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Model-Based Design for Hybrid Electric Vehicle Systems

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ABSTRACT

In this paper, we show how Model-Based Design can be applied in the development of a hybrid electric vehicle system. The paper explains how Model-Based Design begins with defining the design requirements that can be traced throughout the development process. This leads to the development of component models of the physical system, such as the power distribution system and mechanical driveline. We also show the development of an energy management strategy for several modes of operation including the full electric, hybrid, and combustion engine modes. Finally, we show how an integrated environment facilitates the combination of various subsystems and enables engineers to verify that overall performance meets the desired requirements.

1. INTRODUCTION

In recent years, research in hybrid electric vehicle (HEV) development has focused on various aspects of design, such as component architecture, engine efficiency, reduced fuel emissions, materials for lighter components, power electronics, efficient motors, and high-power density batteries. Increasing fuel economy and minimizing the harmful effects of the automobile on the environment have been the primary motivations driving innovation in these areas.

Governmental regulation around the world has become more stringent, requiring lower emissions for automobiles (particularly U.S. EPA Tier 2 Bin 5, followed by Euro 5). Engineers now must create designs that meet those requirements without incurring significant increases in cost. According to the 2007 SAE's DuPont Engineering survey, automotive engineers feel that cost reduction and fuel efficiency pressures dominate their work life [1] and will continue to play an important role in their future development work.

In this paper, we explore key aspects of hybrid electric vehicle design and outline how Model-Based Design can offer an efficient solution to some of the key issues. Due to the limited scope of the paper, we do not expect to solve the problem in totality or offer an optimal design solution. Instead, we offer examples that will illustrate the potential benefits of using Model-Based Design in the engineering workflow. Traditionally, Model-Based Design has been used primarily for controller development. One of the goals of this paper is to show how Model-Based Design can be used throughout the entire system design process.

In section 2, we offer a short primer on HEVs and the various aspects of the design. Section 3 is devoted to Model-Based Design and the applicability of the approach to HEV development. Sections 4, 5, and 6 will focus on examples of using Model-Based Design in a typical HEV design.

2. HYBRID ELECTRIC VEHICLE DESIGN

CONCEPT

A block diagram of one possible hybrid electric vehicle architecture is shown in Figure 1. The arrows represent possible power flows. Designs can also include a generator that is placed between the power splitter and the battery allowing excess energy to flow back into the battery.

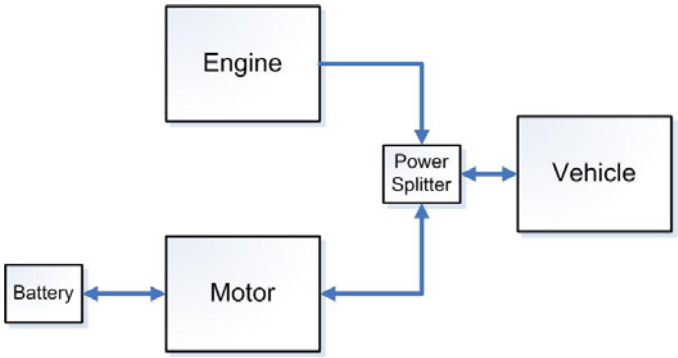


Figure 1: The main components of a hybrid electric vehicle.

Conceptually, the hybrid electric vehicle has characteristics of both the electric vehicle and the ICE (Internal Combustion Engine) vehicle. At low speeds, it operates as an electric vehicle with the battery supplying the drive power. At higher speeds, the engine and the battery work together to meet the drive power demand. The sharing and the distribution of power between these two sources are key determinants of fuel efficiency. Note that there are many other possible designs given the many ways that power sources can work together to meet total demand.

DESIGN CONSIDERATIONS

The key issues in HEV design [2] are typical of classical engineering problems that involve multilayer, multidomain complexity with tradeoffs. Here, we discuss briefly the key aspects of the component design:

Engine design - The key elements of engine design are very similar to those of a traditional ICE. Engines used in an HEV are typically smaller than that of a conventional vehicle of the same size and the size selected will depend on the total power needs of the vehicle.

Battery design - The main considerations in battery design are capacity, discharge characteristics and safety. Traditionally, a higher capacity is associated with increase in size and weight. Discharge characteristics determine the dynamic response of electrical components to extract or supply energy to the battery.

Motor - Motors generally used in HEV systems are DC motors, AC induction motors, or Permanent Magnet Synchronous Motors (PMSM). Each motor has advantages and disadvantages that determine its suitability for a particular application. In this list, the PMSM has the highest power density and the DC motor has the lowest. [3].

Power Splitter - A planetary gear is an effective power-splitter that allows power flows from the two power sources to the driveshaft. The engine is typically connected to the sun gear while the motor is connected to the ring gear.

Vehicle dynamics - The focus is on friction and aerodynamic drag interactions with weight and gradability factors accounted for in the equations.

Overall System Design - The first step in the design process of the hybrid powertrain is to study the maximum torque demand of the vehicle as a function of the vehicle speed. A typical graph is shown in Figure 2. Ratings of the motor and the engine are determined iteratively to satisfy performance criteria and constraints. The acceleration capabilities are determined by the peak power output of the motor while the engine delivers the power for cruising at rated velocity, assuming that the battery energy is limited. Power sources are coupled to supply power by the power-splitter, and the gear ratio of the power-splitter is determined in tandem. The next steps include developing efficient management strategies for these power sources to optimize fuel economy and designing the controllers. The final steps focus on optimizing the performance of this system under a variety of operating conditions.

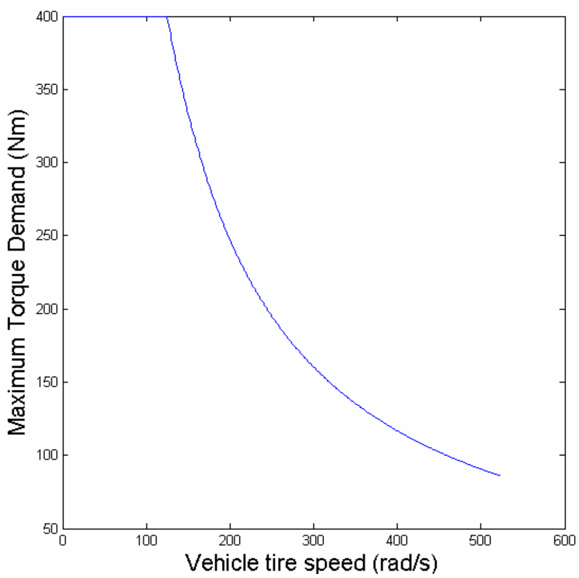


Figure 2: Maximum torque demand as a function of vehicle tire speed.

3. MODEL-BASED DESIGN OF AN HEV

MOTIVATION

In this section, we outline some of the challenges associated with HEV design and explain the motivation for using Model-Based Design as a viable approach for solving this problem.

Mathematical complexity - The mathematical complexity of an HEV design problem is reflected in the large number of variables involved and the complex nonlinear relationships between them. Analytical solutions to this problem require advanced modeling capabilities and robust computational methods.

Requirements - Equally challenging is defining the right set of requirements to meet the vehicle performance and functionality goals. Requirements refinement proceeds iteratively and depends on implementation costs and equipment availability.

System-level realization – The systems engineer has to conceptualize the operation of the system’s various components and understand the complex interactions between them. This often requires experimentation with various system topologies. For example, studies may include comparing a series configuration with a parallel configuration. Because the goal is a better understanding of the overall system behavior, the models must include the appropriate level of detail.

System integration – As the design progresses from a system level to a more detailed implementation, engineers elaborate the subsystem models to realize the complete detailed system model. This can be accomplished by replacing each initial model of a component with the detailed model and observing the effects on performance. Completing this process and realizing a detailed model of the system requires robust algorithms for solving complex mathematics in a timely fashion.

Multidomain complexity – The HEV system has electrical and mechanical components. Typically these components are designed by domain specialists. To speed development, these engineers need to effectively communicate and exchange design ideas with a minimum of ambiguity.

Power management strategy – A principal goal of a typical HEV design is to increase the fuel efficiency of the vehicle while maintaining performance demands. Intuitively, one can look at this problem as finding the optimal use of the power sources as a function of the vehicle internal states, inputs, and outputs satisfying various constraints. This translates to the requirement for switching between various operational "power modes" of the vehicle as a function of the states, inputs, and measured outputs [4]. In a true environment for Model-Based Design the power management algorithms co-exist with the physical system models.

Controller design - Because of the multidomain complexity of the various subsystems, HEV controller design is typically a complex task. A variety of control algorithms specific to each subsystem may be required. For example, the controller that manages the frequency of the input voltage to the synchronous motor will be different from the simple control used for torque control of the same motor. Typically, this will manifest itself as a multistage, multiloop control problem. Successful implementation of the controllers requires deployment of these algorithms on processors that are integrated while interfacing with the physical plant.

Verification and validation – As the design evolves, testing ensures that it continues to meet requirements. Detection of errors early in the process helps reduce costs associated with faulty designs. As design errors trickle down the various workflow stages the costs associated with correcting them increase rapidly [5]. The ability to continually verify and validate that requirements are being satisfied is a key aspect of Model-Based Design.

A software development environment for Model-Based Design must be able to address the aforementioned challenges. Additionally, a single integrated environment facilitates model sharing between team members. The ability to create models at various levels of abstraction is needed to optimize the simulation time. A mechanism for accelerating the simulation as the complexity increases will also be important.

PROCESS OF MODEL-BASED DESIGN

Model-Based Design can be thought of as a process of continually elaborating simulation models in order to verify the system performance. The overall goal is to ensure first pass success when building the physical prototype. Figure 3 shows the key elements of Model-Based Design.

The system model forms the "executable specification" that is used to communicate the desired system performance. This model is handed over to the various specialists who use simulation to design and further elaborate the subsystem models. These specialists refine the requirements further by adding details or modifying them. The detailed models are then integrated back into the system level realization piece by piece and verified through simulation. This goes on iteratively until a convergence to an optimal design that best meets the requirements results. During Model-Based Design, C-code generation becomes an essential tool for verifying the system model. The control algorithm model can be automatically converted to code and quickly deployed to the target processor for immediate testing. Code can also be generated for the physical system to accelerate the simulation and/or to test the controller with Hardware in the Loop simulation.

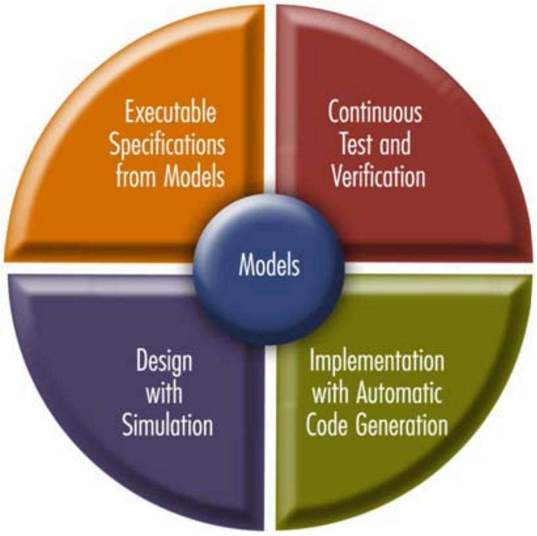


Figure 3: The key elements of Model-Based Design.

4. SYSTEM LEVEL MODELING OF AN HEV

In the first stage of the HEV design, the system-level description of the system is realized. Experimentation enables the system designer to explore innovative solutions in the design space resulting in optimal architectures. Our approach has been inspired by an earlier SAE paper [6].

REQUIREMENTS

In the initial stages of the project, it is not uncommon for the specifications of subsystem components to shift. The requirements are in a preliminary form, and are based on previous designs, if available, or best engineering judgment.

Requirements are refined when each of the component models is delivered to component designers for additional refinement. There are, however, certain requirements that the system architect understands fully, and can lock down. As the project moves from requirements gathering to specification, the concepts of the system architects can be included in the model. Collaboration between architects and designers leads to a much better and more complete specification. The system can be expressed as a series of separate models that are to be aggregated into an overall system model for testing. Breaking down the model into components facilitates component-based development and allows several teams to work on individual components in parallel.

This kind of concurrent development was facilitated by the parallel configuration we chose for our example, in which the electrical and mechanical power sources supply power in parallel.

The broad design goals were:

> Improve fuel efficiency to consume less than 6.5 liters per 100 km (L/100 km) for the driver input profile shown in Figure 4.
> Cover a quarter mile in 25 seconds from rest.
> Attain a top speed of 193 kph.

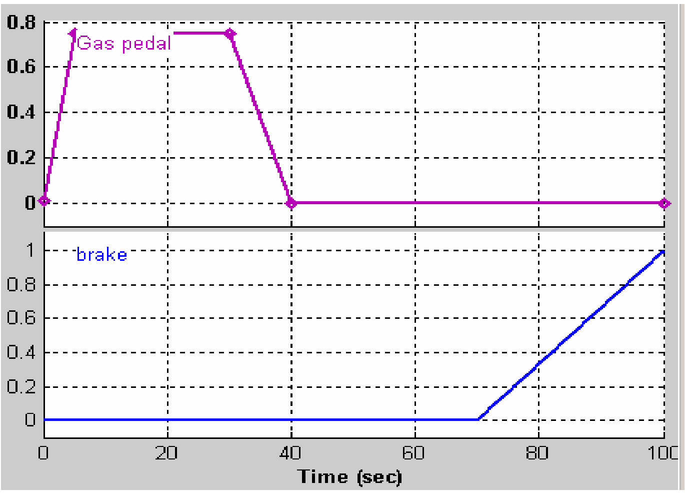


Figure 4: Driver input profile as outlined in the requirements document.

These and other such requirements are typically captured in a requirements document that engineers can associate with the design models. This provides the ability to trace the requirements throughout the model, a key component of Model-Based Design.

VEHICLE DYNAMICS

Modeling the vehicle dynamics can be a challenging task. When creating any simulation model it is important to consider only the effects that are needed to solve the problem at hand. Superfluous details in a model will only slow down the simulation while providing little or no additional benefit. Because we are primarily interested in the drive cycle performance, we will limit our vehicle model to longitudinal dynamics only. For example, the vehicle was initially modeled as a simple inertial load on a rotating shaft connected to the drive train.

ENGINE

A complete engine model with a full combustion cycle is also too detailed for this application. Instead, we need a simpler model that provides the torque output for a given throttle command. Using Simulink® and SimDriveLine™, we modeled a 57kW engine with maximum power delivery at 523 radians per second, as shown in Figure 5.

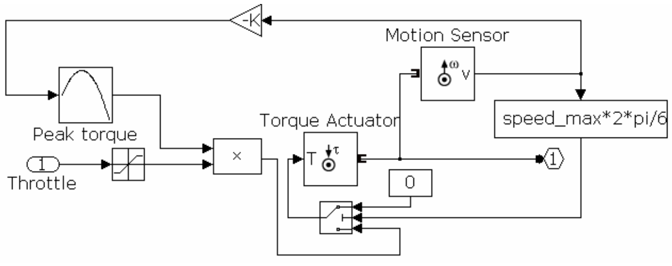


Figure 5: Engine modeled using blocks from the SimDriveline™ library.

SYNCHRONOUS MOTOR/GENERATOR

The synchronous motor and generator present an interesting example of electromechanical system modeling. Standard techniques for modeling synchronous machines typically require complex analysis of equations involving electrical and mechanical domains. Because the input source to this machine drive is a DC battery and the output is AC, this would require the creation of complex machine drive and controller designs – often a significant challenge at this stage.

An averaged model that mathematically relates the control voltage input with the output torque and resulting speed is a useful alternative. This simplification allows us to focus on the overall behavior of this subsystem without having to worry about the inner workings. Furthermore, we can eliminate the machine drive by simply feeding the DC voltage directly to this subsystem.

With this averaged model, we only need a simple Proportional-Integral (PI) controller to ensure effective torque control. The Motor/Generator subsystem design will be explored in more detail in the next section.

POWER-SPLITTER

The power-splitter component is modeled as a simple planetary gear, as shown in Figure 6. With these building blocks, more complex gear topologies can easily be constructed and tested within the overall system model.

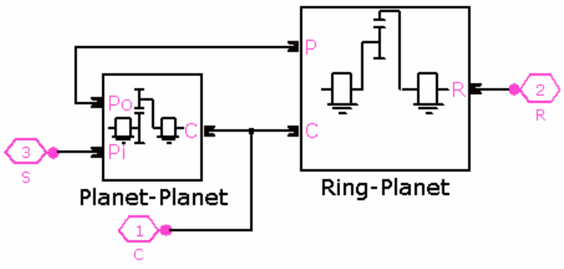


Figure 6: Power-splitter modeled as a planetary gear with connections.

POWER MANAGEMENT

The power management subsystem plays a critical role in fuel efficiency.

The subsystem has three main components:

- Mode logic that manages the various operating modes of the vehicle.
- An energy computation block that computes the energy required to be delivered by the engine, the motor, or both in response to gas pedal input at any given speed.
- An engine controller that ensures the engine is the primary source of power and provides most of the torque. The motor and generator controllers provide torque and speed control.

MODE LOGIC

For efficient power management, an understanding of the economics of managing the power flow in the system is required. For example, during deceleration, the kinetic energy of the wheels can be partially converted to electrical energy and stored in the batteries. This implies that the system must be able to operate in different modes to allow the most efficient use of the power sources.

We used the conceptual framework shown in Figure 7 to visualize the various power management modes.

Algorithm design starts with a broad understanding of the various possible operating modes of the system. In our example, we identified four modes—low speed/start, acceleration, cruising, and braking modes. For each of these modes, we determined which of the power sources should be on and which should be off.

The conceptual framework of the mode logic is easily implemented as statechart. Statecharts enable the algorithm designer to communicate the logic in an intuitive, readable form.

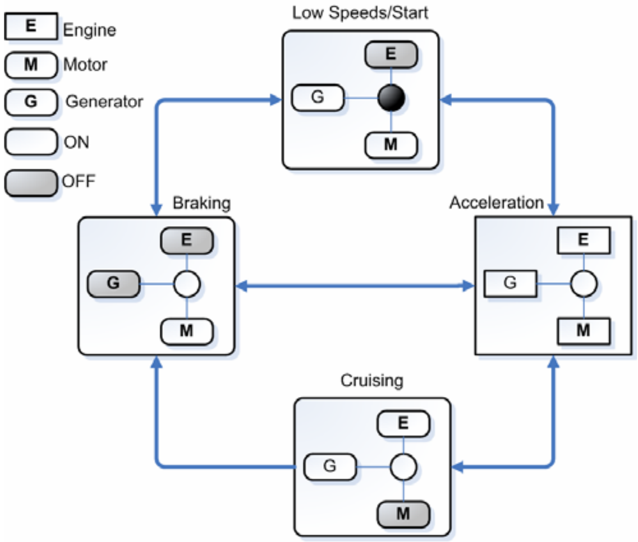


Figure 7: Mode logic conceptualized for the hybrid vehicle.

The Stateflow® chart shown in Figure 8 is a realization of the conceptual framework shown in Figure 7. While very similar to the conceptual framework, the Stateflow chart has two notable differences. The “acceleration” and “cruise” states have been grouped to form the “normal” superstate, and the “low speed/start” and “normal” states have been grouped together to form the “motion” superstate. This grouping helps organize the mode logic into a hierarchical structure that is simpler to visualize and debug.

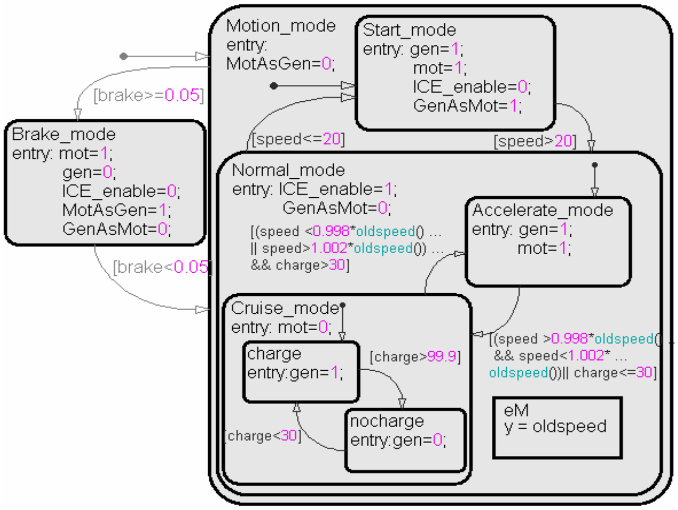


Figure 8: Mode logic modeled with Stateflow®.

SYSTEM REALIZATION

After the HEV components have been designed, they can be assembled to form the parallel hybrid system shown in Figure 9.

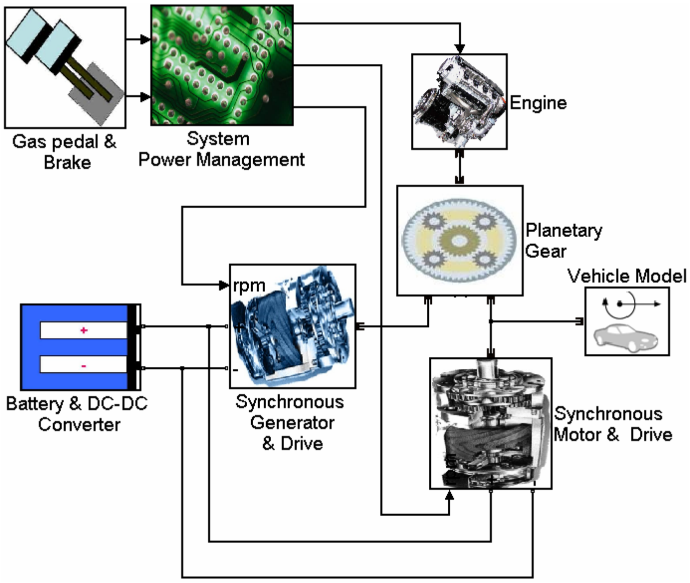


Figure 9: System-level model of the parallel HEV.

This system model can then be simulated to determine if the vehicle meets the desired performance criteria over different drive cycles. As an example, for the input to the system shown in Figure 4, the corresponding speed and the liters per 100 km (L/100 km) outputs are shown in Figure 10. Once the baseline system performance has been evaluated using the system model, we begin the process of model elaboration. In this process, we add more details to the subsystems models to make them more closely represent the actual implementation. During this process, design alternatives can be explored and decisions made based on the analysis results. This is a highly iterative process that is accelerated using Model-Based Design.

5. MODEL ELABORATION

In the model elaboration stage, the subsystem components undergo elaboration in parallel with requirements refinement.

A subsystem block is an executable specification because it can be used to verify that the detailed model meets the original set of requirements.

As an example, we show how the generator machine drive undergoes requirements refinement and model elaboration. We assume that the engineer responsible for the machine drive design will carry out the model elaboration of the plant and the associated controller.

REQUIREMENTS REFINEMENT

The machine drive is an aggregated model of the machine and the power electronics drive. In the system level modeling phase, the key specification is the torque-speed relationship and the power loss. This information was sufficient to define an abstract model to meet the high-level conceptual requirements.

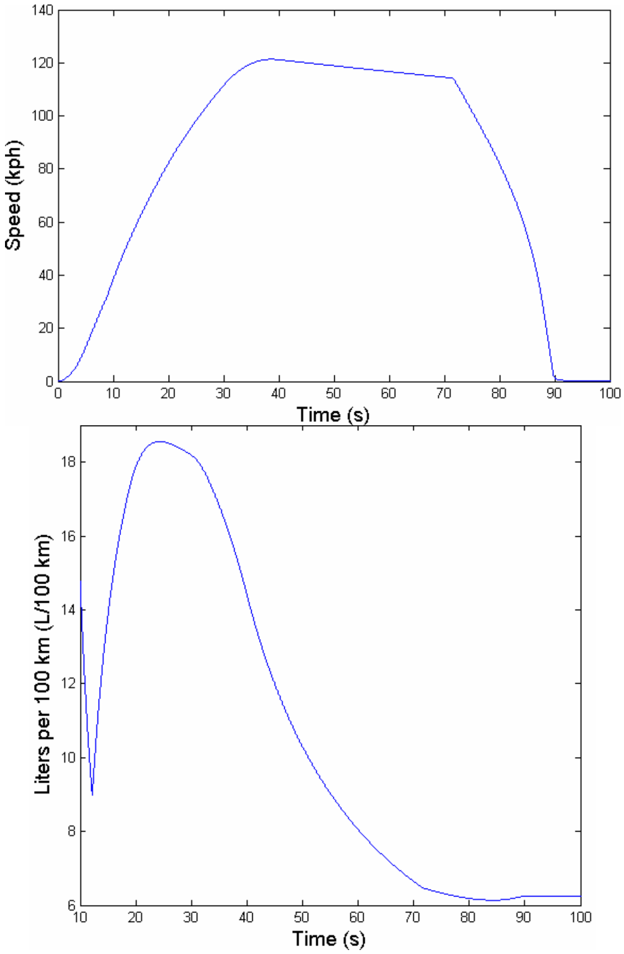


Figure 10: Output speed and L/100 km metric for the averaged model.

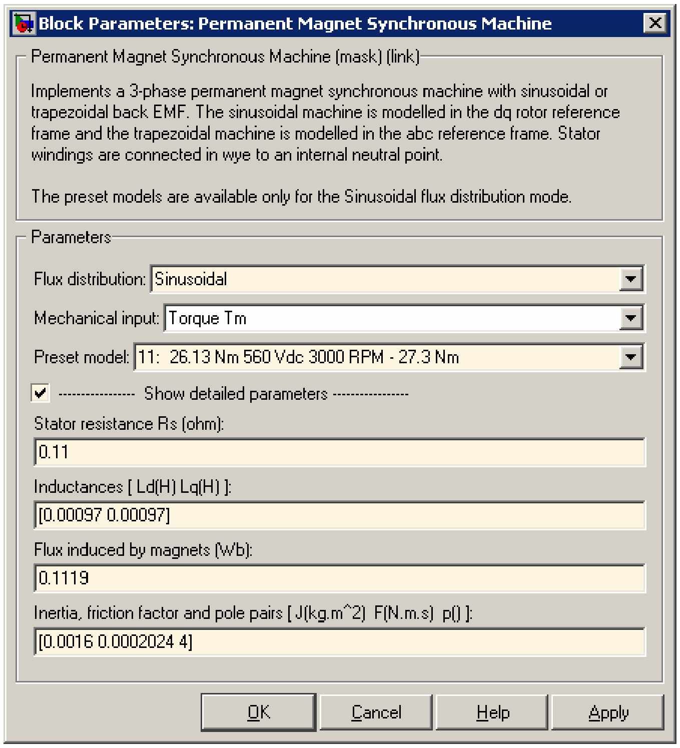
As additional design details are specified, the model must become more detailed to satisfy the subsystem requirements. For example, the generator model will need parameters such as the machine circuit equivalent values for resistance and inductance.

Engineers can use this specification as the starting point towards the construction of an electric machine customized for this HEV application.

In the case of the generator drive, as the machine model is elaborated from an averaged model to a full three phase synchronous machine implementation, the controller must also be elaborated.

PLANT ELABORATION

The machine model for the synchronous generator is elaborated using SimPowerSystems™ blocks that represent detailed models of power system components and drives. For this model, the electrical and mechanical parts of the machine are each represented by a second-order state-space model. Additionally, the internal flux distribution can be either sinusoidal or trapezoidal. This level of modeling detail is needed to make design decisions as the elaboration process progresses.



Block Parameters: Permanent Magnet Synchronous Machine

Permanent Magnet Synchronous Machine (mask) (link)

Implements a 3-phase permanent magnet synchronous machine with sinusoidal or trapezoidal back EMF. The sinusoidal machine is modelled in the dq rotor reference frame and the trapezoidal machine is modelled in the abc reference frame. Stator windings are connected in wye to an internal neutral point.

The preset models are available only for the Sinusoidal flux distribution mode.

Parameters

Flux distribution: Sinusoidal

Mechanical input: Torque Tm

Preset model: 11: 26.13 Nm 560 Vdc 3000 RPM - 27.3 Nm

☑ --------------- Show detailed parameters ---------------

Stator resistance Rs (ohm): 0.11

Inductances [Ld(H) Lq(H)]: [0.00097 0.00097]

Flux induced by magnets (Wb): 0.1119

Inertia, friction factor and pole pairs [J(kg.m^2) F(N.m.s) p()]: [0.0016 0.0002024 4]

Figure 11: Detailed PMSM model parameters.

The details of this model are captured in the model parameters shown in Figure 11, which specify the effects of internal electrical and magnetic structures.

CONTROL ELABORATION

The controller used in the averaged model of the AC machine drive is a simple PI controller. In model elaboration of the synchronous machine plant, a DC battery source supplies energy to the AC synchronous machine via an inverter circuit that converts DC to AC. These changes in plant model structure and detail require appropriate changes to the controller model to handle different control inputs and implement a new strategy. For example, the power flow to the synchronous machine is controlled by the switching control of the three phase inverter circuit. This added complexity was not present in the initial model of the machine drive because we focused on its behavior rather than its structure. We implemented a sophisticated control strategy, shown in Figure 12, that included cascaded speed and vector controllers [7]. The controllers were developed using Simulink® Control Design™ to satisfy stability and performance requirements.

VERIFICATION AND VALIDATION

At every step of the model elaboration process, the model is verified and validated. Figure 13 shows the averaged and detailed models as they are tested in parallel.

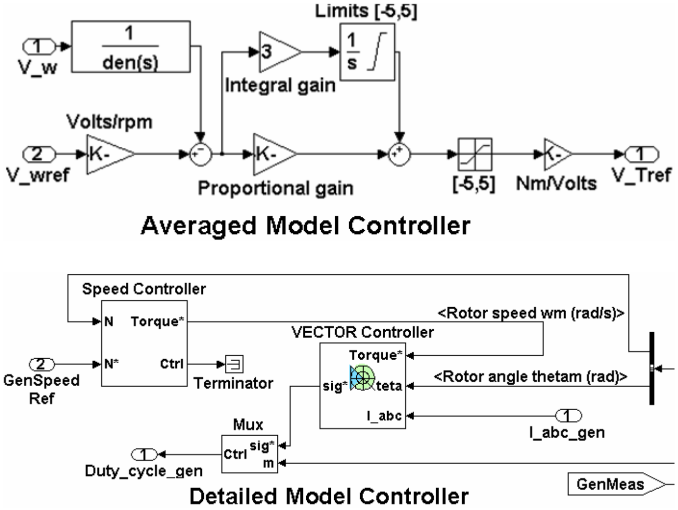


Figure 12: Controller elaboration as we move from averaged (top) to detailed (below) model.

The test case is a 110 radians per second step input to the machine. The response, shown in Figure 14, reveals comparable performance of both models. This serves as a visual validation that the detailed model is performing as desired. More elaborate testing schemes and formal methods can be devised with test case generation and error detection using assertion blocks from Simulink® Verification and Validation™ [8].

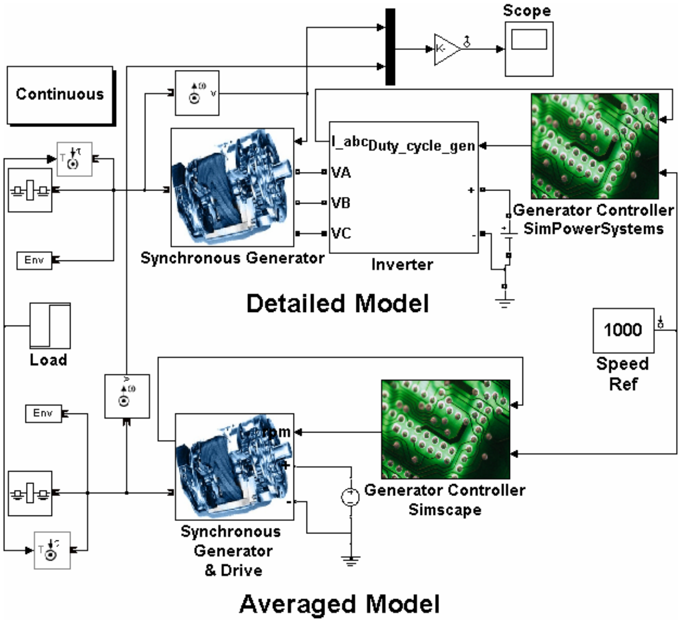


Figure 13: Testing of the averaged and the detailed models for speed control with a 1000 rpm step input.

SYSTEM INTEGRATION

After the component model elaboration and testing is complete, the subsystem containing the averaged model is replaced with the detailed model and the overall system is simulated again.

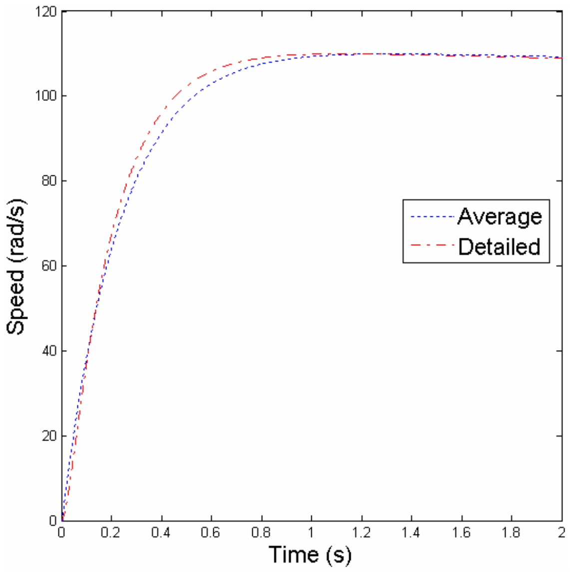


Figure 14: Comparison between the averaged and the detailed models of the machine drive.

This integration will proceed, one component at a time, until the overall system level model contains all the detailed models for each component. This ensures each component is tested and verified in the system model. A single modeling environment for multidomain modeling facilitates the integration. In our example, we used Simulink for this purpose. In Figure 15, we compare the results of the averaged and the detailed models for the driver input profile shown in Figure 4. The detailed model shows deterioration in the speed and L/100 km performance metrics, which can be attributed to the additional detail incorporated into the model.

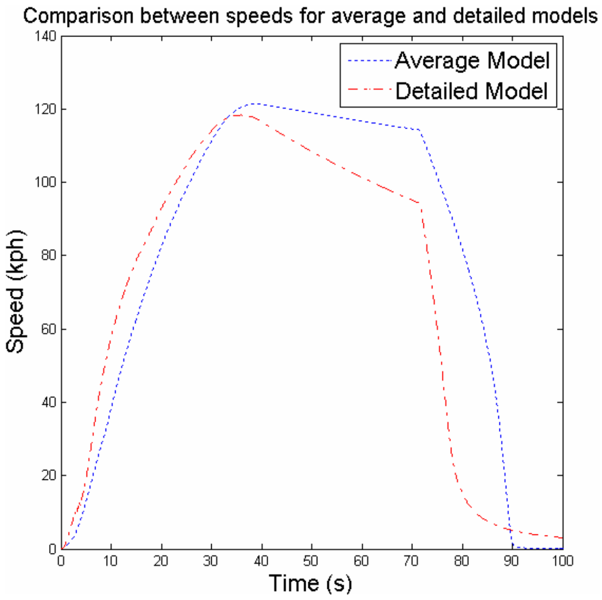
4. CONTROLLER DEPLOYMENT

The electronic control unit (ECU) layout, deployment, and implementation are challenging problems that require innovative thinking. Typically, this requires exploration of the design space to optimize various criteria.

Once the design of the system controllers is complete, ECU layout strategy must be considered. In a typical vehicle, we would likely keep some of the controllers inside a centralized ECU, while distributing the others throughout the car.

One potential layout would implement the controller for the synchronous motor on a dedicated floating point microcontroller situated closer to the machine, instead of incorporating the controller as part of the centralized ECU. Such a strategy would allow for faster response times from the motor controller for efficient control.

If a mix of centralized and distributed controller architecture is under consideration, then the extra layer of complexity introduced by the communication network should be accounted for in the modeling.



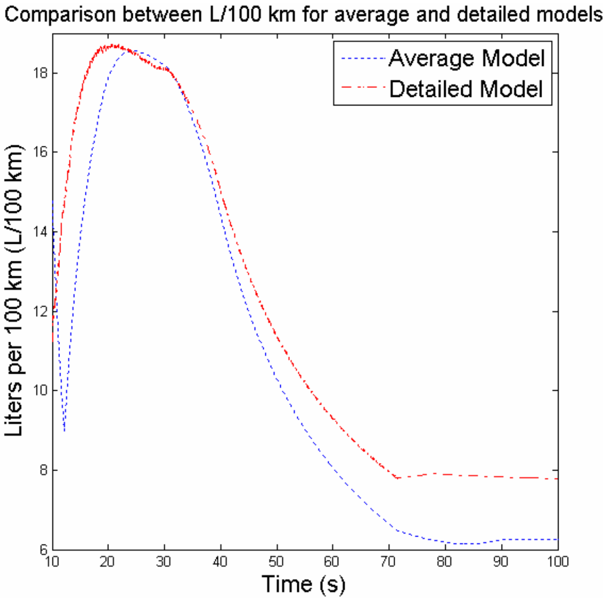


Figure 15: Speed and L/100 km metric comparisons for averaged and detailed models for the HEV.

Cost and performance considerations will drive design decisions regarding the selection of floating point or fixed point implementation of each controller. For example, one may consider implementing the controller for the synchronous generator on a fixed-point processor to lower the cost of the overall architecture.

6. SIMULATION PERFORMANCE

The final system-level model of the HEV will contain detailed lower-level models of the various components. As model complexity increases, it will take longer to simulate the model in the software environment. This behavior is expected because the model contains more variables, equations, and added components which incur an additional computational cost. Intuitively, this can be visualized as an inverse relationship between simulation performance and complexity of the model as shown in Figure 16.

Running the simulations in a high-performance computing environment can offset the increase in simulation times that comes with increased complexity. . With the advent of faster, multicore processors, it is possible to run large simulations without having to invest in supercomputer technology.

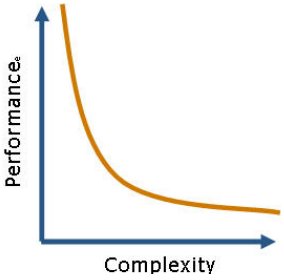


Figure 16: Simulation performance deteriorates with increasing model complexity.

We used Simulink simulation modes that employ code generation technology [9] to accelerate the simulation of our model. The improvements in the simulation performance are shown in Figure 17.

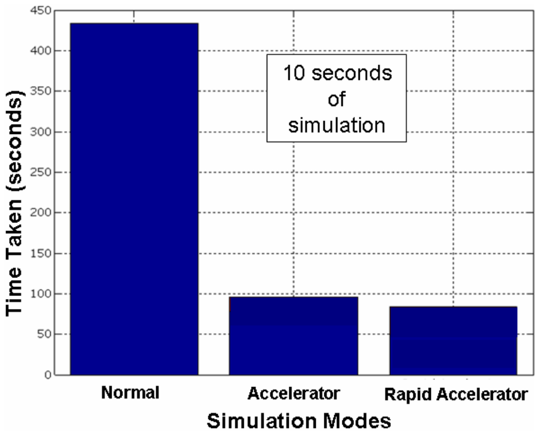


Figure 17: Comparison of Simulink® simulation modes for the detailed HEV model.

CONCLUSION

In this paper, we first described a typical HEV design and gave an overview of the key challenges. We discussed how the multidomain complications arise from the complex interaction between various mechanical and electrical components—engine, battery, electric machines, controllers, and vehicle mechanics. This complexity, combined with the large number of subsystem parameters, makes HEV design a formidable engineering problem.

We chose Model-Based Design as a viable approach for solving the problem because of its numerous advantages, including the use of a single environment for managing multidomain complexity, the facilitation of iterative modeling, and design elaboration. Continuous validation and verification of requirements throughout the design process reduced errors and development time.

Our first step in the development process was the realization of a system-level model of the entire HEV. The subsystem components were averaged models, which underwent model elaboration with requirements refinement and modifications in parallel. We showed how statecharts can be used to visualize the operating modes of the vehicle. After each component model was elaborated, we integrated it into the system-level model, compared simulation results of the averaged and detailed models, and noted the effect of model elaboration on the outputs. When simulation times grew long as we moved towards a fully detailed model, we introduced techniques to alleviate this issue.

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APPENDIX: Parameters of key HEV components

Component	Parameter	SI Units
Vehicle	Mass	1325 kg
	Horizontal distance from CG to front/rear axle	1.35 m
	Frontal area	2.57 m^2
	Drag coefficient	0.26
	Tire rolling radius	0.3 m
	Tire rated vertical load	3000 N
	Tire slip at peak force at rated load	0.1
	Tire inertia	0.5 kg-m^2
Planetary Gear	Ring-to-Sun gear ratio	2.6
Engine	Maximum power	57 kW
	Speed at maximum power	523.33 rad/s
	Maximum speed	628 rad/s
	Shaft inertia	1 kg-m^2
Battery	Capacity	6.5 Ah
	Initial voltage	201.6 V
	Initial state-of-charge	33.33 %
	Maximum power output	21 kW
Synchronous Generator (Permanent Magnet)	Shaft inertia	4 kg-m^2
	Maximum voltage	500 V
Synchronous Motor (Permanent Magnet)	Shaft inertia	1 kg-m^2
	Maximum voltage	500 V
	Maximum power output	50 kW
	Maximum torque	400 Nm