Model-Based Design for Hybrid Electric Vehicle Systems

Hybrid Electric Vehicle (HEV) development requires collaboration and optimization across multiple engineering domains.

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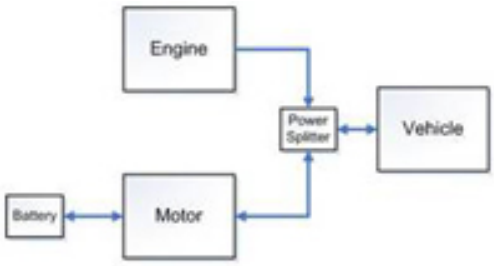
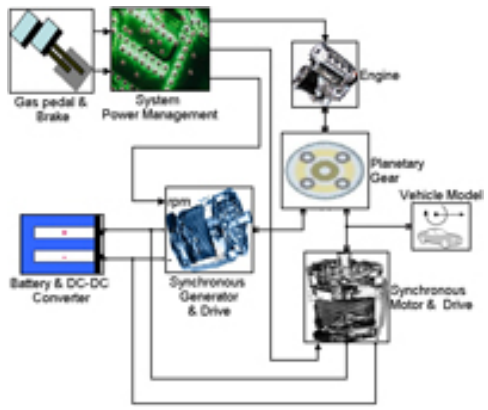


Energy security, fuel prices, and environmental concerns have increased pressure on the automotive industry to create energy-efficient and environment-friendly vehicle designs. Research in the last decade and a half has led to a range of vehicle designs based on electric drives. These designs include pure electric, hydrogen fuel, and various forms of hybrid electric vehicles (HEV). Challenges abound for electric drive design in general and HEV in particular. Model-Based Design can help automotive engineers effectively address the challenges inherent in implementing these designs in an organization.

The general concept of a hybrid electric vehicle is to combine the right proportion of an electric drive with an internal combustion engine depending on driving conditions, so both can work in their optimal operating range as much as possible.

Figure 1 shows a simplified schematic of one possible arrangement for an HEV. The electric motor and the gasoline engine are coupled through a power splitter and supply energy to the driveshaft. In practice, planetary gears are used for the power-splitter function. This leads to coupling of the nonlinear dynamical equations governing the electromechanical components, leading to added mathematical complexity of the system. To improve fuel efficiency, the design requires a strategy for managing these coupled power sources. To increase the energy density further, permanent magnet synchronous machines (PMSM) are often used. Also, optimizing the core design of the various components such as the engine, the motor, the planetary gear, the generator, and the battery can also bring about significant fuel savings.

HEV Design Challenges



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In addition to the inherent design complexity, there is also development process complexity involved in building an HEV. The high coupling of various components requires that the various engineering teams collaborate and share their designs with each other. This leads to a design with multi-domain complexity. For example, there will be specialized teams involved in engine design, battery design, and power electronics design. To ensure that the final design meets the overall design goals, these teams need to collaborate, communicate, and exchange their component designs regularly. At the system level, these components need to be integrated to form the overall design. Also, the teams need to conform to time lines while ensuring that their design meets requirements and is free from errors. Such constraints impose the need for a concurrent design process that will let the various teams collaborate productively.

Traditional approaches such as paper-based processes with linear workflows increase the possibility that design bugs will be detected late in the development process, leading to higher costs. Such a process is not amenable to implementing an HEV design that requires nonlinear workflows. Even with design approaches based on software tools, the diversity of development environments used by the different teams can make it very challenging to create interfaces for the different component designs.

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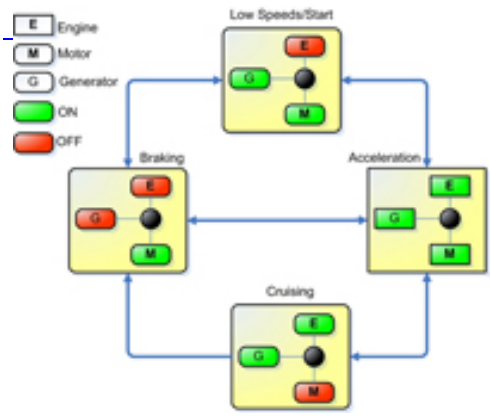
Model-Based Design seeks to resolve and improve upon many of the weaknesses associated with these processes. The key idea is that the development process centers on a system requirements capture and design to implementation and test. This system model is an executable specification that is elaborated throughout the design using simulation as a key verification and validation step. In other words, this executable specification forms the sole "truth" source for all the teams to check their designs against requirements via simulation. When software and hardware implementation requirements are included, such as fixed-point and timing behavior,

code can be automatically generated for embedded deployment and test benches created for system verification, saving time and avoiding the introduction of hand-coding errors.

Using Model-Based Design for highly complex systems such as an HEV, with its highly specialized functional components, typically fits into the "divide and conquer" methodology. The initials steps are to come up with an executable specification for a model of the overall system with the interconnected components that meets broad-level requirements. With the right level of detail or model fidelity, faster simulations can be carried out to address feasibility concerns early in the development process. Specialist teams can then elaborate on the component designs by using these executable specifications as a guideline. As model elaboration progresses, the requirements undergo refinement both at the system and the component levels. After design iterations, the components are integrated to form the final solution. In the next section, a case study illustrates how Model-Based Design supports these key ideas.

Case Study

The case study is based on a design experiment to understand how Model-Based Design, in particular the use of an executable specification and design with simulation, along with the latest design tools can be effectively applied to HEV development.



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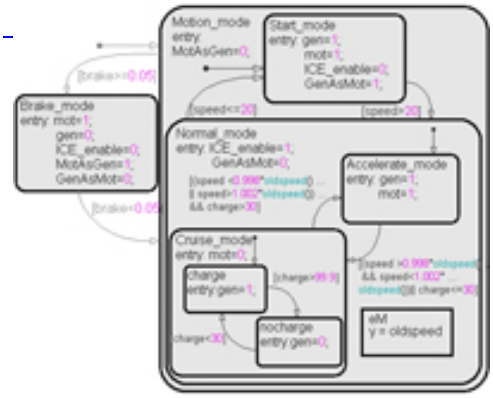
In the initial stages of the HEV design, it was very easy to define the broad requirements for the entire system. For example, requirements centered primarily on fuel economy. We were willing to compromise with the performance requirements if necessary. We used the following modest fuel economy and performance requirements for a set of drive cycles:

• Fuel efficiency: Greater than 36.5 mpg
• 0-1/4 mile in 25s: Initial acceleration helps in identifying the motor requirements because the engine cannot provide torque at low speeds, and most of the power is supplied by the motor.
• Top speed of 120 mph: Maximum velocity is necessary because the power required at this speed should be met by the combination of the engine and the

motor supply. It guarantees that all speeds between rest and this maximum speed can be attained by the combination of electric battery and gasoline engine power sources.



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A functionally componentized system-level model of the HEV realized in Simulink is shown in Figure 2. Note the similarities with Figure 1. System-level modeling enables visualization of the system architecture with modular interconnectivity, aiding in understanding the complex system better.

Next, we illustrate the design of the synchronous generator and drive component with Simulink. Figure 3 shows a low-fidelity model based on mathematical relationships between the generator drive torque, speed, and control voltages. This level of detail greatly enhanced the speed of simulation, because we did not have to deal with the high-frequency switching that would be present in the associated power electronics circuitry.

In Figure 4(A), we show the conceptual framework consisting of ON/OFF states of the engine, motor, and generator. We define the vehicle modes as follows:
• Low speeds/Start: The electric motor provides all the torque for initial acceleration.
•Acceleration: As the vehicle reaches a predefined speed, the engine kicks in to supply power along with the motor.
• Cruising: If the car maintains constant speed, the motor is switched off and the generator is switched on. A portion of the engine's power is used by the generator to recharge the battery.
• Braking: If brakes are applied, the engine and the generator are switched off. The motor is made to behave like a generator to recharge the battery.

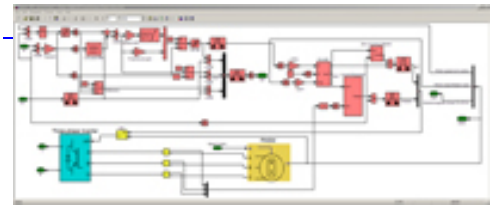
Figure 4a. On the left is the conceptual framework (A), and on the right is the associated executable specification in Stateflow (B).

In Figure 4b, we translated this conceptual design into a hierarchical state chart modeled in Stateflow. This executable specification is simulated and tested with the rest of the model.

The following results came from simulating and testing the system-level model

compared with the requirements:
• Fuel efficiency greater than 6.5 mpg (requirement met)
• 0-1/4 mile in 25s: 0-1/5 mile in 25 s (requirement not met)
• Top speed of 120 mph: top speed of 100 mph (requirement not met)

Since fuel economy is more important for us than performance, we leaned toward compromising the last two requirements. Once we were satisfied with the level of fidelity and the results, the components in the system-level model were handed over to the domain specialists to elaborate on them.



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We offer an example of how such elaboration took place for one of the components mentioned earlier the synchronous generator and drive. The electric machines and drives specialist researched various machine manuals and checked specifications of available machine drives and their library of Simulink controller models. The broad-level requirements in the system-level components provided enough opportunity for the engineer to refine and improve upon them while ensuring the practicality of the design.

Figure 5 shows the elaborated model consisting of the machine, power electronics circuitry, and the associated controllers. The use of a three-phase AC permanent magnet synchronous machine with a DC battery source entailed the use of a three-phase inverter/rectifier. As the machine design was elaborated, the associated controllers became increasingly complex with the use of speed and multiple control loops.

These elaborated designs were integrated into the same system-level model by replacing each of the components piece by piece. Here is a snapshot of the results of the first design iteration of the elaborated system-level model:

• efficiency greater than 36.5 mpg (requirement not mpg)
•0-1/4 mile in 25s: Requirement met
• Top speed of 120 mph: top speed of 96 mph (Requirement not met)

Through this first iteration of the design, it is clear that model elaboration has led to many requirements not being met. Using a model as the executable specification and design with simulation helped us to detect these difficulties early. Also, using a collaborative environment enabled us to be innovative with our choices to relax system-level requirements, to redo the entire system-level design with better requirements, or to redo the component design. In this case, we found that power losses in the synchronous machine and drive were primarily responsible for the

deterioration in performance, and we focused our limited resources more on improving that aspect of the design. Going through several more design iterations helped us to meet our design requirements.

Summary

HEVs have become an important trend in the automotive industry. However, compared to traditional gasoline vehicles, their designs are significantly more complex. HEV development requires collaboration and optimization across multiple engineering domains. Model-Based Design allows for the reuse of design information across all teams and through various stages of development. This approach modeling and simulating the system behavior prior to building the actual hardware leads to the added benefits of lower costs, increased time savings, and customer satisfaction.

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