



EPS TDS - Electric Power Systems Time Dependent Simulation Tools For Verification, Validation, and Prediction

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I. Nomenclature

<i>EPS</i>	=	Electric Power System
<i>Excel</i>	=	Microsoft Excel Application
<i>Excel VBA</i>	=	Excel Visual Basic for Applications
<i>LMSSC</i>	=	Lockheed Missiles and Space Systems Company
<i>PTS</i>	=	Power Tools Suite
<i>TDS</i>	=	Time Dependent Simulation

II. Introduction

A group of computer code simulation tools has been created to predict the time dependent behavior of electrical power systems used in aerospace and satellite applications. These tools can also be used to simulate accurate power systems behavior in virtually all other power system applications and architectures, including vehicles, aircraft, solar powered facilities, power plants, and nuclear generating stations. It is important to note that although these tools can be used in many classified or secure areas, that the models and codes themselves as written and coded are not classified. Only the input and output data used in the codes could be considered to be classified. Also, many models that can be used in the codes may be considered to be proprietary. Any such models or data would then be allowed to be used only by those agencies that have legal access to that proprietary data. Generic models and user generated models can also be used wherever necessary.

III. Needs and Applications

There is a clear and definite need for the ability to accurately simulate the time dependent behavior of the variables in an electrical power system (EPS) during the life of the system, and also during specific system transients of interest, such as “what-if” transients. In aerospace satellite systems, the voltage and current in the EPS are needed to be accurately known in order to determine the state-of-charge of the battery cells during periods of charging and discharging. This is extremely important in satellite space applications, as many types of battery cells will not be able to be recharged if they discharge beyond a certain point. For these systems, knowing the state-of-charge at any time is a mission success criteria.

IV. Background

The EPS TDS models and tools were inspired from the Power Tools Suite (PTS) models and tools that were originally developed at the Lockheed Martin Space Systems Company during 1997 to 2013. The development and use of those PTS models and tools has been documented in several conference papers and presentations that have been presented and published in the open literature during that time as listed in Refs. [1-24].

The current TDS models and codes reported in this paper have been developed and written completely independently of the PTS effort at Lockheed Martin. Also, these TDS models and codes also do not contain any proprietary or restricted data, equations, models, or information. In addition, while the older PTS models allowed only one type of solar cell or battery cell in the EPS description, the newly developed TDS models can allow many

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different solar array wings and strings with many different types of cells in the solar array, and many different types of strings of battery cells to compose the battery.

V. Computer Platform - Excel

The TDS tools package is written entirely in Excel Visual Basic, and uses only the normal Excel computer code application as released by Microsoft Corporation. The use of these “macro commands” is exactly equivalent to the writing of large computer codes in FORTRAN, C, C++, or BASIC. It allows fast and accurate numerical simulation with the added capability of using the worksheets and workbooks unique to the Excel application. The use of Excel allows the use of these tools without the need of any special computer application code or license, such as needed for FORTRAN, MATLAB, and Simulink. Also in TDS, the use of the model data and non-linear numerical simulation with nested iteration loops allows for the convergence of the EPS variables throughout the system during each time step, which may be impossible or very inaccurate to simulate using other application codes and models.

A further advantage of using Excel is its unique ability to store and easily create plotted results, up to over 1 million rows per worksheet. Many extensive plotting routines have been created that were released to the local Excel Users Group over many years. These include the ability to easily define and enlarge the plotted data in any given region.

VI. EPS Simulation Strategy

The entire Electric Power System (EPS) is simulated by a collection of EPS Components, which are in turn connected by wiring. The EPS is then be considered to be composed of major components, such as: a solar array, a battery, diodes, resistances, wiring, switching circuits, other equipment, and several loads. Each major component is considered to be composed of several sub-components, arranged in either parallel or series. The wiring connection of a group of sub-components then determines the model of the major component. The wiring of the major components then determines the design and the specific architecture of that entire EPS model.

Time dependent calculations are performed by dividing the simulation time of interest into several time steps, perhaps hundreds or thousands, and with experience have usually taken as one minute each. All of the EPS parameters such as voltage, current, etc., are assumed to constant over each time step.

The usual simulation technique is to define the input conditions required by the EPS, and to then determine the output conditions at the end of each time step during the simulation. Major input requirements at each time step would include the power required by each load and the input conditions to each major component; such as the amount of light and the angle of the light striking each individual solar array cell, and the temperatures of each cell and component. Initial conditions would also include the state-of-charge of each battery cell, and any other required initial conditions. The resulting output variables would include the new state-of-charge in each battery cell, the voltages produced in and by the battery, the voltages present on each solar array cell, and the currents in each wire.

The systems variables at the end of each time step then become the input values for the next time step. The most important task is to balance all of the voltages over the entire EPS at the end of the time step. In TDS, the use of the model data and non-linear numerical simulation with nested iteration loops allows for the convergence of the EPS voltages and currents over each time step.

VII. EPS Parameter Modeling

Each EPS Component Model is represented by a “lumped parameter model”, which models and simulates the operation of that component for the input operating regions specified. For short time durations, on the order of milliseconds, this model may consist of individual electrical components, such as resistors, capacitors, inductors, and solid-state microchips. However, the mission simulations that we are concerned with have transient behavior over the duration of weeks, days, hours, and perhaps minutes. For these cases, the component is modeled by equations or tabular data in the models that recreates and duplicates the actual measured response of the component. This allows long mission transients over the order of 7 to 10 days to be easily simulated, by as little as one minute time steps, in a very short amount of real time. The results of these calculations are therefore accurate for overall component and system behavior. Fast transients, such as rapid current spikes and inductance effects, should be separately analyzed using other models and applications, such as PSPICE. These applications, however, usually require thousands of time steps to simulate just one second, and are not suited for long term transient simulation or mission analyses.

A specific advantage of TDS is its ability to model the solar array and the battery by several unique sub-components. Each EPS component is defined by the user input data. The solar array can be designed to be any number of wings, where each wing is composed of any number of strings, each string having any number of cells, and the cells in each string are usually the same type, and TDS allows the use of mixed cells in a string. Many solar array wings can be modeled using separate surfaces and orientations, composed of many strings, with different solar array

types in each string and wing. The battery is composed in a similar manner, with any number of cell stacks in parallel, and with each stack being composed of any number of battery cells and of any type. In addition, each battery cell can be given an initial and different state-of-charge and at a different temperature, and each cell can be degraded or dropped out of the battery model at any given time by user command. Initial conditions and other time-dependent model data are then required to be given for each solar array wing and each battery cell over each time step. In this manner, very complex and multiple solar array wings can be modeled, as well as batteries of any cells in series and stacks in parallel configuration. The EPS components and their subsystems with their input and output variables is shown in Table 1.

EPS Component	
Subcomponent	
Next Sub	
Next Sub	
Input Variables	
Output Variables	
Solar Array – Any number of Wings in parallel	
Wing – Any number of Strings in parallel	
String - Any number of Cells in series, mixed types allowed	
Cell – Specific models by operational data in user defined plots, equations, or tabular data	
Type	
Sunlight Orientation	
Temperature	
Age	
Degradation	
Voltage	
Voltage and Current	
Battery – Any number of Battery Units in parallel	
Battery Unit – Any number of stacks in series or parallel	
Stack - Any number of Cells in series	
Cell – Specific models by operational data in user defined plots, equations, or tabular data	
Type	
State of Charge	
Temperature	
Age	
Degradation	
Drop out cells	
Voltage and Current	
Voltage and Current	
Diode – Usually one component with no subsystems	
Voltage and Current	
Voltage and Current	
Special User Defined Components – As inserted into the EPS Architecture Diagram with wiring	
Usually one component with no subsystems	
Voltage and Current	
Voltage and Current	
Wiring – Between Components	
Gauge	
Length	
Temperature	
Resistance (voltage loss)	
System Power Required	
Constant Voltage	
Constant Current	
Constant Power	

Table 1. EPS Components, Subcomponents, and Variables

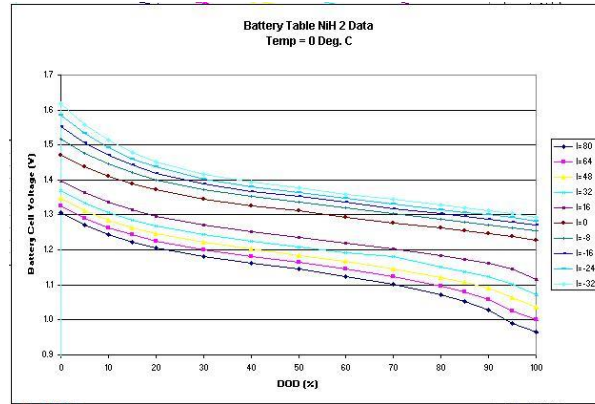


Figure 3. Typical NiH Battery Voltage Characteristics at BOL Conditions [20]

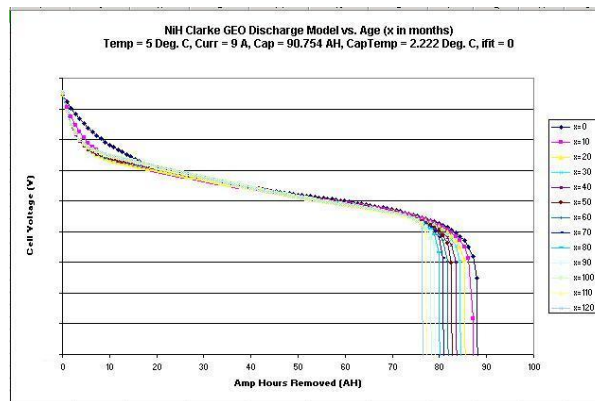


Figure 4. Typical NiH Battery Discharge Model, Effects of Capacity and Age [15]

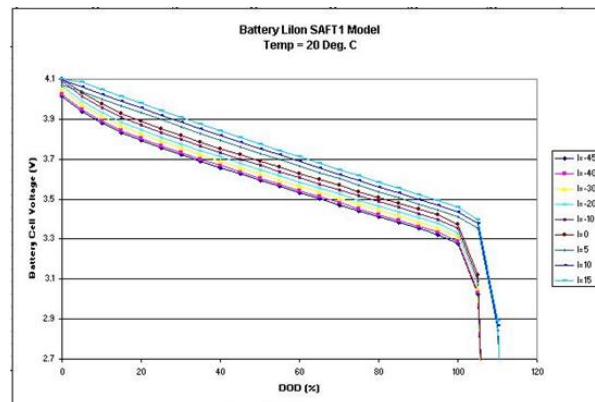


Figure 5. Typical LiIon Battery Voltage Trends at BOL Conditions [20]

IX. Simulation Numerical Accuracy and Techniques

The TDS tools use double numerical precision accuracy, as provided in Excel. During the simulations, iteration loops are used to calculate the voltages and the currents to their required “converged” values over each time step. This allows the use of these non-linear EPS component models, such as for the solar array cells and diodes, as well as any connected configuration of the components to simulate any desired architecture. An obvious path of convergence is between the battery voltage, the solar array currents, and then in turn back down to the battery voltage.

X. Verification and Validation of Models and Results

The EPS component models use equations and tabulated data that fit the given measured behavior of that component in all of the given range of conditions. Each model is individually run and tested to ensure that each component produces the intended results and reproduces the given or tested data. This verifies the use of the model for that component. Performing simulations with that component in use with other components against known results are used to validate the accuracy and performance of the models. In this manner, the validated models can then be used to accurately predict future system behavior.

XI. Tabulated and Plotted Results

The results of any of the EPS component variables can be tabulated at any time step during the simulation. The data are stored in Excel spreadsheets and not in arrays. This allows the automatic creation and storage of plots for each system variable of interest. In addition, a user interface is provided which allows the user to select any portion of the time domain of the results, and to choose and plot the data for that given range of time. This allows the user to see both the plotted results of the entire simulation, and to “zoom in” on any time domains of interest.

XII. Documentation

The documentation describes the use and the application of the tools for several EPS applications. All of the EPS component models used in the tools are individually tested to insure accuracy. The equations used in the various models are documented with the code itself..

XIII. Expandability

The TDS tools are easily expandable by including additional EPS component models and by creating additional EPS architectures. When necessary, unique EPS architectures can be used in separate Excel files to model complex system behavior. All of the EPS component models are available for use in any EPS architecture model.

XIV. Future Plans

The EPS TDS models and codes are currently being used to simulate the behavior of aerospace satellite systems, both for orbital missions and deep space missions. The tools are very useful for sizing power systems for proposals, design reviews, mission operation, and predicted mission behavior. It is also expected that the tools will be very useful for mission verification and validation, prediction, and they also provide an on-orbit ground simulation tool to predict possible future system behavior. This will be extremely useful in analyzing future “what-if” operational behaviors.

Additional models and data are also being created to allow the simulation of any power system, including vehicles, electric vehicles, automobiles, airplanes, fighter jets, unmanned submersibles, solar powered homes, electrical generating stations, and nuclear plants. User input would then determine the models and the EPS architectures to be simulated.

XV. Results

Several results have been using an EPS composed of a generic Lithium Ion battery and generic solar array cells during a simulated orbital mission. Studies included battery charging and discharging, effects of solar array orientation, and the effects of battery degradation on system behavior. For example, Figures 6 and 7 show the results from a study of a simulated geosynchronous satellite using a LiIon battery charging over multiple orbits.

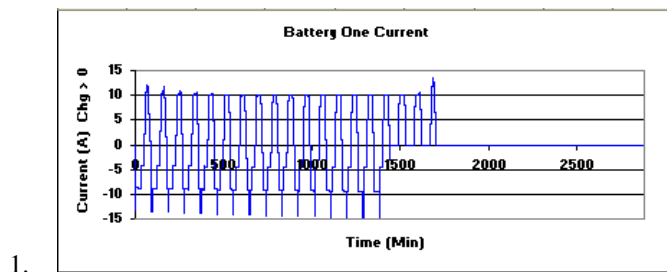


Figure 6. Sample LEO Simulation of 48.4 Ah LiIon Cells – Battery Current

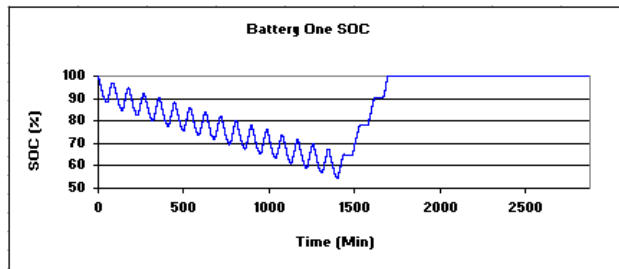


Figure 7. Sample LEO Simulation of 48.4 Ah LiIon Cells – Battery Current

XVI. Conclusion

The TDS codes are a vast improvement over other EPS system simulation codes. They run on Excel and are easily transportable. The codes themselves are not classified, while the input and the output data may be. This allows easy transportability from the TDS code development area to the classified mission areas. Extremely detailed EPS system architectures can be easily model. The EPS component models generate actual measured data over their given ranges of operation. Time dependent missions can be modeled using 1 minute time steps. Long mission durations from launch to final orbit or during orbit can be simulated in very quickly in real time. The codes can be used for EPS sizing, prediction of mission behavior during the life of the system, and also during specific system transients of interest, such as “what-if” transients.

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