# Statistical Evaluation of Voltage Variations via Physically Based Modeling and Simulation

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**Abstract**:

The majority of power quality problems are associated with voltage variations at the customer site. The voltage variations may be (a) temporary disturbances that may originate anywhere in the system and (b) waveform distortion from nonlinear loads. The sources of disturbances are multiple and with varying parameters. For example in many places of the world, the most frequent disturbances originate from lightning activity near electric installations. Lightning may result in flashover causing voltage sags to some portion of the distribution system, voltage swell to other areas, as well as interruption of power. The number of customers affected depends on the design of the system and placement of interruption devices, while the level of voltage sags or swells may depend on the grounding system, size of neutral, etc. Three-phase distribution systems circuits may consist of 3-wires, 4-wires or 5-wires. Each of these topologies results in different behavior in the presence of disturbances. Furthermore, the advent of distributed generation exacerbates these differences. To properly capture these effects, new system modeling tools are needed that explicitly represent these design details of the system. This paper discusses various modeling methodologies suitable for voltage variation assessment. Since many of the parameters affecting voltage variations are random, emphasis is placed on statistical methods. The modeling approaches discussed include steady state analysis, transient analysis and statistical techniques (Monte Carlo simulation). The methods are demonstrated on a number of example systems.

## Introduction

Disturbances that affect power quality are multiple: (a) lightning, (b) switching, (c) power faults, (d) feeder energization inrush currents, (e) motor start, (f) load imbalance, (g) harmonics and resonance, (h) EMI, etc. The effects on the end user could be voltage distortion, voltage sags, voltage swells, outages, voltage imbalance, etc. These effects may have different levels of impact depending on the susceptibility of the end-user equipment. For a specific susceptibility of end-user equipment, the impact of disturbances can be mitigated by design modifications of circuit layout, grounding system design, overvoltage protection, filters, use of steel conduit, use of additional transformers, etc. Traditional power system analysis methods are based on models that do not capture these phenomena, for example, the most usual models of sequence components do not predict the voltages in neutrals or grounds and therefore are not appropriate for accurate prediction of voltage variations. This paper proposes a new modeling approach and analysis method for better voltage disturbance evaluation. We address the steady state case as well as transient case.

The proposed method is based on modeling electric power system in their physical configuration, i.e. 3-wire, 4-wire or 5-wire system without the use of any transformations such as the symmetrical component transformation. We also propose a new analysis method for the overall electric power system modeled with physical models. The proposed methodology is capable of modeling systems with three phase wires, four wires (three phase and a neutral/or ground wire), five wires (three phase wires, neutral and a ground wire), single and double phase circuits, grounding and bonding points, grounding systems, etc. Here we discuss analysis methods with these capabilities. The proposed methodology has additional desirable features. For example a physically based model can explicitly represent grounding systems, the size of the neutral wire, the ground wires, etc. These practices have been known to have great effects on power quality. Another important property is that a physically based model and analysis procedure provides the means to expose the interrelationship between the physical parameters and power quality. This property naturally leads to comprehensive cost-benefit analysis.

The paper presents the proposed methodology and provides two practical examples.

## Models for Power Quality Assessment

Power quality is affected by design issues such as 3-wire system (three-phase wires), 4-wire system (three-phase wires plus a neutral or ground wire) and 5-wire system (three-phase wires, a neutral and a ground wire), relative size of neutral and ground wires, bonding arrangements, etc. Models for power quality assessment should be able to capture the phenomena occurring in various possible arrangements. It is quite often that the same system may transit from 3-wires into 4-wires, 5-wires and back to 3-wires, etc. In addition, many voltage transformations can occur. Consider for example a typical distribution system consisting a typical overhead distribution system, underground feeders, electric loads motors, etc. The medium voltage distribution system may be a 4-wire system, some of the secondary voltage circuits may be 5-wire systems, some 3-wire systems, etc. The loading of the system may consist of three phase loads as well as single phase loads. This system may be subjected to a number of disturbances, exogenous such as lightning as well as system internal disturbances such as motor start-up and shutdown, distorting loads, switchings, etc. Typical phenomena to be studied may be transient (lightning, motor start-up, etc.) and/or phenomena that can be described as quasi-steady state, for example, conditions during faults, imbalances, etc. In this section, we present modeling and analysis methodologies that are applicable to these systems and capable of capturing the phenomena that affect power quality. We present time domain analysis methods as well as steady state analysis methods. The common part of the proposed methodologies is the general model of the system that accommodates 3-wire, 4-wire and 5-wire subsystems interconnected in any arbitrary fashion. Specifically, a unified time and frequency domain modeling approach is proposed, using a specific modeling principle. The modeling principle results in physically based quadratized component models and the use of Newton's method to obtain the network solution. A brief description of the method (both frequency domain and time domain) is presented next.

**Time Domain Analysis:** Any power system device is described with a set of algebraic-differential-integral equations. These equations are obtained directly from the physical construction of the device. It is always possible to cast these equations in the following general form:

$$\begin{bmatrix} i \\ 0 \end{bmatrix} = \begin{bmatrix} f_1(\dot{v}, \dot{y}, v, y, u) \\ f_2(\dot{v}, \dot{y}, v, y, u) \end{bmatrix} \qquad (1)$$

where
- i : vector of terminal currents,
- v : vector of terminal voltages,
- y : vector of device internal state variables
- u : vector of independent controls.

Note that this form includes two sets of equations, which are named *external equations* and *internal equations* respectively. The terminal currents appear only in the external equations. Similarly, the device states consist of two sets: *external states* (i.e. terminal voltages, v(t) ) and *internal states* ( i.e. y(t) ). The set of equations (1) is consistent in the sense that the number of external states and the number of internal equations equals the number of external and internal equations respectively.

Note that equation (1) may contain linear and nonlinear terms. Equation (1) is quadratized, i.e. it is converted into a set of quadratic equations by introducing a series of intermediate variables and expressing the nonlinear components in terms of a series of quadratic terms. The resulting equations are integrated using a suitable numerical integration method. Assuming an integration time step h, the result of the integration is given with a second order equation of the form:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} (v^T(t), y^T(t)) F_1 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ (v^T(t), y^T(t)) F_2 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ \vdots \\ \; \end{bmatrix} + \begin{bmatrix} b_1(t-h) \\ b_2(t-h) \end{bmatrix} \qquad (2)$$

where $b_1(t\text{-}h)$, $b_2(t\text{-}h)$ are past history functions.

The network solution is obtained by application of Kirchoff's current law at each node of the system (connectivity constraints). This procedure results in the set of equations (3). To these equations, the internal equations are appended resulting to the following set of equations:

$$\sum_k A^k i^k(t) = I_{inj} \qquad (3)$$

internal equations of all devices (4)

where $I_{inj}$ is a vector of nodal current injections (external injections), $A^k$ is a component incidence matrix with:

$$\left\{A_{ij}^k\right\} = \left( \begin{matrix} 1, \; \textit{if node } j \textit{ of component } k \textit{ is connected to node } i \\ 0, \; \textit{otherwise} \end{matrix} \right)$$

$i^k(t)$ is the vector of terminal currents of component k.

Note that Equations (3) correspond one-to-one with the external system states while Equations (4) correspond one-to-one with the internal system states. The vector $v^k(t)$ of component k terminal voltages is related to the nodal voltage vector v(t) by:

$$v^k(t) = (A^k)^T v(t) \qquad (5)$$

Upon substitution of device equations (2), the set of equations (3) and (4) become a set of quadratic equations:

$$Ax(t) + \begin{bmatrix} x^T(t) B_1(t) x(t) \\ x^T(t) B_2(t) x(t) \\ \vdots \end{bmatrix} + b(t-h) = 0 \qquad (6)$$

where x(t) is the vector of all external and internal system states.

These equations are solved using Newton's method. Specifically, the solution is given by the following expression.

$$x^{\nu+1}(t) = x^{\nu}(t) - J^{-1}\left(Ax^{\nu}(t) + \begin{bmatrix} x^{\nu T}(t) B_1(t) x^{\nu}(t) \\ x^{\nu T}(t) B_2(t) x^{\nu}(t) \\ \vdots \end{bmatrix} + b(t-h)\right) \qquad (7)$$

where: J is the jacobian matrix of equations (6) and $x^{\nu}(t)$ are the values of the state variables at the previous iteration.

**Frequency Domain Analysis:** Starting from the quadratized equations (1) and assuming that the device operates under steady state (single frequency) conditions, equations (1) are transformed into the following set of complex equations:

$$\begin{bmatrix} \tilde{I}^k \\ 0 \end{bmatrix} = y^k_{eq\_cmpx} \begin{bmatrix} \tilde{V}^k \\ \tilde{Y}^k \end{bmatrix} + F\left\{ \begin{bmatrix} x^{k^T} f^k_{eq\_real1} x^k \\ x^{k^T} f^k_{eq\_real2} x \\ \vdots \end{bmatrix} \right\} - b^k_{eq\_cmpx} \quad (8)$$

Where $\tilde{I}^k$ : vector of terminal currents,

$\tilde{V}^k$ : vector of terminal voltages,

$\tilde{Y}^k$ : vector of device internal state variables,

$\tilde{X}^k = \begin{bmatrix} \tilde{V}^k & \tilde{Y}^k \end{bmatrix}^T$,

$x^k = vector\ \tilde{X}^k\ in\ cartesian\ Coordinates$

and $y^k_{eq\_cmpx}$, $b^k_{eq\_cmpx}$, and $f^k_{eq\_real}$ are matrices with appropriate dimensions. $F(\bullet)$ denotes a function mapping from a real vector to a complex vector. Note that this form includes two sets of equations, which are named *external equations* and *internal equations* respectively. The terminal currents appear only in the external equations. Similarly, the device states consist of two sets: *external states* (i.e. terminal voltages, $\tilde{V}^k$) and *internal states* $\tilde{Y}^k$. The set of equations (8) is consistent in the sense that the number of external states and the number of internal states equals the number of external and internal equations respectively. The form of equations (8) resembles the Norton form for electrical components. For this reason we have named the model (8) the Generalized Norton Form (GNF).

The network equations are obtained by application of the connectivity constraints among components. For electrical circuits, the connectivity constraints are simply Kirchoff's current law at each node of the system. This procedure results in the set of equations (9). To these equations, the internal equations are appended resulting in the set of equations (9) and (10):

$$\sum_k A^k \tilde{I}^k = 0 \quad (9)$$

internal equations of all devices (10)

where $\tilde{I}^k$ is component *k* terminal currents composed of the currents at the composite nodes *k1*, *k2*, etc. $A^k$ is a component incidence matrix. This matrix has been defined earlier.

Let $\tilde{V}$ be the vector of voltages at all the nodes of the system grouped by composite nodes. Then, the following relationship holds:

$$\tilde{V}^k = (A^k)^T \tilde{V} \quad (11)$$

where $\tilde{V}^k$ is component k terminal voltages. Upon substitution of device equations (1) and incidence equations (11), the set of equations (9) and (10) become a set of quadratic equations:

$$\tilde{Y}\tilde{X} + F\begin{bmatrix} x^T f_1 x \\ x^T f_2 x \\ \vdots \end{bmatrix} - \tilde{B} = 0 \quad (12)$$

where $\tilde{X}$ is the vector of states composed of all the components' state $\tilde{X}^k$; $x$ is the vector of network states composed of all the components' state $x^k$; $\tilde{Y}, f, B$, etc., are matrices with appropriate dimensions. These equations are the network equations. The simultaneous solution of these equations is obtained via Newton's method described next.

The numerical algorithm for solving the network equations (12) consists of two steps. First, we convert the network equations (12) into cartesian coordinates by simply replacing each complex variable with its cartesian form and separating the real and imaginary parts of the complex equations. The procedure is equivalent with replacing each element in $\tilde{Y}$ with its corresponding $2 \times 2$ Hermetian matrix. In particular, $\tilde{Y}_{ij}$ is replaced by:

$$\begin{bmatrix} \tilde{Y}^r_{ij} & -\tilde{Y}^i_{ij} \\ \tilde{Y}^i_{ij} & \tilde{Y}^r_{ij} \end{bmatrix}$$

where superscript *r* denotes real part and superscript *i* denotes imaginary part. Then, equation (12) is transformed into Equation (13) below:

$$Y_{real}\, x + \begin{bmatrix} x^T f_1 x \\ x^T f_2 x \\ \vdots \end{bmatrix} - B_{real} = 0 \quad (13)$$

Equation (13) is solved using Newton's method. Specifically, the solution is given by the following algorithm:

$$x^{\nu+1} = x^{\nu} - J^{-1}\left\{ Y_{real}\, x^{\nu} + \begin{bmatrix} x^{\nu^T} f_1 x^{\nu} \\ x^{\nu^T} f_2 x^{\nu} \\ \vdots \end{bmatrix} - B_{real} \right\} \quad (14)$$

where $\nu$ is the iteration step number; $J$ is the Jacobian matrix of equations (13). In particular, the Jacobian matrix takes the following form:

$$J = Y_{real} + \begin{bmatrix} x^{v^T}(f_1 + f_1^T) \\ x^{v^T}(f_2 + f_2^T) \\ \vdots \end{bmatrix}$$

Algorithm (14) guarantees quadratic convergence since it is Newton's method applied to a set of quadratic equations. In fact, algorithm (14) converges in two or three iterations.

## Applications

The proposed methodologies have been implemented and their application for power quality analysis is described next. We focus on voltage variations and specifically the distribution of voltage disturbances and how they are related to design parameters.

**Example Test System**: Figure 1 illustrates the example system. Note that it is a small section of a typical distribution circuit with voltage correction capacitors placed at specific points of the system. Note also that the grounding of the system is modeled.

**Voltage Sags and Swells**: Sequences of fault initiation, fault clearing and reclosing result in voltage sags for certain customers and voltage swells for others. The level of the voltage swells and sags depends on grounding system design. This fact had been recognized long time ago. For example, an IEEE committee has published expected values of overvoltages on unfaulted phases during a ground fault. Similarly, international standards have published similar results. These calculations have been based on power system models that assumed symmetry (symmetrical components). Because the power system components are not symmetric, the voltage swells that will appear in unfaulted phases are different from what the symmetric models predict. The method presented in this paper provides the exact voltage swells and voltage sags for any fault at any location and for any design system in terms of neutral size, grounding design, etc. As an example, Figure 4 illustrates the voltage swells and sags along a circuit during a single line to ground fault. Note that the two unfaulted phases experience a different level of voltage swells due to the asymmetry of the system.

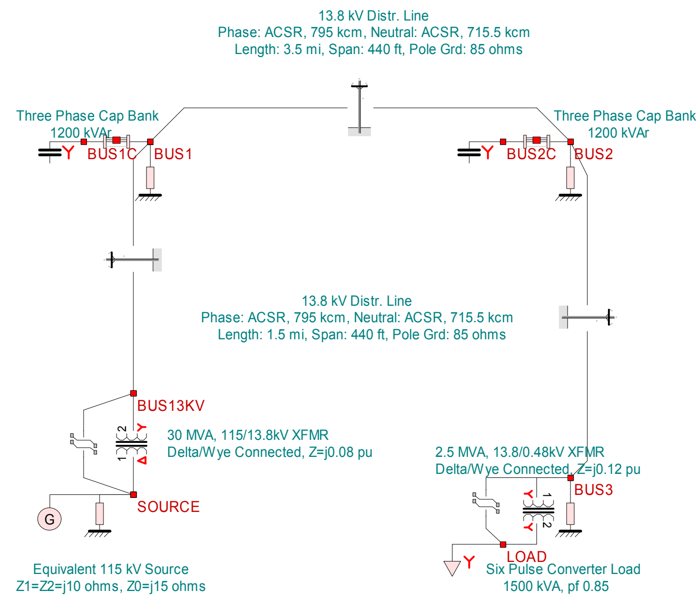


**Figure 1. Example Test System for Harmonic Resonance**

The faulted phase experiences voltages sags that vary along the length of the circuit. Figure 4 illustrates the voltages with respect to the neutral. Figure 5 illustrates the absolute voltages of the same phases and same fault condition as well as the voltage of the neutral. Note that the neutral voltage varies along the length of the circuit. It is also important to note here that the absolute voltage swells of the unfaulted phases are lower than the voltage swells relative to the neutral. The difference is due to the voltage elevation of the neutral due to the ground fault. The level of the neutral voltage elevation is dependent upon the design of the grounding system.

What is more important is the statistical distribution of the voltage swells or voltage sags for various types of faults that may occur in the system. This topic is discussed next.

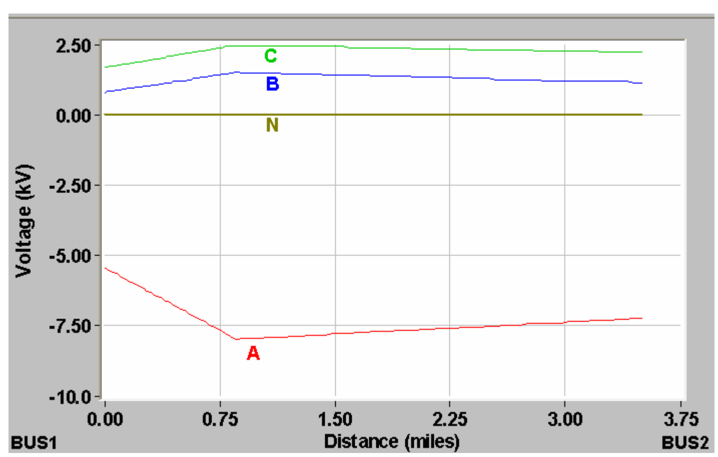


**Figure 4. Distribution of Voltage Swells and Sags for a Specific Fault Condition and Circuit Design – Deviation from Nominal, Voltages to Neutral**

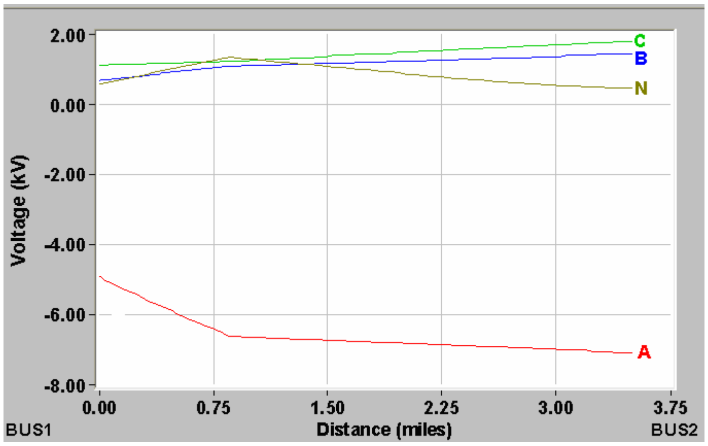


**Figure 5. Distribution of Voltage Swells and Sags for a Specific Fault Condition and Circuit Design – Deviation from Nominal, Absolute Voltages**

A powerful method to statistically assess the performance of the system relative to power quality is the Monte Carlo simulation. For this purpose, probability distribution functions of random events must be modeled. Then the method consists of the following procedure: first an event is selected (randomly from the known distributions). Then, the condition is simulated and the effects of the condition on power quality are quantified. The procedure is repeated many-many times and the results are summarized into statistical distribution of maximum overvoltages or current at any selected point in the circuit or as a maximum violation of a criterion, etc. The method is applied to to determine the statistical distribution of voltage swells and sags. Specifically, the test system of Figure 1 has been used to illustrate the computation of voltage sags and swells distribution using a Monte Carlo simulation. For this purpose, an electric fault type is randomly selected (phase A to neutral, Phase A to Phase B, etc), the fault is applied to a randomly selected location of the system (along any circuit) and the condition is simulated to determine the voltage at a specific customer point. The process is repeated many-many times and the results are tabulated into a probability density function, or a cumulative distribution function. Figure 6 illustrates the results of this simulation for a customer location at BUS2. Note there is substantial probability for voltage sags to the range (0 to 2 kV) and another substantial probability for voltage swells in the range (8 kV to 11 kV). Figure 7 illustrates the probability density function of the absolute voltages. Note the difference that is mainly due to the voltage elevation of the neutral during faults. The proposed model provides a quantitative method to assess this effect.

**Transient Voltage Disturbances**: Switchings and lightning can initiate transients that propagate through the system and reach sensitive customer equipment. The described time domain simulation method computes the transients reaching any point of the system. Thus the transient voltage waveforms at specific devices terminals are computed and can be compared to the withstand capability (susceptability curve) of the equipment. This procedure is illustrated in Figures 8 and 9. Figure 8 illustrates the system, the disturbance and the calculation of the transient voltage waveforms. Figure 9 illustrates the identification of the frequency and duration content of the waveform and the placement of the disturbance on the susceptibiulity curve of the equipment. In this way one can determine, by inspection, the effect of the disturbance on the equipment. Note that the computation procedure requires two components: (a) transient voltage computation by means of system-wide disturbance analysis, and (b) characterization of the disturbance at a specific site in terms of frequency content and peak value.

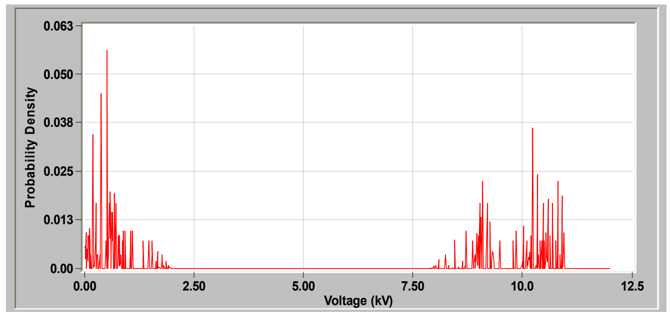


**Figure 6. Probability Density Function of Voltages (Phase to Neutral) at BUS2**

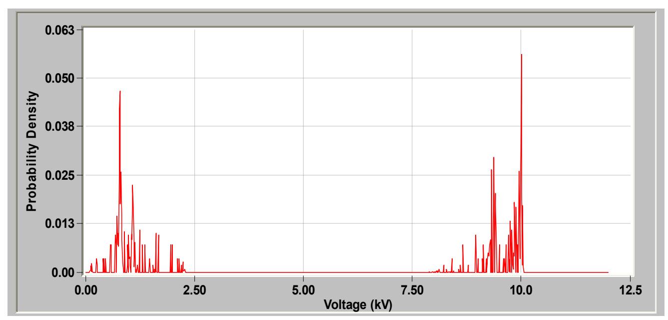


**Figure 7. Probability Density Function of Voltages (Absolute Voltages) at BUS2**

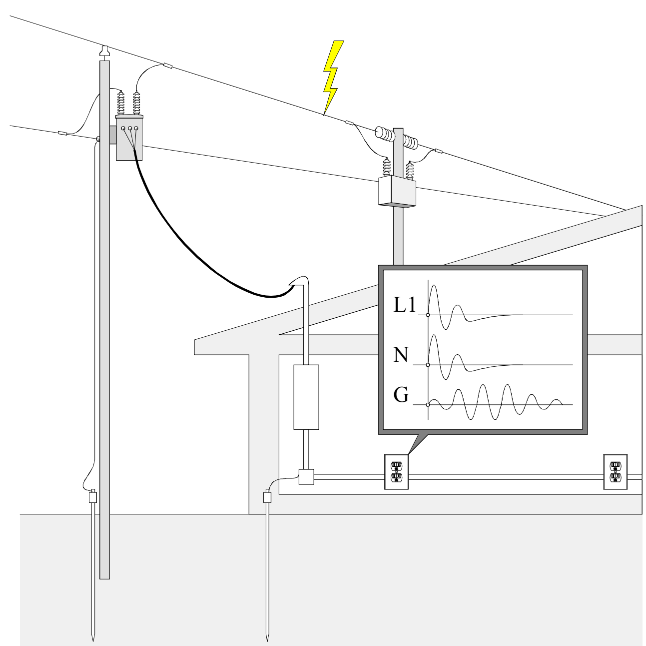


**Figure 8. Time Domain Simulation of Transient Voltages**

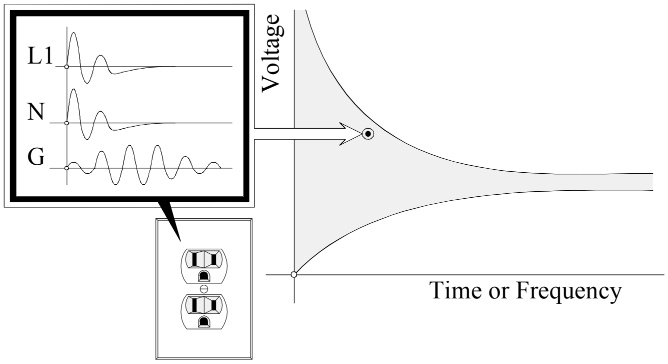


**Figure 9. Disturbance Characterization Relative to the Susceptibility Curve**

The transient disturbances can occur in many different forms and they are dependent upon parameters that exhibit random variations, such as lightning crest and rise time, switching time relative to the power frequency cycle, etc. For these reasons, it is important to evaluate the transients under all possible variations of the important parameters. A useful method for this purpose is the Monte Carlo simulation described earlier. The Monte Carlo simulation is applied to an example system for the purpose of providing the distribution of transient voltages due to lightning and their relationship to the susceptibility curve of a specific end use equipment.

The example system is illustrated in Figure 10. The system consists of an industrial facility with electronic equipment. It is fed from an overhead 12 kV distribution circuit via a 0.5 mile underground distribution cable. The facility has a ground loop around the building and the transformer neutral is bonded to the ground loop.

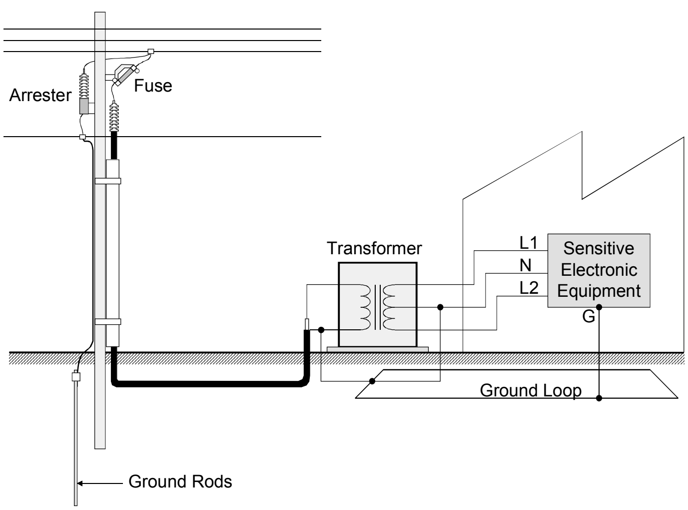


**Figure 10. Disturbance Characterization Relative to the Susceptibility Curve**

The system of Figure 10 has been evaluated with a Monte Carlo simulation. The point of interest is the sensitive electronic equipment illustrated in Figure 10. A large number of lightning and switching trials have been simulated and the transients at the terminals of the electronic equipment have been recorded, characterized and superimposed on the susceptibility curve. The results are illustrated in Figure 11. The results illustrate that there are two clusters of overvoltages, one resulting from lightning and another resulting from switching. The results also provide information on the magnitude of these disturbances as related to the susceptibility of the electronic apparatus. One view of the results of Figure 11 is enough to realize that there is a significant number of events that will result in power quality problems for this system. It should be also apparent that the method can be used to assess the effectiveness of specific design modifications on improving the power quality of the system. For example, the grounding of the facility and the 0.5 mile long cable can be modified (improved) by adding another ground conductor. Then the Monte Carlo simulation can be repeated. The performance gains then can be assessed and the cost effectiveness of the design modification can be quantified.

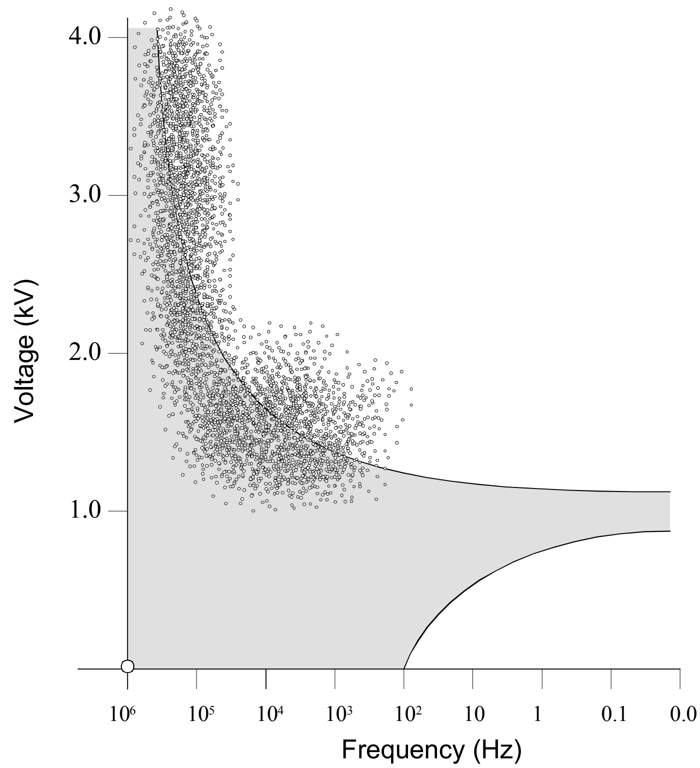


**Figure 11. Statistical distribution of Disturbance Voltages Relative to the Susceptibility Curve**

## Needs and Future Developments

The electric power system is continuously evolving. Recent emphasis is in distributed generation. At the same time, most power quality problems are associated with secondary distribution systems, i.e. systems operating at 480 volts or 2x120 volts. Distributed generation has the potential to contribute a fair amount of power quality problems or to provide nice solutions for premium power quality. For example, most newer distributed generation systems are interfaced to the system via power electronic devices that have the capability to provide additional controls to the system, for example to control the level of imbalance in the system, the neutral voltage under normal operating conditions (stray voltages), etc. It is important to address these issues and the associated design problems with new methodologies that help to understand the behavior of the system and to provide appropriate solutions. In addition to voltage disturbances, one should be concerned with the stability properties of the system, the capability of distributed generation to maintain synchronism under voltage disturbances and a host of other problems. The proposed methodology is a start towards addressing these issues. We expect that the proposed modeling and analysis methodologies will result in better tools for power quality assessment band improvements in the new complex electric power systems.

## Summary and Conclusions

This paper presented a physically based modeling and analysis method of power systems with explicit representation of 3-wire, 4-wire and 5-wire systems. The method provides frequency domain solutions as well as time domain solutions. The model can be used to evaluate typical power quality problems on distribution systems. Because the modeling is physically based, one can directly relate design parameters to power quality performance of the system. Application examples have been presented that clearly correlate power quality performance to the design of the system.

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## Biographies

**A. P. Sakis Meliopoulos** (M '76, SM '83, F '93) was born in Katerini, Greece, in 1949. He received the M.E. and E.E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1971, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the Faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the books, Power Systems Grounding and Transients, Marcel Dekker, June 1988, Ligthning and Overvoltage Protection, Section 27, Standard Handbook for Electrical Engineers, McGraw Hill, 1993, and the monograph, Numerical Solution Methods of Algebraic Equations, EPRI monograph series. Dr. Meliopoulos is a member of the Hellenic Society of Professional Engineering and the Sigma Xi.

**George J. Cokkinides (M '85)** was born in Athens, Greece in 1955. He obtained the B.S., M.S., and Ph.D. degree at the Georgia Institute of Technology in 1978, 1980, and 1985, respectively. From 1983 to 1985, he was a research engineer at the Georgia Tech Research Institute. Since 1985, he has been with the University of South Carolina where he is presently an Associate Professor of Electrical Engineering. His research interests include power system modeling and simulation, power electronics applications, power system harmonics, and measurement instrumentation. Dr. Cokkinides is a member of the IEEE/PES and the Sigma Xi.

**András M. Dán** (SM'90) received MSc degree from Budapest Technical University in 1966, PhD degree in Electrical Engineering from the Hungarian Academy of Sciences in 1983. He has been at Budapest Technical University since 1970 where he currently holds the rank of professor and acts as a consultant for local industry. His expertise is in power electronics, reactive power compensation especially associated with power system harmonics. Dr Dán is a member of the Hungarian Electrotechnical Association.