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Modeling of Power Quality Disturbances using Parametric Equations in MATLAB

[1] M.S.Priyadarshini, [2] Dr.M.Sushama
[1] Research Scholar,Faculty of Electrical Engineering, [2] Professor
[1] [2] Department of Electrical and Electronic Engineering
J.N.T.U Anantapur,India.
Hyderabad,
[1]mspriyadarshini.raj@gmail.com, [2] m73sushama@yahoo.com

Abstract: **— The aim of this paper is to present modeling of power quality disturbances based on parametric equations. Parametric equations are considered for transients, short-duration voltage variations, harmonics, voltage sag with harmonics, voltage swell with harmonics, voltage fluctuations, and voltage flicker. The short-duration voltage variations include voltage interruption, voltage sag and voltage swell for a short period. The classification of power quality disturbances is based upon the magnitude of the disturbance and duration of occurrence. The power quality disturbances results in reduction of stability of the power system. So there is a necessity for proper evaluation of power quality disturbances. Power quality solutions along with required monitoring equipment are chosen by evaluating the type of power quality disturbances. The effect of power quality disturbances can be reduced only after their identification by providing an accurate analysis. The modeling of power quality disturbances performs an important role in power quality evaluation. Any of the signal processing techniques can be applied for extracting useful information from the signals. Waveforms for transients, interruption, sag, swell, harmonics, voltage sag with harmonics, voltage swell with harmonics, voltage fluctuations, and voltage flicker are generated using a suitable code based on parametric equations in MATLAB environment.**

Index Terms**: IEEE Standard, parametric equations, power quality disturbances, signal processing.**

I. INTRODUCTION

Electric power is produced at the generating stations and then transmitted and distributed through transmission and distribution systems for industrial and domestic load applications. Different types of power system loads are electric heating loads, lighting loads, motor loads and power electronics based loads. Electricity is supplied to the loads with an assurance of continuity of supply under normal and contingency conditions. In order to produce high quality electric power supply certain standards must be convened with regard to the factors of level of reliability. Continuity of service is to be provided by utilities to load by keeping the magnitude of voltage constant. Power quality is concerned with deviation of either voltage or current from their respective ideal voltage or current and this deviation is termed as power quality disturbance. The Institute of Electrical and Electronics Engineers (IEEE) dictionary states that "power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment" [1]. The power produced must be free of any interruption or disturbance that affects normal operation of electrical equipment. The International Electro technical Commission (IEC) definition of power quality is as follows: "Characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters" [2]. In order to improve electric power quality, the sources and causes of disturbances must be known. Preventive measures can only be taken by proper recognition of the disturbances. IEEE standard 1159-1995 [3], "IEEE recommended practice for monitoring electric power quality" describes power quality disturbances by organizing into seven categories as:

1.Transients
2.Short duration rms voltage variations
3.Long duration rms voltage variations
4.Voltage imbalance
5.Wave form distortion
6.Voltage fluctuations and
7. Power frequency variations.

Short duration rms voltage variations are categorized as sags, swells, and interruptions. Long duration rms voltage variations are categorized as overvoltage, under voltage and sustained interruptions. The five primary types of waveform distortion are DC Offset, Harmonics, Inter harmonics, Notching and Noise. The voltage signals having sag with harmonics and swell with harmonics also come under the classification of waveform distortion. By analyzing voltage disturbance waveforms, power quality events can be recognized. Power quality is the combination of voltage quality and current quality [4]. All the power quality disturbances, depending upon their category effects the utility system in the form of loss of data, equipment damage or reduced life, system halts, and shut down. Power quality disturbances are generated for an evaluation to find possible solutions for each of these disturbances. The paper is organized as section 2 with the description of parametric equations of some of the electrical power quality disturbance signals and section 3 with the obtained results in MATLAB. Section 4 with signal processing techniques available for the analysis of power quality disturbances and section 5 draws the conclusion.

II.PARAMETRIC EQUATION BASED MODELING OF POWER QUALITY DISTURBANCES

The fundamental voltage component characterization approach is qualified to power quality disturbances featured in remarkable magnitude changing situations, such as sags, swells, and interruptions [5]. A numerical model framework to generate various power quality waveforms is proposed in [6].In all the defined equations, the term$A$represents the maximum value of the supply voltage $V(t)$.Equation (1) represents the mathematical equation of pure sinusoidal supply voltage without any distortions as depicted in Fig.1 given as:

$$\boldsymbol{V(t) = A\sin(\omega t)} \qquad (1)$$

In all the equations defined for transient, interruption, sag, and swell the terms, $u(t_1), u(t_2), u(t-t_1)$ and $u(t-t_2)$ represent amplitude of unit step functions defined for the period's t_1, t_2, duration$(t-t_1)$, and duration$(t-t_2)$respectively.In the parametric equations for voltage interruption, sag and swell the duration $((t_2-t_1)$ is between $T$and $9T$, where T represents the time period of the sinusoidal voltage signal. The values of t_1 and t_2 are 0.08 and 0.16 seconds.All the parametric equations governing each power quality disturbance depend upon controlled parameters. In the process of modeling, based upon the ranges of the controlled parameters the disturbances in a pure sinusoidal signal are controlled.The parametric equations are also termed as mathematical model equations and modeling as mathematical modeling. The fundamental frequency is 50Hz and the amplitude of pure sinusoidal voltage is taken as 1 pu. The dimensionless quantity pu refers to per unit.

A. Transient

Transient denotes an event that is undesirable and momentary in nature. A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity [3].The possible causes of transients are lightning, ESD (ElectrostaticDischarge), utility fault clearing, and switching of inductive or capacitive loads [7]. Oscillatory transients are numerically modelled for $V(t)$ and is given in [8] as:

$$V(t) = A\left[\sin\omega t + \alpha e^{\frac{-(t-t_1)}{\tau}} \sin\omega_n(t-t_1)(u(t_2) - u(t_1))\right] \qquad (2)$$

The controlling parameters α, τ and f_n which are transient magnitude, transient settling time and transient oscillatory frequency respectively. In the parametric equation (2), the ranges for α, τ and f_n are 0.1 to 0.8, 0.008 to 0.04 seconds and 300 to 900 Hz respectively. The transient disturbance is defined for period t_1 by using the parametric equation as:

$$V(t) = \sin(\omega t) + \alpha^{-(t-t_1)/\tau}\sin\omega_n(t-t_1) \qquad (3)$$

Fig.2 depicts transient, simulated in MATLAB using (3), which is a very short duration voltage spike on a sinusoidal supply voltage.

B. Interruption

An interruption is characterized as the complete loss of supply voltage or load current. An interruption occurs when the supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1 minute [3].The possible causes of voltage interruption are switching, utility faults, circuit breaker tripping, and component failures [7]. Interruption is numerically modeled based on parametric equation as in [8]:

$$V(t) = A\,(1 - \alpha\,(u(t-t_1) - \alpha(u(t-t_2))))\sin\omega t \quad (4)$$

By simulating (4) in MATLAB, voltage waveform with interruption is shown in Fig.3 indicating complete loss of voltage for a duration. The rangefor the parameter α,based upon which the amplitude of voltage depends at the time of interruption, is0.9 to 1.

C. Voltage sag

A sag is a decrease in rms voltage to between 0.1 pu and 0.9 pu for durations from 0.5 cycles to 1 minute [3].The possible causes of voltage sags are startup loads and faults [7]. Voltage sag is numerically modeled as in [8]:

$$V(t) = A\,(1 - \alpha\,(u(t-t_1) - \alpha(u(t-t_2))))\ \mathrm{SIN}\ \omega t \quad (5)$$

Voltage sag, shown in Fig.4, is obtained by simulating (5) in MATLAB and indicates a sudden decrease in voltage for a certain duration. The range for the parameter α, based upon which the amplitude of voltage sag depends at the time of disturbance, is 0.1 to 0.9.

D. Voltage swell

A swell is an increase in rms voltage above 1.1 pu for durations from 0.5 cycle to 1 min. Typical magnitudes are between 1.1 pu to 1.8 pu [3].The possible causes of voltage swells are load changes and utility faults [7]. Voltage swell is numerically modeled as in [8]:

$$V(t) = A\,(1 + \alpha\,(u(t-t_1) - \alpha(u(t-t_2))))\sin\omega t \quad (6)$$

Voltage swell, shown in Fig.5, is obtained by simulating (6) in MATLAB and indicates a sudden increase in voltage for a certain duration. . The range for the parameter α, based upon which the amplitude of voltage swell depends at the time of disturbance, is 0.1 to 0.9.

E. Harmonics

The power quality disturbance, harmonics come under the classification of waveform distortion. Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (termed as fundamental frequency) [3]. Harmonics produce waveform distortion and are due to nonlinear characteristics of the load devices, for which the principle of superposition and homogeneity are not satisfied. Harmonics are numerically modeled as in [8],

$$V(t) = A \sum \alpha_n \sin(n\omega t),\ 1 \le n\ \&\ \sum_{i=1}^{n} \alpha_i^2 = 1 \qquad (7)$$

α_n is the magnitude of the nth order harmonic which is the summation of amplitudes of harmonic components. The sum of all the squares of amplitudes of all harmonic components is equal to unity. Third, fifth and seventh order harmonic components are added to the fundamental component of pure sinusoidal voltage.

$$V(t) = \alpha_1 \sin \omega t + \alpha_3 \sin 3\omega t + \alpha_5 \sin 5\omega t + \alpha_7 \sin 7\omega t \quad (8)$$

By simulating (8) for harmonics, in MATLAB, voltage waveform with harmonics as shown in Fig.6 is obtained.

F. Voltage sag with harmonics

Voltage sag with harmonics is a form of waveform distortion, with the combination of both the disturbances, sag and harmonics. The parametric equation governing the power quality disturbance, voltage sag with harmonics as in [9] is:

$$V(t) = A\ (1 - \alpha\ (u(t - t_1) - \alpha(u(t - t_2))))\ (\alpha_1 \sin \omega t + \alpha_3 \sin 3\omega t + \alpha_5 \sin 5\omega t + \alpha_7 \sin 7\omega t) \qquad (9)$$

To obtain the parametric equation for voltage sag with harmonics, the sinusoidal term $\sin \omega t$ in (5) is replaced by the term consisting of odd order harmonics i.e., 3, 5, and 7th order harmonics added to the fundamental frequency component. By simulating (9) in MATLAB, waveform for voltage sag with harmonics as shown in Fig.7 is obtained.

G. Voltage swell with harmonics

Voltage swell with harmonics is also another form of waveform distortion, with the combination of both the disturbances, swell and harmonics. The parametric equation governing the power quality disturbance, voltage swell with harmonics as in [9] is:

$$V(t) = A\ (1 + \alpha\ (u(t - t_1) - \alpha(u(t - t_2))))\ (\alpha_1 \sin \omega t + \alpha_3 \text{ SIN } 3\omega t + \alpha_5 \text{ SIN } 5\omega t + \alpha_7 \text{ SIN } 7\omega t) \qquad (10)$$

To obtain the parametric equation for voltage swell with harmonics, the sinusoidal term $\sin \omega t$ in (6) is replaced by the term consisting of odd order harmonics i.e., 3, 5, and 7th order harmonics added to the fundamental frequency component.By simulating (10) in MATLAB, waveform for voltage swell with harmonics as shown in Fig.8 is obtained.
In (8), (9), and (10) the parameters $\alpha_1, \alpha_3, \alpha_5$and α_7 are used to control the harmonic content in a pure sinusoidal voltage signal by controlling the harmonic variation. The ranges of $\alpha, \alpha_3, \alpha_5$ and $\alpha_7$are 0.1 to 0.9, 0.06 to 0.6, 0.02 to 0.2, and 0.008 to 0.08 respectively. The parameter $\alpha_1$is taken as 1 and is corresponding to fundamental frequency component**.**

H.Voltage fluctuations

Voltage fluctuations are systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges of 0.95 pu to 1.05 pu [3].

$$V(t) = A(1 + a\sin(b\omega t))sin(\omega t) \qquad (11)$$

The controlling parameters a and b correspond to the magnitude and integer multiple of frequency respectively with ranges given as $0.1 \le a \le 0.2$ and $0.4 \le b \le 0.6$. The possible causes of voltage fluctuations are radio transmitters, faulty equipment, ineffective grounding, and proximity to EMI or RFI source [7]. EMI refers to ElectromagneticInterference and RFI refers to Radio Frequency Interference. Fig.9 shows the waveform of voltage fluctuations, with a series of voltage changes, obtained in MATLAB by simulating (11). Flicker is due to the effect of voltage fluctuations.

I.Voltage flicker

An impact of voltage fluctuations on lighting intensity is termed as voltage flicker. Loads that exhibit continuous, rapid variations in load current magnitude can cause voltage variations erroneously referred to as "flicker" and the term flicker is derived from the impact of the voltage fluctuation on lighting intensity [3]. The sinusoidal voltage signal in terms of flicker signal [10], is given by:

$$V(t) = [A_1 + \Sigma A_{fi} \sin(\omega_{fi} t + \Phi_{fi})\ _{Ii=1}]\ \sin(\omega_1 t + \Phi_1) \quad (12)$$

A_1, ω_1 and Φ_1 are amplitude, angular frequency and phase angle of fundamental component of voltage. A_{fi}, ω_{fi} and Φ_{fi} are amplitude, angular frequency and phase angle of flicker component of voltage. I is the number of flicker components. In the mathematical modeling of the voltage equation along with flicker signal the amplitude of fundamental component is taken as 1 and amplitude of flicker signal is taken as 0.2. By choosing a suitable angular frequency and phase angle of

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flicker component of voltage, waveform as shown in Fig.10, is generated in MATLAB. Fig.11 depicts the waveform for voltage envelope comprising of both the fundamental frequency component and the flicker components.

III. RESULTS

The results shown from Fig.1 to Fig.11are obtained in MATLAB by using suitable code based on parametric equations for each of the power quality disturbances. The waveforms obtained in this paper, using parametric equations are:

1. Pure sinusoidal voltage 2. Transient 3. Interruption 4. Voltage sag 5. Voltage swell 6. Harmonics 7. Voltage sag with harmonics 8. Voltage swell with harmonics 9. Voltage fluctuations 10. Voltage flicker 11. Voltage envelope along with flicker components. All the power quality disturbance signals represent variations in pure sinusoidal voltage waveform. For all the waveforms generated from an initial value of 0 to a final value of 0.25 seconds, with an increment of 0.0001

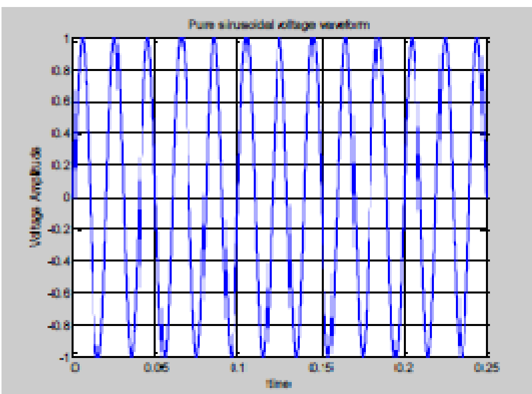

Fig.1 Pure sinusoidal voltage waveform

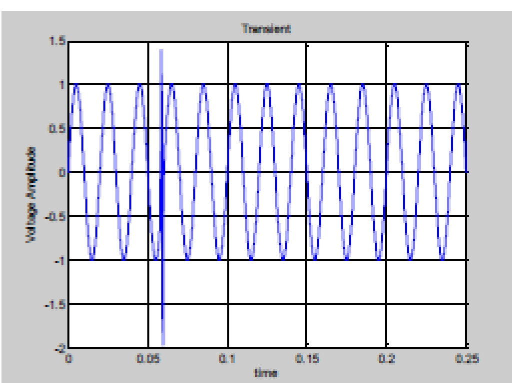

Fig.2 Voltage signal with a transient

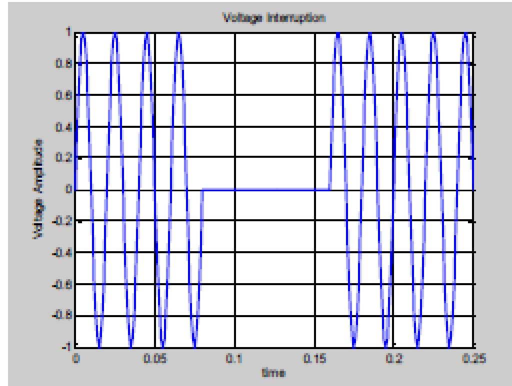

Fig.3. Voltage signal with an interruption

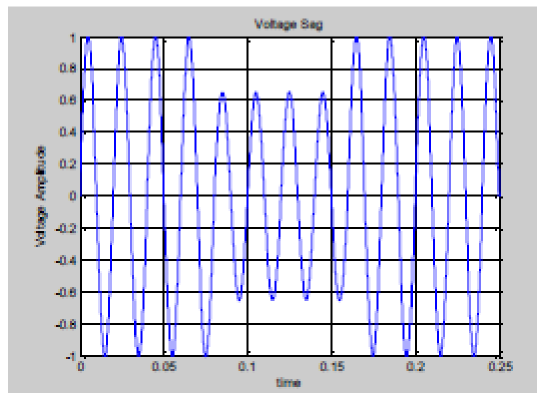

Fig.4 Voltage signal with sag disturbance

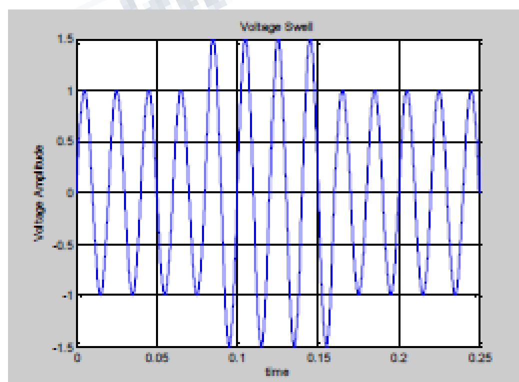

Fig.5 Voltage signal with Swell Disturbance

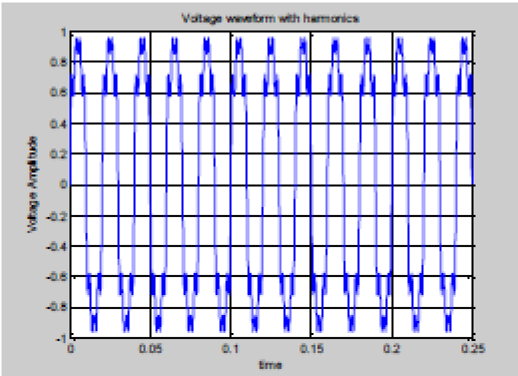

Fig.6 Voltage waveform with harmonics

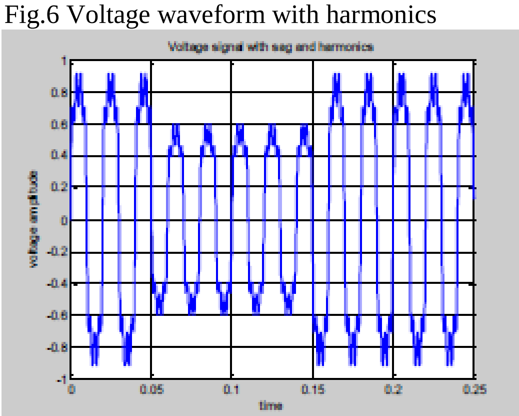

Fig.7 Voltage signal with sag and harmonics

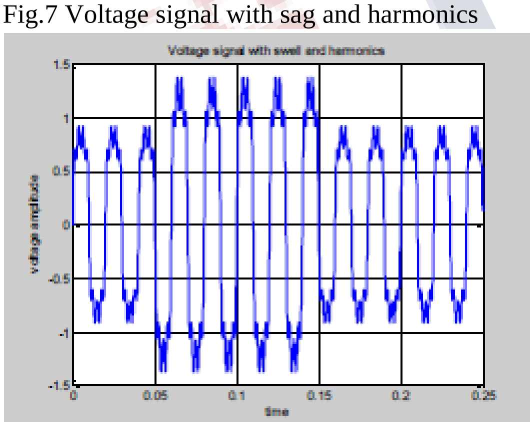

Fig.8 Voltage signal with swell and harmonics

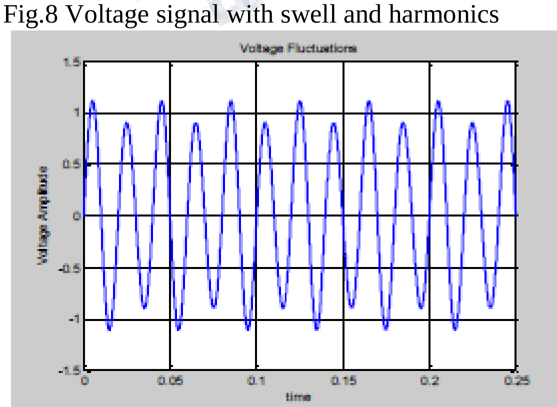

Fig.9 Voltage waveform with fluctuations

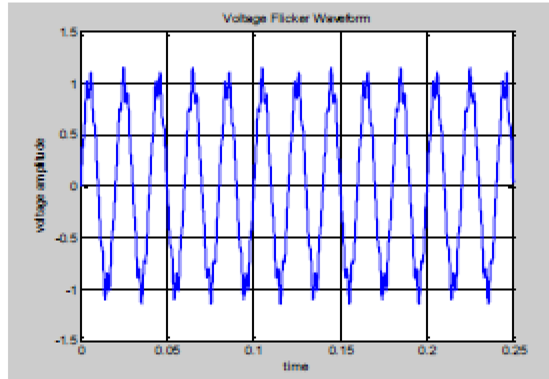

Fig.10 Voltage waveform with flicker

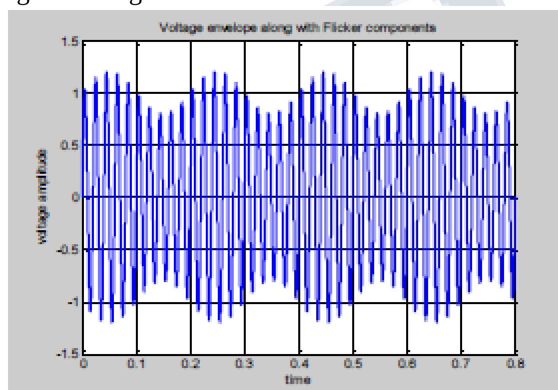

Fig.11 Voltage envelope along with flicker components

IV. SIGNAL PROCESSING TECHNIQUES FOR ANALYSIS OF POWER QUALITY DISTURBANCES

Signal processing techniques are applied to signals to obtain a further information from that signal that is not readily available. Power quality disturbances can be analyzed using any of the digital signal processing techniques. Reference [11] focuses on several power quality disturbances and signal processing techniques that may offer good solution to the problems.

A review of mostly used signal processing techniques is presented in [12], for classification of power quality disturbances.One of the most widely used tools in signal processing is Fourier analysis. This consists of the decomposition of the signal into a sum of sinusoidal signals of different frequencies. Decomposition refers to breaking up of a signal. Wavelet transform is one of the widely used signal processing technique for the analysis of power quality disturbances. For signals whose parameters vary continuously with time, continuous wavelet transform (CWT) is defined. For discrete-time signals, discrete wavelet transform (DWT) is defined. Any of the short time Fourier transform, Wavelet transform, Gabor transform, S-transform allow for obtaining information in time and frequency domain [12].

V. CONCLUSION

The power quality disturbances results in reduction of stability of the power system, as supply voltage of constant magnitude at fuundamental frequency cannot be assured due to disturbances. An important and fundamental step in power quality evaluation is recognition of the type of power quality problem.

The generated power quality disturbances contains information about the voltage magnitude and duration of the disturbance. By proper detection of power quality disturbances, initiation and recovery methods can be identified. In order to improve electric power quality, the sources and causes of disturbances must be known to take preventive measures for avoiding the disturbances. The various power quality disturbances can be detected and classified using signal processing techniques. Power quality disturbances are modeled based on parametric equations. Parametric equations are considered for transients, voltage interruption, voltage sag, voltage swell, harmonics, voltage sag with harmonics, voltage swell with harmonics, voltage fluctuations, and voltage flicker. Waveforms are generated using a suitable code based on parametric equations in MATLAB environment.

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