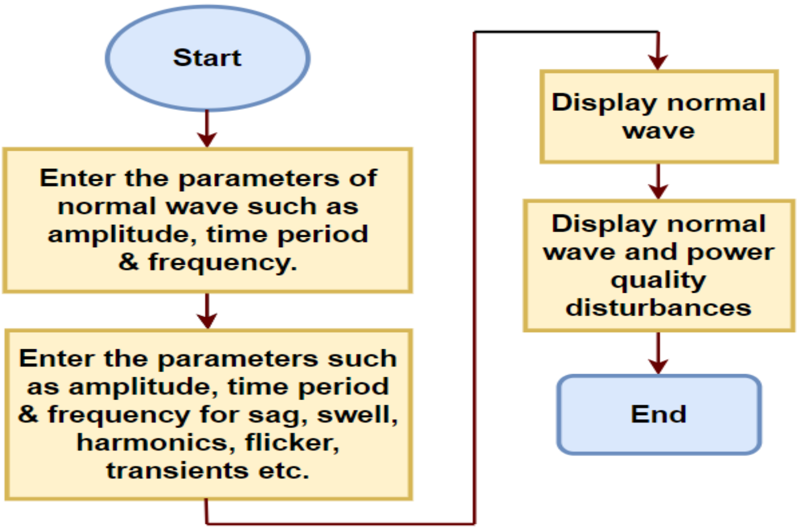

Fig 1. Flow Chart for generation of power quality disturbances.

Generation of Power Quality Disturbances using MATLAB

In this paper, the implementation of integral mathematical models of eleven power quality disturbances which are represented in the form of parametric equations is done using the software program developed in MATLAB software. Total eleven power quality disturbances are generated, namely voltage sag, voltage swell, voltage interruption, harmonics, voltage flicker, voltage notch, impulsive transient, oscillatory transient, voltage sag with harmonics, voltage swell with harmonics, and voltage interruption with harmonics. Figure 2 shows the pure 50Hz sine wave of amplitude 1pu and time duration 0.4 sec generated using the parametric equation.

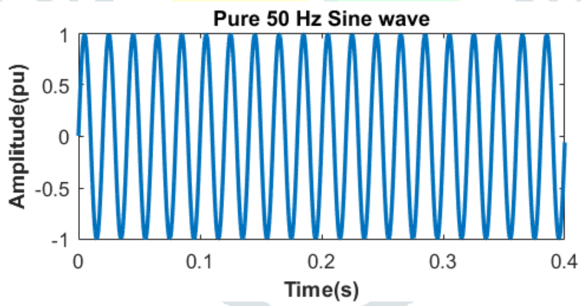

Fig 2. Pure 50Hz sine wave generated using the parametric equation.

Figure 3 shows the voltage signal with a sag of 50% for time duration 0.2 sec generated by controlling the parameters of the parametric equation. The total duration of the waveform is 0.4 sec.

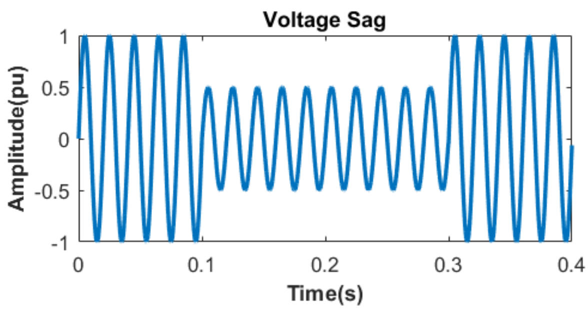

Fig 3. Voltage Sag waveform generated using the parametric equation.

Figure 4 shows the voltage signal with a swell of 150% for time duration 0.2 sec generated by controlling the parameters of the parametric equation. The total duration of the waveform is 0.4 sec.

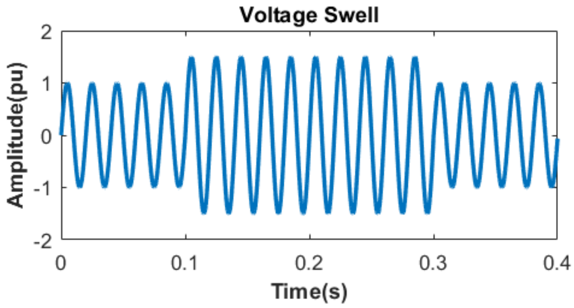

Fig 4. Voltage Swell waveform generated using the parametric equation.

Figure 5 shows the voltage signal with an interruption for time duration 0.2 sec generated by controlling the parameters of the parametric equation. The total duration of the waveform is 0.4 sec.

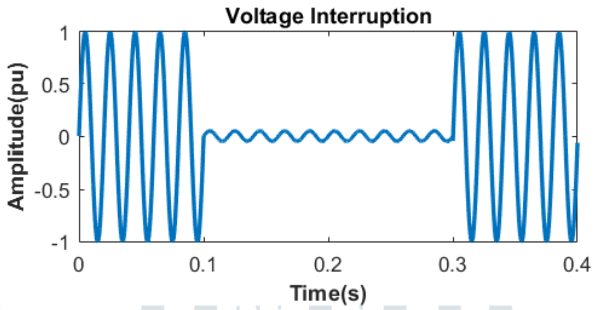

Fig 5. Voltage Interruption waveform generated using the parametric equation.

Figure 6 shows the voltage signal with odd harmonics for time duration 0.4 sec generated by controlling the parameters of the parametric equation. The total duration of the waveform is 0.4 sec.

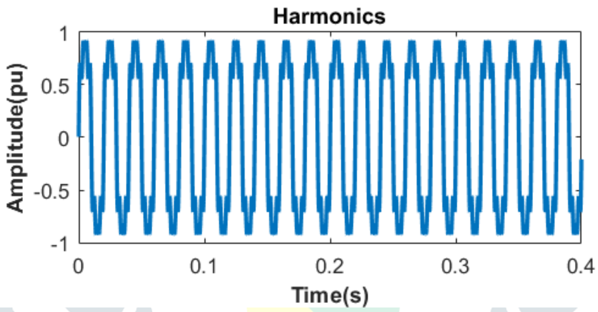

Fig 6. Harmonics waveform generated using the parametric equation.

Figure 7 shows the voltage signal with impulsive transient with a positive peak of 1.4 pu and a negative peak of 2 pu for a time duration in music generated by controlling the parameters of the parametric equation. The total duration of the waveform is 0.4 sec.

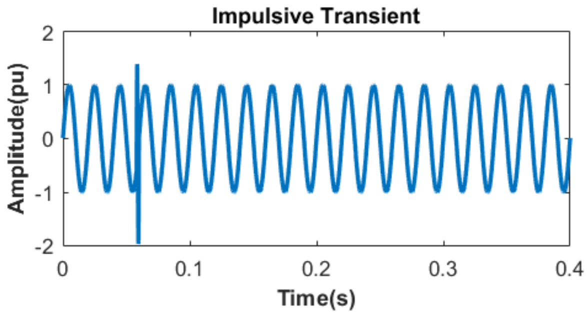

Fig 7. Impulsive Transient waveform generated using the parametric equation.

Figure 8 shows the voltage signal with oscillatory transients of frequency 300 to 900Hz and time duration 0.06 sec generated by controlling the parameters of the parametric equation. The total duration of the waveform is considered to be 0.1 sec for better visualization of the waveform.

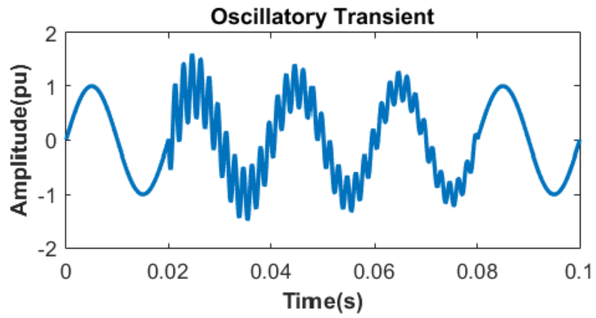

Fig 8. Oscillatory Transient waveform generated using the parametric equation.

Figure 9shows the voltage signal with flicker for time duration 0.4sec generated by controlling the parameters of the parametric equation.

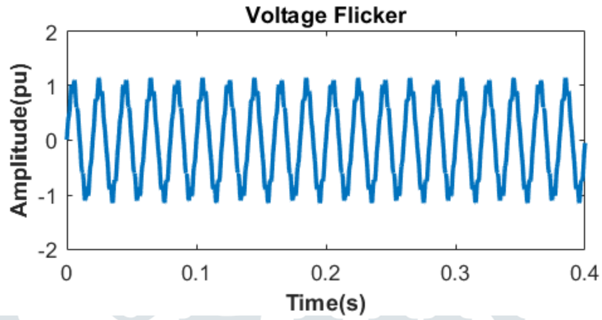

Fig 9. Voltage Flicker waveform generated using the parametric equation.

Figure 10 shows the voltage signal with notches for time duration 0.4sec generated by controlling the parameters of the parametric equation.

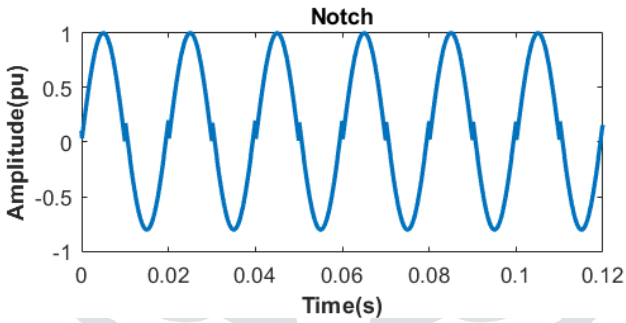

Fig 10. Voltage Notch waveform generated using the parametric equation.

Figure 11 shows the voltage signal with the sag of 50% along with harmonics for time duration 0.4 sec generated by controlling the parameters of the parametric equation.

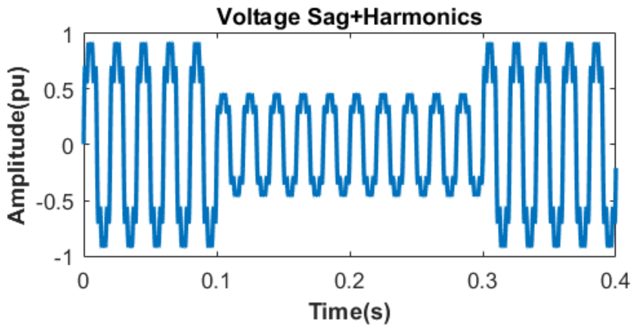

Fig 11. Voltage Sag + Harmonics waveform generated using the parametric equation.

Figure 12 shows the voltage signal with the swell of 150% along with harmonics for time duration 0.4 sec generated by controlling the parameters of the parametric equation.

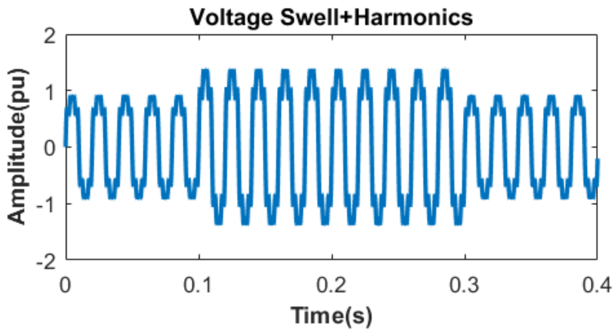

Fig 12. Voltage Swell + Harmonics waveform generated using the parametric equation.

Figure 13 shows the voltage signal with interruption along with harmonics for time duration 0.4sec generated by controlling the parameters of the parametric equation.

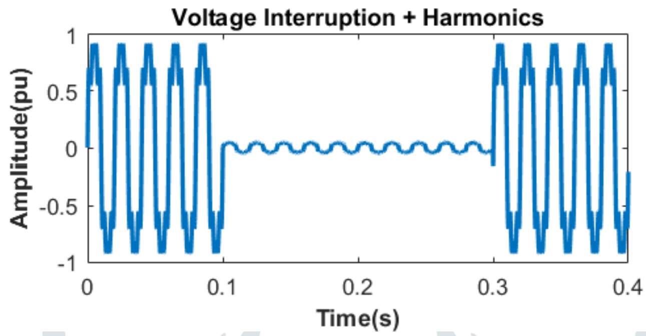

Fig 13. Voltage Interruption + Harmonics waveform generated using the parametric equation.

CONCLUSIONS

In this paper, the implementation of the integral mathematical models of power quality disturbances is done in the form of the parametric equation using the software program developed in MATLAB. Generation of both single and multiple power quality disturbances is done as per the parameters defined by IEEE1159 and IEC61000 standards. The power quality disturbance signals generated using the integral mathematical models will be useful in the research of detection and classification of power quality disturbances. Researchers working in the field of power quality can use mathematical models to generate the synthetic PQ signals and the data set required for training, validation, and testing the algorithms used for detection and classification PQDs. This will help in testing the feasibility of the algorithms, which signifies the importance of implementing the integral mathematical models of power quality disturbances. This work is of special interest in the initial stage of research which will reduce the effort and time spent on algorithm development.

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