White Paper

FPGAs Enable Energy-Efficient Motor Control in Next-Generation Smart Home Appliances

Introduction

Home appliances are at the heart of the modern lifestyle. Consumers want them "smart," "green," and, of course, always cheaper. All those diverging requirements have pushed today's home-appliance designers to create genuine pieces of high technology.

For years, smart appliances used general-purpose electronic devices, such as microcontroller units (MCU) and digital signal processing (DSP) blocks, to manage functionalities such as the user interface and motor control. The performance of these devices is limited because these are made with generic hardware, leaving software as the only method to create application-specific functions by the home-appliance designer.

In comparison, FPGAs give home-appliance designers the freedom to create custom functions, completely adapted to their specific application requirements, by enabling customization of both hardware and software at a very low cost. This additional freedom opens up a new universe of enhanced system performance possibilities, especially for motor-control energy efficiency. Considering that 50 percent of domestic energy consumption is due to home appliances (in industrialized countries), and that energy prices and the importance of environmental regulations are increasing daily, FPGAs can help home-appliance designers create greener products that achieve Energy Star certification and provide additional rebates to their customers.

This white paper shows how home-appliance designers can take advantage of FPGA technology and Alizem motor-control intellectual property (IP) to design the next generation of home appliances, with every functionality, including motor control, integrated on a single chip.

Motor Control Basics

The tremendous increase in the home-appliance energy efficiency in recent years largely is due to a major change in motor-control technology. The use of a power-converter-based variable-speed motor drive makes it possible to save up to 60 percent more energy than the previous generation of home appliances. This technology converts the power outlet's fixed-frequency/fixed-amplitude voltage to a variable-frequency/variable-amplitude voltage using power transistors managed by a motor controller on an electronic circuit. Hence, the function of the motor controller is to obtain the best power conversion in terms of performance and overall energy consumption.

Motor Control in Home Appliances

Motor-control systems are at the heart of washing machines, dryers, refrigerators, and dishwashers, but the motor-control technique depends on the type of motor being used. The two most popular types of motors in home appliances are permanent magnet synchronous motors (PMSMs) and induction motors (IMs). The quality of the appliance's design in terms of energy consumption and noise is fundamental to meet customer expectations, to be cost competitive, and to comply with environmental and power utility regulations. According to the U.S. Department of Energy, using power converter-based variable-speed motor drives in washing machines can save up to 140 kWh per year and influence another 2,374 kWh per year in hot water savings.(1)

Advantages of Using FPGAs and Custom IP for Motor Control

Motor control is a non-linear and time-varying parameter application that demands large amounts of computing power due to the inherently fast dynamics of current flow in the motor and electronics switches. Previously, this computing power requirement was met by having the motor-control software scheme running on a stand-alone MCU/DSP chip that integrates a generic one-size-fits-all pulse-width modulation (PWM) block. However, this kind of system architecture cannot provide the optimal power, performance, or integration needed for motor-control applications. The following sections explain how the power, performance, safety, reliability, system cost, and

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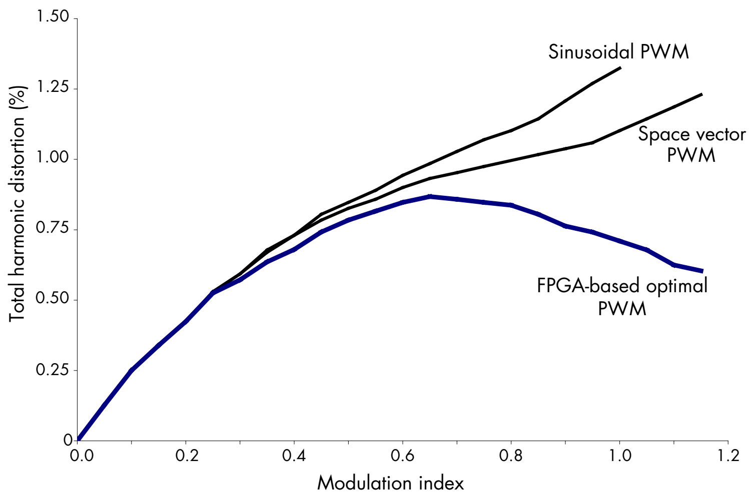
integration advantages of Altera® low-cost FPGAs and Alizem motor-control IP help designers create high-performance and more energy-efficient home-appliance motor-control systems.

Power Advantages

A central part of any current control strategy is the actuation of the voltage command by using one of many PWM techniques. A PWM technique controls the power-converter transistor states in order to meet the time-average value of the voltage command. These techniques can reduce losses in the motor and in the power converter while optimizing the voltage utilization of the DC bus.

The true advantage of FPGAs is that it can make customizable what previously was fixed generic hardware in MCUs or DSP blocks. Hence, an application-specific PWM IP core in a FPGA, completely optimized in terms of energy efficiency and based on motor parameters, can replace the standard PWM block found in a MCU- or DSP-based motor-control chip. Figure 1 shows how an optimized PWM in a FPGA can reduce the total harmonic distortion (THD) by nearly 50 percent at a high modulation index, compared to the standard PWM in MCUs or DSP blocks. In turn, this reduces time-harmonic losses in the motor, reduces audible noise, and increases global motor reliability.

Figure 1. THD Comparison of FPGA-Based vs. MCU-Based Motor Control



Experimental validations on PMSM show that such THD reductions may provide a 50 to 55 percent reduction of motor and power converter losses, thereby providing tremendous gains in global efficiency. These new margins of loss reduction can make the difference in helping home appliances meet Energy Star ratings and/or for designers to add new product differentiating features, such as an enhanced HDTV-based human-machine interface.

Performance, Safety, Reliability, and System-Cost Advantages

The FPGA's hardware programmability enables easy implementation of dedicated high-performance logic circuits. Dedicating logic circuits for motor current and torque control, as opposed to software running on generic MCUs or DSP blocks, allows a very high-frequency (more than 100 kHz) control-loop bandwidth.*(2)* Such high-control bandwidth has a positive impact on current quality due to better regulation. This also allows the motor controller to extract critical information about the health of the motor during its operation, which then can be sent to the main home-appliance controller to notify the user about the risk of motor failure and to adjust motor-control parameters to reduce risk of failure and increase safety of operation.*(3)*

FPGAs provide system cost advantages. One benefit of using FPGAs to increase performance in motor-control applications is that they provide great flexibility in the arrangement of components, allowing the integration of computing-intensive functions to run parallel to the main control scheme. Such functions may be adaptive, with real-time motor parameters and state estimations used to increase motor-control performance and allowed to run without speed or position transducers (sensorless operation). Another example would be to use advanced DSP techniques for measurement signal conditioning, allowing the use of lower quality current, speed, and position transducers, as well as a reduction in cost.

Implementing such functions on MCUs or DSP blocks forces the designer to compromise on either motor-control performance or system performance. In comparison, these functions are completely independent on an FPGA. Hence, a FPGA-based motor controller offers completely deterministic performance and enhanced product reliability, compared to the serial instruction-execution approaches of MCUs or DSP blocks.*(4)*

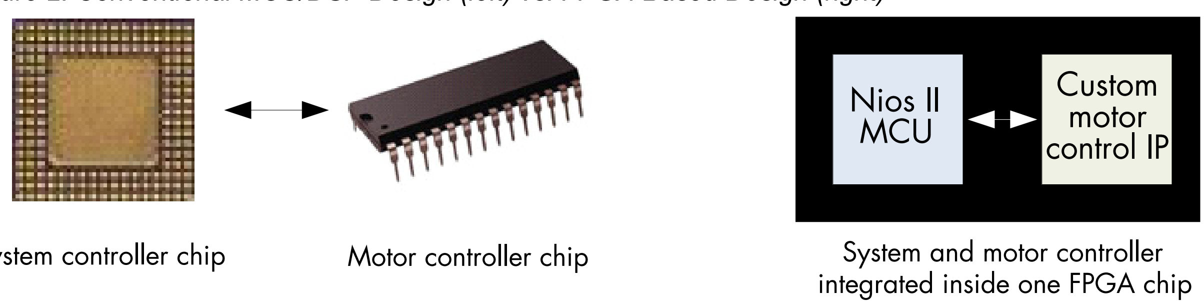
Integration Advantages

FPGA hardware integration is completely different from that of discrete components. Every step of integration is performed within Altera's Quartus® II development software, an electronics design automation (EDA) application that enables the designer to integrate and test system component operations in a completely virtual environment. In this way, the home-appliance designer can start a design from scratch and have a complete operational system in a matter of minutes, allowing more design time for product differentiation. Such easy component integration in a motor controller allows the home-appliance designer to:

- Reduce the number of components
- Reduce system complexity
- Increase system reliability
- Customize motor system configurations to fit every design's performance and price point

Another benefit of FPGA hardware integration is the ability to integrate many independently controlled motor controllers on the same chip (as shown in Figure 2). This feature is particularly useful for home appliances where more than one motor is involved, such as a combined washing and dryer machine.

Figure 2. Conventional MCU/DSP Design (left) vs. FPGA-Based Design (right)



In addition, since FPGAs are reprogrammable devices, they can be easily updated in the field. This allows home-appliance manufacturers to fix issues without costly service calls and replacement parts, as well as to offer the latest firmware version to their customers.

Alizem Motor-Control IP

Alizem offers a complete range of advanced control and fault-diagnosis IP for power converter-fed PMSMs and IMs, designed to provide very high energy efficiency and safety in home appliances. The perfect motor-control IP for each application can be achieved by selecting and integrating the right combination of each of these IP products:

- *Zem-PWM™ IP* enables the integration of high-performance PWM for voltage actuation, and ranges from standard space-vector PWM to custom-optimized PWM.
- *Zem-CC™ IP* enables the correct cost/performance compromise for motor current regulation, and ranges from standard scalar control to adaptive sensorless vector control.
- *Zem-Diag™ IP* monitors measurement signals and machine states to proactively detect and diagnose faults in the motor, the power converter, the sensors, and the load. This information then can be used to plan future maintenance and to switch to safe operation mode.

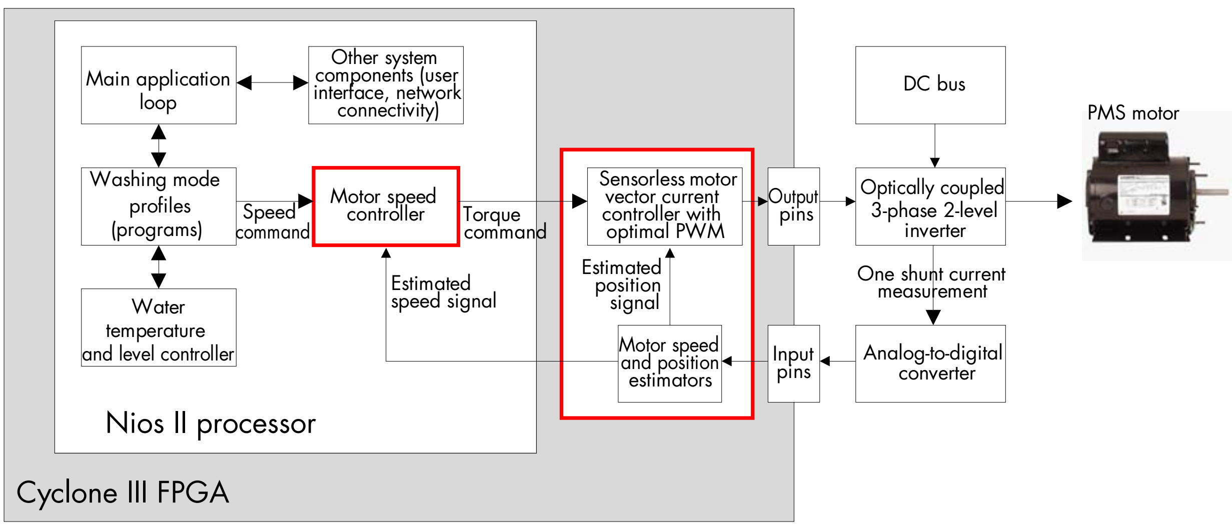
All Alizem motor-control IP cores are designed with a proprietary DSP algorithm that offers the best compromise of performance and FPGA resources, such as logic elements (LEs). For example, a complete motor drive for a PMSM, including PWM and current control, needs less than 500 LEs on a low-cost Altera Cyclone® III FPGA. In addition to reducing silicon costs, using IP with such a small footprint leaves enough FPGA resources for the home-appliance designer to add other high-value features for product differentiation.

Another advantage of Alizem's motor-control IP, compared to using MCUs and DSP blocks, is that it is soft IP that can be programmed into FPGA, and not hard IP. This feature provides significant benefits for the home-appliance manufacturer, including unlimited supply (no risk of obsolescence), constant quality of product, easy integration, and a guarantee to have the state-of-the-art virtual motor-control chips in every shipped product.

Altera Home-Appliance Motor-Control Development Kit

The Altera Home-Appliance Motor-Control Development Kit is a Cyclone III-based platform with a Nios® II processor that enables home-appliance designers to design custom motor-control quickly using Alizem motor-control IP (shown in red on Figure 3). Alizem IP is split in two parts: a software part running on the Nios II processor for speed control (slow dynamics) and an hardware part packaged as a Quartus II SOPC Builder component for current/torque control and PWM (fast dynamics).

Figure 3. Alizem Motor-Control IP Inside the Altera Home-Appliance Motor-Control Development Kit



This schematic of a washing machine design with sensorless permanent-magnet synchronous motor is a perfect example of how high-computational FPGA capabilities benefit home-appliance design in reducing cost and increasing reliability. Motor position and speed sensors have been replaced by high-performance estimation algorithms inside the controller that reconstruct the signals based on previous current measurements. Depending on the washing machine model type, added reliability and performance could be easily integrated in this design with a fault-diagnosis Zem-Diag component (for unbalanced load detection, for example) without compromising the overall system performance or fighting for shared computational power.

Conclusion

Because of their low-cost programmable hardware, integration of Nios II embedded processors, and ability to incorporate Alizem's motor-control IP, Altera's FPGA-based systems offer new features for many applications that cannot be found in any MCU- or DSP-based system (see Table 1). These features include enhanced motor-control capabilities to help home-appliance designers create highly differentiated products that offer very low power consumption and added reliability while reducing costs and accelerating time to market.

Table 1. MCU/DSP and FPGA Comparison

Feature	MCUs/DSP Blocks	FPGAs
Custom PWM		✔
Multiple motor controllers on one chip		✔
Custom motor drive configuration		✔
Easy component integration		✔
Parallel component architectures		✔
Necessary amount of ICs	2+	1
Deterministic performance	No	Yes
High control loops bandwidth		✔
High reliability		✔

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