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AN INTELLIGENT ELECTRICAL POWER MANAGEMENT STRATEGY FOR MILITARY VEHICLES

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ABSTRACT

An efficient and collaborative process for the realization and implementation of an electrical power management strategy for a modern military vehicle is demonstrated. Power, software and hardware engineers working together and using simulation and emulation tools are able to develop, simulate and validate a power strategy before prototype vehicle integration, reducing integration cost and time. For demonstration, an intelligent electrical power management strategy is developed for a generic military vehicle with conventional engine/transmission propulsion and an inline generator. The challenge of this architecture is maintaining electrical bus stability/regulation at low engine speed given that electrical power demands may exceed power supplied. The intelligent electrical power management strategy presented limits the total power demand to power available by overriding the demands of the individual loads. Based on load prioritization and vehicle system dynamics, power limits are issued to the individual electrical load controllers. The collaboration process to develop, model, simulate, and validate this intelligent power management strategy is presented. In addition, the tools used to facilitate this collaboration; Mathworks Simulink/StateFlow/Real-Time Workshop and the Vehicle Electrical Power System Test-bed, are detailed.

INTRODUCTION

Vehicle electrical power management will continue to grow in complexity as a result of the continual electrification of military land vehicles. This complexity will require an increase in collaborative efforts between power, software and hardware engineers. Modeling tools such as Mathworks' Simulink and Real-time Workshop [1] and the use of a 'hardware in the loop' test-bed will enhance this collaborative effort, resulting in reduced cost and integration time.

In the past, the basic process of realizing electrical power management started with the power engineer developing requirements documents which stated on/off conditions for electrical loads. These conditions were based on power available and vehicle operating conditions. The documents were peer-reviewed and handed off to the software engineer, who wrote the necessary code to implement the strategy. The code was peer-reviewed and software validated. During prototype vehicle integration this code was implemented in hardware known as the vehicle supervisory controller. The controller commanded power distribution hardware, which connected/disconnected electrical loads from the bus. These electrical loads, i.e. pumps, compressors, and fans, are designed by hardware engineers on the assumption that enough power is supplied to complete the assigned local task. During prototype build, all the major electrical system components – the electrical loads, the electrical power distribution hardware and supervisory controller – along with the electrical source and batteries are integrated, tested and debugged. Generally, the more complex the overall electrical system is, the more time that is needed for trouble shooting and tuning. The extra time required is at the expense of integrating other systems onto the vehicle, therefore increasing overall lead time.

The integration time of complex electrical power systems can be significantly reduced if a greater percentage of testing and tuning is accomplished before prototype build. To accomplish this, power, software and hardware engineers should begin working together sooner and utilize simulation and emulation tools. In the following section, an efficient and collaborative process will be presented for the development and realization of a vehicle electrical power management strategy.

THE DEVELOPMENT PROCESS

From the vehicle specifications and requirements, the power engineer designs the vehicle electrical architecture with a controllable distribution system and with optimized power generation and storage. In addition, the requirement is added that all electrical loads be responsive to power limit commands. Based on vehicle electrical power capability and load prioritization, from mission requirements, the power management strategy is developed. This strategy, along with the necessary feedback and command signals, is modeled using Mathworks/Simulink's Stateflow and is called the Intelligent Electrical Power Controller (IEPC). Modeling the IEPC in Stateflow has several advantages. First, the model is a visual aid, allowing other engineers to obtain a more detailed understanding of the functionality of the power management strategy. The second advantage of modeling the IEPC is the ability to test and verify the strategy. There are two levels of testing: 1) using a Simulink 'Test Rig' model to manually input test vectors and confirm outputs; and 2) integrating the IEPC with the vehicle electrical architecture model consisting of the electrical sources and loads. The third advantage of developing an IEPC model is the ability to generate code directly from the model.

Working together, the power and software engineer generate code from the model using Mathworks' Realtime Workshop auto-coding capability. The software engineer has two major tasks: 1) set up the model template; and 2) develop the software wrapper. The model template consists of the auto-coding compiler rules and the global input/output s-function blocks with variable names and format. These variables link the IEPC application to the wrapper application.

The wrapper software is responsible for establishing the system clocks, data acquisition, interface with the user, and interface with the vehicle hardware (generator controller, distribution equipment and electrical loads). The software and hardware engineer work together to establish the communication protocol between the IEPC and all the components on the bus. Once the IEPC application and wrapper are realized in hardware and the communication bus has been established and tested, the next step is to validate the vehicle's electrical power management using the Vehicle Electrical Power System (VEPS) test-bed.

The test-bed is designed to emulate the electrical loading dynamics of the vehicle. Actual or emulation hardware is integrated with the IEPC. The flexibility and fidelity of the VEPS test-bed allows all three engineers to work together to focus on integrating the vehicle electrical system prior to vehicle integration.

As is shown in the following sections, more complex vehicle electrical architectures and the resulting power management strategies will require greater interaction between the IEPC, electrical loads, and electrical sources. A demonstration of this process is presented in the following sections. An example of an intelligent electrical power management strategy is developed for a generic military vehicle with conventional engine/transmission propulsion. The vehicle's electrical power source is a 50kW inline high voltage generator. A brief description of the electrical power challenges of such a system is described. The process of realization of the power management strategy is detailed with the modeling and simulation of the IEPC. The software wrapper is described including the communication interfaces. The test-bed used for validation is described and experimental results are presented.

DEMONSTRATOR

In the case of vehicles with conventional engine/transmission propulsion with inline generators, electrical power management presents a unique challenge [2]. Mechanical power from the diesel engine is split between propulsion and electrical power generation. The maximum output power of the generator is dictated by engine speed as shown in equations (1, 2).

$$P_{engine} = P_{propulsion} + P_{electric} \tag{1}$$

$$P_{engine} = \omega_{engine}(\tau_{wheel} + I_{generator}K_t) \tag{2}$$

As shown in (2), the generator current must increase with a decrease in engine speed if electrical power is to remain constant. The generator system, including the power electronics, is designed to produce maximum power at a rated engine speed. At speeds less than rated, less electrical power is available. Increasing the generator system's current and flux capacity will produce more power at lower engines speeds, but will be at the cost of weight and space. For military vehicles, weight requirements are not driven solely by overall efficiency but also by operational requirements such as air transportability. As a result, there is a power versus weight/space trade-off in the selection of the generator. However, reduced electrical output at lower speeds can be compensated for by intelligently managing the distribution of that power.

Power Management Strategy Overview

The automotive industry is continuously improving the management of the vehicle's electrical power. Using various control and optimization schemes for electrical power allocation, [3], [4] and [5], the overall fuel efficiency is improved. The basic strategy for electrical power management is to distribute power based on load prioritization, when demanded power exceeds available power. For this effort, power is selectively allocated by issuing power limits to each electrical load. The electrical loads adjust their power consumed accordingly, despite their local requirements. This results in a complex interaction between local and global power needs [6]. For example, one possible scenario is a cooling fan may be commanded by the thermal controller to operate at 75% rated power, however, the IEPC temporary overrides the thermal controller by limiting the fan to 50% rated power. When power is available the fan is allowed to reach 100% rated power to compensate the increased temperatures.

The IEPC monitors the power consumed by each electrical load and compares the value to the load's nominal power requirement, establishing the percentage of allotted power consumed. This information in addition to the load prioritization determines which loads have to fold-back power and by how much. For example, reducing power limits on several loads by 25% may be preferable to reducing the power limit on one load by 75%. Also, if a load already is operating at 10% of rated power it may not be preferable to reduce the power limit to less than 10% but rather to reduce the limit on another load. The hardware and power engineer have to work together to ensure global power demand does not exceed power available, ensuring critical tasks are met and less critical tasks are most efficiently fulfilled.

The IEPC also monitors the engine and transmission. If the vehicle is in neutral and the demanded power exceeds power available, the IEPC issues an increased throttle command, closing the power loop between the engine and generator.

If the demanded power is greater than the available power, the generator becomes current limited, resulting in a loss of voltage regulation. The IEPC maintains bus voltage regulation by ensuring power demanded does not exceed power available. In addition, employing power fold-back to the loads, instead of load shedding, reduces bus transients improving the overall stability of the bus.

For this demonstration the representative vehicle electrical loads include: an air handling unit (AHU), an auxiliary hydraulic pump, a compressor, electronic load banks and engine cooling fan. The main cooling fan and pump have the highest priority, followed by the compressor, and finally the AHU.

IEPC Model Development

The power management strategy is best implemented in terms of state transition logic. The transition from one state to another depends on power available and operational mode, i.e. combat or training. The tools chosen to model the IEPC were Mathwork's Simulink and StateFlow. Stateflow provides a visually interpretive structure for ease of understanding the logic of the IEPC. Simulink provides the environment for simulation.

The following figures illustrate how the logic of the IEPC is modeled in Stateflow. Figures 1 and 2 illustrate the logic for managing the power to the vehicle's compressor. Figure 1 shows the logic for determining the available and requested power. In figure 2, the power limits on the compressor are determined based on current power state and load priorities.

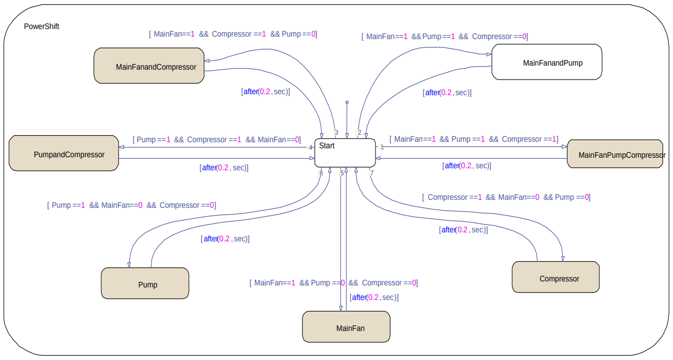


Figure 1: Logic for determining Power

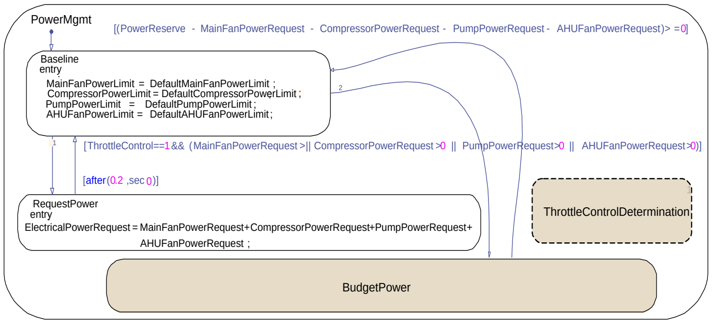


Figure 2: Logic for establishing compressor power limits

IEPC Model Simulation

Once the IEPC model is completed, the power engineer can validate the management strategy in the Simulink environment. Using a Simulink test rig, the functionality of the IEPC model can be validated. Input vectors of different states and conditions are applied to the model and the resulting states and conditions are confirmed. Next, the IEPC model is inserted into a high fidelity vehicle electrical system model. The system model consists of all of the components on the bus. For this demonstration, the system model is of the reduced, generic vehicle electrical architecture. The model consists of:

- 50kW Interior Permanent Magnet (IPM)
- Generator Controller: 6-leg IGBT Inverter with current and voltage loops

- Four servo motor with controllers and constant power loads
- A Resistive Load
- DC/DC Converter with Load
- Switched Load Controllers

Figure 3 shows the system model with the IEPC embedded. The generator is an IPM 50kW machine with maximum torque per ampere control (MTPA), implemented with Rotor-Flux Orientated Control (R-FOC).

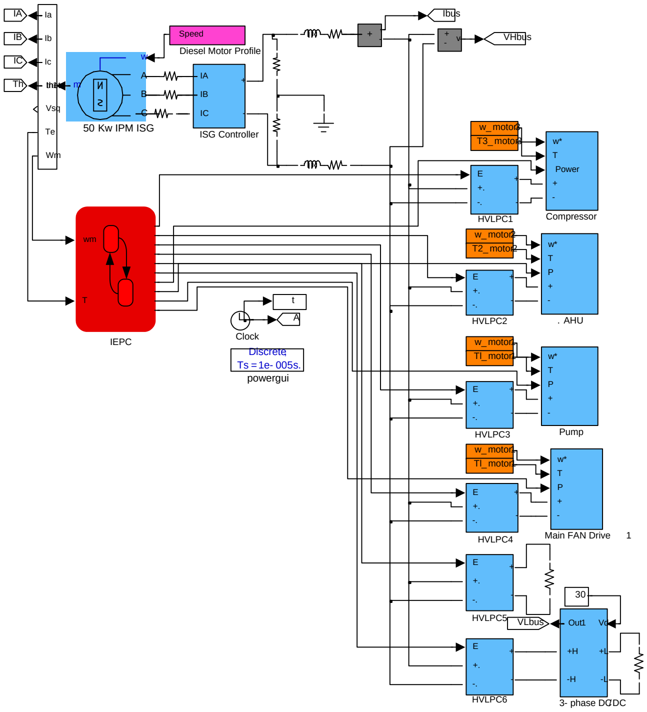


Figure 3: Simulink Model of the Vehicle Electrical System

Figure 4 shows the simulation results of the vehicle electrical model. From 0.1 to 0.6 seconds the bus voltage is ramped up in order to charge the capacitors on the bus. At 0.8 seconds the DC/DC converter is brought online. The compressor and fans are sequentially brought online and ramped up. Between 1.3 to 1.8 seconds the engine speed is increased. At 3.5 seconds the speed is decreased, as a result the available power is less. The IEPC commands the compressor to reduce power in order to maintain bus voltage regulation.

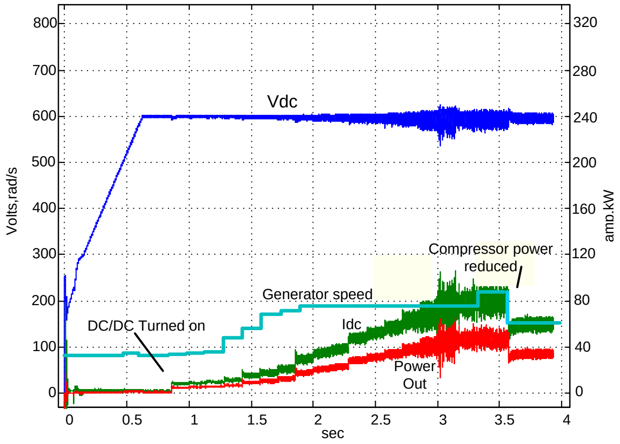


Figure 4: Simulink Model of Electrical System.

Realization of the IEPC in Hardware

Figure 5 shows the hardware implementation of the IEPC. The model is auto-coded and embedded into the wrapper code. The code is developed and maintained by the software engineer. The wrapper provides the interface between IEPC and electrical hardware via the CAN driver. Power measurements are passed from each of the loads and the distribution hardware to the IEPC. Power limits and switch commands are passed from the IEPC to the loads and the distribution hardware. The wrapper code also performs several other tasks:

- Loads the user gains into the IEPC upon startup
- Provides the timing signals for the IEPC and CAN driver.
- Manages the interface with the data logger and user GUI

The Data Logger is used for diagnostics and tuning of the system. The user interface allows the soldier to monitor the electrical system and to have override capability.

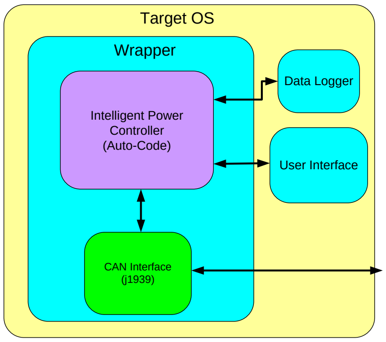


Figure 5: Software Architecture

Once the IEPC is implemented in hardware, the next step is to validate the power management strategy with actual hardware and loads. For this demonstration, a generic vehicle electrical power system (VEPS) test-bed was developed to validate the power strategy and hardware interaction, especially the concept of power limiting of the electrical loads. The following section describes how the VEPS test-bed is used to validate the system.

Hardware Validation of Power Management

Managing demanded electrical power by issuing power limits requires significant coordination between the IEPC and the electrical components on the bus. Extensive tuning is required on both the IEPC and the electrical components. One major IEPC issue that requires attention is tuning the persistence/hysteresis times for state transition. Relatively slow communication rate loops and signal noise can result in "chattering" in the power limit commands. For the electrical components, the issue is maintaining stability when receiving conflicting commands. A simple example is when the fan controller is issued a speed command by the thermal controller and unable to obtain that speed due to a decreased power limit, resulting in a saturation of speed loop. The VEPS test-bed allows engineers to work together to tune and validate the electrical power system. Figures 6 and 7 show the generic VEPS test-bed built for this demonstration.

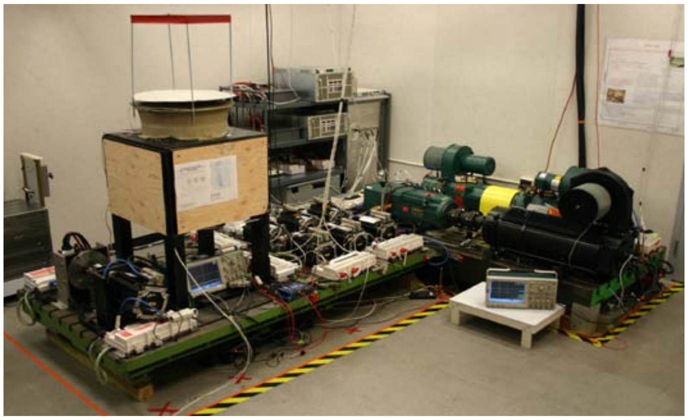


Figure 6: VEPS Test-bed

Ideally much of the actual hardware would be used in the test-bed setup. However, if the actual hardware is not available, a hardware emulator can be used. Likewise, a load emulator can be used if it is not practical to implement a vehicle load. For example, loading a vehicle fan requires a restrictive air duct. Instead, a 4-quadrant dynamometer can be used to emulate air flow loading and resulting power draw.

The VEPS test-bed can be described as two systems, each supplied by separate HV buses: (1) the Load Emulating Bus (LEB); and (2) the Vehicle Emulating Bus (VEB). In the following sections, these buses and the hardware attached to each will be described.

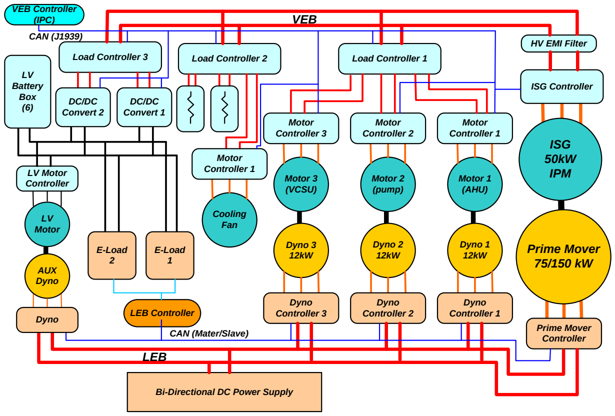


Figure 7: VEPS Test-bed Schematic

Load Emulating Bus (LEB)

Connected to the LEB are 5, four-quadrant dynamometers. Four of the dynamometers emulate dynamic loads on the vehicle, such as the turret drive, cooling pump, cooling compressor and fan. The fifth dynamometer emulates the diesel engine, which is the prime mover.

All five dynamometers are controlled by the LEB controller over CAN. Similar to the IEPC, the LEB controller was developed in Simlink/Stateflow and embedded in a C++ wrapper. The controller is responsible for issuing the load emulating speed/torque commands to the dynamometers at a rate of 100Hz. The torque applied by the dynamometers consists of two parts, a static component and a speed dependent component. Figure 8 shows the resulting torque output of the load emulator for a simple fan.

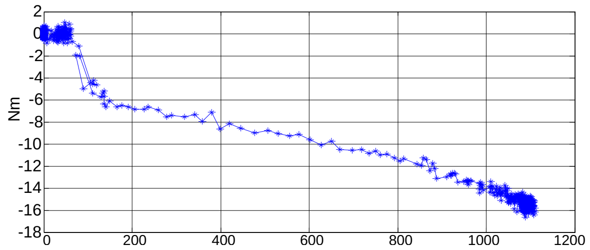


Figure 8: Fan Speed/Torque Emulation

Vehicle Emulating Bus (VEB)

The part of the VEPS test-bed that emulates the vehicle electrical components is called the VEB. It consists of an IPM generator, five servo motor drives, two DC/DC converters, a low voltage battery box and the IEPC.

The 50 kW IPM generator is loaded/driven by the prime mover (75kW IPM). MTPA control, [7],[8], is used for the generator current loops. Dc link voltage and load current feedback are used for the voltage loop (active boost rectification [9]). All electrical machine code was developed in house in order to provide maximum flexibility. Figure 9 shows experimental data of the bus voltage and the IPM generator currents during developmental testing. The controller is optimized for both speed and load disturbances.

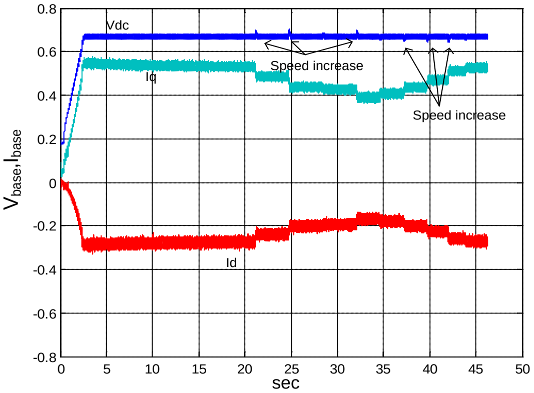


Figure 9: Generator Currents and Voltage

Also part of the VEB are two High Voltage Load Power Controllers (HVLPC). These devices are commanded by the IEPC to connect or disconnect hardware from bus. The HVLPCs control the power distribution and protect upstream and downstream components. They monitor the current of each channel as well as its input voltage. In addition, the HVLPCs monitor power quantity and quality. The real power of each device is measured and sent to the IEPC. Power quality is determined by calculating the Total Harmonic Distortion (THD) of the direct currents of each device. This information is used by the IEPC for system and component diagnostics and prognostics.

HVLPC 1 supplies power to three permanent magnet servomotor drives, emulating a fan, compressor and pump. HVLPC 2 supplies the cooling fan (sensorless controlled PMSM motor) and two resistive load banks. HVLPC 3 supplies power to two DC/DC converters supplying low voltage power to: two e-loads, a gun turret servomotor drive, a resistor bank, and a battery bank. Figure 10 shows the functionality of the VEPS test-bed. The compressor and pump react to the local cooling needs of the vehicle. The AHU is manually adjusted. The generator speed is constant and the demanded load is less than the available load; power management is not required. Shown are the bus voltage, Vdc, the generator phase current, Iphase_a, and bus current, Idc.

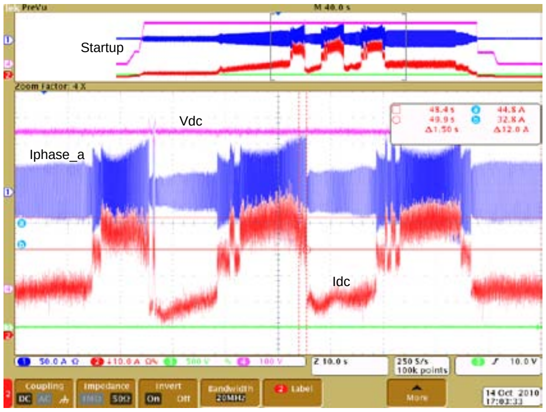


Figure 10: Demanded power less than available power

POWER MANAGEMENT EXPERIMENTAL RESULTS

Procedure

The IEPC commands the generator to begin voltage regulation when the prime mover has obtained speed. Next, the IEPC sequentially commands the vehicle loads. The first load commanded to turn on is the cooling pump, next is the main cooling fan and finally the compressor. The speed of the cooling fan is determined based on the speed of the prime mover. The two resistive loads are commanded to turn on at different speeds to emulate additional main fan loading. The AHU is manually turned on (Low, Medium or High) via the soldier's GUI. After power startup, the drive profile is enabled. The prime mover speed profile is enabled from the LEB GUI. Figure 11 shows the plot of the drive profile.

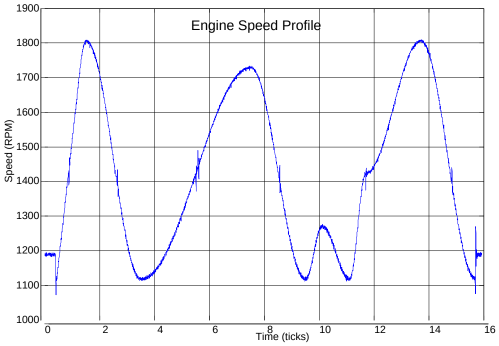
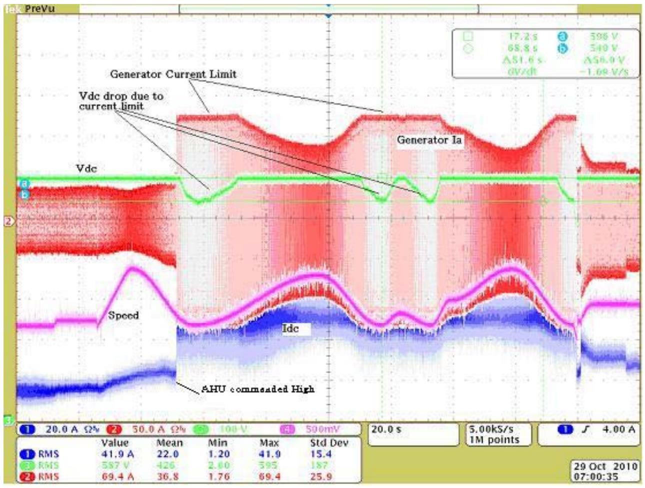


Figure 11: Engine (primer mover) speed profile

Baseline Run: Without Power Management

For the first test, the power management is turned off. The vehicle loads are still sequentially turned on but there is no power fold-back of the loads. The resistive load is commanded to turn on 20 seconds after the drive profile has begun. In order to maintain voltage regulation and meet the increased power demand, the generator applies more torque against the prime mover. As a result, the phase current increases. When the phase current limit is reached, the generator is unable to sufficiently increase its torque to maintain bus voltage regulation which. When the speed increases, the required torque decreases, as does the phase current, and the generator comes out of current limiting mode. The bus voltage level returns to the commanded level. The dc bus voltage drops three more times due to increase load and lower engine speeds. Figure 12 shows the dc bus voltage, dc bus current, the generator phase current, and the prime mover speed.

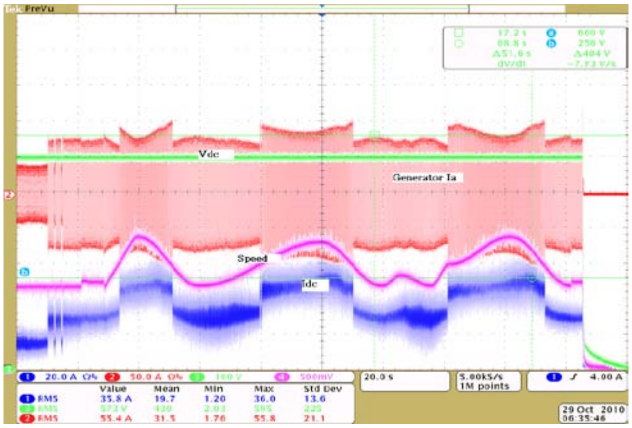


	Value	Mean	Min	Max	Std Dev
1 RMS	41.9 A	22.0	1.20	41.9	15.4
RMS	537 V	426	2.60	595	187
2 RMS	69.4 A	36.8	1.76	69.4	25.9

Figure 12: Without Power Management

With Power Management

For the second run, the power management strategy is implemented. As shown in figure 13, the resistive load is commanded to turn on 5 seconds into the drive profile with the speed increasing. When the speed begins to decrease, the IEPC commands the resistive load off (the lowest priority load). When the speed decreases further, the power of the AHU is folded-back as seen by the decrease of I_{dc} at 37 and 115 seconds. When the speed increases beyond 1250 rpms the IEPC commands the resistive load to turn back on. The AHU also is allowed to return to full power.



	Value	Mean	Min	Max	Std Dev
1 RMS	35.8 A	19.7	1.20	36.0	13.6
RMS	573 V	430	2.03	595	225
2 RMS	55.4 A	31.5	1.76	55.8	21.1

Figure 13: With Power Management

Figure 14 shows data recorded from the IEPC during the run. Plotted are the Power Available, Power Consumed, main cooling fan Power Limit and speed curves. The Power Consumed is the instantaneous power of the system. The total Power Available is based on the capability of the generator (speed vs. power curve).

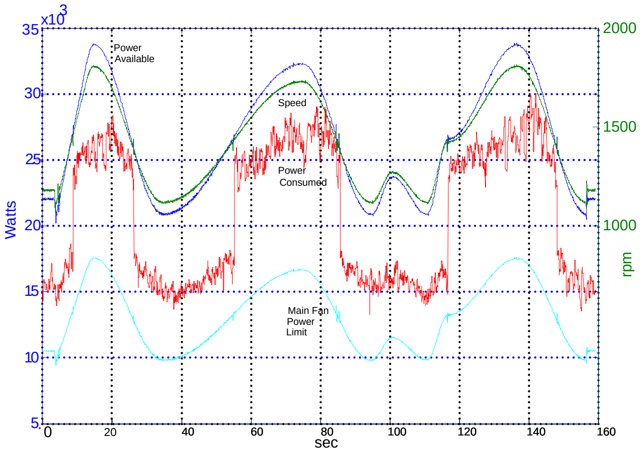


Figure 14: Power Available (blue), Power Consumed (red), Main Fan Power (light blue) Limit and speed (green) curves

CONCLUSION

A collaborative process between power, software and hardware engineers using modeling/simulation tools and hardware emulation tools reduces the integration risk at vehicle build. The technique of centralized control of power limits gives the power engineer the ability to guarantee voltage regulation, and flexibility to best meet the local power needs of the vehicle, when available power is limited. However, this technique increases the complexity of the interaction between the vehicle's electrical components. An electrical system test-bed facilitates the validation of the power management strategy and the refining of the source and load interactions.

ACKNOWLEDGMENTS

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