

Efficient Virtual Prototyping of Electric Drive Systems

Improving electrical, mechatronic, power-electronic, and electromechanical systems.

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 drivetrains by combining fuel cells, batteries, power electronics, and electric motors in one model.

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With increasing interest in the development of electric traction and hybrid-electric vehicles, the demand for comprehensive systems design and analysis to aid the development process is rising. Due to a current globalization environment the decentralized design process brought a real challenge to the automotive engineering design community. The particular stages of the product design as the component testing and the system/sub-system integration became more and more difficult to be managed. Consequently, a uniform and easy platform of emulating those stages became a must.

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.

Ansoft's unique solution for electrical machines and drives is characterized by the flexibility it offers its users. Many phases of the design process can be investigated with respect to one another to insure proper interoperability among domains. Designers, components engineers, analysts, and systems engineers no longer are limited in their interaction by stand alone software packages.

This work illustrates a simulation-based design environment capable of simulating the overall system behavior in connection with a detailed electrical model. The design environment combines either the RMXprt solution, an electric machine-specific tool equipped with analytical-solver that automates the model creation process for the user, or Maxwell solution, an electromagnetic finite element solver that includes static, harmonic, and transient analysis under a common Simplorer environment, a sophisticated design tool offering electrical, electromechanical, and control simulation capabilities. In Simplorer the virtual prototyping is using VHDL-AMS language to model and to implement the control scheme model. The VHDL-AMS is a superset IEEE Std. 1076-1993, and is designed for the description and simulation of multi-disciplinary mixed-signal systems.

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Software Packages Description

RMxprt is a versatile software program that speeds the design and optimization process of rotating electric machines. RMXprt is the entry point for the Ansoft automated motor and drive design flow. RMXprt automatically produces both system-level models and geometric data, allowing the preliminary design to be refined and integrated with power electronic and control circuitry.

Maxwell2D/3D is the leading electromagnetic design software for the simulation and analysis of high-performance electromagnetic and electromechanical components common to automotive, military/aerospace, and industrial applications. Maxwell2D/3D provides users a virtual laboratory on their desktop to study static, frequency-domain, and time-varying electromagnetic fields in complex structures. Maxwell2D/3D features a powerful Microsoft Windows®-based user interface that provides a highly integrated architecture, unmatched automation, and productivity enhancements.

Simplorer is multi-domain, system simulation software for the design of high-performance electromechanical systems commonly found in the automotive, aerospace/defense, and industrial automation industries. With a wide range of modeling techniques, statistical analysis capability and adherence to IEEE standards, Simplorer greatly reduces engineering time and prototype iterations while improving design performance of electrical, mechatronic, power-electronic, and electromechanical systems.

Powertrain - General Description

An auto's drivetrain or powertrain consists of all the components that generate power and deliver it to the road surface. As seen in Figure 1, this includes the engine, transmission, energy storage, electrical machine, motor controller, driveshafts, differentials, and the final drive

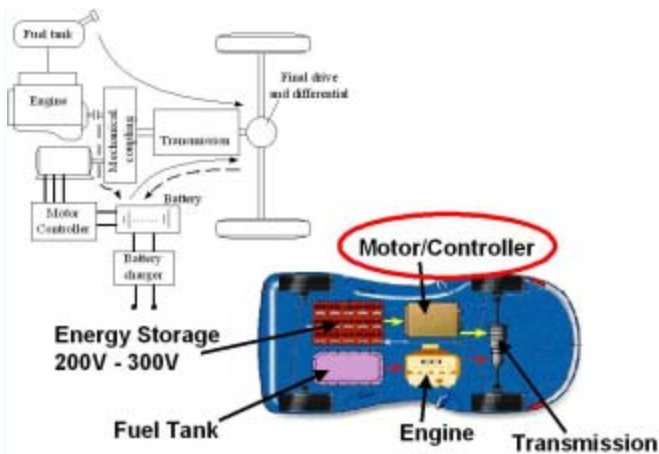


Figure 1. Hybrid Electric Vehicle use advanced electric motors and controllers within the transmission

(drive wheels). Sometimes "powertrain" is used to refer to simply the engine and transmission, including the other components only if they are integral to the transmission. A vehicle's driveline consists of the parts of the drivetrain excluding the engine and transmission. It is the portion of a vehicle, after the transmission, that changes depending on whether a vehicle is front wheel drive, four wheel drive, or rear wheel drive.

Mechanically actuated automotive systems, such as power steering,

fuel and water pumps and even the traction system are being replaced with systems that utilize electric motor technology. Consequently, the presence of semiconductors in automobiles is increasing geometrically, in part due to automotive systems developers' desire for electronic motor control to address consumer requirements for safer, more efficient cars.

One major contingent of the electrical machines group, brushless type motors, are ideal for automotive applications that continuously rotate, such as pumps, cooling fans, and stepper motors. Brushless motors equip positioning systems with start and stop functions where high reliability is required. Furthermore, the electronic control that brushless motors offer is critical to statutory vehicle requirements, including energy-savings, reduced environmental and emissions impact, and the creation of safer vehicles. Brushless motors are also useful for variable-speed applications where space is tight, as in fuel pump control and electronic/electric power steering. In these types of applications, electronic control is essential because of the need for fault diagnostics and wide temperature and voltage operational ranges.

The embedded processor is a critical tool for automotive system designers as they address the increasing needs and demands of today's driver. The increased use of electronic controls enables automotive system designers to meet these needs, while meeting their own requirements to develop low-cost, low-noise, high-accuracy systems with faster time-to-market. A multitude of embedded-processor solutions is available to automotive design engineers.



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More Electric Drive System Topology

An example of electric drive system architecture is shown in Figure 2. This topology can easily accommodate under the same simulation environment both the system level analysis and the very detailed study taking into consideration different behavioural aspects of each component.

Stacked steel laminations on the stator equip the brushless motor with windings placed in slots, which are cut axially along the inner periphery. While the stator, in general, is similar to that of an induction motor, the motor windings can be configured in a non-distributed format. Each winding is constructed of numerous small coils that are placed in

rotor to compress further for the same torque. Alloy magnets improve the size-to-weight ratio and deliver higher torque than a motor of the same size that is comprised of ferrite magnets. A method to detect the position of the rotor magnets is required for such motors.

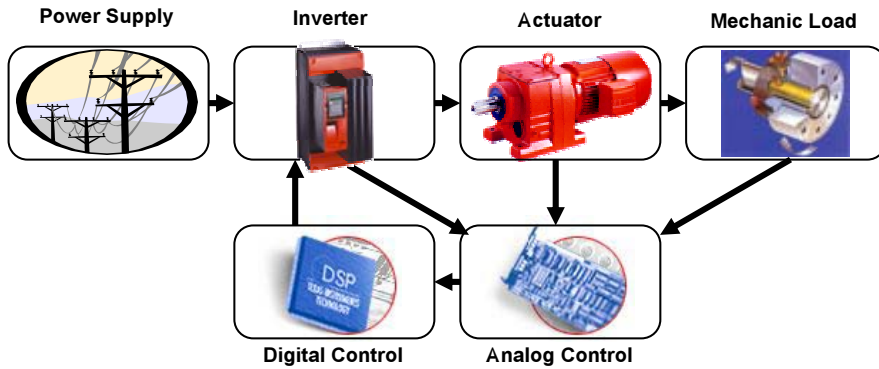


Figure 2. Electric Drive System Topology

As seen in Figure 3, either RMXprt design or Maxwell solution can be employed in Simplorer environment to define the rotational actuator behaviour in such system. The main advantage of using this strategy is to count accurately the electrical machine nonlinearities and the end-effects on the system configuration when analog/digital control parameters design is involved.

the slots and interconnect to form the larger winding. Each winding is distributed over the stator periphery to form an even number of poles. Stator windings can be either trapezoidal or sinusoidal, with each generating different types of back electromotive force (EMF). The phase current also has trapezoidal or sinusoidal variations.

Brushless type motors are popular because they are fast, noiseless, efficient, and exhibit a longer operating life. Brushless motors are also popular due to their compact size, controllability, high efficiency, low EMI (Electromagnetic Interference) and high-reliability. Their compact size is a direct result of technological advances in magnets noted earlier that deliver efficiency improvements. Additionally, the ratio of torque delivered in brushless type motors relative to motor size is higher than in brush type motors, making brushless motors an excellent match for space and weight-sensitive applications.

Brushless type motors can be designed into systems that are sensor-based or sensorless. The implementation of sensorless motor systems eliminates the cost of Hall Effect or optical sensors and their supporting electronics. The sensorless operation is also desirable if the rotor is operating while immersed in fluid such as fuel, oil, or water. In sensorless control, back EMF zero crossing is used for commutation.

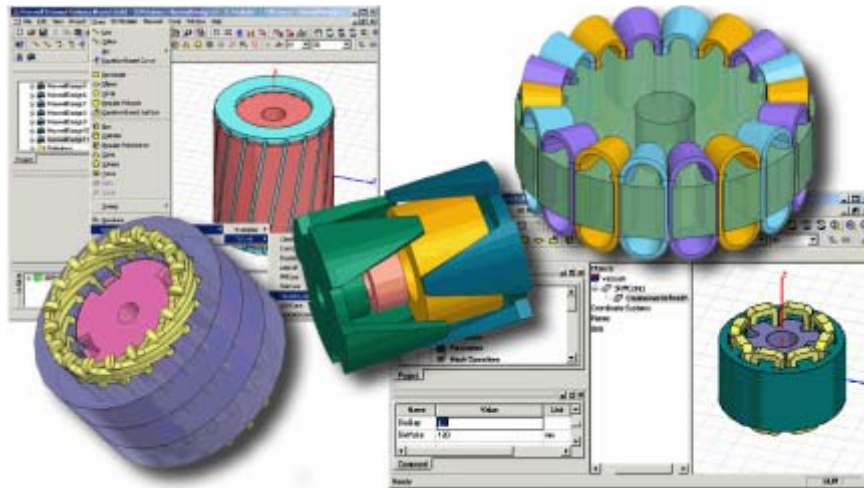


Figure 3. Ansoft's RMXprt allows users to evaluate machine performance using advanced analytical algorithms and creates a finite element model for detailed transient evaluation.

For the current application the technology of brushless type motor is employed. The brushless motor does not use brushes for commutation. Instead, the brushless motor contains a rotor with permanent magnets and a stator with windings, and performs commutation electronically. Commutation is the act of changing the motor phase currents at the appropriate times to produce rotational torque.

All rotors have permanent magnets of some type, and can vary from two to several pole pairs. The proper magnetic material with which to create the rotor is selected based upon the required magnetic field density. Ferrite magnets have traditionally been used to make permanent magnets. However, rare earth alloy magnets are becoming more popular, as they generally have a higher magnetic density per volume and enable the

Since AC variable speed drives started to gain popularity in the 1970s, their basic mode of operation has hardly changed. The incoming AC supply is rectified by a diode bridge to produce DC, and the DC then feeds an output bridge that, in turn, produces an AC output to drive the motor. The frequency and voltage of the drive's AC output are continuously adjusted by a control loop so that the motor delivers the required speed and torque.

Almost invariant to the arrangement of the components, the electric drive system has a number of shortcomings. For example, rectifier systems are notorious for feeding high levels of harmonics back into the supply, and they also have a poor power factor. In addition, the so-called DC link between the rectifier and the output bridge requires the use of large electrolytic capacitors. These not only occupy a lot of space, they are also the components most likely to limit the useful life of the drive, since they lose capacity over time, especially when operated at high ambient temperatures.

Finally, the link between the incoming supply and the motor in this conventional design is

irreversible - there is only the path available for energy from the motor to be fed back to the supply with a special converter - which is very expensive. In general during braking, not only is energy wasted, it also has to be dissipated, usually in a bulky, heat-producing braking resistor.

The presented power electronic design is related to the implementation of a modular matrix converter topology into the electro-mechanical system as illustrated in Figure 4. The three phases of the drive's incoming supply are connected directly to the motor, via a matrix of bi-directional semiconductor switches. By correctly sequencing the operation of these switches, the voltage and frequency of the output to the motor can be precisely controlled.

The benefits of the technology include minimal generation of harmonics, regenerative braking without the need for additional resistors, automatic return of energy to the supply during braking and enhanced operating life. Matrix-converter drives offer efficient operation in all four quadrants. Ordinary drives convert the incoming AC supply to DC, and then convert the DC back to AC at the required frequency and voltage. In contrast, the matrix converter drives use an array of semiconductor switches - packaged insulated gate bipolar transistors (IGBTs) - to connect the three phases of the supply directly to the motor in a precisely timed sequence. This method of operation reduces harmonic generation to approximately 8% of the level

associated with conventional drives, while also offering almost unity power factor.

The voltage converters are based on pulse-width modulation (PWM) of their AC output voltages, which is performed through countless switching operations running at high frequencies. Modern semiconductor power devices (GTO thyristors, MC thyristors, IGBT transistors) are nowadays used for this purpose. The switching operations are controlled through sophisticated algorithms which at present are based almost exclusively on microprocessors (for instance Intel 87C196MC, Siemens SAB 80C166), signal processors (Texas Instruments TMS320C40, Motorola DSP 96002) and application of specified integrated circuits (ASIC, FPGA).

The Simplorer environment provides with a very efficient way to implement this digital control strategy by using advanced hardware description language as VHDL-AMS as seen in Figure 5. Immediate advantages of using this language for such system designs are due to its features in supporting analog, digital, and mixed signal modeling, offering solutions in different design domains at different levels of abstraction, co-simulating with specialized simulation packages and proprietary code, linking to Maxwell for high-fidelity modeling of electromechanical components.

Increasing demands laid upon accuracy, stability and efficiency of electric drives operation require careful selection and optimization of criteria for the PWM strategies. This

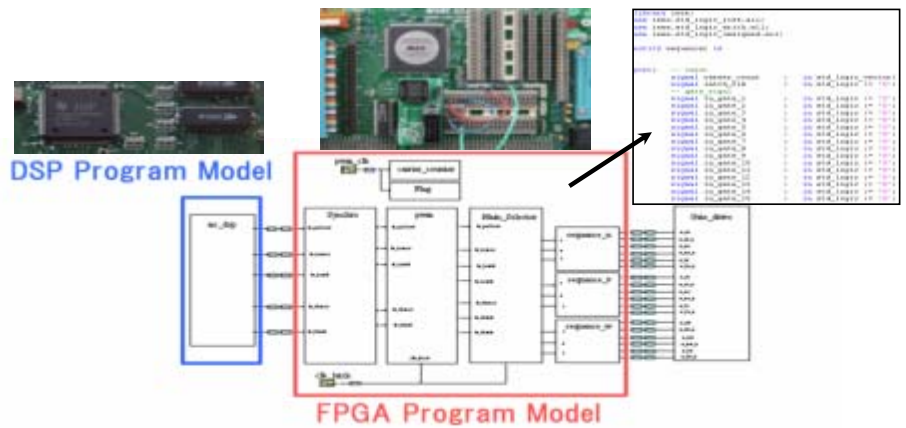


Figure 5. Analog and Digital system control can be defined using VHDL-AMS within the same schematic.

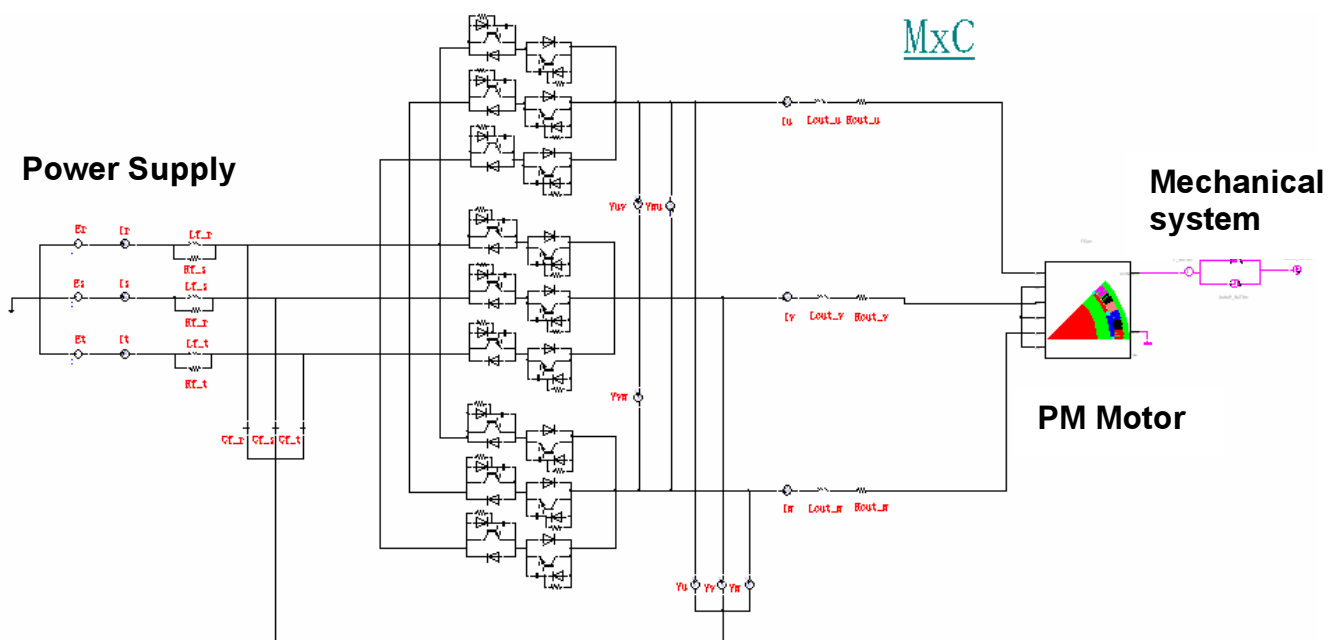


Figure 4. Detailed schematic view of the hybrid-electric power system. Users can analyze the mechanics, electromechanical device and power electronics operation and interaction within a single view.

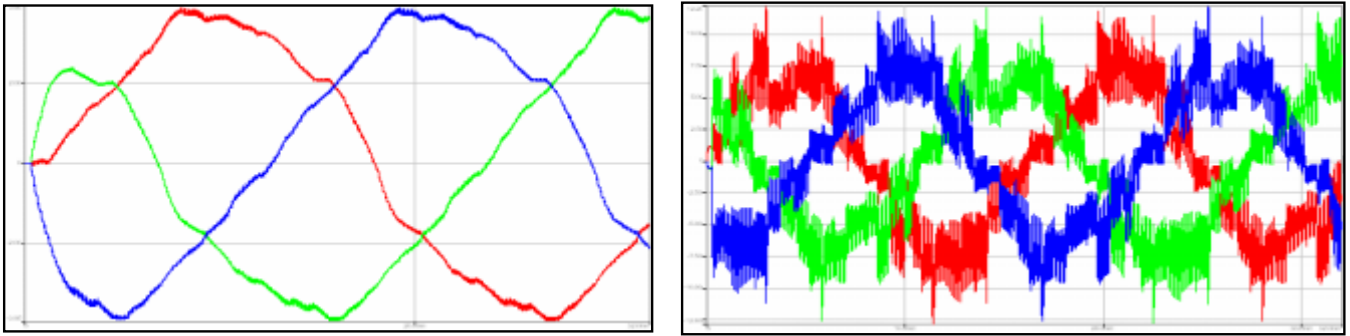


Figure 6. PM Motor Load Currents and the MxC Input currents

is a complicated multidimensional problem especially in the case of feedback modulations. The simulation results of entire analog-digital system are presented in the Figure 6-7. Figure 6 presents the line permanent motor currents (left) and the matrix converter input currents (right) since the Figure 7 shows the digital control signals representing the FPGA response which are further converted into the IGBTs' gates switching pulses.

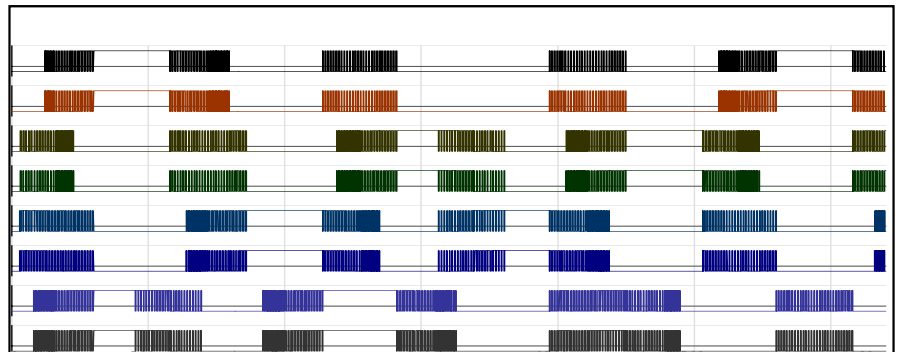


Figure 7. MxC digital control signals

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