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The Development and Evaluation of a Simulink Based Power Model for High Power Systems

by

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Abstract

MATLAB, and by extension Simulink, is a staple within the engineering industry for modeling and the simulation of complex systems behavior. With extensive libraries available, custom function applications and parameter variability, physical systems can be recreated in a virtual environment with the ability to modify outputs through manual manipulation.

Simulink was utilized to create a large model representing the power distribution of a high voltage system (up to 600 VDC and 480 VAC) to ensure each load will receive proper power supplied. Unfortunately, these virtual models are only as useful as they are accurate to physical design. The power system model for the program in question quickly became outdated and inaccurate when left unattended, bogged down by irrelevant power sources and lacking fidelity throughout. To bring the model back to a relevant state, it was necessary to create accurate labelling systems in accordance with program documentation, account for physical phenomena originally ignored such as voltage drop across wire length, as well as display data in an informative and easy-to-understand manner. Simulink software provided a powerful tool to create a relevant, easily managed model of the physical project system that provided accurate estimates of total power usage as well as a breakdown of all power requirements per load. The model also allows for continual updating of system power needs based on manual user inputs, ensuring the system is always performing to necessary parameters.

1. Background

1.1 Power Generation

Despite the standardization of electricity as the primary power source within society, electricity is often stereotypically thought of as "magic" by those who are not familiar with its principles. To properly classify the behavior of high-power systems within digital models it is necessary to understand the fundamentals of electrical power.

Power generation and distribution is the main goal of all power management systems within complex products. It is the purpose of these power management systems to ensure each load is receiving both the correct amount of power and the correct type of power.

The two types of electrical power production include direct current (DC) and alternating current (AC). Direct current, as implied by the term "direct", is a constant level of power as the polarity of the system remains constant. In comparison, altenating current continually changes polarities between positive and negative terminals causing a sinusoidal behavior of the excited electrons. Similarly, the sinusoidal structure of AC power allows for the introduction of multiple phases, separated by an angle phi, ϕ, known as phase angle. The introduction of these phases provides multitudes of benefits such as increased voltage, greater system efficiency and reliability (Rajput, 2009, sect. 6.1).

1.1.2 Power Systems

As larger and more complex system are developed it is necessary to also develop greater sources of power. Within large electrical systems, "high voltages are crucial for power transmission over long distances…"; AC power is preferred for power distribution for this reason as it allows for the safe transmission of these higher voltages (Von Meier, 2006, p. 148). Unfortunately, many commercial products are operated using direct power at a lower voltage, creating a need for transformers (stepping AC voltage up/down), converters (transforming AC to DC power), and inverters (transforming DC to AC power). These three components are imperative to high power manipulation and distribution to required loads, but they are only a small portion of an entire power system.

Understanding the physical components necessary for high power manipulation is the most basic portion of power system design. Many more considerations are given to the other main sections of power systems: control equipment and protection equipment. An overview of basic multilevel power system structures is illustrated in Figure 2.

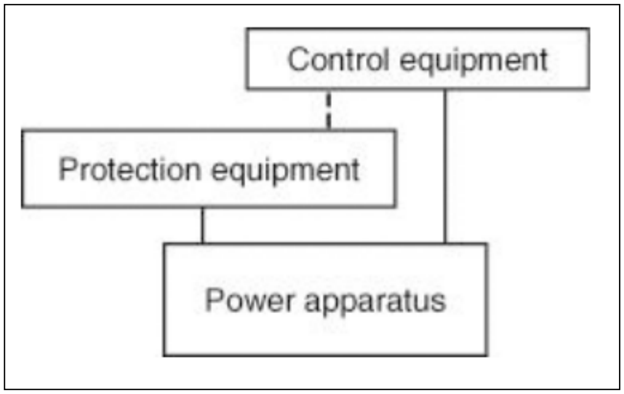


Figure 2: Three-layered Structure of Power Systems (Horowitz et al. 2014)

Electrical systems present unique dangers not only to users but also to themselves. Particularly within high power systems, it is extremely easy for unprotected components to be overloaded with current, voltage, or heat and cause catastrophic failure. This failure can affect not only the overloaded component but also other components that are integrated into the system. The possibility of this cascading failure is a major concern of engineers during design and testing to prevent delicate, expensive and/or custom components from being compromised, jeopardizing any forward work. As described by Horowitz et al., it is necessary to include protections within power systems “that detect abnormal power system conditions and initiates corrective action as quickly as possible in order to return the power system to its normal state”. This quickness in response not only continually protects the equipment being powered – preventing possibly program-ending setbacks – but also prevents any failures from harming engineers or operators. The control equipment necessary to properly protect these systems is most commonly circuit breakers and relays of various ratings installed at specific locations to prevent overcurrent/short circuit and control the applied voltages. Circuit breakers are applied to “trip” or prevent power from being supplied when the current is above a desired threshold while relays serve as an electrically powered switch supplying or denying the system power. The power apparatus requires these safety precautions in conjunction with control systems to ensure that components remain undamaged and continue to operate as expected, supplying the seemingly magical electrical power to the user.

1.1.3 Power System Implementation

Power management systems are the basis of all electrically dependent systems. Throughout residential and commercial buildings power management systems serve to control the power usage of occupants in both quantity and quality. In *Smart Building Systems for Architects, Owners and Builders,* James Sinopoli describes an electrical power management system as “a tool in managing and ensuring the quality of the power… free from surges, sags, and outages that may affect the facility’s reliability and safety”. Along with this constant monitoring of specific power consumption, error event alarms, and maintenance needs, power systems are also capable of monitoring the electric loads of major equipment. This silent monitoring of the necessary power draw of systems is present within massive facilities within power grids but also within many devices that are powered autonomously through batteries. The design of power management systems allows users to properly distribute and monitor a possibly limited energy budget for a designed system; the data collected by these systems on overall and specific power consumption depicts the behavior of an entire system to track the success or failure of component operation. Power management serves as an overarching monitor of system behavior ensuring that user-commands are safely executed through the direction of uninterrupted supplied power to the system components.

1.2 System Modelling

The development of digital computer models of physical systems, or digital twins, has provided designers with the opportunity to mediate major testing expensive through computer aided predictions. Software, such as Simulink by MathWorks, provides engineers with the opportunity to create digital replications of components and test their behaviors within differing configurations. Proper modelling of an operational high-power system is dependent upon the consistency and fidelity that is applied while the model is created. A set of basic rules or standards provides both the developer and the user with a common understanding of how the model operates as well as how its user operations will display. The creation of an accurate model allows for both initial testing of a design before physical construction as well as providing a visual representation of system behavior.

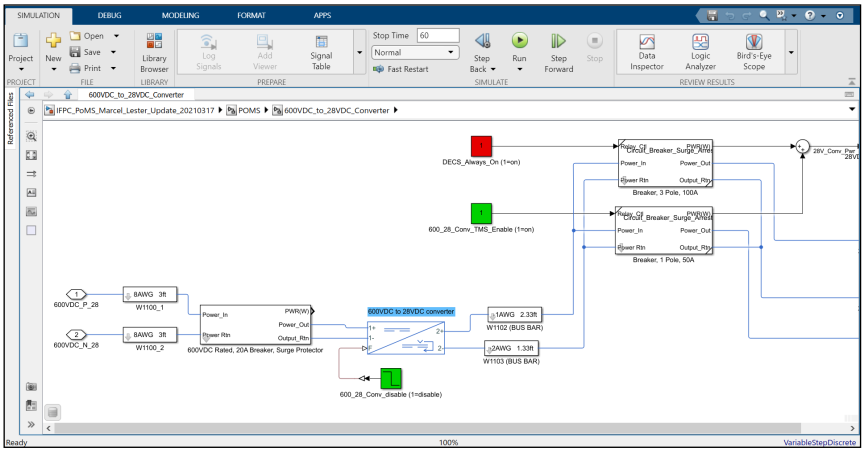
1.2.1 Modelling a Digital Twin

A digital twin is a designed virtual model that corresponds to an actual physical system utilizing data, sensors, and software to analyze the predicted behavior of a system (Melesse, 2020). Digital twins are often applicable within production, and predictive maintenance. Unlike physical systems, this digital representation can quickly integrate and test possible design changes without incurring the cost and labor requirement of large physical system changes. By predicting behavior of a system during normal operations as well as testing abnormal conditions, digital twins allow engineers to characterize a physical systems behavior without jeopardizing system components. This prediction also allows design engineers to vary operating conditions to optimize system performance and identify potential problems within the design. Through the analysis of digital twin models engineers are able to identify possible failure points within a design as well as allowing multiple configuration tests on a more accelerated timeline than physical tests and configuration changes would allow.

1.2.2 Simulink Basics

Simulink, created by MathWorks, is a widely used simulation software. Based upon visual components and connections, this software is often utilized by universities as an introductory learning tool for system engineering and control system development. Simulink models are built in a visual-heavy environment, with components represented as small moveable icons and connected by color coordinated lines representing the type of data being communicated. This heavy reliance on visualizing a system makes Simulink an extremely easy to use software. Its multitude of library components provide a blank slate for a nearly unlimited number of systems permutations within the software.

The basic principle behind Simulink modelling is the recreation of physical system using either library components or custom components/functions. These components are developed through MATLAB code, the cooresponding coding language developed by MathWorks. Figure 4 displays the base view of the Simulink environment in which a power system is modelled.



Stop Time 60

Normal

Figure 4: Simulink Modelling Environment

All models discussed utilize Simulink and MATLAB version R2021b. The implimentation of Simulink library and custom function components allow users to characterize physical systems as digital models for demonstration, verification and testing purposes.

1.2.3 Mathematical Background/Principles

Simulink, like many other coding and modelling tools, is based upon basic mathematical principles. These base equations are easily accessed within each components MATLAB documentation; this documentation thoroughly describes the coded behavior of each component as well as the settings that can be customized by the user. Through the creation of systems and subsystems, component-specific differential equations are defined by the software to represent the behavior of mechanical parts. These equations are then quickly combined and solved given user-defined initial conditions to produce the modelled system output (Aree, 2013, sect. 3). In the case of dynamic power systems, a system-accurate model can be created through the initialization of variables, a proper initial start of model (i.e. motors start from stall), define desired outputs via graphs or dials, and model outputs that match desired results (Aree, 2013). As an intuitive graphics-based modelling program, Simulink is an extremely effective tool in ensuring physical systems behave as expected as well as simulating model outputs in specific configurations.

1.2.4 Modelling Best Practices

Due to the sheer number of components and configurations available within Simulink, it is extremely important that basic guidelines are defined and followed throughout. Standard practices within modelling allow for consistency along system and subsystem levels as well as the seamless exchange of information between multiple designers or the designer and customer. Without consistent practices, models can quickly become inconsistent and disorganized causing more labor hours and money to be spent on updating and upkeeping the model. Generally, modelling guidelines are set by an overarching entity such as a program or company-wide policies. Guidelines can also be requirements of the system for industry compliance, as stated by Simulink's parent company MathWorks, "Industry standards such as ISO 26262, EN 50128, IEC 61508, and DO-178C make modeling guidelines a prerequisite" (Jaffry, 2014, para. 2).

General modelling guidelines are created by first defining and implementing the rules of the model and validate each guideline throughout model behavior (Jaffry, 2014). In comparison, Simulink also has several required guidelines for modelling within the software. These guidelines, unlike those mentioned previously set by industry or organizations, are required for any Simulink model to function properly and accurately without errors. For example, within physical domain libraries such as the Electrical library it is necessary for: at least one reference block to exist for proper grounding, all circuitry is simplified, parasitic resistance is included, and no excess sources are present to prevent excessive run time and warning messages (*Modeling Best Practices*, n.d.).

Most Simulink models that are utilized for testing purposes are not held to industry specific ISO, EN, or IED standards and are only held to Simulink defined standards which are almost always required. Generally, these testing and prediction models utilize common-sense guidelines to maintain organization and prevent overcomplication. The basic applicable guidelines include proper labelling of all components, implementing as many physical components as possible to mimic system, and organizing the model as clearly as possible while maintaining some resemblance to physical subsystem organization. These most basic requirements are often the most difficult to maintain within a model during the testing and development stage of a program as designs quickly change; if the model is not revisited to include these updates it will become less and less applicable to current system design.

The same steps for defining guidelines are also utilized for model updating. For a model to be considered up to date the previous guidelines are first reevaluated and redefined, if necessary, any new guidelines are implemented, previous guideline conformance is verified, and another final validation is necessary.

1.3 Purpose of Model

Power management is a major necessity when dealing with high power systems. It is imperative that not only does each load receive the expected amount and type of power but also that there are safety precautions working in tandem with control equipment to protect the system and the user. In the case of this high-power system, it is the purpose of the Power Management

System or PoMS, to manage the intake of power, its conversion, and its distribution to two other subsystems. This system consists of a rack holding several trays (similar to a server rack) each of which are utilized to control, invert, filter, and monitor the power associated with the load and its subsystems. Within this discussion, reference to “the program” or “product” refers to the entire deliverable system in which PoMS is integrated, other “system” or “load” references refer to the other subsystems or components that PoMS will provide power to.

The model in question is a digital twin of this PoMS system, verified and updated alongside the physical system. This model was beneficial early within the design process as it provided a visual example of designed power outputs for the customer; later within the design and development process the model served as a secondary verification of test outputs as well as a digital pre-test for any redesign concepts before they were applied. As a digital twin, this model included many of the same components as the physical model. The power requirements of the product are diverse; beginning with 600 VDC supplied power and various loads requiring 480 VAC, 270 VDC, and 28 VDC. It is necessary for the model to mimic these conversions within subsystems, many of which are organized to resemble the physical system configuration. Unfortunately, when left unattended, the PoMS model became obsolete as major program changes were implemented to the physical design without being reflected within the digital model.

2. Methodology

2.1 Model Evaluation

Within early stages of production, the product design is extremely fluid and major changes can be made in a matter of days. Due to this, it is imperative that models are continually managed and updated; when left unattended, models become inaccurate and no longer applicable to current design. When this occurs, it can be an extremely daunting and time-consuming task for an engineer to remodel the system under the new design. The PoMS model was left unattended for nearly a year as the product design was finalized and was only revisited once production and initial testing had already begun.

Modelling engineers must rely heavily on the most recent system schematic as well as coordinate with the system engineers to evaluate the current state of a model and understand the changes that need to be applied. Through collaborative discussion, the necessity of model modifications and the compromises to convert from a physical to digital environment become clear. Generally, the components that are central to this discussion are those that have become obsolete and the elimination of these irrelevant portions of the model. Similarly, it is necessary to further evaluate the fidelity necessary within each subsystem: which subsystems require the greatest level of similarity to the physical system, where can physical components be disregarded in leu of faster run time, as well as where physical/digital component similarity is clearly lacking and needs to be included. After this cooperation between the model and design engineers for the PoMS system, a list of action items was created: itemizing all components that were no longer necessary, defining components that needed higher fidelity, identifying new physical phenomena to incorporate, and outlining a goal list of visual user outputs.

2.2 Identification of Problems

Through comparison to the current schematic, a comprehensive list of inaccuracies was defined for the PoMS model. Throughout the model there were several components that were identified to no longer be relevant within the model. For example, the original PoMS system included three sources of 600 VDC power which were later combined within final design. Due to this, the original differential equation solver within the model involving three possible power options became obsolete. Outside of this primary simplification, the main changes necessary within the PoMS model included adding or updating the necessary protection equipment such as circuit breakers, relays, and surge protectors. These components required specific ratings for allowable voltage and current levels as well as a user-input screen or “mask” allowing for these ratings to be manually changed without manipulation of the subsystem. Similarly, the other major changes that were designated action items included updates to the physical principles of the model using a model specific function. Finally, small but significant changes were necessary within the organization and labelling of the model to be in accordance with the overall schematic labelling and physical model organization. This major list of action items was extremely fluid throughout the model redesign and was continually revisited as components were updated to ensure the most accurate Simulink model of the PoMS system was developed.

2.3 Application of Updates

In attempts to streamline the often-daunting workload of model updates, it is beneficial to first begin with the smallest, easiest errors and work upwards through the more complex tasks. Primarily, the first issue that should be addressed within a model is the presence of outdated and unnecessary components. These components and the organization of the system provide the model developer with a starting point to move on to larger issues. Within the PoMS model it was first necessary to overhaul the power sources being fed into the system. By eliminating two irrelevant power sources the model was extremely simplified visually and eliminated the switch between power sources and improved system run-time. Secondly, the organization of the model was revisited to replicate the organization more closely in the physical system. At the time of the original model design the PoMS system was not organized within a rack/tray configuration; however this organization is imperative to understand the basics of the system. A model organization mimicking this physical construction is much more beneficial in terms of translating between the digital twin and the actual system and more clearly communicates the path of power within the trays before being passed to the respective loads. To create this new organization scheme the subsystems of the model were created and/or rearranged vertically within the model to represent corresponding trays. Figure 5 demonstrates the final reorganization of the tray system within the PoMS model.

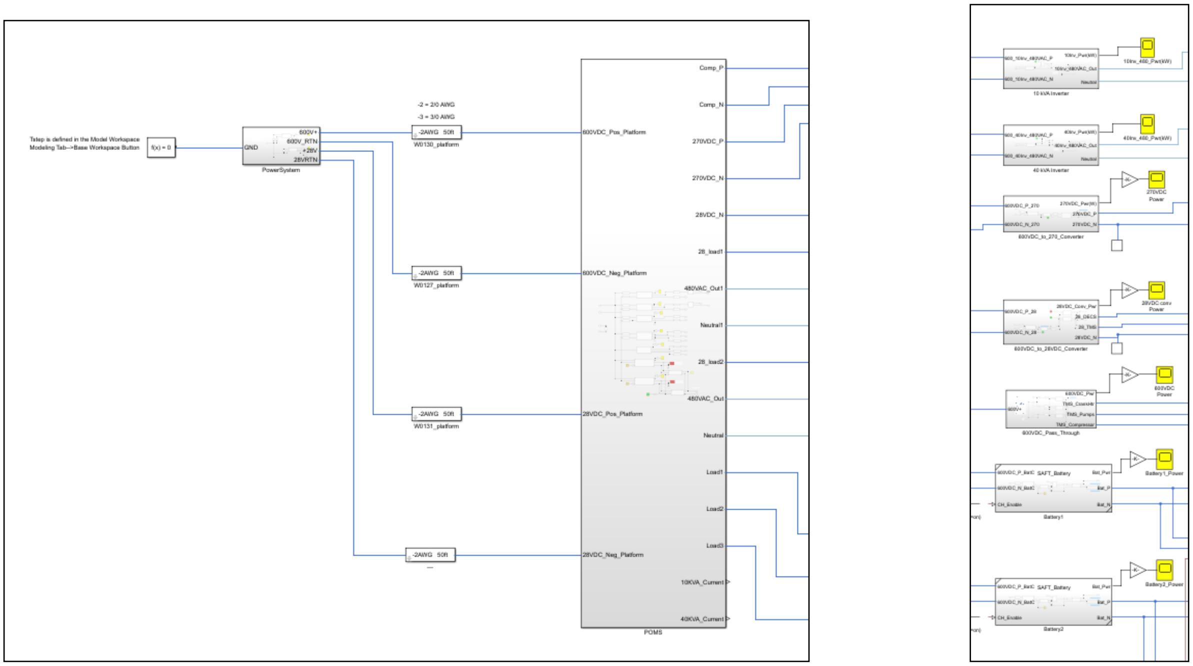


Figure 5: PoMS System [left] and Subsystem [right] Model Organization

Once the model properly mirrored the physical system it was much easier to identify the areas in which components were missing or lacking in fidelity. The greatest area of missing components within the model was protection equipment. These subsystems, including a combination of circuit breakers, relays, and surge protectors, are necessary throughout the physical model to properly control and protect system components and cause changes in the electric properties. Without these components present in the model it is impossible to see possible errors in system configuration that would cause these protective devices to engage and stop the simulation. For example, the inclusion of circuit breakers allows engineers to test if specific configurations would overload the system (trip the breaker) without risking physical damage to the integrated part. These protection components were added as a subsystem behind a user-input mask, allowing for the safety parameters to be easily manipulated. A subsystem containing both a circuit breaker, relay and surge protector is displayed in Figure 6; Figure 7 displays the user-input mask and Figure 8 displays the entire subsystem.

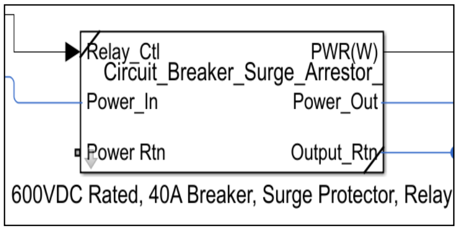
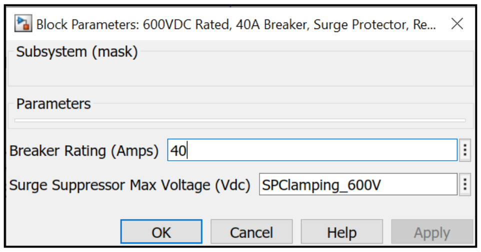


Figure 6: Protection Subsystem Display



Block Parameters: 600VDC Rated, 40A Breaker, Surge Protector, Re...

Subsystem (mask)

Parameters

Breaker Rating (Amps) 40

Surge Suppressor Max Voltage (Vdc) SPClamping_600V

Figure 7: Protection Subystem User-Input Mask

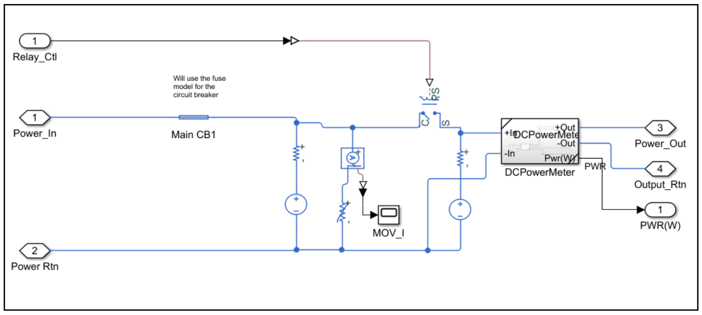


Figure 8: Protection Subsystem Components

As shown in Figure 7, user-input parameters can be defined by another vairable. In this case, the variable “SPClamping_600V” references the max voltage allowable by all 600 VDC rated circuit breakers. Through this variable several breakers can be manipulated at one time, ensuring that all modelled 600 VDC breaker parameters match their physical counterparts throughout the entire system. Although this protection subsystem was present in the outdated Simulink model, it was applied sparatically and did not differentiate between subsystems that require all three protection components (circuit breaker, surge protector, and relay) or only a specific combination of these components. Once updated the model included all of these necessary subsystems where they are present in the physical prototype.

Once protection systems were included, the model very nearly modelled the physical system. The expansion of the custom wire function continued this increase in model fidelity and similarity to current design. This unique MATLAB function was created to represent the physical effects of wire size and lengths on electrical variables. Within wires, the movement of current must overcome the resistance of the wire matieral, causing a small drop in measured voltage across the wire. A digital twin model must account for this small change in order to maintian the necessary level of fidelity. In order to properly apply this created function, the function was expanded to include a larger array of wire sizes and the function was applied to wire connections throughout the entire model. This function requires a user-input of wire size (gauge) as well as length to accurately calculate the voltage drop of the wire; an example of the user interface (UI) for this wire function is shown in Figure 9.

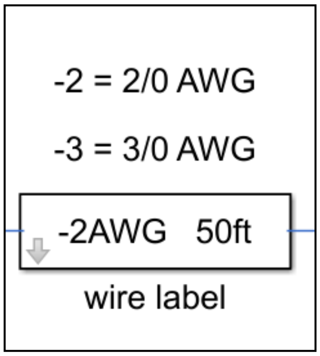


Figure 9: Custom Wire Function Applied within Model

The consistent addition of both the protection subsystem and wire function throughout the entire PoMS model increased the overall fidelity of the system by accounting for physical phenomena that were previously ignored, improving the accuracy of each measured power output to the system loads.

In order to properly conclude the update the PoMS digital model the user interface output and proper component labelling were finalized. Within modelling it is extremely important that a model is easily understood by all engineers or customers that may be utilizing it. In order to do this it is imperative that the labelling scheme within the model correspond to the most recent system diagram. Within the custom wire function labelling (seen in Figure 9, “wire label”), users are also able to identify which wires stretch between componenents in accordance with internal program documentation as well as its characteristics. After each of these labels were updated and included, the Simulink model of the PoMS system was considered updated and verification against physical measurements could begin. In order to properly verify the outputs to each load, it is necessary to display these outputs within the model. Simulink includes an extensive library of measurement displays including dials, gauges as well as user-input switches in order to properly display the data for user interpretation. An example of these dials can be seen in Figure 10.

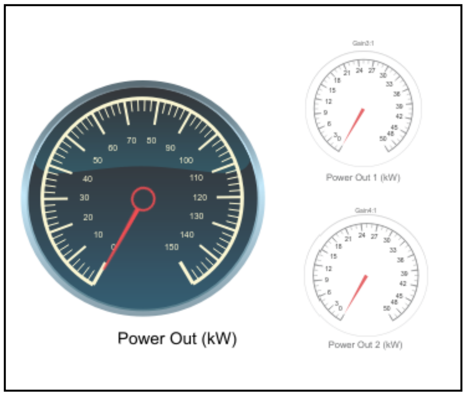


Figure 10: Example of System Visual Output

These output dials are compared to the calculated expected power per load and serve as verification that the digital behavior properly mimicks the measured output of the prototype system under the same configuration.

2.4 Verification Against Physical Design

In order for the PoMS model to be considered an accurate digital twin of the physical system, the model outputs were verified against baseline configuration measurements and calculations. The multiple user interface dials displayed the power output to each load of the system. The resultant power values, measured in Watts, displayed on these dials were then compared to the expectedcd output as calculated through the design schematic as well as the true measured values of the tested system. The model was considered an accurate depiction of system behavior if these displayed values were within 20% of the physical system. Once verified the output dials of the model served as an accurate demonstration tool for customers who either do not understand the complexities of a Simulink model or are solely concerned with system performance. Each output of the PoMS model was verified to fall within the determined margin of accuracy and the model was deemed an accurate depiction of the physical system.

3. Results

Once updated, the Simulink model of the Power Management System was significantly more accurate than the previous version; all physical system components were properly represented, and the power delivered to each load was verified against the current design schematic. To properly verify these loads the updated model was simulated and the power outputs were recorded; these were then compared to the most updated schematic which detailed the expected current and voltage values for each load. Each output of the PoMS model fell within 20% of the expected value, many of which fell within 10% of measured values with one outlier with a 17% difference. These margins were deemed acceptable to the design engineers and the model was considered an accurate digital twin of the system. The model was run with several user-input configurations through manipulation of switches and dials; these outputs further confirmed the accuracy of the digital model and performed as expected with additional parameters. Each portion of the PoMS model was additionally verified by engineers throughout the modelling process in order to ensure proper configuration and model outputs performed correctly.

4. Conclusion

Through the evaluation, development, and verification of the Power Management System (PoMS) model within the Simulink modelling environment, it was possible to utilize the model as a digital twin for testing system changes. This model also allowed engineers to verify the performance of the product under various user-defined configurations. The Simulink modelling software is an extremely powerful tool for model development with near innumerable number of systems that can be digitally mimicked. However, this tool is only as useful as it is applied consistently with high rates of fidelity. Without management, models – such as the PoMS system

– quickly deteriorate in accuracy and require a large amount of work to bring back to a usable state. The evaluation and further development were necessary in the case of the PoMS model which had been unmanaged and unattended for just under one year causing it to become outdated and no longer reflect the current deliverable design. To properly return this model to a useful state it was necessary to coordinate with design engineers to understand where the model was lacking in fidelity or missing components, then create a list of action items that were implemented throughout the model. The three main problems that were discovered within the previous model included: irrelevant components being present, lacking fidelity in physical phenomena, as well as missing design organizations, labels, and components. Once these issues were resolved, the power outputs to each load were and the model was considered an accurate digital representation.

The digital modelling of complex systems allows for changes to be thoroughly explored and tested prior to any physical hardware modification. As programs such as Simulink become more powerful and incorporate more custom functionality the use of digital twin models will become more standard within engineering practices. Computer aided simulation and test will allow programs to predict the success of several solutions before the additional hardware cost, labor cost, and loss of time incurred by failed physical changes. The creation of a systems digital twin provides engineers with a valuable resource for testing, demonstrating, and validating the behaviors of ever-changing systems at every step of the development process.

Appendices

Appendix A: Works Cited

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