

Power Quality Assessment through Stochastic Equivalent Circuit Analysis

Rodney Yeu and Jason Wells
PC Krause & Associates

Chad Miller
US Air Force

Jane Thompson
Air Force Research Lab

ABSTRACT

Movement toward more-electric architectures in military and commercial airborne systems has led to electrical power systems (EPSs) with complex power flow dynamics and advanced technologies specifically designed to improve power quality in the system. As such, there is a need for tools that can quickly analyze the impact of technology insertion on the system-level dynamic transient and spectral power quality and assess tradeoffs between impact on power quality versus weight and volume. Traditionally, this type of system level analysis is performed through computationally intensive time-domain simulations involving high fidelity models or left until the hardware fabrication and integration stage. In order to provide a more rapid analysis prior to hardware development and integration, stochastic equivalent circuit analysis is developed that can provide power quality assessment directly in the frequency domain.

Stochastic equivalent circuit analysis calculates network voltage probability distribution utilizing stochastic equivalent circuits assembled into a candidate power system. Utilization of stochastic equivalent circuits allows for rapid analysis of the electric power system under different configurations where the effect of device insertion/removal on power quality is assessed through comparison of the resulting voltage probability distributions with and without the device. In this paper, the stochastic equivalent circuit analysis is introduced along with the methodology to derive the stochastic equivalent circuits, a MATLAB GUI that enables easy configuration and execution of the analysis is presented, and analysis of a representative power system is presented in the context of both traditional EPS power quality metrics as well as new metrics made possible through the stochastic nature of the analysis.

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INTRODUCTION

Movement to more-electric architectures during the past decade in military and commercial airborne systems has led to electrical power system (EPS) design advancement with complicated power flow dynamics. Loads often exhibit high peak-power ratios in excess of 5-to-1 for short durations (50-5000 ms) and may produce regenerative power equal to their peak power draw in a short time span (20-200 ms). These loading characteristics are found in electrical actuation [1], power and thermal management systems [2], electrical starting demands, and pulsed-power loads.

These dynamic load characteristics coupled with complex and varied sources under varying EPS configurations can result in undesirable spectral content and unsatisfactory dynamic-transient performance.

While traditional mitigation strategies such as filtering and/or utilization of a generator with significant transient overload capability may be a solution, they add considerable weight and volume and new

alternative solutions are continuously being proposed to improve power quality. One simple approach is to float large energy storage devices (ESDs) such as ultra-capacitors or Li-ion batteries on the bus as described and tested in [3]. However, this approach tends to significantly underutilize the energy storage capacity of the ESDs and a more advanced strategy utilizing actively damped EMI-filters was also explored in [3]. In [4], the authors explored a more advanced load-shedding strategy to eliminate transient power overload by removing minimum amount of power by accounting for dynamic EPS loading. In [5], PC Krause and Associates (PCKA) developed and demonstrated a speed estimation technique that corrects for resolver errors in high-performance actuators. This improved technique results in significant current injection reduction to the EPS at frequencies related to the mechanical speed of the drive motors. The electrical accumulator unit (EAU) is another promising approach to enhance power quality [6]. An EAU provides peak-power fill-in and regenerative power absorption capabilities similar to hydraulic accumulator units (HAUs) that have been used in previous aircrafts to

address issues related hydraulic actuators driving primary flight surfaces [7,8,9]. It enables a bi-directional power bus to reduce or eliminate de-rating the generator mechanical drive-train for regenerative power returned to the generator. Additionally, it can reduce the generator peak-power demands allowing for either a reduction in weight or an expansion of EPS capability.

While all these devices aim to improve EPS power quality in a variety of ways, it is often difficult to analyze their dynamic transient and spectral impact at an integrated system level. Understanding such interaction is critical to justifying the additional weight and volume of device insertion. In order to provide a rapid system-level analysis, a stochastic equivalent circuit analysis was developed to quickly analyze spectral content under various system configurations. In this paper, the stochastic equivalent circuit, a fundamental component of the analysis, and its use in assembling a representative EPS is discussed. Next, the Power Quality GUI, a tool to perform stochastic equivalent circuit analysis is presented along with detailed discussion of the equivalent circuit analysis calculations. Finally, the paper will present an analysis of an example model and summarize key findings in the conclusion.

STOCHASTIC EQUIVALENT CIRCUIT

In the stochastic equivalent circuit analysis, all sources and loads are represented by their equivalent circuit shown in Figure 1. This circuit has a similar form to the Thevenin equivalent circuit of a voltage source behind an impedance with one important distinction. Instead of a constant voltage source, the stochastic equivalent voltage source is defined over a magnitude, phase, and frequency domain with an associated probability distribution. This representation accounts for active spectral injections being made by the source/load while the passive response is captured by the impedance.

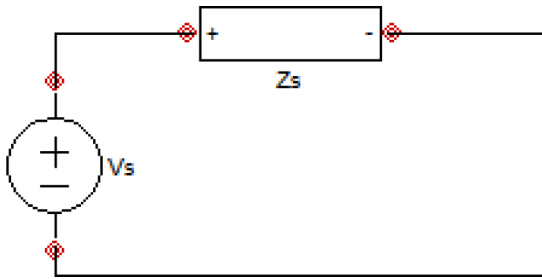


Figure 1. Stochastic equivalent circuit

The stochastic equivalent voltage source probability is assigned to each combination of magnitude, phase, and frequency divisions to form the probability distribution matrix. This three-dimensional matrix potentially has a large number of zero probability entries, which makes it ideal for sparse matrix implementation. The sparsity level is dependent on the harmonic content of a source/load and also on the fidelity of the model. Equivalent models defined with finer resolution in the magnitude, phase, and/or frequency divisions are more likely to be sparse since smaller divisions lead to a greater number of divisions. In practice, many analyses will utilize smaller divisions for increased accuracy and, as such, the authors have

leveraged both sparse matrix storage and computational techniques to reduce data storage requirements and computation time required to complete the proposed analysis.

Once all sources and loads have been characterized and their associated stochastic equivalent circuit has been derived, a representative EPS can be assembled by connecting the equivalent models to an appropriate distribution network representing the desired architecture. The harmonic content of the equivalent circuit allows for spectral analysis as the system is solved over the defined frequency range. The stochastic equivalent method calculates the source and load spectral injection interactions through the equivalent model impedance and any passive network interconnection. The solved system calculates all network node voltage probability distributions which can be analyzed for power quality. Comparing solutions of different EPS configurations allows for sensitivity analysis by observing the impact to power quality under different configurations. Specifically, studying a system with and without a particular device shows the impact of the device on power quality.

While power quality can be defined in a variety of ways, in the proposed stochastic equivalent circuit analysis, it is defined as the cumulative distribution margin against a metric where positive values means there is margin available before a metric violation and negative values mean the margin is in violation of a metric. The difference in cumulative distribution instead of probability distribution was chosen since the cumulative probability gives the margin at and below the value instead of just at one specific value. The default metric in the Power Quality GUI is the MIL-STD-704F distortion limit as this allows for comparisons to a well-established metric; however, it should be noted and it will be shown that the proposed stochastic equivalent circuit analysis enables the definition of more complex metrics that allow the system designer to potentially specify not only the magnitude at which a violation is declared but also the probability of seeing a specified magnitude, which may enable further EPS system optimization beyond that which can be achieved with traditional metrics.

POWER QUALITY GUI

To assist system designers in the application of the proposed stochastic equivalent analysis, the authors have developed the power quality GUI in Figure 2, which steps the user through all stages of stochastic equivalent circuit analysis. The GUI has three major panels that mirror the major steps in the work flow of the proposed analysis: Source and Load Characterization, Power System, and Analysis. The user is able to characterize and derive a stochastic equivalent circuit in the Source and Load Characterization panel. Once all equivalent models have been derived, a representative power system can be assembled and solved in the Power System panel. After the power system has been solved, the results can be viewed in the Analysis panel. The calculations being made in the stochastic equivalent analysis will be described in conjunction with major sections of the Power Quality GUI in the order of steps needed to make stochastic equivalent circuit analysis. The following sub-sections will provide additional detail regarding the analysis performed in each step.

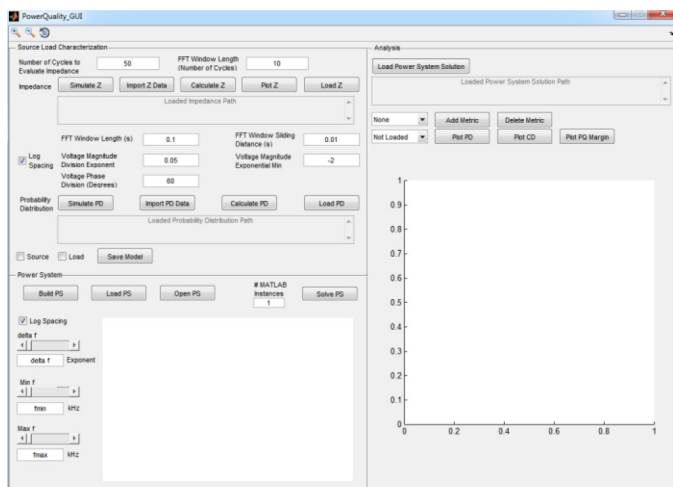


Figure 2. Power quality GUI

Source and Load Characterization

The equivalent circuit is characterized and created in the Source and Load Characterization panel. This panel has two major sections, one for calculating impedance and another for determining the voltage probability distribution. Once the impedance and probability distribution are derived, the equivalent model is saved by selecting the Save Model button.

Impedance Characterization

Impedance is calculated by exciting a model being characterized with sinusoidal excitation at frequencies in which the impedance is to be calculated. Selecting the Simulate Z option opens the PowerQualityToolset MATLAB/Simulink library with the Impedance Calculation block shown in Figure 3. This block steps through simulations at each user specified frequency while outputting a sinusoidal signal with the respective frequency and user specified amplitude. The derivative of the sinusoidal signal is also provided to accommodate certain simulation toolboxes that require it to simulate certain configurations. Each simulation is run until a specified number of steady-state cycles elapses or the maximum simulation time has been reached.

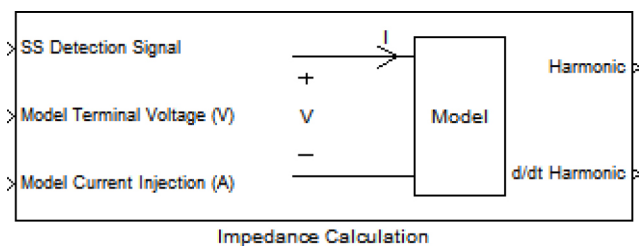


Figure 3. Impedance Calculation block

Once simulations at all frequencies have been completed, the frequency content of the collected terminal voltage and current signals at the frequency of excitation is calculated to produce the impedance given by (1) in which the overbar indicates phasor values. In this equation, it is assumed that the entire voltage drop at the excitation frequency is across the impedance. Obviously this assumption holds true if the internal voltage source has no injection

at this frequency. However, this may always be true and the model must be sufficiently excited to make any voltage source drop negligible. Thus it is recommended to excite the model at or close to its rating.

$$\bar{Z}(\omega) = \bar{V}(\omega) / \bar{I}(\omega) \quad (1)$$

The voltage and current phasors are calculated using the short-term Fourier transform (STFT) in which the FFT calculations are made across a specified number of steady-state cycles over a traveling window. Ideally, an FFT over a single cycle of data would be sufficient for characterization; however, system nonlinearities, noise, and numerical imprecision can cause distortion and calculation over multiple cycles is preferable to reduce the impact of such nonidealities. In the STFT calculation, the voltage and current phasor is produced at each instance of the FFT window, which travels at five percent of the window length. The resulting impedance phasor is calculated at each traveling window instance and all impedances are then averaged to derive the final impedance value.

The calculated impedance value is needed in probability distribution calculation and is automatically loaded once it is calculated using the Calculate Z button. Conversion of voltage and current data collected outside the impedance calculation block is made through the Import Z Data function. Previously calculated impedances are loaded through the Load Z button and the loaded impedance is plotted in a pop up figure window by selecting the Plot Z button.

Probability Distribution Characterization

Probability distribution is based on data collected from a statistically representative usage case scenario of a device. Selecting the Simulate PD option opens the PD Calculation block in the PowerQualityToolset library. This block is used to collect the model terminal voltage and current values and save it in a structure for use by the Power Quality GUI. Data collected through other means can be converted to a compatible format by selecting the Import PD Data function.

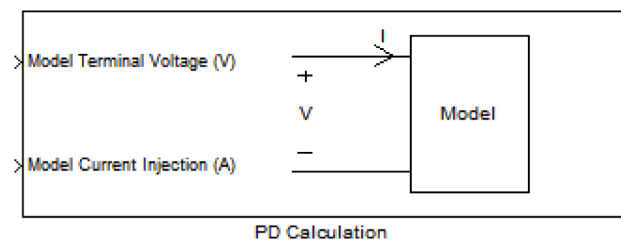


Figure 4. Probability Distribution Block

As done with the impedance calculation, STFT is used to calculate FFT on a traveling window as it transitions through the entire data. It is left to the engineer to specify the window size and its traveling distance since such settings are application specific and can alter the observability of short term harmonics and transient behavior if not properly selected. As described in [10], a larger FFT window increases the frequency resolution but reduce the ability to observe short term spectral content as it tends to smooth out the short term behavior. A smaller traveling window distance allows the user to view frequency content transient behavior in more detail, however, too