Rapid multi-physics approach to the development of electric drive systems for hybrid and electric vehicles

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Abstract

Developing electric drive systems for hybrid or electric vehicles requires modeling in the magnetic, mechanical, electrical, thermal, and control domains. MTS Systems Corporation has successfully designed and built many electric drive systems for the highest levels of motorsports, including Formula 1, Le Mans and Formula E. Through this experience, MTS has created the necessary modeling and simulation tools for rapid development and optimization of electric drive systems, and the test lab to verify these models. This paper presents MTS' rapid development process for electric drive systems, which includes Finite Element Analysis, Control Design, System Simulation, Data Analysis, Hardware Design, Code Generation, and Testing & Verification.

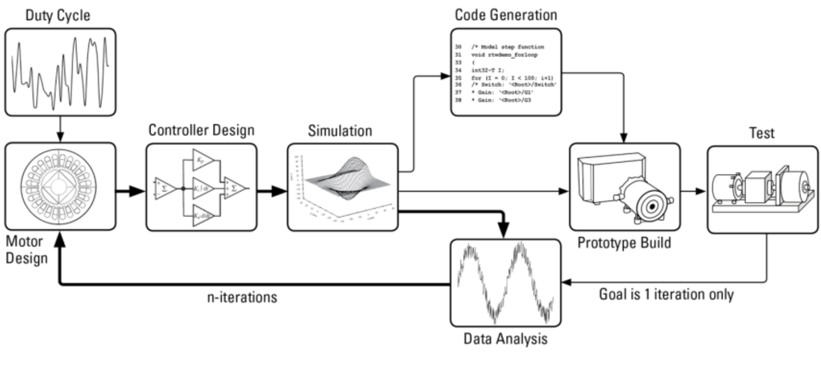
1 Introduction

For the development of automotive electric and hybrid powertrain systems, a key objective is to develop motors, inverters, and control algorithms in the shortest possible time, achieving the highest performance without multiple hardware iterations. The authors present a development approach that has been used successfully in Formula 1, Le Mans and most recently Formula E applications. Experience with this technology was initially gained from the development of high performing mechanical test systems with electric drives, and then applied to motorsport energy recovery systems and motorsport electric vehicles. In all applications, the key parameters to satisfy are, durability, efficiency, and performance (power, torque, weight, density, inertia, and reliability). The dynamic nature of the motorsport industry - intense competitiveness and continual regulation changes - necessitates a rapid development approach that delivers actual hardware for in-race use in the shortest time possible.

2 Multi-physics Development Approach

Developing an electric drive system requires modeling in the magnetic, mechanical, electrical, thermal, and control domains. Figure 1 below shows an approach using modeling and simulation tools for the rapid development and optimization of these electric drive systems. Development activities span the domains of Finite Element Analysis, Control Design, System Simulation, Data Analysis, Code Generation, Hardware Design and Build, and Testing & Verification. All simulation is supported and ultimately validated using a mechanical test bench.

Figure 1



Rapid Development Cycle Flow Chart

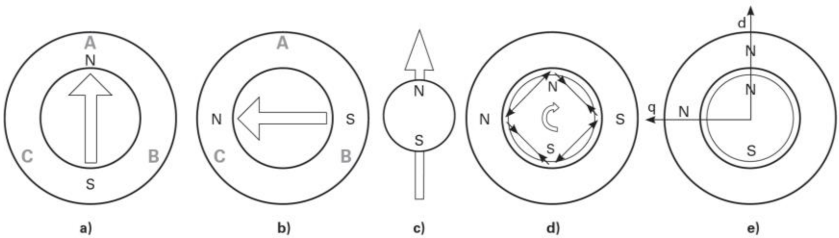
2.1 Duty Cycle

The starting point for any electric drive system design consisting of a motor, inverter, and control scheme is the application-specific desired synthetic duty cycle. This is typically defined by requirements for vehicle and respective motor speed [rpm], acceleration and respective torque [Nm] and battery supply capability and respective bus voltage [V].

2.2 Motor Design

An initial design for a motor is outlined by defining the base topology (number of poles) and the electromagnetic principle to be applied; typically, a surface-mounted permanent magnet for highest performance to weight ratio. The initial design is laid out as a Finite Element Model for rotor and stator. The motor is “driven” by the magnetic attracting and repelling force between the rotor and the stator, see Figure 2 below.

Figure 2



Motor principle: a) induced stator magnet field due to phase currents (A, B, C); b) rotating stator field due to varying phase currents; c) rotor magnet field due to surface mounted magnets, fixed with the rotor; d) maximum torque position for a 2 pole motor; e) stator field in the “d” direction creates no torque, stator field in the “q” direction creates maximum torque (d and q are coordinates that are fixed relative to the rotor, in short “dq”).

For any motor design, the key parameters for optimization include the inductance and magnet strength, as these will define motor performance and controllability.

For optimum performance, theoretically, the current in the d direction, “Id”, should be zero as Id does not contribute directly to torque. However, as the rotor moves it creates (induces) its own voltage into the stator windings. This voltage is proportional to the rotor magnet strength (Lambda_pm) and rotor speed and can exceed the voltage that the controller can direct to the windings, at which point control is lost. This can be avoided by superimposing a certain amount of current in the d direction (also called field weakening), enabling continued control of the motor - albeit at “reduced” performance.

2.3 Controller Design

For any chosen topology of motor design, a hardware inverter and appropriate control logic and control parameters must be selected. The role of the controller is to regulate the motor Id and Iq currents to achieve the desired torque. The controller is designed in the discrete time domain. The synthetic duty cycle that is desired to be met, consisting of torque, speed and bus voltage, is used to calculate the required command Id and Iq currents from first principles. Maximum torque per ampere (MTPA) and field weakening can be applied when needed to improve the performance and are calculated using motor parameter look-up tables from Finite Element Analysis that describes the relationships between the dq currents and dq inductances, and the dq currents and Lambda_pm. The measured phase currents and the rotor position are used to calculate the dq currents, which are the feedbacks for the controller.

2.4 Simulation

Given a starting point for both motor and control design, rapid iterations for optimizing motor efficiency and controller stability can be performed. These iterations occur without building any hardware and serve to prompt the evolution of a design that meets the established duty cycle, while optimizing efficiency.

A library of pre-defined blocks of control schemes facilitates quick iterations through a range of controller designs. Scenarios that can be studied include motor operation without a position sensor and various control gains. This enables the quick comparison of multiple control strategies and inverter hardware topologies (e.g., two-stage or three-stage inverters).

Further, an estimation of the power electronic conduction and switching losses, using the simulated device currents, can be performed based on component data sheets. Capacitor losses are estimated based on simulated RMS current and the equivalent series resistance of the capacitor. All other miscellaneous losses (bus bar, gate driver board, control card) are also calculated using the simulated data as an input. For the motor, simulated phase current data, which includes inverter switching effects, are fed to the Finite Element Analysis model to calculate losses for stator and rotor.

With all such losses considered, a very accurate estimate of overall efficiency for all duty cycle operating points of the motor/inverter system can be obtained, allowing for an optimal design vis-à-vis the given requirements.

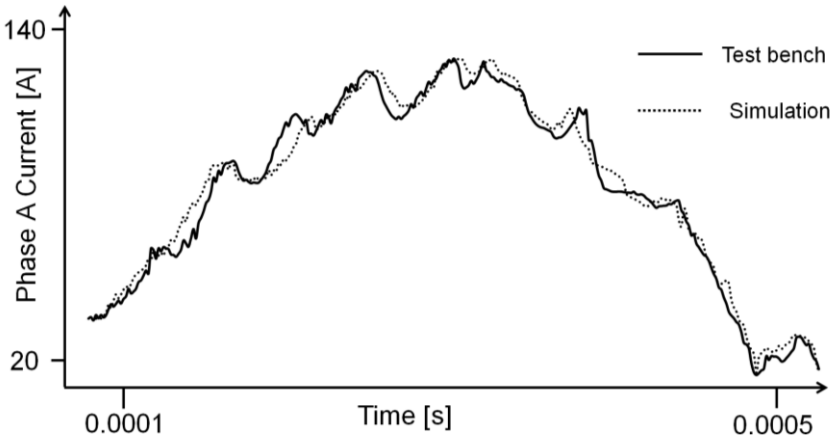
After progressing through a number of motor and controller design iterations (with regard to topology and control algorithm), the simulation results are then used for motor and inverter hardware design and the generation of control code, which can be loaded onto the firmware of actual hardware.

2.5 Data Analysis

Data analysis tools are employed during the design iteration of the motor and controller, as well as for validating simulated performance with test measurements.

Figure 3 below plots phase current for a simulation and an actual prototype: in this case, a good correlation of peak values and phase relationship validates the simulation via hardware tests. Feedback from test results to the design also enables the calibration of models with real world values. Another type of analysis is in the frequency domain, where, for example, peaks in the Fast Fourier Transformation of the phase currents indicate harmonics that would lead to rotor heat up and potential inefficiency or damage.

Figure 3



Phase current of simulation and realized hardware

2.6 Code Generation

Another output from the simulation is automatically generated code that defines the behavior of the digital signal processor of the controller. This gives exact code to be used in the hardware and ties hardware behavior directly to the simulation and can also serve as the basis for further rapid iterations, if needed.

2.7 Prototype Build

Simulation results of the synthetic duty cycle are used to select components for the inverter, and to estimate losses in both the inverter and motor. For the inverter, simulated power electronic device currents and voltage ripples are used to select the correct power electronic modules and size the DC link capacitors. Simulated DC bus current and AC phase currents are used to select the bus bar sizes.

2.8 Testing & Validation

The first step is to calibrate the drive by supplying the digital signal processor inside the controller with real world values for the currents and voltages being exhibited. The second step is to verify that the "back emf" (electromotive force) of the spinning motor falls into an expected range. At this stage, no inverter is connected to the motor. This can uncover problems, such as a wrongly placed magnet, without jeopardizing inverter components.

Another objective of bench testing is to perform bearing break-in, which is especially critical for lubricated oil bearings. This procedure starts at low speeds, which are then increased stepwise as temperatures stabilize.

Further testing validates the control design. For example, the field-weakening controller will increase the Id current automatically when running out of bus voltage to reach a specific torque. The primary control parameter is the current in the motor, but its relationship to the desired torque is not always linear. Therefore, a lookup table between Iq and torque is generated from measurements on the test bench for the controller to achieve better predictability for motor operation when no torque sensor is present.

For a motor where no position sensor is available (e.g. the electric motor in a hybrid powertrain driving a supercharger needs to be optimized for robustness, minimal space and inertia while running at high speed and temperature and therefore may not have a position sensor) the "back emf" can be used to estimate the rotor angle. Bench testing is used to calibrate that signal via the bench resolver.

Another test will map motor and drive efficiency from the test data to simulation data for the entire duty cycle loading profile. Finally, for quality assurance, a test to maximum torque and rpm is performed.

3 Summary

MTS has developed a rapid prototype approach for the development of electric drive system hardware, control algorithms, and software. The methodology has been, and continues to be proved and improved through test validation and real world experience in various motorsports applications. The authors are now in the process of deploying this methodology to be used in the development of hybrid and pure electric powertrains for passenger cars and commercial vehicles.