A complete co-simulation-based design environment for electric and hybrid-electric vehicles, fuel-cell systems, and drive trains

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ABSTRACT

With increasing interest in the development of electric and hybrid-electric vehicles, the demand for comprehensive systems design and analysis to aid the development process is rising. The combination of fuel cells, batteries, and other energy-storage devices and their complex interactions with the other electrical components in a vehicle, require a sophisticated design approach. This paper will present a co-simulation-based design environment capable of simulating the overall system behavior in connection with a detailed electrical model. The design environment combines ADVISOR, a system-level vehicle design tool from NREL (National Renewable Energy Laboratory) and Ansoft's SIMPLORER®, a sophisticated design tool offering electrical, electromechanical, and control simulation capabilities. Automotive engineers can now predict efficiency and fuel economy of vehicle designs, power management strategies, and the electrical design in one integrated design environment. With SIMPLORER, engineers can simulate complete drive trains by combining fuel cells, batteries, power electronics, and electric motors in one model.

This paper shows the general design approach and the link between the design tools. As an example, the co-simulation between a system-level small car platform setup and its electrical system model is illustrated. Additionally, ways to simulate a drive-train configuration, including a fuel cell as a power source, the power-electronic converters, controls, and a detailed electrical machine model with mechanical loads will be shown.

INTRODUCTION

With the limited availability of fossil resources and an increasing demand for cleaner vehicles, new vehicle propulsion concepts are explored by a number of automotive manufacturers, suppliers, and research institutes. Worldwide there is a tremendous amount of research into using fuel cells as power sources for vehicles. But the research is not limited to automotive and aerospace; stationary power applications seem to be an interesting field for the application of fuel cells as well. Although fuel cells for transportation applications are still fairly heavy and impracticable, it is expected that research will lead to small, lightweight results in the coming years.

The application of fuel cells for drive-train applications represents a major design challenge. Fuel cells themselves are complex electrochemical systems involving a variety of design issues. The specific current voltage characteristic, the ability to deliver current with a limited response time, and the fact that fuel cells provide only a low output voltage, create challenges for the design of the power electronic system and its control. Furthermore, in a drive-train application, there are influences from the electrical machines with their nonlinear behavior and the mechanical loads. Complex controls observe a variety of system parameters and incorporate extensive control algorithms, frequently implemented in DSPs and embedded controllers.

Once the drive-train design is completed, engineers focus their attention on the behavior of the drive train as part of the overall vehicle. At this level, details of each individual component are only of secondary interest. System design involves higher abstraction levels and requires modeling the entire vehicle. While for drive-train design, individual component responses such as voltage and current waveforms are of interest, system-level analysis requires long-term transients to be considered.

With the high degree of complexity and the wide variety of domains involved in this kind of design, there is a high demand for simulation and analysis tools. Experimental setups are too expensive and frequently only deliver a snapshot of the actual configuration. The exploration of design variations requires repetitive experiments that are economically questionable.

DESIGN CHALLENGES

Automotive design and, specifically, the design of electric and hybrid-electric vehicles, involve a variety of challenges that have to be considered by an appropriate design environment. The following sections describe the three major challenges.

MULTI-DOMAIN

The convergence of more and more electronics with controls and mechanics makes the design process very complex and involves a variety of technical disciplines. With the complex interactions between the individual system parts, a disconnected consideration of each individual domain is not sufficient anymore. Each individual domain requires specific algorithms and modeling languages to achieve optimal performance for the analysis of that specific domain. A single algorithm usually does not perform for all domains equally; therefore the combination of different algorithms via co-simulation expands the design capabilities of the system considerably.

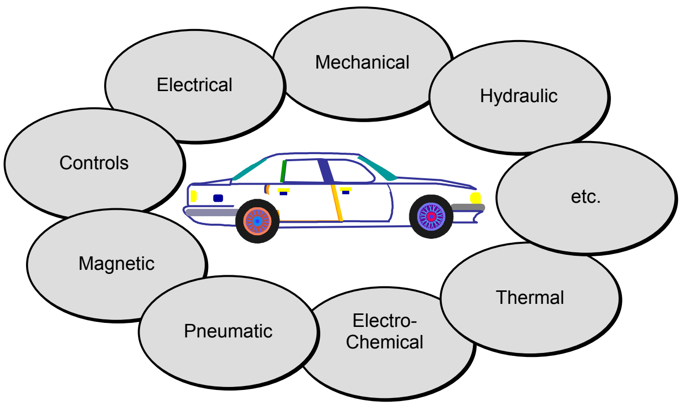

Fig. 1 Multi-Domain Design

MULTI-LEVEL

Depending on the design stage, different accuracy levels of models and different numerical algorithms are required. Frequently, at the component level (e.g., the traction motor), finite element analysis (FEA) is used. FEA provides excellent accuracy for a wide variety of analyses. However, this accuracy comes at the expense of a high computation effort caused by the huge number of equations generated by the finite discretization of the component geometry.

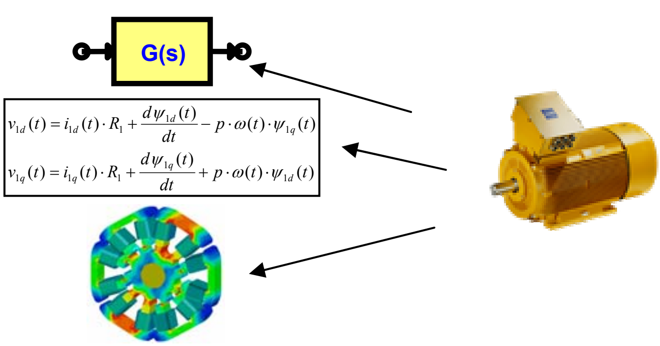

Fig. 2 Multi-Level Design

At the subsystem level (e.g., the drive train), the interest shifts from field and stress information to more integral quantities, such as voltage, current, speed, and torque. The traction motor is no longer considered a geometry- and material-based entity but rather a lumped parameter circuit element with mechanical connectivity. And finally, at the overall vehicle-analysis level, the traction motor could be considered a nonlinear characteristic consuming power depending on the actual drive cycle requirements. For each design level different tools and algorithms are available and a combination of these tools via co-simulation enables engineers to easily combine designs developed with different tools.

MULTI-ORGANIZATIONAL

The complexity of the OEM-supplier relationship adds additional requirements to the design process. Depending on the position in the OEM-Supplier relationship, different accuracy levels are required. However, the larger issue is the exchangeability of design information. Depending on the design tools used by the supplier, models can be delivered in many different languages. The attempt of OEMs to focus on specific proprietary languages did not succeed for several reasons. Therefore, a standardized model exchange language is required.

The only way of addressing these challenges is an integrated design solution combining multiple simulation methods with appropriate modeling languages and the ability to integrate existing designs fast and efficiently. Again co-simulation can be a valuable solution combining models from different suppliers delivered using different modeling languages in a combined simulation environment.

COMPLETE DESIGN ENVIRONMENT

The solution for the above mentioned problems is a combination of different modeling languages and algorithms in an integrated design environment. For the design of electrical machines, solenoids, sensors, and other electromagnetic or electromechanical components, FEA methods are appropriate and proven to deliver viable results. The tools used in the design environment are Maxwell® 2D and Maxwell® 3D. These tools provide this functionality for many different electro-magnetic and electromechanical components. The tools allow the design and optimization of components with static, harmonic, or transient solvers and under consideration of moving parts, such as rotors or plungers and the connection to the external driver circuit. To provide the design results from the FEA level to the subsystem design level, model extraction technology is required. The proposed solution provides ECE, an Equivalent Circuit Extraction technology describing the electromechanical component behavior using multi-dimensional lookup tables.

At the subsystem and system level, the design requires a multitude of algorithms for different problems of complex technical systems. Usually the design is performed combining conservative methods (recognizing the conservation of energy such as Kirchhoff's Law in electrical engineering) with nonconservative methods, such as state machines for event-driven systems, and block diagrams for continuous systems. However, traditionally, these different methods were used independently and were not integrated.

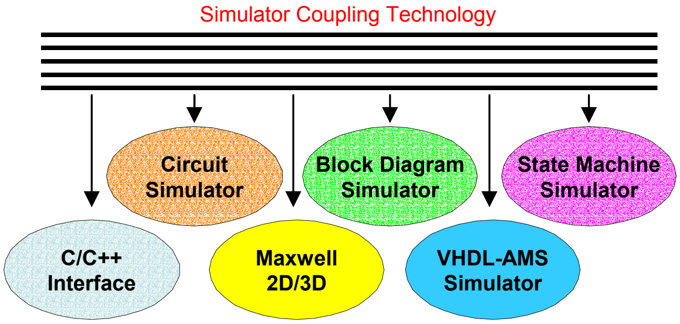

Fig. 3 SIMPLORER Simulator Coupling Technology

SIMPLORER®, the system-level design tool of the design environment, combines these three major languages under one roof and makes them available simultaneously. Based on a unique simulator coupling technology, the SIMPLORER kernel co-simulates a fast and numerically stable circuit simulator, an analog and digital block diagram simulator, and a state machine simulator. Providing the according modeling languages, engineers can simultaneously use different level modeling components at the same model. This co-simulation approach allows to use different abstraction levels of modeling languages for the appropriate application and utilizes the most efficient algorithm for each of the languages.

OPEN SIMULATOR COUPLING INTERFACE

Although SIMPLORER offers a wide variety of modeling capabilities, designers frequently ask for the use of existing legacy models. There are basically two methods to introduce external models in the design environment. Frequently we can find a simple translation of models. While it seems to be an obvious choice, this way is error prone and requires a permanent adaptation of translators to meet language derivatives and extensions. A typical example is SPICE, where different manufacturers added different language constructs which are constantly changing. Another problem that can be avoided by co-simulation is the usage of non-conservative simulation algorithms (usually block diagram based) for conservative systems. This approach usually leads to long simulation times and high modeling effort while loosing accuracy.

Therefore, SIMPLORER offers an open simulator coupling interface, allowing a direct co-simulation with external simulation packages. A typical example is a co-simulation-interface with Simulink®, a tool frequently used for control and system design. Both simulators are running simultaneously and exchange data during each simulation time step. With some special provisions, it is possible to run Simulink with a constant time step while letting SIMPLORER use a variable time step in between. The concept of co-simulation allows the user to reuse existing models without any translation. The method is not dependent on translators and does not have to keep up with frequent language changes. Model compatibility stays an issue within the original tool.

EV/HEV DESIGN

Electric and hybrid-electric vehicle (EV/HEV) design expands the complexity of automotive electrical system design. It adds a number of related design issues, such as:

- Electrical Drives
- Power Management
- Electro-Chemical Components (battery and fuel cell)
- AC/DC, DC/DC Converters and Inverters
- Fuel-cell Controller
- Battery Charging
- Motion Control
- Electrical Machine Design
- …

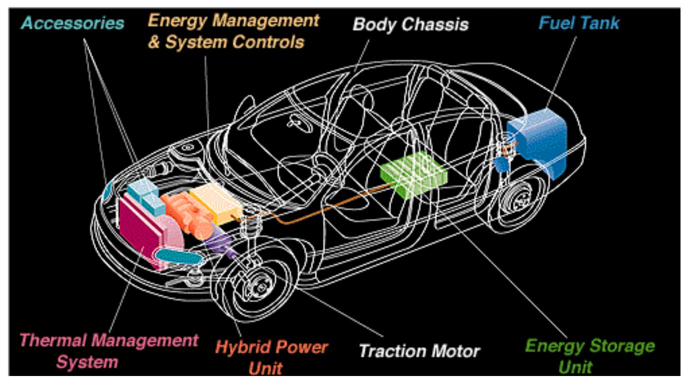

Fig. 4 Components of an HEV

Fig. 4 shows all major components of a hybrid electric vehicle. All of these different parts of the system are interconnected and have significant impact on each other's behavior. Therefore, only an overall analysis including different domains simultaneously can be applied. The design is performed in several sequential and parallel steps. The following paragraphs illustrate how the proposed co-simulation approach can help designing HEV. Especially the traction unit requires a combination of FEA based analysis with circuit and control design. For the design of the power management unit and the analysis of the overall vehicle performance a combination of system level analysis tools and electrical system level simulation can be used advantageously.

Traction Motor Design

The design of electrical machines involves several algorithms. Usually the first step is an analytical design process narrowing the design space to an acceptable solution, meeting required performance specifications. RMxprt™, (Fig. 5), an analytical design approach for the analysis of electrical machines, allows the graphical input of performance data and different configurations. It also can perform optimizations to minimize geometrical dimensions to maximize power output and other criteria.

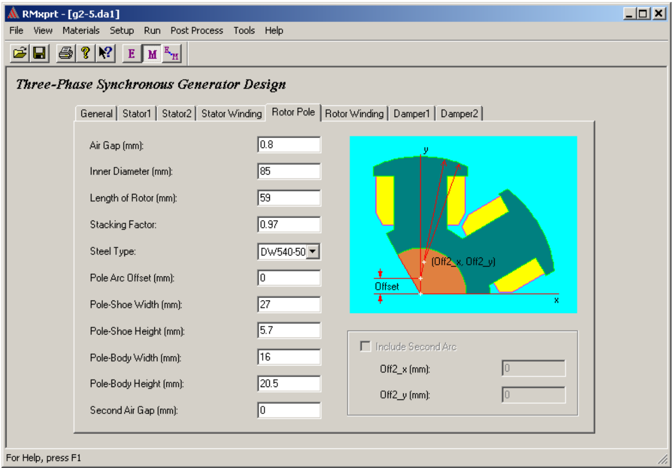

Fig. 5 RMxprt PM Synchronous Machine Input

After the design is settled, models can be extracted for both the FEA analysis process and a system-level design. With the help of Maxwell, designers can improve the machine design using several analyses and coupling to mechanical and electrical components. Fig. 6 shows a field plot of a permanent magnet synchronous machine design for the traction motor.

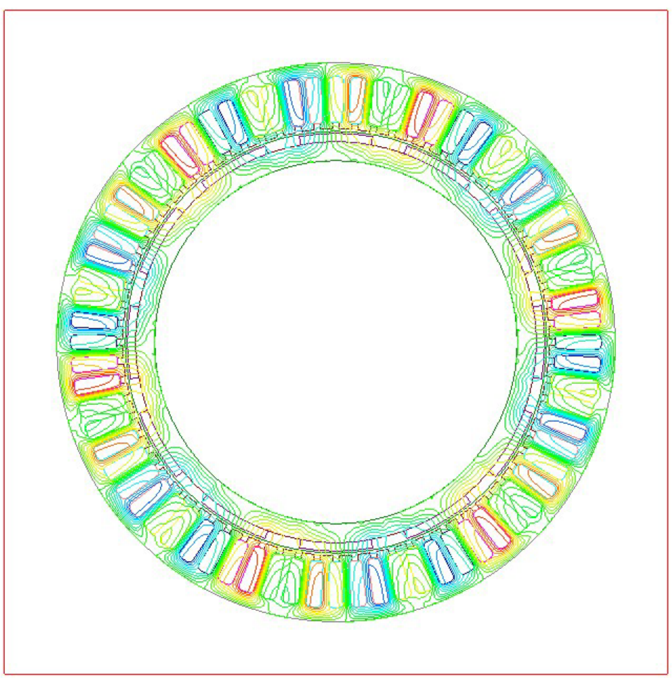

Fig. 6 Traction Motor Design Using FEA

While the analytical delivers sufficiently accurate models for system design tasks, ECE provides highly accurate model information using multidimensional lookup tables. This model is ready for import into SIMPLORER as an electromechanical component and can be connected easily with the driver circuit and with the mechanical load model. Fig. 7 shows the model included in a schematic and connected on the electrical side to the inverter, on the mechanical side to a rotating mass. The mass element comes from a mechanical library containing mechanical elements with a variety of nonlinear friction and rigidity effects, such as stick friction and backlash.

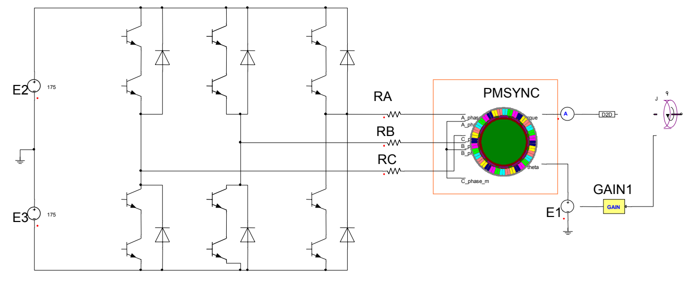

Fig. 7 PM Synchronous Machine with Circuit and Mechanics

The built-in control design capabilities of SIMPLORER allow for an easy implementation of the current and phase switching control. It is modeled using a combination of block diagrams, providing a hysteretic current band and a state machine determining the rotor position and switching on/off the according phases. Fig. 8 shows the current control for one phase of the inverter; Fig. 9 shows the position dependent phase switching control.

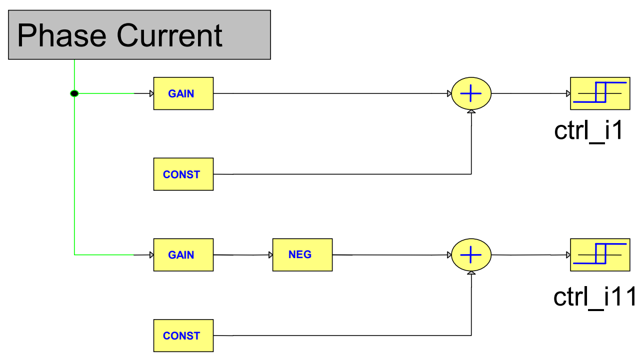

Fig. 8 Hysteretic Current Controller

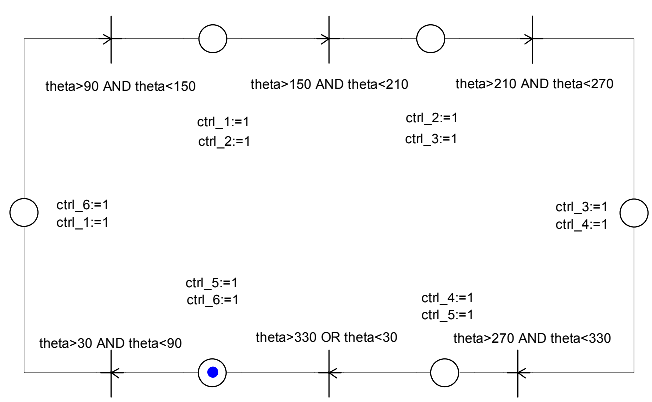

Fig. 9 Rotor Position Dependent Phase Control

Due to the equivalent circuit nature of the machine model and the combination of different modeling languages, the model runs fast and with high accuracy. Fig.

10 shows the motor torque ripple and the phase currents causing the ripple.

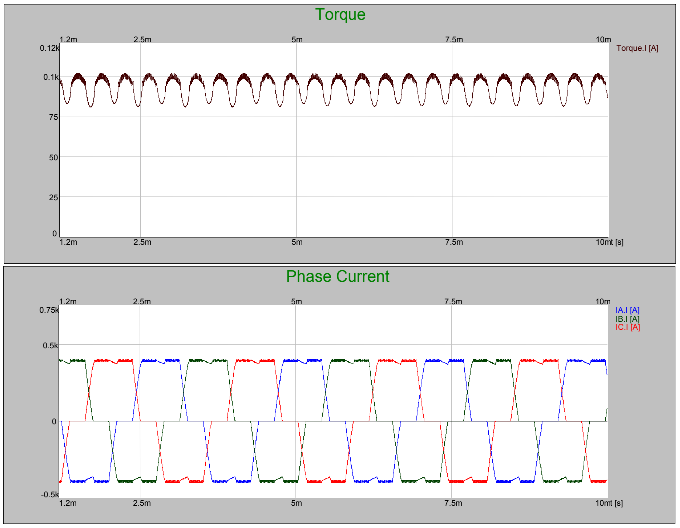

Fig. 10 Motor Torque and Phase Currents

In the first step, the power supply was assumed to be an ideal voltage source. However, depending on the vehicle configuration, the source may be a battery with a DC/DC converter providing the required voltage or a fuel cell. In each case, models can be obtained from the automotive system component library. Fig. 11 shows the replacement of the ideal electrical sources by two fuel cells, including their pneumatic control for the oxygen/air flow.

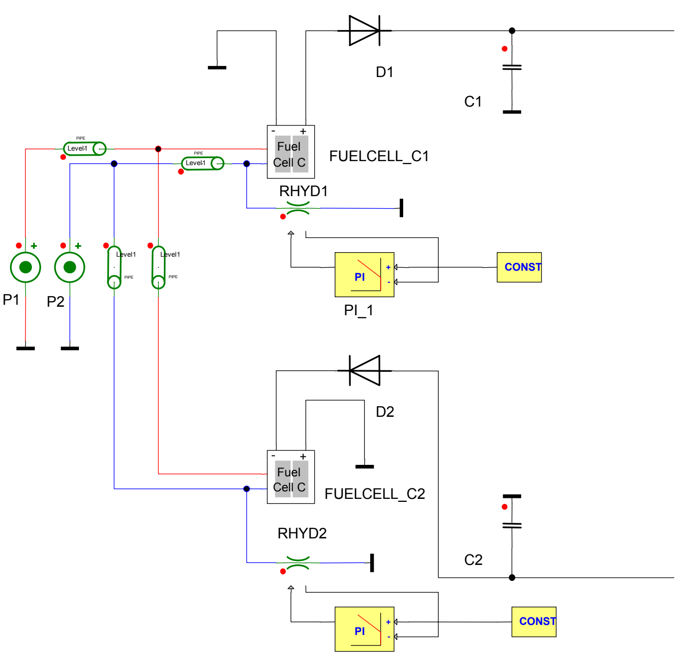

Fig. 11 Fuel Cell Models as Power Sources

Fuel cells seem to be a viable alternative for both stationary and portable power generation and currently receive a lot of attention from automotive manufacturers for propulsion systems. The fuel cell itself is a multi-domain system. It includes electrical, chemical, and pneumatic processes that influence each other and create a specific component characteristic. The design of the fuel cell, its control and the auxiliary facilities, such as reformers, involve a variety of domains, such as electrical drives for pump applications actuators for valves, controls, mechanics, pneumatics and chemical process simulation.

So again, a multi-domain simulation capability combining different languages and algorithms could be a helpful tool for the design of fuel cell applications. Especially combining chemical process simulators with electrical system simulators seems to be an interesting approach to bring the traditionally not very related scientific disciplines together and enable communication between the designers from the different domains.

On the electrical side engineers are looking for models that accurately represent the electrical characteristic of a fuel cell. With increasing current the voltage of the cells drops and on top of this the behavior is dependent on the air/oxygen and hydrogen pressure (Fig. 12). This specific behavior has to be taken into account in order to predict the system dynamics and response times.

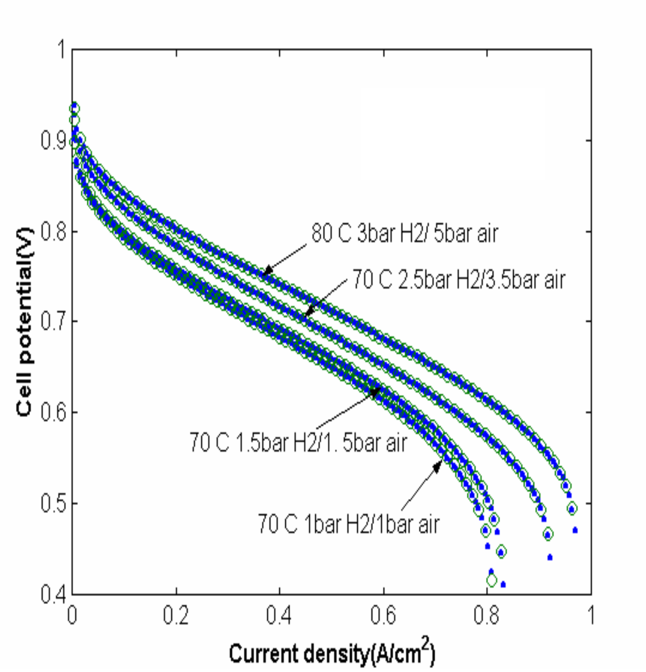

Fig. 12 Typical Current-Voltage-Characteristic of a Fuel Cell

The model that was used in the traction system simulation internally represents the electrochemical behavior based on fundamental electro-chemical equations. Beside the electrical connections it provides pins for the pneumatic environment, where the hydrogen and oxygen flow need to be controlled. The schematic shows a simple pneumatic circuit with a constant pressure source and a valve regulating the flow of oxygen to a constant value. More sophisticated control could take electrical requirements into account as well.

Obviously there is a changed behavior of the drive train when using fuel cells as the power source. With ideal voltage sources in the first simulation, the response time for the current is only limited by the inductances in the circuit. Therefore the torque waveform is mainly determined by the switching of the inverter and the magnetic properties of the synchronous motor. However due to the nonlinear characteristic of the fuel cells, where the current response is limited by the electro-chemical processes and the response time of the pneumatic system to increase the flow of oxygen in order to compensate for the higher power requirements and the required buffer capacitances there is a different current wave form supplying the inverter and consequently the torque ripple is distorted. Fig. 13 compares the two torque wave forms between an ideal voltage source and a fuel cell as power sources. In Fig. 14 the transient behavior of the fuel cell current and voltage is represented. Clearly the voltage drop due to increased current requirements – as suggested by the fuel cell characteristic in Fig. 12 – can be seen.

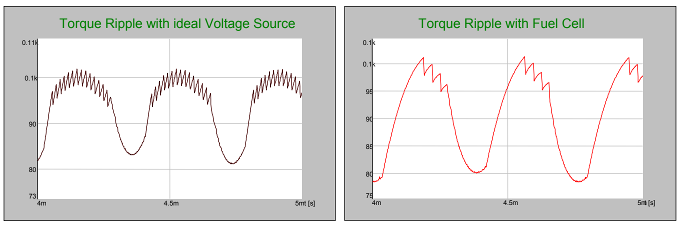

Fig. 13 Asymmetric Torque Ripple Cause by limited current response capabilities caused by the fuel cell

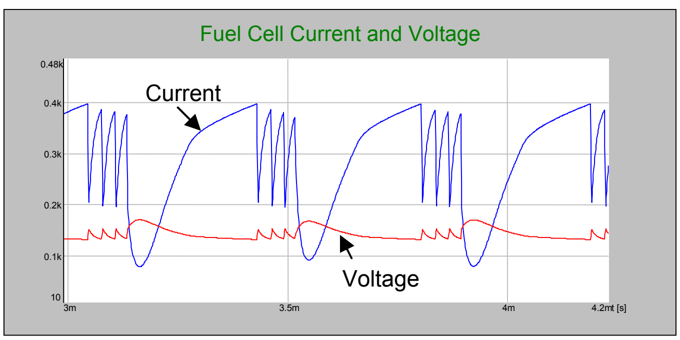

Fig. 14 Fuel Cell Current and Voltage

COMPLETE VEHICLE ANALYSIS

In addition to the design of the drive-train system and other design issues, the overall vehicle performance, its emissions, and the fuel economy play an important role in different design stages. Especially in early conceptual studies, an accurate prediction of the vehicle performance based on computer analysis can save significant time and money and can be decisive about the success of the design stages that follow. With the increasing electrical content of vehicles and new alternative drive train concepts, the electrical system increasingly impacts the fuel economy and emissions. Therefore, an early analysis of vehicle system data combined with realistic electrical behavior is required.

Another important issue is the power management of the vehicle. It is necessary to analyze the power requirements under realistic conditions. The demand for more power automatically increases the load on the battery. However, a larger battery adds weight, which, in turn, leads to poorer fuel economy and less space. So it is necessary to analyze the overall electrical system under different drive cycles with different initial conditions for the battery state of charge (SOC) in order to make sure, that under all operating conditions the battery can provide sufficient power to operate critical electrical loads. A more and more important issue is the battery state of health (SOH). Manufacturers start to implement monitoring software that allows the power management controller to make educated decisions if a certain operation can be performed or not depending on factors like aging, corrosion, electrolyte quality or temperature. For any kind of power management analysis battery models are critical. To represent SOC, SOH and temperature dependency, sophisticated models are required, representing the electrochemical processes in the battery.

For the electrical and electromechanical components of the electrical distribution system, it is sufficient to represent them as a nonlinear characteristic with the capability of turning them on and off. Nonlinear voltage controlled current sources are an ideal candidate for that type of characteristic. The nonlinear behavior is assigned using a file reference pointing to the file containing the 2D-lookup table representing the nonlinear load characteristic. Fig. 15 shows the model for a single load element, used for different electric loads in the vehicle.

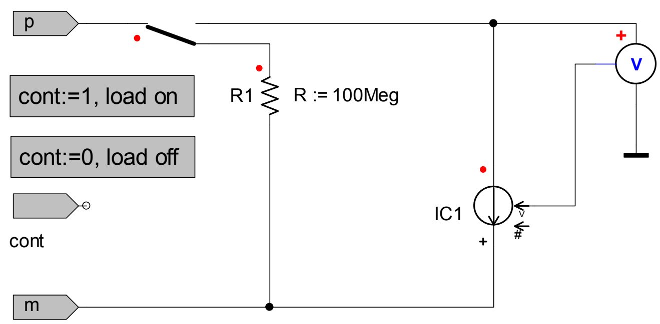

Fig. 15 Load Model Represented by a Non-Linear Controlled Source

The generator can be considered as working in two operating modes. If the bus-voltage is below the set point voltage, the generator delivers the maximum current available for the given speed. The maximum current vs. speed characteristic is available from measurements that automotive manufacturers and suppliers usually have available. With the bus voltage at or around the set point voltage, the generator must deliver a current that is high enough to maintain the current voltage levels. There are several control concepts that can be used to model this behavior. The control shown in Fig. 16 is an analog PI controller. The model of the generator was developed as a mixture of all SIMPLORER modeling languages. The state machine makes the decision if the regulator has to perform at the maximum current characteristic or using the PI control. The output of the controller is directly supplied to a current source connected to the vehicle voltage bus.

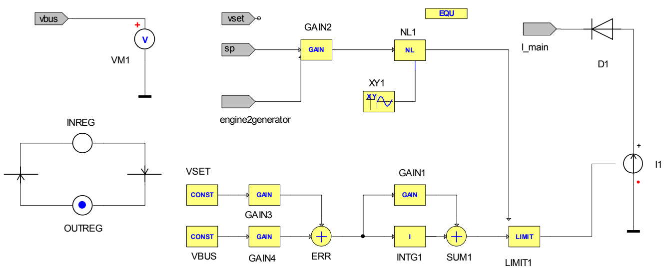

Fig. 16 Generator Model

Fig. 17 shows the setup of a typical small car platform with its major electrical loads. For EV/HEV analyses, the drive train, DC/DC converters, fuel cells, and other devices would have to be added.

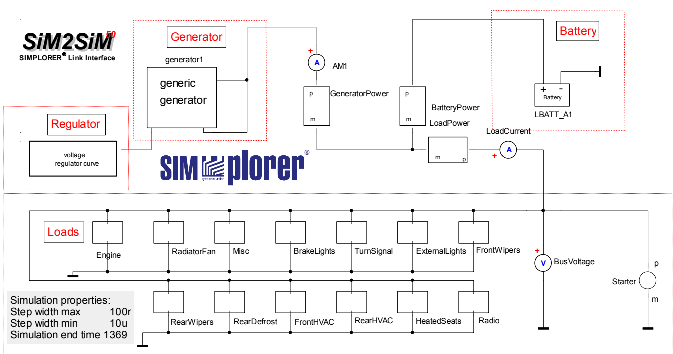

Fig. 17 Electrical Distribution System of a Car

The input for the generator is the engine speed. Depending on the complexity of the analysis, it can be supplied by a data file with the rpm vs. time information or from a system-level vehicle simulation program. In the example, ADVISOR 2002 from NREL (National Renewable Energy Laboratory) was used. The program allows setting up several vehicle configurations with a variety of vehicle systems. Using SIMPLORER's co-simulation capabilities with Simulink, ADVISOR can be connected to a realistic model of the electrical system. The link is achieved by placing link blocks in either simulator. SIMPLORER receives the speed information and the switching information for each individual load. In return, SIMPLORER delivers data about the bus voltage, battery state of charge, load, generator power, etc.

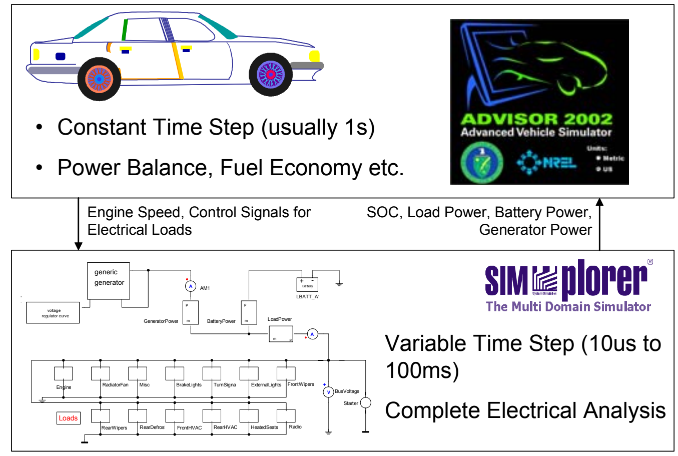

Fig. 18 Co-Simulation Principle between Advisor and SIMPLORER

ADVISOR runs the system analysis at constant time step, usually 1s. For the electrical system, this time step is too big; especially the regulator loop runs at significantly smaller time constants, usually in the range of milliseconds. Additionally, the electrical simulator requires back stepping and variable step size to achieve optimum performance. The synchronization manager ensures that SIMPLORER is running on a variable step size between the ADVISOR time steps and that the data exchange is performed at each ADVISOR time step (Fig. 18).

Fig. 19 shows the vehicle setup in ADVISOR. As an example platform, a conventional vehicle setup was selected. For conventional vehicles the main power source is the generator the performance of which is determined by the engine speed. The speed is obtained form the mechanical accessories block and transferred to SIMPLORER using an S-function based link-DLL. The engine speed and also the ON/OFF information for the electrical loads of the vehicle are defined by the selected drive cycle. Advisor provides an extensive drive cycle database allowing the simulation of realistic engine speed and load usage scenarios.

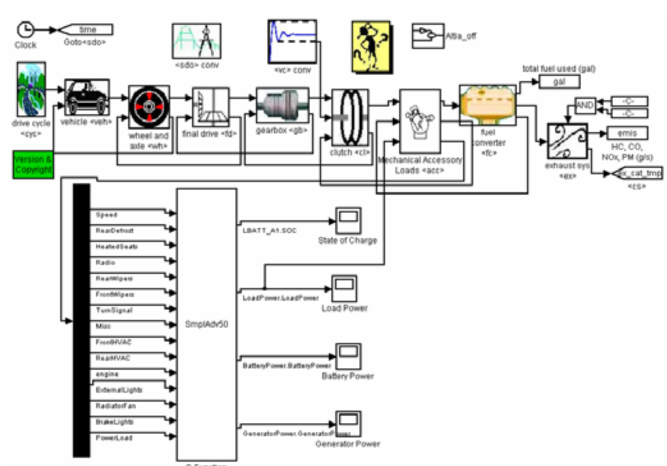

Fig. 19 Advisor Model incl. SIMPLORER Link Block

The implementation of the direct memory data exchange between both simulators enables a very high simulation speed. Fig. 20 shows the simulation results for an urban drive cycle running over 1365s. This drive cycle will be computed in about 1min on a 1GHz Pentium®-type personal computer with a fixed time step of 1s on the ADVISOR side. To take advantage of the variable time stepping in SIMPLORER, the integration parameters were set to h_{min} = 10us and h_{max} = 100ms.

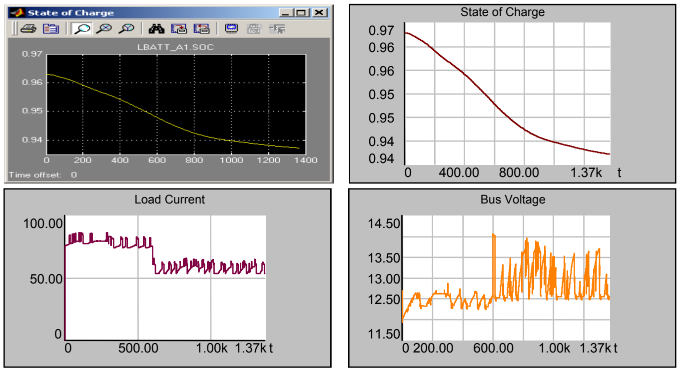

Fig. 20 Simulation Results in Both Simulators

CONCLUSION

The proposed solution based on SIMPLORER's simulator coupling technology solves a wide range of problems in the design of complex multi-domain systems for transportation applications. It offers a combination of multiple modeling languages providing several modeling levels. Model extraction technologies help with the transfer of design data from one design level to another. Finally, co-simulation with tools outside SIMPLORER's internal simulation capabilities opens a wider range of analyses and preserves existing investments in design tools.

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ADDITIONAL SOURCES

For additional information on SIMPLORER, Maxwell, and RMxprt, visit www.ansoft.com. Free student versions are available for download. ADVISOR can be obtained from the NREL web page (www.nrel.gov).