Theory and Application of the Power Tools Suite (PTS) 
For General Orbital EPS Applications

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The Power Tools Suite (PTS) is being used to calculate various Electric Power System (EPS) sizing studies and also to provide detailed transient analysis for various given orbital satellite missions. Greater accuracy is now being demanded in these EPS simulations to not only reduce the satellite weight, but to also accurately predict the battery, solar array, load, and radiator power responses immediately after liftoff, during ascent, during the mission phase, and at end-of-life. The PTS code provides detailed subsystem models to accurately calculate all of the EPS system parameters, and predict future EPS mission behavior. Improvements recently made to the tools suite include several user-defined solar array and battery models, additional solar array wings, as well as constant power and constant current load subsystems. Iterative numerical techniques are used during each time-step of the calculation to insure accurate and stabilized EPS currents and voltages, even at and near the maximum power point of the solar array. The presentation will include descriptions of the various EPS subsystem models, and comparisons of PTS model results to data and various proposed missions.

I. Introduction and Background

Electric Power System (EPS) modeling and simulation tools continue to play a very significant role in the design and sizing of Electric Power System components for both general satellite applications and various ground-based electric power generation stations. Most sizing and simulation tools utilize simplistic models and time-averaged power requirements to arrive at best-guess component sizes and capabilities, which are then over-sized by selected design engineering margins depending upon their specific application.

Lockheed Martin has developed detailed simulation models for each component and each subcomponent of the entire general EPS to allow detailed non-linear simulations, design analyses, component sizing, and transient performance for all EPS applications of interest. Previous IECEC papers in 2004 and in 1997 have documented many of the models used in the past for these simulations.1,2 These models have now been further developed and updated in the Lockheed Martin Power Tools Suite (PTS) code.3,5 As all of these EPS component models are all modular and interconnect, both very simple and very detailed models can be selected and used to compare and verify results. These tools are being used to size and study several planned missions. A summary of the capabilities of the component models and detailed example results are given in Ref. 1 and in this paper. EPS components including the battery cells and solar array cells can be evaluated and sized for any life, eclipse, and load combination. Using more historic and simpler models for the EPS components, these detailed results can be easily compared to design studies performed several years ago. It is found that the use of these detailed models can result in EPS designs that are significantly lower in cost and lighter in weight than those designed by other design tools.

II. EPS Simulation

EPS Simulation Tools are generally divided into the following two classes:

- EPS Component Sizing Tools
- EPS System Transient Performance Tools

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A detailed EPS simulation model should provide the following results:

- Ability to Calculate at Any Orbital Position
- Ability for Any Sun Angle or Sun Intensity
- Instantaneous Voltages and Currents
- Instantaneous Thermal Effects
- Transient Behavior
- Component Aging
- Launch Effects
- Orbital Cycle and Life Cycle Effects

The EPS Component Sizing Tools in the PTS code allow the input of average orbital component parameters to determine average component sizes and weights. The inputs may include: EPS life, sun and eclipse profile, component average temperatures, cable lengths and sizes, and battery size and composition. The outputs include: component sizes, dimensions, weights, costs, electronic cards types and counts, solar array series and parallel cell counts, battery sizing, and power use summaries.

Depending upon what input parameters are specified, the user can specify what output variables are to be calculated. This allows the input and output parameters to be chosen by the user.

The EPS System Transient Performance Tools in the PTS code allow the input of instantaneous orbital, sunlight, and load conditions to determine the instantaneous operating characteristics over user specified time steps in each of the EPS components, such as voltage, current, temperature, and heat transfer. Performing these calculations at each position over the orbit or several orbits in a mission will result in the time-dependent, transient EPS response of each component within the EPS. The inputs include: EPS life, sun angle and intensity, load, component detailed designs, component temperatures, and battery charging methods. The outputs include: voltages and currents anywhere in the EPS, battery depth-of-discharge, maximum depth-of-discharge, battery heat generation, and EPS temperatures.

A. EPS Component Models

The component models contain the necessary data to be able to provide cost, size, weight, performance, reliability, technology, and power consumption information. These data can be included to make each component scalable for any defined application. These models are “lumped parameter” models, in that they simulate the operation of the component over seconds or minutes – not milliseconds. The use of these models, rather than models of complete electrical circuit systems, results in fast simulation time with little loss in accuracy.

In the past, several EPS modeling tools have been written in FORTRAN or C code, allowing the defined outputs to be easily calculated from the defined inputs. In these codes, the solution is then determined by defined sequential causality; i.e. in the manner in which the equations are written. A drawback of the use of these models is that the input and output variables are rigidly defined and linked by that causality. If the user wishes to arbitrarily choose what the input and output parameters are for a given component model, then those EPS codes must include the proper decision trees to select which causality model (e.g. which subroutine) is to be used, and provide such a model for each case that may be encountered. When updating the equations of such a model, all the equations in each causality model must also be carefully updated. This is not difficult to do for most linear subsystem models. However, it is extremely difficult to do for non-linear subsystem or component models.

With the advent of high-speed desktop computers, other EPS models are now being written and used in SPICE, PSPICE, SABER, and in EXCEL (and similar equivalent modeling platforms). These application platforms allow the component models to be identified and linked by defined equations that are then iteratively solved until a converged solution is found. The use of these platforms allows greater flexibility and complexity in the way in which the components are modeled, and also allow the inclusion of non-linear and feedback effects which cannot be easily incorporated into the above FORTRAN or C program simulations. However, the numerical convergence to a steady-state or equilibrium solution at each time-step may require a much longer period of time than that of the direct sequential methods above, and in some cases, depending upon the application platform and the models, the solution may not even converge!

B. Numerical Solution Concerns

Several comparison studies had been previously performed using the PSPICE platform and the EXCEL spreadsheet applications to simulate the complex, non-linear EPS component models used as described below.\(^2\) It was found that while the PSPICE application was very useful in several respects and did solve the non-linear convergence and numeric solution problems, it also required very small time step sizes (much less than a second) and generated very large and lengthy output files that are very difficult to process, edit, and understand. On the other hand, the use of the automatic conversion algorithm inherent within the EXCEL spreadsheet program is also usually able to easily converge and solve these complex systems without the generation of such overhead. In addition, the use of Visual Basic (VB) Macros within EXCEL 2000 has made the use of this application much easier.
(over the use of the old EXCEL 4 Macros) and much faster. The use of the latter applications can guarantee a convergence to a stable system solution.

In addition, the use of EXCEL with VB macro coding also allows for the automatic storage of data in spreadsheets, user-friendly debugging, automatic real-time user interfaces, and easy plotting of selected results - which are all valuable assets to the design engineer and the EPS power systems analyst.

C. EPS Architecture Types

The EPS architecture types that have been incorporated into the EPS tools include:

- Battery dominated bus with direct connect, series switched solar array segments
- Battery dominated bus with peak power tracked solar array
- Sunlit regulated bus with direct connect, series switched solar array segments
- Sunlit regulated bus with peak power tracked solar array
- Fully regulated bus with direct connect, parallel shunted solar array segments, and battery charge / discharge regulators connected to the regulated bus

These architectures have been used to model some of the LMSSC EPS satellite bus systems, such as: LM700, several Peak Power Tracker based systems, A-2100, and A-2100M.\textsuperscript{1,2}

III. EPS Components and Models

A summary representation of the general EPS that can be defined by the EPS component models used is shown in Figure 1.

![Figure 1. EPS Component Models and EPS System Representation](image-url)
A review of what is included in each of these component models is given in reference 1, and is tabulated below:

**Mission Characteristics**

- Average Life
- Average Sun Load
- Average Eclipse Load
- Transient Sunlight Intensity
- Transient Sunlight Angle
- Transient Load Required
- Transient Radiator Load Allowed
- Transient Temperature Conditions

**Orbit Characteristics**

- Duration
- Eclipse
- LEO, MEO, or GEO
- Equinox:
  - Intensity of Sun
  - Normal Inclination
  - Inclination Error
- Solstice:
  - Intensity of Sun
  - Normal Inclination
  - Inclination Error
  - Dual Axis Tracking
  - Charge or Discharge in Sun
- Charge Load
- Discharge Load

**Simulation Parameters**

- Start and Stop Times
- Given Time Step Size
- Auto-calculated Time Step Size
- Numerical Convergence Criteria
- Restart Options
- Results Plotting Options

**Solar Array Parameters**

- Fraction Provided by Solar Array 1
- Fraction Provided by Solar Array 2
- Maximum Number of Solar Array Groups
- Number of Solar Array Circuit Groups
- Static or Automatic Solar Array Cell Number Calculations
- For each Solar Array:
  - Solar Cell Type
  - Number of Cells per String
  - Number of Strings per Group
  - Operating Temperature
  - Testing Temperature

![Figure 2. Solar Array Power vs. Voltage for Various Temperatures](image)

![Figure 3. Battery Voltage Model (Generic) for One Temperature](image)
The solar array cell models define the operational characteristics of the solar array. The output power is usually modeled as a function of the voltage and temperature on the solar array, as shown in Figure 2, which also illustrates that the maximum power point of the solar array changes with temperature.

**Solar Array Switching Network Capabilities**

- Increases or Decreases String or Circuit Count
- Extra Solar Array Power Set Point
- Automatic or Step-Function SA Count Changes

**Resistance** (Linear) (Wire, Cable, Bus Bars)

**Diodes** (Non-Linear)

**Power Regulation Unit**

**Power Switching and Distribution Unit**

**Battery Parameters**

- Type of Battery Cells
- Number of Batteries
- Number of Cells per Battery
- Number of Failed Cells
- Required Capacity
- Voltage
- Sequenced Charging
- Maximum Depth-of-Discharge
- Available Charge Time
- Available Discharge Time
- Operating Temperature
- Recharge Ratio or Eff. Curves
- State-of-Charge Effects
- Cycling and Age Effects

The battery component model allows the use of a 2-D characteristic surface or tabular data tables to model the battery voltage as a function of both the depth-of-discharge and the discharge-rate at a specific temperature. The battery model accepts both life aging parameters and run-time parameters. Life adjustments are included for calendar life, cycle life, average life temperature and average life depth of discharge. Run time parameters include instantaneous current, instantaneous temperature, and instantaneous depth of discharge. Outputs include instantaneous voltage and instantaneous charge efficiency. Figure 3 illustrates an example battery voltage as a function of rate and depth of discharge, with temperature held constant and life degradation set to beginning of life.

As part of the PTS code development and application for various Lockheed Martin programs, a battery/cell performance model for the NASA Hubble Space Telescope (HST) program has also been developed that predicts actual discharge data as a function of both the depth-of-discharge and the discharge-rate at a specific temperature. PTS is being used to model the decreasing battery capacity observed during the HST Mission. Many recent NASA coordinated studies have shown that the HST battery cells are degrading at a faster rate than anticipated, and that the telescope itself may need to be placed in a safe mode in the near future, unless the existing batteries can be replaced. Since a Space Shuttle Mission is no longer being planned to replace these batteries, NASA is considering contracting a robotic mission to place new batteries in parallel with the existing ones.

**Current Control**

**Battery Charging and Discharging Control**

**Battery Heaters and Radiators**

**Loads**

- Constant Power
- Constant Current
- Complex
IV. Solution Techniques

The PTS transient code simulation uses forward time-step techniques, where all system values are assumed to be known at the beginning of each time step, and results updated at the end of each time-step. The time-step size is user selected, and may be different for different time steps, thus allowing smaller sizes to model rapid changes, and larger sizes to model durations where system parameters are relatively constant. Internal calculation loops are included to balance the solar array voltage with the battery discharge current, the battery discharge current to the required total load power, and battery charging and heating. Mathematical solution stability of the EPS after each time-step is guaranteed using such convergence techniques. Variational analyses, when changing only one or a few input parameters at a time, has confirmed these converged results.

V. Benchmark Problems and Results

Various variational analyses and benchmark problems have been run with PTS to confirm its accuracy and benefit of use. The following transients have been studied:

- Null Transient (no drift)
- Discharge Only
- Discharge Limits
- Charge Only
- Charge Limits
- Charging Voltage < SA V at Peak Power
- Charging Voltage = SA V at Peak Power
- Charging Voltage > SA V at Peak Power
- Trickle Charge Only
- Constant Parameter Values (over Orbit)
- Single Parameter Variations
- Single Parameter Comparisons
- Smaller Time-Step Comparisons

The PTS code is now being used in various mission applications and programs.

VI. Summary And Conclusions

Several EPS simulation models are in use today within the aerospace industry for both individual EPS component sizing, component simulation studies and EPS system transient performance. Simple models can be coded in digital programs, and generally give conservative results that are usually increased by including large engineering margins which in turn can be associated with higher costs. Detailed non-linear EPS models can be made that model and reproduce actual test data; however, the use of these models in digital system simulations can be very difficult, and the numerical results can be questionable.

An EPS Sizing Tool and an EPS Transient Performance Tool have been developed in the Power Tools Suite at Lockheed Martin for use in general orbital satellite and ground-based power station applications. The PTS tool allows the use of complex, non-linear EPS component models whose results reproduce actual test data. EPS simulations are constructed from these models for both component sizing and performance studies. The use of EXCEL with Visual Basic Macros allows general user selected input and output variables while maintaining modularity. Proper causality coding guarantees numerical convergence over each time step in the simulation. The EPS component models have been shown to reproduce actual test data, and the EPS system models using the same components have been shown to produce accurate results in both EPS component sizing and transient system analysis calculations. Results from other studies have shown that the models very closely reproduce contractor's data and results.

The PTS code is now being used in a variety of detailed EPS component sizing and performance calculations for various programs, architectures, and missions within Lockheed Martin.
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References


