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SCALABLE POWER-COMPONENT MODELS FOR CONCEPT TESTING

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ABSTRACT

This paper describes next generation modeling tools to solve a basic problem of concept analysis, which is the lack of component models that realistically estimate the performance of technology that has yet to be fully reduced to specific products. Three important classes of electric power components essential to future Army vehicles are addressed: integrated electric machines, battery energy storage, and traction motor drives. Behavior models are delivered in a common software simulation "wrapper" with a limited number of user settings that allow the ratings of the component to be scaled to the performance required by the vehicle concept represented in a larger simulation. This approach captures expert knowledge about components so the systems engineer managing the concept analysis can create reliable simulations quickly.

INTRODUCTION

Advanced electric power components for both prime and non-prime power systems on Army vehicles are now recognized as enabling technology for tomorrow's war fighter. In many cases, equipment that is needed is neither commercially available nor technically ready for production, and yet decisions about current and future investments have to be made to eventually bring innovative technology to legacy or future combat systems. Concept analysis, followed by systems engineering, are essential tools to begin rigorous quantitative assessment of what future technology can do and what requirements it will satisfy, almost always in the context of multiple competing technical options.

Under the Simulation Based Reliability and Safety (SimBRS) research consortium, researchers within MSU/CAVS and TARDEC/CASSI organizations are developing next generation modeling tools to solve the basic problem of concept analysis, which is the lack of component models that realistically estimate the performance of technology that has yet to be fully reduced to specific products. Three important classes of electric power components essential to future Army vehicles are addressed by this research program: integrated electric machines, battery energy storage, and traction motor drives.

Behavior models are delivered in a common software simulation "wrapper" with a limited number of user settings that allow the ratings of the component to be scaled to the performance required by the vehicle concept represented in a larger simulation. For example, an internally integrated starter-generator model has been developed that allows a user to specify torque and speed ratings and machine type from which the model's scaling algorithm automatically generates representative torque-speed-efficiency tables for four-quadrant operation, including estimates of thermal loading on an associated cooling system. The user of the model does not have to be an electrical machine expert to scale the model. Similar features are delivered for the battery and inverter models.

The paper is organized as follows. The model environment section describes the basic wrapper as a graphical user interface with embedded domain-specific behavioral models of components. Then in successive sections, a short example is provided for three different component domains: electromechanical rotating machines, batteries, and power electronics. The final section is a conclusion and description of continuing work.

MODELING ENVIRONMENT

The modeling environment is Matlab/Simulink because of the ease with which reusable software we call the "wrapper" can be developed integrating different physical domains (for example electrical and thermal) while presenting a similar model interface across very different application domains (for example electrical machines and batteries). Two generic scalable models have been created with this wrapper concept, one for an integrated starter generator (ISG) component and one for a large-format battery. The ISG model includes associated controls and the option to select competing technologies (for example, permanent magnet vs. induction machines). Similarly, the battery model can capture different chemistries (for example, lithium ion vs. nickel metal hydride) and different capacities. The battery model diversity is intended to support application differentiation, such as power-optimized batteries for hybrid traction drives versus energy-optimized batteries for deep dischargeable energy storage. Proprietary chemistries can be captured during model development, but the objective is to permit concept analysis to identify design trades available from known battery performance. Therefore, the user interface is designed to be generic in nature, scalable, and suitable for a notional vehicle platform.

Each domain-specific model includes and accounts for thermal considerations. The models are "tuned" for

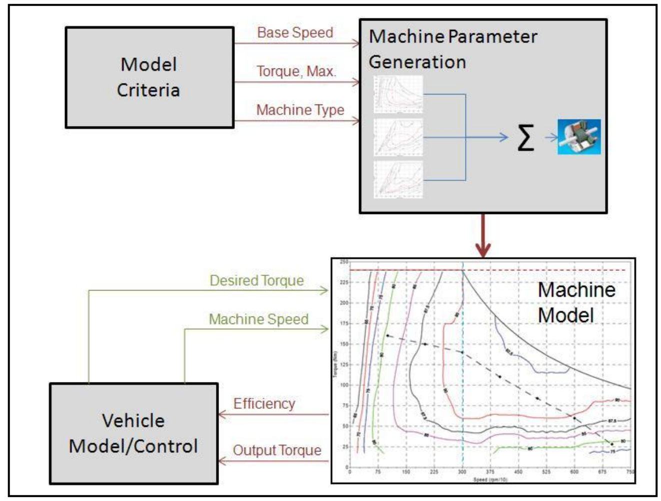

Figure 1: Overview of the generic ISG model.

applications in the range of 40-110 kW; however this range is not exclusive.

In each application domain, a generic model is presented to the user that is based upon a domain-specific embedded algorithm that takes a selected (and limited) set of input parameters to yield approximate performance and efficiency curves. For example, with the ISG model, these inputs are rated torque and machine speed which the "Machine Model" uses to generate composite efficiency maps and torque/speed curves that represent average operating characteristics for a selected machine type. The resulting model self consistently interacts with the simulation during system simulation execution.

DOMAIN SPECIFIC EXAMPLES

In this section short descriptions are given of two models (the ISG and battery wrappers) that have already been developed and that are in advanced validation. The section concludes with a discussion of the approach used to develop the algorithm embedded in the power electronics wrapper under development.

Integrated Starter Generator

A block diagram of the ISG model implementation is depicted in Figure 1. The generic motor model is designed to be user friendly while providing realistic motor behavior for the type and size of motor desired. By reducing the model criteria required from the user to define the motor characteristics, this machine model is much easier to use for rapid simulation. The motor criteria needed are the maximum output torque, the base speed, and the peak output time of the motor. Once the motor information is entered, the ISG model can then be used in conjunction with a vehicle simulation. The ISG model requires vehicle simulation inputs of requested torque and motor speed to provide output torque and efficiency.

The maximum output torque of the motor is the peak torsional effort in Newton-meters that the motor can provide at or below the specified base speed. The maximum output torque is related to motor size, construction, and cooling capability. Higher maximum output torques generally indicate physically larger motors. This maximum torque value is one of two parameters that define the peak output power of the motor. This maximum torque value also determines the performance requirements of the traction/generation application, such as acceleration, gradability, or electrical power output.

The base speed of the motor is the point on the torque/speed curve where the output transitions from (nearly) constant torque to constant power. Below the base speed, the maximum output torque is constant, and the power output increases linearly with motor speed. Above the base speed, torque drops as motor speed increases, creating a constant power output. The base speed is illustrated in Figure 2.

The base speed of a motor is a consequence of input voltage, maximum output torque, and motor construction. Since input voltages and torque requirements for traction

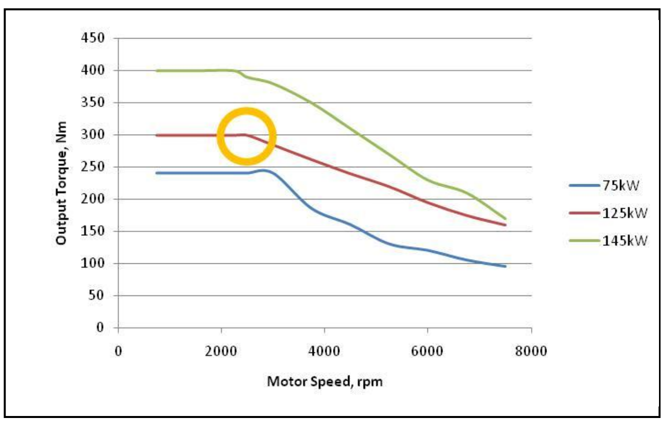

Figure 2: Typical output torque vs. speed curves. The“base speed” is highlighted with orange circle.

applications tend to be similar, base speeds usually fall within the 2000 – 5000 rpm range for typical motors. base speed, torque drops as motor speed increases, creating a constant power output. The base speed is illustrated in Figure 2.

The peak output time parameter refers to the time that the motor can operate at maximum output before overheating during nominal running conditions, and is always greater than zero. These conditions are specified by manufacturers' motor datasheets and are not subject to a particular standard. However, they generally specify the cooling medium at maximum temperature. The peak output time is primarily dependent upon the type of cooling system, air or liquid cooling. Reasonable values for air cooled motors range from 8 – 15 seconds, whereas liquid cooled motors have peak operating time limits in the 30 – 45 second (s) range.

Once the given motor information is inserted, the model then requires inputs from the vehicle simulation. The first of these is the requested torque. This is the torque value that the simulation requires from the traction drive to propel or brake the vehicle during simulated operation. It is specified in Newton – meters (Nm). The second input is the speed of the traction motor. Because the vehicle dynamics and gearbox ratio will dictate the speed and acceleration of the vehicle, the speed of the electric motor must come from the simulation. This speed is then used to determine the available torque that the motor can provide.

The model incorporates four quadrant control. The input torque and motor speed can be either positive or negative dependent upon the propelling or regenerative braking scenario.

The simulation provides three outputs: motor torque, efficiency, and power flow. The output torque is generated by the model from the parameters entered in the model criteria, and is specified in Newton – meters. The efficiency value is the combined motor and inverter efficiency at the current operating point, and can range from 0 to <100%. The power flow is the amount of electrical power in Watts that is required by the motor to produce the current operating condition. Positive values indicate power being used by the machine, such as vehicle propelling operation. Negative values indicate power being produced by the machine during generation or regenerative braking.

To use the model, the user modifies the motor model criteria parameters by double-clicking on the model block "*Scalable ISG Version 2.0*" in Simulink, as shown in Figure 3. The dialog box shown in Figure 4 will then appear. This box allows the model criteria parameters, as defined above, to be entered and applied. Once the motor model criteria are applied, the correct values should appear inside the model block.

Figure 3: Scalable ISG Version 2.0 Simulink block.

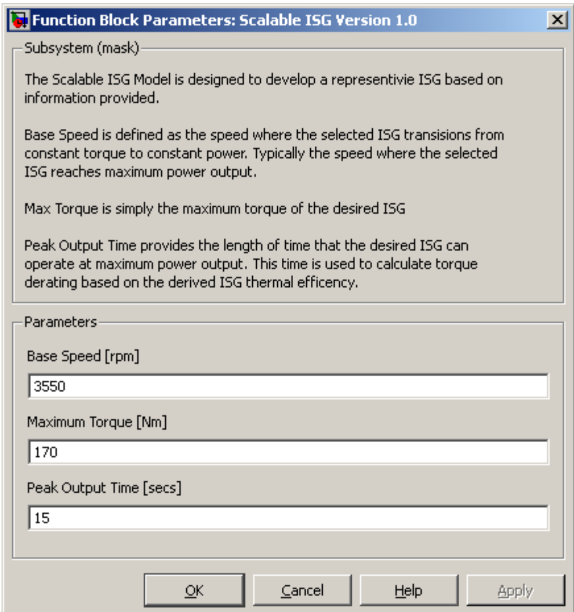

Figure 4: Motor model criteria dialog box.

To create a generic model, many motor characteristics were blended to create a single parameter-based unity model. The blending algorithm used three known PMDC motors (75kW, 125kW, and 145kW). Their characteristics were then normalized for base speeds and maximum torques [1-3]. From that information, a composite was developed.

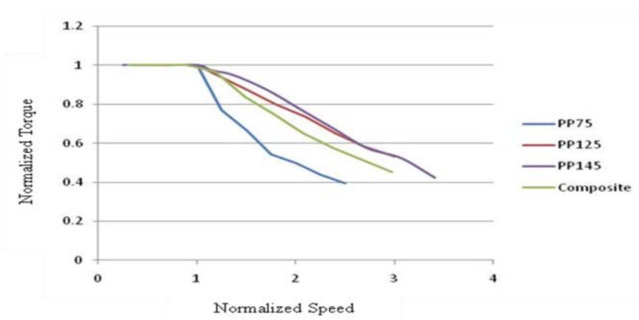

Figure 5: Normalized Torque/Speed Curves with Composite for PMDC Machines

Figure 5 visualizes the outcome of the blending. The green line represents the average torque/speed characteristics of all three motors, and thus the average characteristic of a generic PMDC motor, given a sufficient sample size. This basic mathematical process was then realized in MATLAB/Simulink. Then, the structure of the model was developed according to the outline of Figure 1 that allows the model to be used in vehicle simulations.

Continuous torque limits and efficiency mapping were normalized and scaled in the same manner as the maximum torque. This provides realistic continuous performance capabilities for the motor, as well as the basis for the thermal behavior calculations. Also, the motor behavior in the continuous and intermittent operational regions was modeled by determining heat flow in and out of the motor casing. The continuous power limit of the motor at any given speed is dictated by the thermal dissipation capability of its cooling system. At this limit, the heat from motor operation is equal to the maximum possible heat dissipation. Operation above this power limit can only continue until a maximum acceptable heat load is reached, after which the output of the motor must be reduced to avoid overheating and damage. The peak output time parameter is the amount of time that the motor can operate at maximum output. It is required to determine this maximum acceptable heat load and is usually in the range of 15 – 45 seconds. This model determines the heat load of the motor given its operating point, output, and efficiency to accurately determine how long the motor can operate at greater than continuous torque levels.

The model, then, accurately reflects changes in motor torque output due to thermal concerns at intermittent loading. This is a major difference from other motor models, many of which have no provisions for torque reduction based on thermal considerations. Such assumptions can be considered valid for vehicle simulations where traction loads in the intermittent operation zone are of short duration, like a light car. However, this is a simulation compromise and is not valid for severe use operations. If the motor is operated in the intermittent zone, heat load will accrue according to output. Operation in the continuous zone allows heat to be dissipated, also at a rate proportional to output. If the simulation operates the motor model at peak torque beyond the thermal limits, the torque will be ramped down to the maximum continuous level and remain there until the torque request is reduced. At the continuous torque limit, little to no reduction in heat load occurs, as all of the cooling capability is required to sustain the motor operation.

The first beta version simulated only PMDC machines. The integration of different machine types, such as induction motors, is also a priority, as well as expanding the number of each machine type used to create the average generic motor output and efficiency curves.

Large-Format Battery Model

Figure 6 gives an overview of the battery model structure. The model is behavioral in form, so it is computationally efficient for use in fast turn concept evaluations or in large, detailed system simulations. The model uses the typical state-of-charge (SOC) based open-circuit voltage calculator common to "fuel gauge" models but also includes a dynamic impedance model that significantly improves the fidelity. While the model is intended to be an approximation of true battery behavior, rather than a physical battery model, the combination of computational simplicity and validated fidelity makes it a preferred choice for most simulations at the system level. No more than a second-order differential equation solver plus a 9th order polynomial calculator is required to execute self-consistent calculations. A reduced-order, non-self-consistent option was included in the wrapper to allow the model to operate as a SOC calculator for system simulations that do not include circuit analysis.

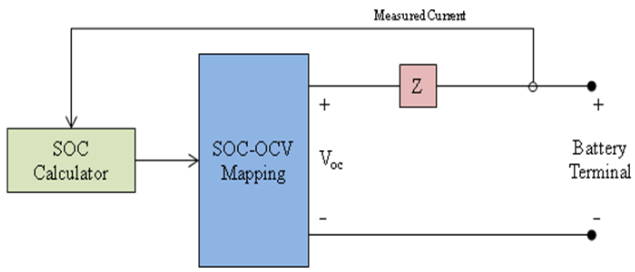

Figure 6: Behavioral battery model.

The generic battery model is designed to be user friendly while providing realistic battery behavior for the nominal voltage and capacity chosen. The performance criteria required to define the battery model have been reduced to that available by most users when constructing a concept analysis. The battery criteria needed are the nominal pack voltage, battery capacity, and model type. These terms are defined in the following paragraphs. Once the battery information is entered, the model can then be used in conjunction with a vehicle simulation. The battery model requires a vehicle simulation input of load current to provide state of charge (SOC), voltage, and battery heat load.

The battery voltage parameter defines the nominal rest potential of the battery pack, and is dependent on the cell chemistry and arrangement. Higher pack voltages allow for larger power outputs for a given current, usually limited by practical conductor size. The battery capacity is a measure of the charge that the battery can store, and is specified in Ampere-hours (Ah). This value, when multiplied by the nominal pack voltage, indicate the total electrical energy stored in the battery in Watt-hours. The battery capacity is also dependent on cell arrangement and chemistry. The minimum SOC value is the lowest acceptable battery charge level for the modeled chemistry. Simulation in charge counting mode below this value will produce invalid results, thus the simulation will be stopped by a flag when the limit is reached and an error dialog will be reported. The model type drop down menu allows the user to select the charge counting or self consistent models for simulation.

The external requirements of the full order self consistent battery model may not be available in all simulations, as it requires a complete electrical model of the desired load. For this reason, a reduced order charge counting model is available to the user to accommodate simpler simulation requirements. Once the battery information is inserted, the reduced order charge counting model requires one input from the vehicle simulation. The load current input represents the electrical current required by the load to meet the demands of the simulation. For example, if the simulation commands a torque from an electric traction drive that requires 250 A, then the requested current to the battery model will be 250 A. The charge counting option of the model is easier to implement, but must be monitored by the user to avoid unphysical zones of operation. Because the load current is provided by the user and is not determined by electrical network analysis of the battery and load models, it is possible for the user to source current from the battery at 0% SOC, regardless of the collapse of the battery terminal voltage in this state. The self consistent model avoids this issue by integrating the electrical models of the battery and load, but requires a self consistent electrical model for all loads. The full order self consistent model requires the terminal voltage of the battery to be computed using circuit analysis of the simulated system. The terminal voltage allows the current flow to be computed in the next time step. The model input pin label will change automatically between voltage and current as the model option is changed.

The simulation provides four outputs: battery output voltage, current, SOC, and thermal heat load. The battery output voltage is dependent on load, with higher loads corresponding to lower terminal voltages. As the battery is depleted, the current available without incurring excessive voltage drop is reduced. The SOC represents the amount of energy available in the battery as a percentage of the total capacity. The thermal heat load indicates the amount of heat generated by the battery due to losses during operation. This value is provided as an indication of the required performance capability for the thermal management system.

Figure 7 illustrates the user interface in the charge counting mode. Figure 8 illustrates the same Simulink block if the user selects the self-consistent mode. The similarity to the ISG model is intentional. These generic blocks are intended to require very little training to use and knowledge of component definition and performance criteria available to a systems engineer who is not a subject matter expert in the domain of the model.

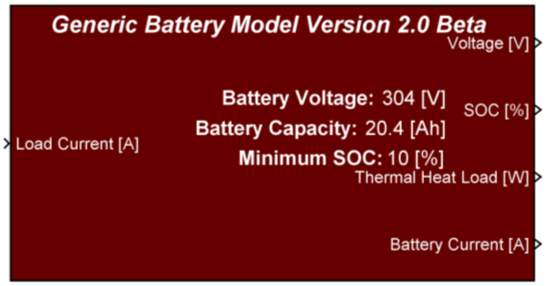

Figure 7: Generic battery model 2.0 Simulink block in charge counting mode.

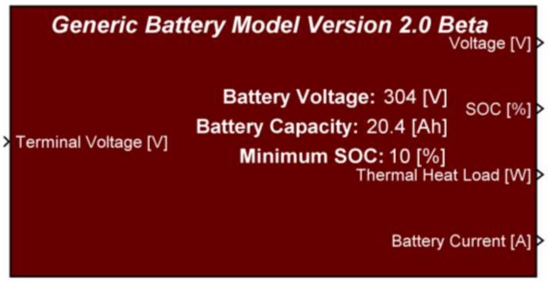

Figure 8: Generic Battery Model 2.0 Simulink block, in self consistent mode

The electrical battery model [4] is an electrical analog circuit representation designed to functionally predict battery performance. Although this model was originally developed for and tested on small format batteries in [4], this model has proven to be robust when applied to larger format batteries. Further, it is also known to be capable of accurately modeling multiple chemistries such as Li-ion, Nickel-Metal-Hydride (NiMH), and Lead-acid batteries [4]. The combined flexibility and accuracy of this modeling technique is the basis for it selection in this task.

The model contains two basic parts, a state of charge calculator and the electric circuit battery analogue. The state of charge calculator is governed by (1), where SOC is calculated from coulomb-counting with measured terminal current as its input. In (1), *C(t)* is the battery capacity in A·sec. *i(t)* is the battery terminal current in Amperes.

$$SOC_{new} = SOC_{old} - \frac{1}{C(t)} \int i(t)dt \qquad (1)$$

The second part of the model consists of a controlled voltage source and an impedance block. This portion of the model comprises the electrical analogue part that represents the battery dynamic characteristics. The Z-impedance is represented by a series resistor and *n* RC networks (Figure 9). The series resistor is responsible for the initial voltage drop during charge/discharge as tied to the time based resolution of the model, and the RC networks approximate non-linear transients with the equivalent of a truncated *n*th order series. The number of RC networks in part determines the dynamic response and resolution of the model. These two parts are connected by a SOC– Open Circuit Voltage (OCV) mapping, which is most often represented by a polynomial equation.

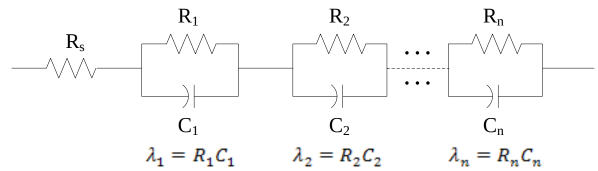

Figure 9: Z-impedance network.

It is important to note that although an analog circuit is used in this electric battery model, it is not a continuous time system but rather a bandwidth limited approximation. The bandwidth dependency of the electrical battery model is reflected in the RC networks of the model. Since the battery is a highly non-linear dynamic system, in theory the terminal voltage can only be approximated by an infinite number of RC networks – as an infinite number of exponential basis functions. However, in reality the larger simulation that contains the battery model has only a finite need for component model bandwidth, and so a finite number of exponential models (number of RC networks) should be selected based on the required dynamic performance expected by the simulation of the model. The ranges of the time constants of the model should be selected based on the limited bandwidth of the battery application, thus the bandwidth of the battery model can be redefined as needed. Dynamics outside the range of the model bandwidth are supported by limiting cases. On the high-frequency side this is the series resistance. On the low-frequency side this is the open-circuit voltage of the SOC calculator.

The proposed approach has been experimentally verified on a 6.8 Ah UltraLife UBBL10 Li-ion battery module. A two mode RC network battery model has been selected as a compromise of model accuracy and computational efficiency. The bandwidth of the model is selected to be 0.001 Hz—0.017 Hz, thus the time constants of the two RC networks are calculated as: $\lambda_1 = R_1C_1 = 60$ s and $\lambda_2 = R_2C_2 = 900$ s. Figure 10 shows the terminal voltage estimation results (the upper graph) and the estimation error (the lower graph) compared with the measured data. Note the estimation error is plotted on a logarithmic scale with a mean value of 0.0029V. From these example results, confirmed with extensive validation using arbitrary battery modulation with charging and loading cycles, we conclude that accurate terminal voltage estimation can be achieved using the proposed approach. A scaling algorithm was also developed for the wrapper that is beyond the scope of this paper, but it was validated with multiple permutations of UBBL10 packs. Validation with a 21 kWh Li-Ion battery and a consumer vehicle NiMH battery is planned.

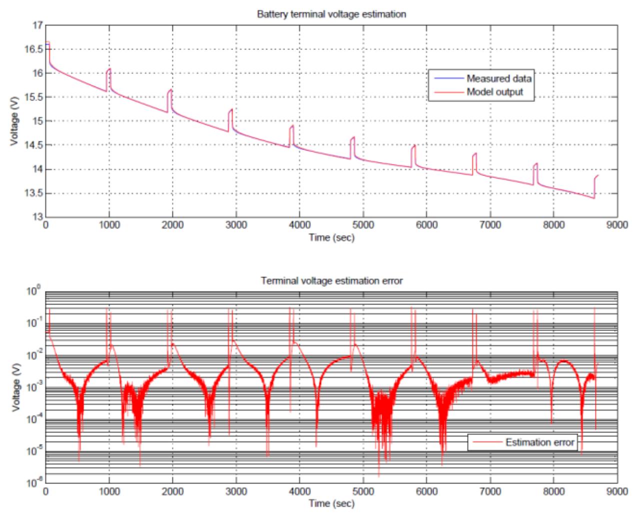

Figure 10: Battery terminal voltage estimation results vs. experimental data.

Power Electronics Converter Model

The need in concept analysis for an empirically based modeling methodology for proprietary power converters such as is commonly used in prime and non-prime power Army ground vehicle applications has risen significantly. This is equally true whether the need is to rapidly solve power management and energy conversion problems for the war-fighter on legacy vehicles or to continue support for the Army's larger goals for integration of electrical systems into future combat and non-combat vehicles. This need motivates the investigation of black-box models, which require little or no knowledge of the internal workings of a system.

To evolve the "wrapper" shown in Figures 3, 7 and 8, we propose a black-box modeling method for the construction and validation of a large-signal averaged model for specific commercially available inverter/converter products. A scaling algorithm is then applied based on a small number of system relevant component ratings and performance parameters. The benefits of this approach include the known computational advantages of averaged (also known as sub-switching-frequency) models in simulation and the availability of a simple procedure to create models for concept analysis and design evaluation without vendor supplied models or "white-box" information needed to create a circuit description of the part.

The focus of this investigation is the development of a complete average model of a converter module using a black-box approach. A similar investigation is reported in [5]. This work extends that investigation to include dynamics as a function of the output voltage as well as current limiting behaviors found in many practical power converters used for vehicle applications. The model interfaces to the simulation through a software "wrapper" that manages the large-signal aspects of the model, including an embedded small-signal model that computes operating point dynamics. The generic small-signal model structure is a two-port *g*-parameter network, comprised of four dynamic models: input admittance $Y_i(s)$, reverse current gain $H_i(s)$, forward voltage gain $G_o(s)$ and output impedance $Z_o(s)$ as shown in **Error! Reference source not found.**1.

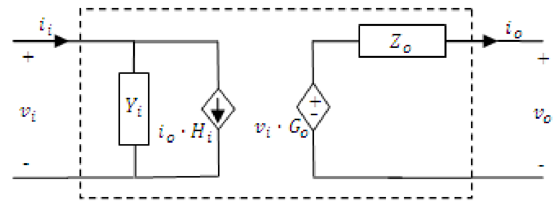

Figure 11: Black-box g-parameter network.

As an example, a model was created for the Linear Technologies LTM4612 power supply on a chip product. A load step excitation was applied to both the Simulink model and the LTM4612. The transient response of the LTM4612 and the transient response of the black-box model are compared on the same plot in Figure 12.

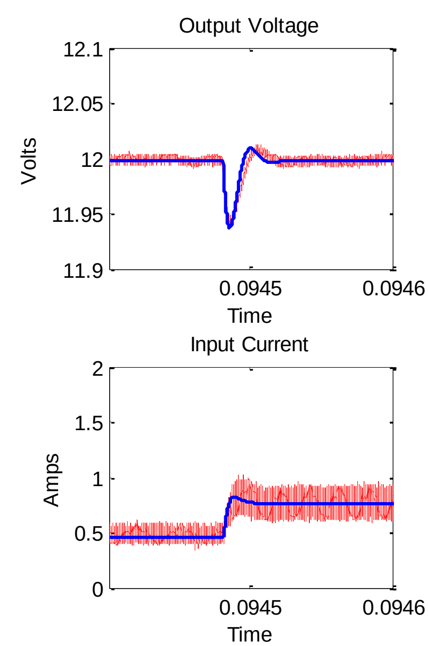

Figure 12: Transient Response Comparison of the Model (Blue) and the LTM4612 (Red)

Figure 12 shows that the Simulink model predicts the response of the LTM4612 due to a load transient at different operating points, confirming the successful integration of the small-signal model into the large-signal "wrapper."

A process similar to that of the ISG wrapper model will be used to abstract a generic large-signal black-box model for a vehicle-scale voltage transformation converter for non-prime-power system concept evaluations. A generic inverter model could be developed in the future.

CONCLUSIONS

This paper has described three different generic, scalable models for implementing rapid concept analysis and detailed systems engineering by professionals working in analytics rather than professionals who are subject matter experts in the domain of the components themselves. Key features of these generic models and the software "wrapper" that delivers them include (1) a small number of adjustable parameters from the domain of the simulation that define the performance of the modeled components so that the user does not have to be a subject matter expert in components; (2) scalability to the domain of the simulation to allow concept evaluations with advanced-technology "what-if" components (e.g., the battery model is validated with large-format batteries, rather than single cells); and (3) discrete adjustments for differences in technology (e.g., Li-ion vs. NiMH battery chemistry).

Future work includes further empirical validation with components within the scale range of the models and augmentation of the generic models with additional technology selections; including an induction motor option for the ISG model, a NiMH chemistry option for the battery model, and an inverter option for the power electronics model.

ACKNOWLEDGEMENTS

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