NATIONAL RENEWABLE ENERGY LABORATORY

Electric Drive Dynamic Thermal System Model for Advanced Vehicle Propulsion Technologies

Cooperative Research and Development Final Report

CRADA Number: CRD-09-360

NREL Technical Contact: Kevin Bennion

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC.

CRADA Report
NREL/TP-7A10-59230
October 2013

Contract No. DE-AC36-08GO28308

NOTICE

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) photo by Pat Corkery, NREL 16416, photo from SunEdison, NREL 17423, photo by Pat Corkery, NREL 16560, photo by Dennis Schroeder, NREL 17613, photo by Dean Armstrong, NREL 17436, photo by Pat Corkery, NREL 17721.

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Cooperative Research and Development Final Report

In accordance with Requirements set forth in Article XI.A(3) of the CRADA document, this document is the final CRADA report, including a list of Subject Inventions, to be forwarded to the Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

CRADA Number: CRD-09-360

CRADA Title: Electric Drive Dynamic Thermal System Model for Advanced Vehicle Propulsion Technologies

Parties to the Agreement: Ford Motor Company

Joint Work Statement Funding Table Showing DOE Commitment:

Estimated Costs	NREL Shared Resources
Year 1	$ 100,000.00
Year 2	$ 50,00.00
Year 3	$ 00.00
TOTALS	$ 150,000.00

Abstract of CRADA Work:

Electric drive systems, which include electric machines and power electronics, are a key enabling technology for advanced vehicle propulsion systems that reduce the dependence of the U.S. transportation sector on petroleum. However, to penetrate the market, these electric drive technologies must enable vehicle solutions that are economically viable. The push to make critical electric drive systems smaller, lighter, and more cost-effective brings respective challenges associated with heat removal and system efficiency. In addition, the wide application of electric drive systems to alternative propulsion technologies ranging from integrated starter generators, to hybrid electric vehicles, to full electric vehicles presents challenges in terms of sizing critical components and thermal management systems over a range of in-use operating conditions.

This effort focused on developing a modular modeling methodology to enable multi-scale and multi-physics simulation capabilities leading to generic electric drive system models applicable to alternative vehicle propulsion configurations. The primary benefit for the National Renewable Energy Laboratory (NREL) is the ability to define operating losses with the respective impact on component sizing, temperature, and thermal management at the component, subsystem, and system level. However, the flexible nature of the model also allows other uses related to evaluating the impacts of alternative component designs or control schemes depending on the interests of other parties.

Summary of Research Results:

The CRADA between Ford Motor Company and NREL produced a modular modeling methodology to support collaborative design of electric drive systems incorporating complex system interactions, multiple physical domains, and multiple simulation scales.

Electric drive systems for vehicle propulsion involve the interactions of multiple components over multiple physical domains. The complex interactions require simulation tools that support the design and testing of electric drive systems and components. Simulation tools support designers on multiple levels including activities such as component design, system interactions, system optimization, efficiency analysis, thermal design, and controls development.

However, developing a model to simulate a specific component's physical characteristics for a single application is not the final goal. The wide use of simulation or computer aided engineering (CAE) tools for electric drive systems presents challenges that include enabling reuse of validated models, managing and communicating model updates, applying appropriate interfaces or boundary conditions, supporting communication between different engineering disciplines to cover the multiple physical domains, and enabling a flexible model framework that captures the appropriate detail for the intended application. The scope of the project emphasized a multi-scale, multi-physics modular modeling methodology compatible with commonly used commercial codes that enabled cross discipline or organization collaboration. The scope focused on an electric drive system as shown in Figure 1, which highlights an example application using two electric machines and inverters that represent a dual electric drive system The model also has the flexibility to configure itself as a single electric drive system depending on the model configuration settings defined by the user, as shown in Figure 2.

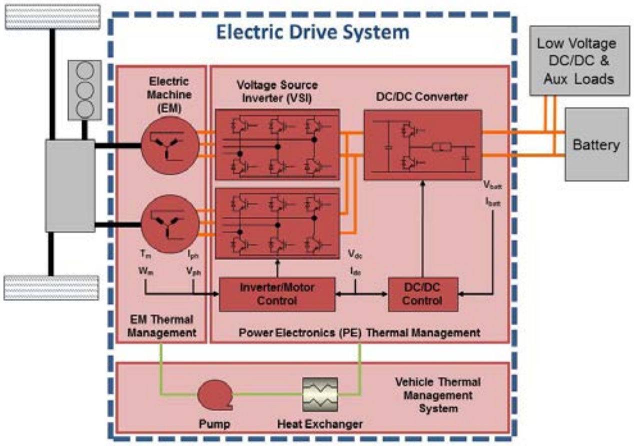

Figure 1. Electric drive system model scope (dual electric drive example)

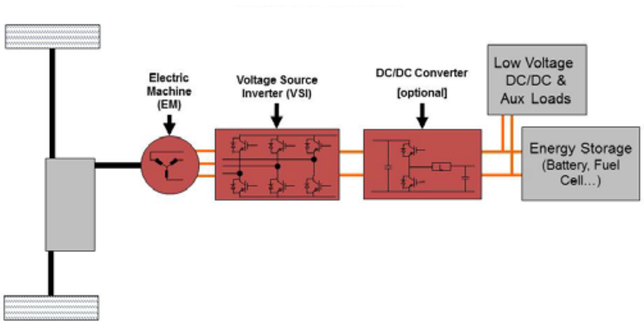

Figure 2. Single electric drive configuration example

The model was also required to run as a stand-alone model or be integrated into a larger vehicle system level model. This flexibility was provided through the external interface definitions. The external interfaces were the electrical energy storage system, such as a battery, and the electric machine shafts that were connected to the vehicle mechanical powertrain as shown in Figure 1.

Another requirement of the electric drive system model was that it needed to have the ability to swap component models based on the desired modeling scale. The ability to swap component models was created by breaking up the electric drive system model into modular component definitions, which are listed in Table 1. The user is able to select component models within each category for their specific application.

Table 1: Scope of Model Components

Model Components Definitions
Electric Machine Power Conversion and Loss Model
Inverter Power Conversion and Loss Model
DC/DC Converter Power Conversion and Loss Model
Electric Machine Thermal and Cooling Model
Inverter Thermal and Cooling Model
DC/DC Converter Thermal and Cooling Model
Vehicle Thermal Management System Model
Electric Drive Control Systems for the Electric Machine, Inverter, and DC/DC Converter
External Interface Definitions: Energy Storage System (such as a battery), Powertrain System (such as motor shaft)

Multi-Scale Flexible Modular Modeling Methodology

We developed a modular modeling methodology—built around MATLAB and Simulink because it is a commonly used program for modeling and simulation of physical systems and controls—leading to a generic electric drive system modeling framework applicable to alternative vehicle propulsion configurations. Supported applications include single and dual electric drive systems. Examples include electric drive systems relevant to hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles, fuel cell vehicles, and integrated starter generator systems. A key feature of the model is the flexibility to simulate alternative electric drive configurations while easily swapping component models depending on the user requirements. The modular modeling approach enables users to swap or exchange component models for the components in Table 1, resulting in a generic model not tied to a specific technology or company. For example a detailed model of the inverter switches can be selected to capture the switching characteristics, or a less-detailed model can be chosen for applications focused on longer time scales. Similarly, a detailed thermal model of the inverter could be selected to capture the transient temperature responses or a less detailed model could be selected that fixes the component temperatures to a specified value.

In addition to simulating a full electric drive system over a range of applications, the developed model framework also allows a designer to focus on a specific component or subsystem. For example it is possible to focus on a single component such as the inverter or electric machine as shown in Figure 3 and Figure 4. It is also possible to focus on specific subsystems, such as the combined inverter and electric machine subsystem, as shown in Figure 5.

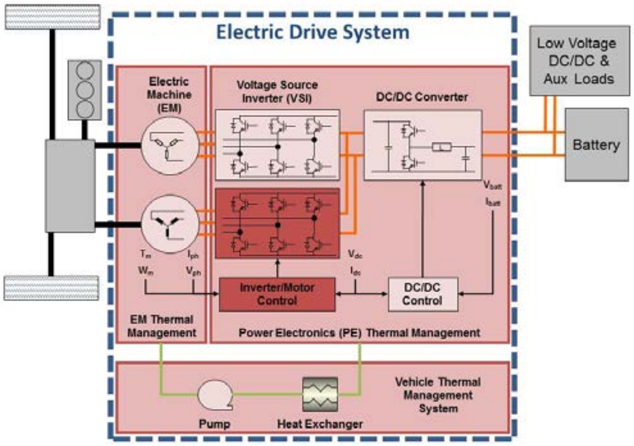

Figure 3. Model configured for inverter component focus

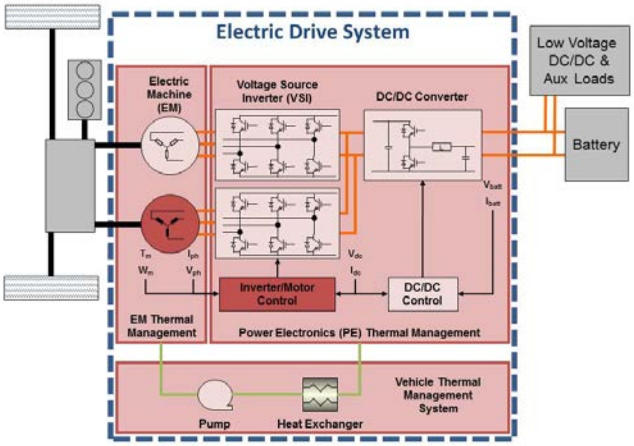

Figure 4. Model configured for electric machine component focus

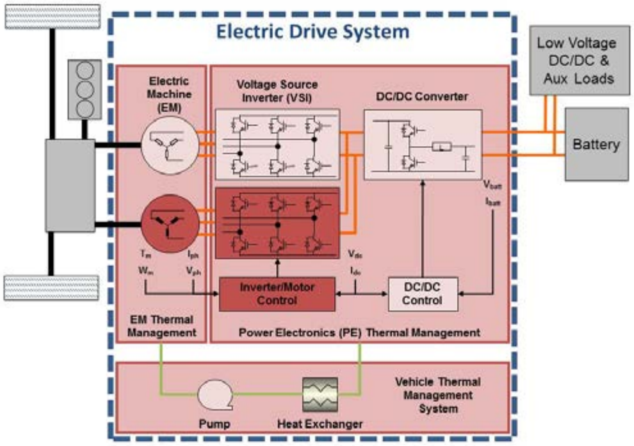

Figure 5. Model configured for inverter and electric machine subsystem focus

The model framework was designed to run in a stand-alone mode with an emphasis on the electric drive system. It is also possible to integrate the model into a larger vehicle system model by applying the necessary external interface definitions for the input DC bus voltage, motor shaft speed, and commanded motor torque. The listed examples of the multi-scale modeling methodology are included to demonstrate the flexibility of the model framework; users can develop custom models based on their simulation needs.

Multi-Physics Capability

The model includes a multi-physics domain capability incorporating electrical, mechanical, thermal, fluid, electromagnetic, and control elements. The project focused on the model framework and methodology with some sample component models. The model includes sample component models as illustrative examples, which can be adjusted or modified as needed based on the user's needs. It is expected that users would develop custom models based on their own needs.

The model framework includes elements for control logic related to specific components, physical plant models representing the physical component, loss models for heat load prediction, thermal models for component temperatures, and a vehicle thermal management system model.

Each of the physical domain models assumes a standard interface definition to ensure compatibility with linked physical domains, which enables the ability to develop models at different scales for the intended application.

Enable Cross Discipline or Organization Collaborations

In addition, the structured modeling approach improves the ability to share models or integrate new component models. The model framework was developed with the need of cross group or company collaboration in mind, allowing users to share relevant models at a component, subsystem, or system level. The structure of the model framework allows engineers or designers to work on specific components related to their area of expertise. For example the power electronics electrical engineer can work on the inverter electrical models, the electric machine designer can support the motor electromagnetic models, the controls engineer can develop the necessary control methods, and the thermal engineer can work on the relevant thermal models. Once the models are validated, the developed models are placed in an established library or model repository to share across the relevant organization. The structured component model interface definitions enable easier integration of new component models developed within or outside of the organization. In addition to supporting collaboration within an organization, the model framework also supports outside collaboration with organizations that do not have access to the full model libraries or repositories; stand-alone electric drive system models can be shared with groups without access to the model libraries.

Conclusions

The CRADA between Ford Motor Company and NREL produced a modular modeling methodology for electric drive systems, subsystems, and components. A key feature of the model is the flexibility to simulate alternative electric drive configurations incorporating single or dual electric drive systems. The modular modeling approach enables users to swap or exchange component models and includes a multi-physics domain capability incorporating mechanical, electromagnetic, electrical, thermal, fluid, and control elements.

The primary benefit for NREL, as the lead U.S. Department of Energy (DOE) laboratory for electric drive thermal management, is the ability to define operating losses with the respective impact on component sizing, temperature, and thermal management at the component, subsystem, and system level. The flexible nature of the model also allows for other uses related to evaluating the impacts of alternative component designs or control schemes depending on the interests of other parties. The modeling methodology can be shared with other interested partners, and through additional DOE and industry collaborations, improved component models can be developed to support the improvement of CAE tools for power electronics and electric machines.

Subject Inventions Listing: None

Report Date: 9/9/2013

Responsible Technical Contact at Alliance/NREL: Kevin Bennion

This document contains NO confidential, protectable, or proprietary information.