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System Design Considerations for Vehicle-based Mobile Electric Power Applications

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ABSTRACT

Many of today's mission systems require mobility and transportability. Therefore, they cannot be tethered to utility power or stationary generators. The industry response has been to use vehicle-based mobile electric power systems. The applications are growing in number, and have common problems that must be solved by the power systems engineers. The purpose of this paper is to discuss design considerations for vehicle-based mobile electric power systems. We will discuss a case study of a vehicle-based mission power system application, the specific needs associated with the application, and technologies being developed to address them. General strategies for vehicle power system architecture, conversion and distribution, control and management, and built-in-test will be outlined. A sample power system simulation model will be demonstrated. Design practices for power system grounding and protection will be summarized. The author will share his experiences and lessons learned developing military and commercial power systems for vehicle-based missions.

INTRODUCTION

Vehicle power trends show that military and commercial mobile vehicle applications are increasing. There are more electrical demands on engines and auxiliary loads. Survivability and safety systems are becoming more advanced. Precision controls for performance, fuel economy and emissions control are increasing. As vehicle electric power architectures become more complex and demanding, the need for robust power systems engineering becomes more critical. This paper will consider vehicle electric power architectures at a system level and describe design strategies and lessons learned from recent development projects to improve the performance and reliability of these systems.

Consider a power system in its simplest form. Table 1 outlines basic functions of a simple power system, the purpose of each function, and typical components that perform those functions.

Table 1: Power System Components

Function	Purpose (Components)
Source	Creates/provides usable energy (battery, engine, external power)
Path	Provides energy transfer (wiring harnesses, distribution channels)
Control	Manage energy flow (converters, protection circuits, dashboard controls)
Load	Energy-using devices (motors, lights, communication equipment)
Indication	Measure power parameters (meters, sensors, diagnostics, feedback)

These functions are integrated in any vehicle power system. We will consider each of these in a sample architecture.

VEHICLE ELECTRIC POWER SYSTEM

A sample power architecture for a military hybrid electric vehicle is shown in Figure 1. The application considered for this system is a high-power expeditionary military mission platform.

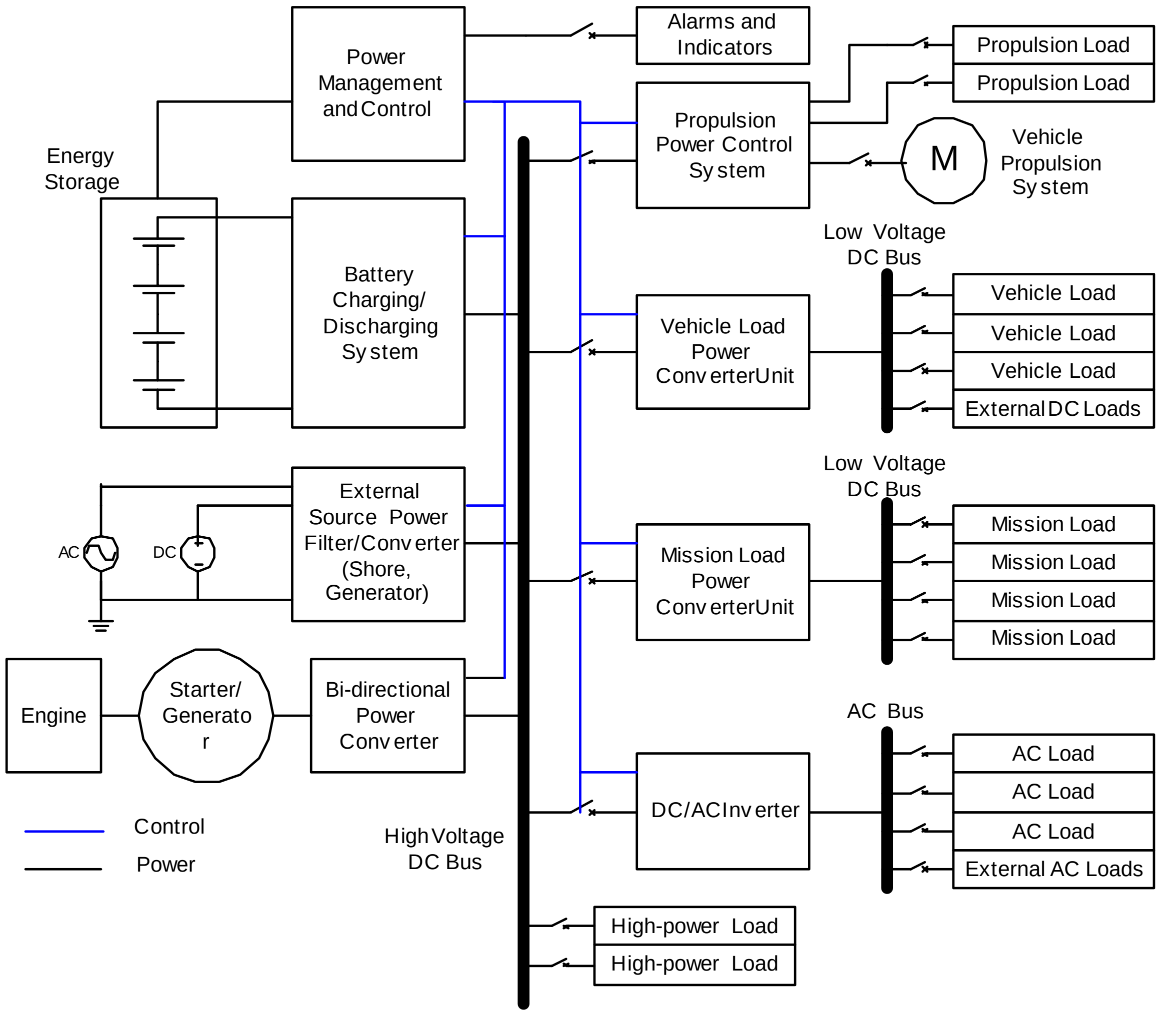

Figure 1: Vehicle Electric Power System

This power system architecture case includes all of the functions described in Table 1.

SOURCE

Primary power can come from several sources. Many vehicle power systems rely solely on the engine to provide mechanical energy which is converted by an alternator or generator to electrical power. Others use external AC or DC sources, such as mobile generators. This case architecture shows both internal (engine, energy storage) and external (shore power, DC generator) power sources.

A high-voltage energy storage system is also provided in the case architecture. This is a fundamental component of a hybrid electric vehicle application and is becoming more prominent in military mobile, expeditionary applications. It provides a portable, rechargeable source for on-the-move high-power demands.

Mission-critical systems often accept multiple and/or paralleled sources such that the mission can continue when the prime power source fails. Uninterruptible power supplies and backup sources can also be used to provide keep-alive power to mission-critical elements when prime power sources fail or during vehicle transport. Source flexibility is a growing requirement in military applications and commercial missions. This case architecture was designed to provide that source flexibility and reliable, uninterrupted power.

External sources require a ground system and power interfaces. When the vehicle stops and the mission is deployed, the ground system is installed and external power sources are applied. Expeditionary systems enable quick-connects of power cables, fuel and grounding systems.

Source conditioning devices, such as EMI filters and surge protection, are usually used to provide a clean power signal to the system. These devices are especially important when connecting to external sources such as utility and shore power. They also are valuable to protect components from propagating failures generated across the power system.

Vehicle platforms may use standard source characteristics. For instance, shipboard systems typically comply with CIL-STD-1399 Section 300, while aircraft power systems usually comply with MIL-STD-704. High-power systems, such as hybrid electric vehicles, aircraft and ships, use DC and three-phase AC.

PATH

Transmission paths transmit energy from the sources to the loads using distribution devices, power busses and wire harnesses. Power distribution designs must consider system and component performance when determining partitioning and conversion architectures. Components with the same voltage level and mission criticality can share a distribution bus.

In our example case, a high-voltage DC bus is used to interconnect the multiple power sources. In a typical hybrid electric vehicle application, this could be the DC link that supports power flow between the generator, battery storage and propulsion control system. A high voltage bus provides effective power distribution with minimal wire losses.

Partitions are created to separate groups of loads by voltage type and function. The low-voltage DC and AC busses provide partitioned distribution to the vehicle and mission loads. By separating the mission loads from the vehicle loads, the mission can proceed with an electrical failure in the vehicle by disabling the vehicle bus. Likewise, if the mission electrical system fails, the vehicle can still operate. These capabilities are crucial in battlefield environments.

The distribution wiring infrastructure is usually derated significantly to minimize power loss in the wire. Larger conductors add weight but their lower impedance improves the power system efficiency. They also support higher current and therefore enable future system growth. It is usually better to build a wiring infrastructure that can support future growth than to upgrade the wiring when the growth options are exercised.

CONTROL

The control elements of a power system form the most complex part of the architecture. Control architectures are usually tailored to the application requirements. Several devices are used to manage energy flow throughout the power system including power converters, condition and protection devices, power management and load shedding.

Converters

Voltage converters are used to create AC and DC voltages and distribution busses for the various application loads. Converters can be passive or actively controlled devices. Passive converters are efficient (>94%), light and reliable, but they do not provide voltage regulation, isolation or power factor correction. Active converters can be used to regulate voltage and provide isolation and power factor correction at a cost of converter efficiency (<90%) and size.

Filtering and Conditioning

Filtering and signal conditioning should occur on all major components and interfaces to provide clean power. Power line conditioning includes voltage and current limiting, rectification, power factor correction (if necessary), regulation and harmonic distortion control. These conditioning devices have a price in that they usually decrease system efficiency and reliability.

In some military applications, TEMPEST filtering is used for red/black isolation of power interfaces. This isolation is needed to prevent coupling of classified data onto the power system. MIL-HDBK-232A and NSTISSAM 2/95 provide guidelines for these installations.

Protection

Power system protection includes devices and architectures to mitigate faults and satisfy engineering design practices, requirements and guidelines. Grounding, lightning protection, bonding/shielding and surge protection improve the safety and reliability of the vehicle power system.

Grounding provides the system with an electrical reference. In most HEV, automotive and aerospace applications, where power is used while the vehicle is in motion, this reference is the chassis. In deployed mobile expeditionary applications, such as military radar and communication systems, the power system ground is referenced to the earth through a ground rod, ring, surface wire, or alternate grounding mechanism.

Lightning and surge protective devices provide a low-impedance path to ground for lightning and electrical surges. This protection minimizes damage to sensitive equipment and personnel during atmospheric or electrical phenomenon. When these anomalous conditions occur, the preferred path for the electrical flow is through the protection circuitry instead of the vehicle electronics.

Bonding prevents charge accumulation on electrical components by providing a leakage path through the vehicle to ground. Electrical components are enclosed in conductive chassis and/or connected through a bonding strap to the ground system. This ensures that the device stays at ground potential and remains safe to persons who may come in contact with it.

Large vehicle power systems will use lockout-enabled emergency stop switches in the prime power backbone. These switches enable the user to interrupt power during a fault or anomalous operation. They can also be used for lock-out/tag-out during maintenance procedures.

Several handbooks and guidelines support military power system protection design, including MIL-HDBK-454A, MIL-STD-461E, MIL-STD-464, MIL-HDBK-1857, MIL-STD 188-124, and MIL-HDBK-419A.

Power Management

Power management devices provide system monitoring and control functions to verify system operation and detect/isolate faults. Figure 1 shows a power management and control device that communicates with the other power system components and distribution devices to coordinate power flow and control logic.

A major function of a power management system is interlock and distribution control. This occurs when loads are mutually exclusive or must power up in a known sequence. For example, in the case architecture there are mission loads and propulsion system loads. It may be desirable to prevent mission load operation when the vehicle is in transport (i.e. propulsion loads are active). Similarly, it may be beneficial to inhibit propulsion system loads when the engine is being started.

Power management devices may manage data and interaction for the entire power system. System components will often require data from other devices to support control algorithms. Power controllers can act as a data concentrator and can hold system calibration and configuration parameters.

Load Shedding

Vehicle loads, propulsion component, mission loads and auxiliary loads are distributed on independent circuits. This enables each functional group to be controlled independently. If the total load on the source power approaches a user-defined limit, auxiliary circuits can be disabled. This approach will maintain power sources for critical mission loads without risk of overloading the prime power source.

Load shedding requirements are becoming more prominent in advanced vehicle systems. Energy storage devices, such as battery banks and uninterruptible power supplies, have a limited amount of energy (in amp-hours) available to support load operation. Load shedding removes non-critical loads to maximize the power operation time of the critical loads.

LOAD

The loads are the end users of the power system. Example loads include vehicle loads (air conditioner, heater, lights), mission loads (military communications, refrigeration system, ambulance equipment, fire engine equipment), survivability and safety (collision avoidance, GPS) and communications and entertainment (radios, game systems, cell phones, laptops). Recent trends show a growing number of loads and corresponding power demands in vehicle applications. Loads should be comprehensively analyzed to determine their power demands (static, transient and peak) over all operating conditions, compliance to standards, and static/dynamic operating characteristics. Power budgets can be developed from load characteristics and operating profiles.

Partitioning

The distribution of loads may be partitioned by load function, mission priority, voltage characteristics and vehicle location. Functionally-similar loads that are co-located and have the same voltage characteristics may be grouped together on the same power bus that is partitioned from the system using an isolated voltage converter. Figure 1 shows several load partitions. Effective partitioning and modular distribution help support designs for load shedding, protection, interlocking, power load flow management, and load prioritization.

Bi-directional Sources

The two internal sources of Figure 1, the engine and the energy storage system, are bi-directional. They can each serve as a power source or a power load. The battery pack is a source during discharging and a load during recharging. Likewise, the engine is a source during operation but a load during startup. It is easy to ignore these loads in load analysis and power budgeting. However, their impact on the power system can be significant, so they must be understood.

External Loads

Many mobile expeditionary systems require support of external user loads such as personnel tools and equipment. For instance, the architecture of Figure 1 provides power interfaces for external AC and DC user loads. These power demands should be included in the load analysis and power budget. Since designers have little control over what loads the user will connect to these interfaces, they should be limited and protected against external fault and overload conditions.

INDICATION

Indication devices, such as voltage and current monitors, built-in-test, and feedback controls, improve the fault tolerance of the power system. Figure 1 shows alarms and indication devices connected to the power management subsystem. When the power management subsystem detects failures and/or warning conditions, the appropriate alarms and indicators are actuated.

Health management functionality is often integrated into a vehicle power system. In the case architecture, this functionality was provided by the power management subsystem. Some of the power system health management functions performed by this subsystem include:

1. Power source integrity test
2. Power protection system monitoring
3. Converter health monitoring
4. Propulsion system command and built-in-test (BIT) response
5. Energy storage system charge management
6. Fault mitigation and operational alerts
7. Fault reporting (data blocks and BIT Logic Inspection (BLIN))

Some indicators, such as hour meters, user displays and indicator lights, are hardware based and can be monitored by users with no special test equipment. Software-based indicators, such as fault logs and timers, are only accessible through testing interfaces.

DEVELOPMENT PROCESSES

The development of vehicle-based power systems requires robust design processes as well as practices. Poor specification, design or testing of new vehicle power applications can result in operational incompatibility between equipment and subsystems, cause power system failures, and even result in user safety concerns.

Design and development processes for vehicle-based power systems follow similar patterns as other product development. Design phases of a typical power system development are shown in Figure 2.

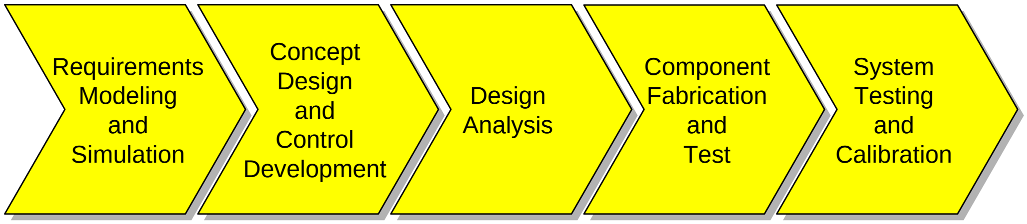

Figure 2: Power System Design Phases

Requirements modeling and simulation are used by the power system architect to determine operating characteristics, identify system requirements, and define the power system architecture. Concept design and control development efforts create the detailed design of the system components. Design analyses verify the designed system performance against system requirements. Component fabrication and test efforts integrate and qualify the operation of each component. System testing and calibration are used to integrate the full system of components and verify performance over all operating conditions.

Safety guidelines are crucial in power system development. Power systems that are designed improperly can cause significant damage and injury. Depending on the industry, platform, application and use of the power system, copmrehensive safety guidelines may be required.

Model-based systems engineering can be a valuable tool to effectively design power systems and understand/validate the integrated system performance. System power budget models help the system designer analyze the power demands and margins available for the system. Power load levels, converter efficiencies, distribution devices, and protective devices are included in the model. By modeling power flow, the designer can determine the necessary ratings of devices and circuitry.

Power simulation helps to mitigate risks during system development. Some of the benefits of vehicle power system simulation include:

- Early feasibility evaluation and benchmarking among a wide array of power system architectures and technologies
- Early change/risk management
- Collaboration and communication across the integrated program team
- Simplified, modular implementation and integration
- Constant and immediate feedback
- Evolving power system platform to meet true application needs without upgrading hardware
- Prototype enhancement throughout project life-cycle
- Life-cycle planning and growth demonstration
- Comparison of field test data with simulated experimental data
- Adjustable demarcation between simulation and hardware-in-the-loop

Hierarchical models should be developed, as in Figure 3, to enable functional decomposition during architecture development, building block integration during performance validation and component-level modification during detailed design. These hierarchical designs can easily be modified and reused for next generation applications.

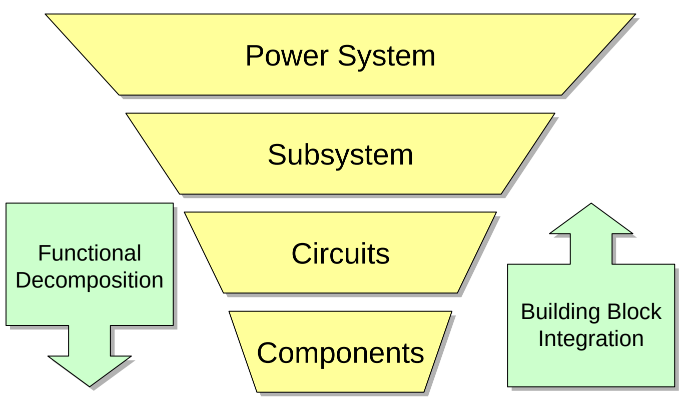

Figure 3: Hierarchical System Models

An example of a power system simulation in SimPowerSystems is shown in Figure 4. This system shows the performance of the startup of an emergency generator after a three-phase fault during operation of an asynchronous motor. This model is analogous to the switchover to keep-alive power in a UPS during a prime power fault. The bottom curve in the rightmost plot shows that the load motor will lose speed but will regain performance within 0.8 seconds. This type of analysis helps the user understand the system response to anomalous conditions without the need for injecting the actual fault in real hardware.

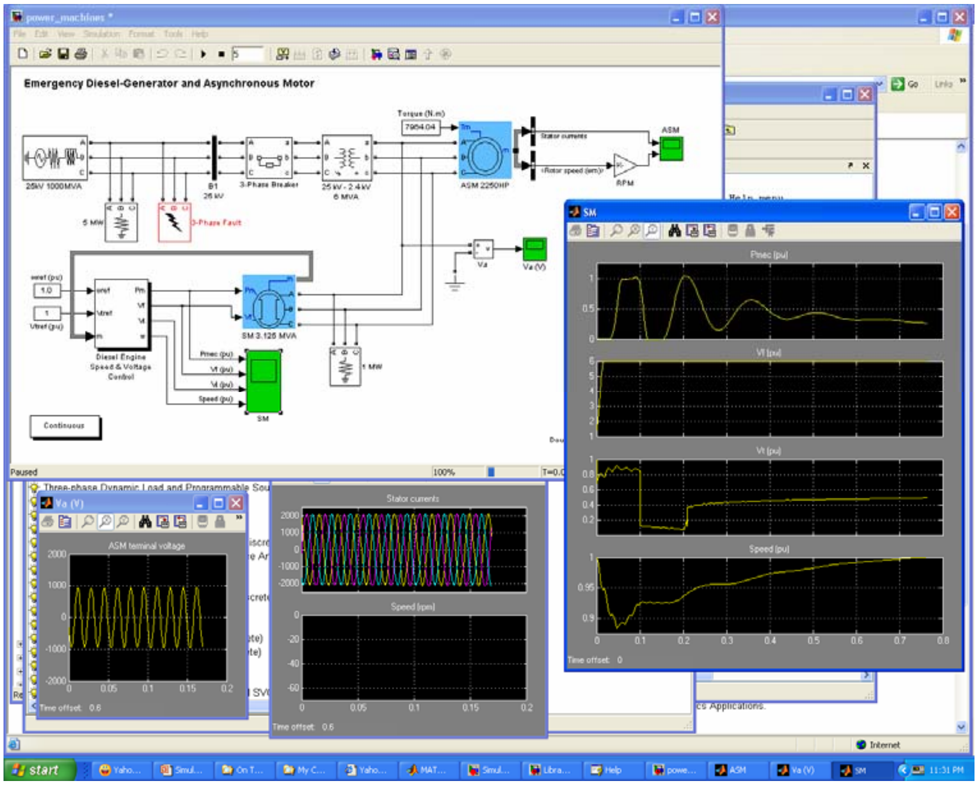

Figure 4: Sample Simulation of a Power System (derived from SimPowerSystems demo)

CONCLUSION

This paper has taken a case study from a recent vehicle-based mobile electric power application of the author and revealed some key system design considerations that should be understood by developers of similar applications. There is a growing trend for more advanced and complex vehicle-based power systems. The concepts presented in this paper provide proven practices and valuable lessons learned to help power systems designers develop effective and reliable applications.

Since this paper could only provide a top-level discussion of power system designs, readers are encouraged to research detailed guidelines and recommendations for component and system-level design and analysis.

CONTACT

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