Driving Higher PV Inverter Efficiencies

through a Customizable System-on-Chip

May 2012

Table of Contents

Overview

Much of the current focus on energy production is on renewable resources: wind, solar, tides, etc. While wind turbines have strict requirements as to location (there must be enough wind and space for the towers), solar systems have a much smaller footprint and can be placed practically anywhere. The most common means of harnessing solar energy is through the use of photovoltaic (PV) panels that are capable of collecting solar energy and converting it directly to electric power. However, the energy from PV panels is direct current (DC) and must be converted to AC via inverters which interface the modules to the electric grid using various DC-to-AC inverter topologies and control structures.

Current PV modules used for harvesting solar energy have low efficiency rates. As a result, the efficiency of the PV inverter used for converting this harvested energy into usable power is critical. In addition to the need for increased efficiency, PV inverters must also adhere to various international standards before they can be placed into commercial use. The market demand for low cost, low power and high efficiency, coupled with the need for high reliability as well as a wide input voltage tolerance, has driven inverter design towards lower component counts and higher degrees of integration. Recent semiconductor technology advances have provided PV designers with the ability to meet such demands.

Microsemi's recently introduced SmartFusion® customizable system-on-chip (cSoC) is the first platform to integrate programmable logic, control, temperature/power sensing and management plus communication functions into a single, low power device. It does so by combining a flash-based FPGA fabric, programmable analog, and a high-performance embedded processor, providing the world's first and only intelligent and fully programmable cSoC. This new class of device provides a low power, low cost solution and minimizes power losses by providing a highly optimized power-smart solution while allowing designers to easily make hardware/software trade-offs dynamically to further optimize their design.

This paper explores the ways in which Microsemi's cSoCs provide designers with the ideal tools for developing high-efficiency PV inverter systems capable of meeting today's market demands. To start, this paper provides background information on the overall design of PV systems and their most pertinent design issues. Second, typical design requirements are introduced in conjunction with a description of how these requirements can be met using design techniques enabled by Microsemi technology.

Photovoltaic Technology

Unlike other forms of renewable energy such as wind and water, solar energy is more prevalent around the world and as a result is being used more frequently as a source of energy. Photovoltaic technology provides a mechanism in which solar modules are used to capture and convert solar energy from the sun into electric energy. In a PV energy system, PV modules can be linked to form arrays or solar panels (Figure 1). These modules contain semiconducting material which absorbs photons of sunlight, which in turn energize electrons in the material, freeing them from their atoms and consequently creating DC current. Unfortunately, the efficiency of converting solar to electrical energy in PV modules is very low (roughly 19%); consequently, it is crucial that the DC-to-AC power converter be highly efficient (greater than 95%) in order to maximize the use of the harvested solar energy and minimize the footprint of the solar modules and the volume of the entire system. It is this challenge that motivates the need for the new technologies provided by Microsemi.

Figure 1: **PV Modules Linked to Form PV Arrays**

PV Energy Systems

PV systems come in two distinct configurations, based on their application. In one case, a system operates independently of the electric utility grid, referred to as an off-grid or a standalone system. Conversely, a system can be integrated with the utility grid so that energy can be shared between the PV system and the grid (surplus power can be sold back to the utility). Naturally, this later configuration introduces additional complexity.

The components for a particular PV system vary depending on the functional and operational requirements of the system (Figure 2 on page 5). The most common components are as follows:

- **PV modules:** These can be combined to create PV arrays and are used to convert sunlight into DC power. Because of this modularity, a PV system can be sized for different applications, ranging from powering a single machine to powering a commercial building.

- **Cooling system**: Required when temperatures rise during operation; for example, in the case of heat generated due to the diodes in the junction boxes of the PV modules.
- **Energy storage/battery bank:** A battery is typically needed in the case of a standalone PV system. When the PV system is producing more power than the load's demand, this excess power can be stored in a battery for later use (for example, at night).
- **Load:** The load connected to the PV inverter can be of any size and AC, DC, or a combination of both.
- **Utility grid interface:** For grid-connected PV applications, a bidirectional interface between the PV system and the utility grid is included to allow the power produced by the PV system to back feed the grid when the PV system output is greater than the load demand. The balance of power required must be monitored in the case when the load demand is greater than the PV system output or when the utility grid is down and power cannot be fed back. Such control mechanisms are implemented as part of the PV system controller (which is part of the inverter system).
- **PV inverter system:** The PV inverter is the heart of the PV system, performing DC-to-AC conversion, power protection, monitoring, and control. The design of the various components of this system depends on the functional requirements of the end system. Moreover, power system interconnection regulations and international standards, such as IEEE 1547 and EN50160, impose constraints—including the necessity for galvanic isolation, the maximum harmonic distortion of the current injected at the point of common coupling (PCC), the maximum permitted DC current injection—all of which must be considered during the design of PV inverters.

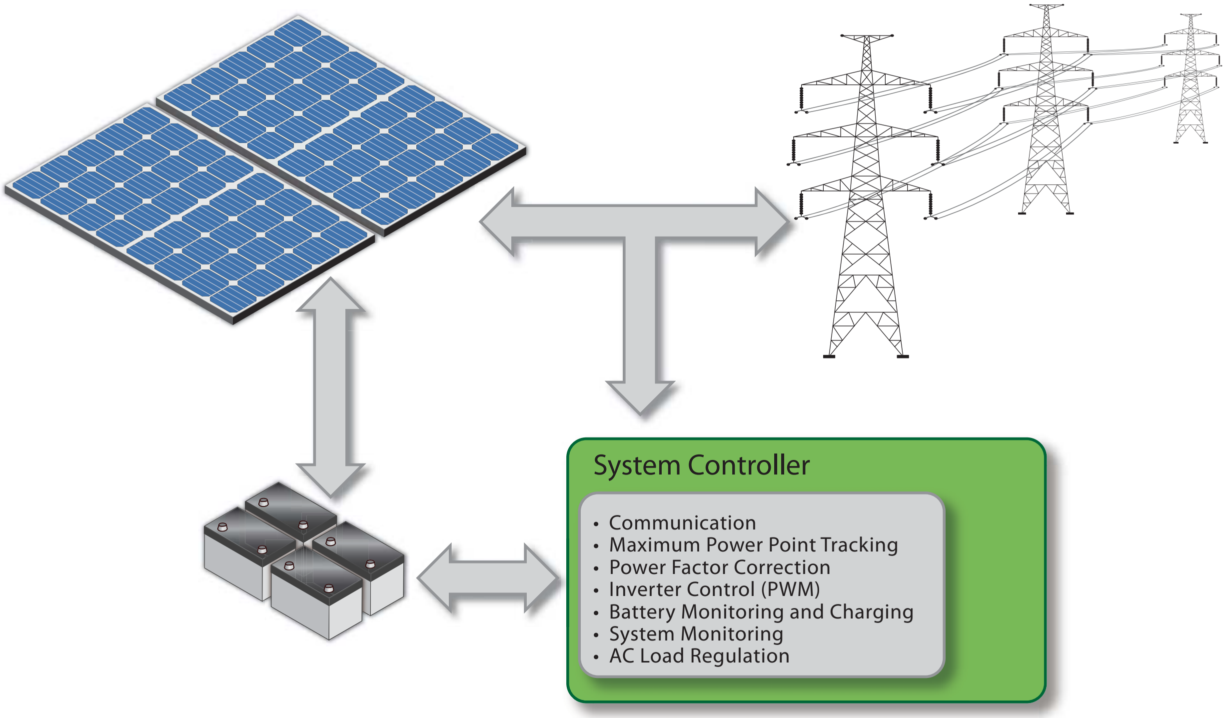

Figure 2: **Typical PV Energy System**

PV Inverter System

PV inverter systems typically have two major sub-components: a controller used to implement system management tasks and control algorithms, and the AC-to-DC conversion circuit. The specifics of the controller depend on the type and configuration of the PV system as well as its functional requirements. The following sections provide a more detailed look at each sub-component and how they impact overall system efficiency.

Controller

Central to any PV system is control. The responsibilities of the controller include:

- Grid and system monitoring
- Synchronization of the system with utility power for grid-connected systems
- Output power quality monitoring
- Protective functions for safety and compliance with standards and regulations
- Data logging, firmware updates, and communications with the system operator
- Battery charge control in the case of standalone systems when the PV produced power exceeds the load demand[1]
- Smart metering used for grid-connected PV systems[2]

An additional relatively demanding responsibility of the controller is the execution of control and energy management algorithms such as maximum power point tracking (MPPT), pulse-width modulation (PWM), and power factor correction (PFC). In addition to being computationally demanding, these algorithms can have a significant effect on power efficiency.

DC-to-AC Conversion Circuit

The DC-to-AC conversion circuit converts the raw DC power from the panels into clean AC power consistent with the voltage and power quality requirements of the utility grid. This conversion is accomplished by using a set of switching power devices such as MOSFETs or IGBTs. The inverter circuit also includes active filtering circuitry to reduce the distortion caused by harmonics resulting from high-frequency switching.

There are a number of possible configurations in which the PV conversion circuit can be configured. These configurations are dictated by the number of power processing stages, the type of power decoupling, the types of interconnections between the stages, and the type of the grid interface. Further, various architectures of inverters that are appropriate for different power levels can be used. For example:

- Micro Inverters integrated in the PV module for power levels up to 400 W
- String inverters for those up to 10 kW
- Multi-string inverters for levels between 5 to 50 kW
- Central inverters for higher power levels

---

[1] *The controller prolongs the battery life by preventing over-charging. Constant monitoring and adaptive trickle charging are functions necessary for optimal battery performance. Careful avoidance of stressing the battery above charging capacity or running the battery past a specified operational output level ensures battery lifetime longevity and removes early replacement or unplanned maintenance.*

[2] *Utility power can be provided when the demand exceeds solar electric power production, and credit of any excess power can be given when PV power production exceeds demand.*

The efficiency of the conversion circuit is crucial in harvesting solar energy and, as a result, careful measures must be taken with its design. The efficiency of the circuit depends on the topology used and the type and operational characteristics of the components used (semiconductor switching devices, magnetic elements and capacitors, for example).

Moreover, the increased voltage stresses of the switching power devices cause high switching power losses. These switching and conduction losses in the inverter circuit should be minimized by using efficient inverter topologies combined with semiconductor switches and drive circuits capable of operating at high frequency with minimal losses.

There are trade-offs between performance and cost of MOSFETs, super-junction MOSFETs and IGBT power devices. In general, MOSFETs are more costly than IGBTs but are more efficient at higher frequencies.

Two of the inverter topologies have achieved higher efficiencies for grid-connected centralised inverters:

- The highly efficient and reliable inverter concept (HERIC), shown in Figure 3
- Multilevel inverters (a typical topology is shown in Figure 4 on page 8).

The HERIC inverter reduces losses by decoupling the output inductor from the input capacitor by incorporating an extra switch and diode pairs at the output.

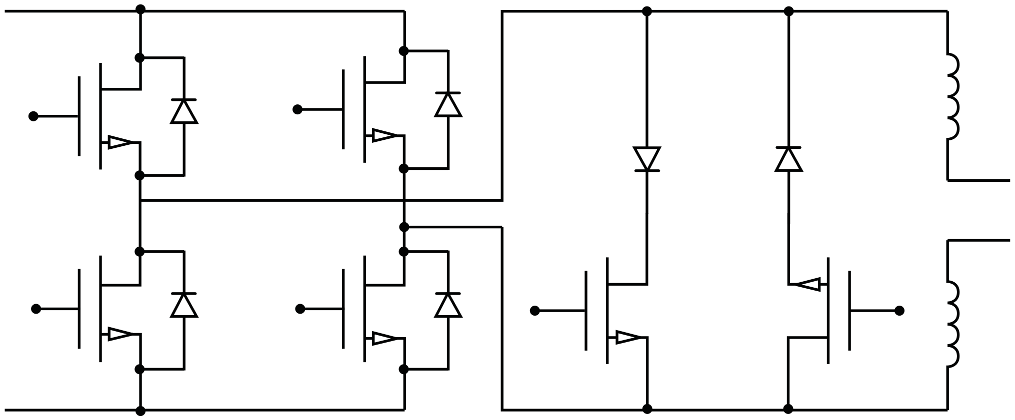

Figure 3: **HERIC Inverter**

Figure 4 shows a three-level central inverter topology targeted for higher voltage power applications. This new topology is more complex than its traditional counterpart, with the most important difference being that each switch has only 50% of the voltage stress. This reduction means that devices with much lower voltage can be used, leading to higher efficiency and lower device costs. Further, the size of the electromagnetic interference (EMI) level and output filter (for cleaning the harmonics) can be reduced, thus lowering the overall cost of the system.

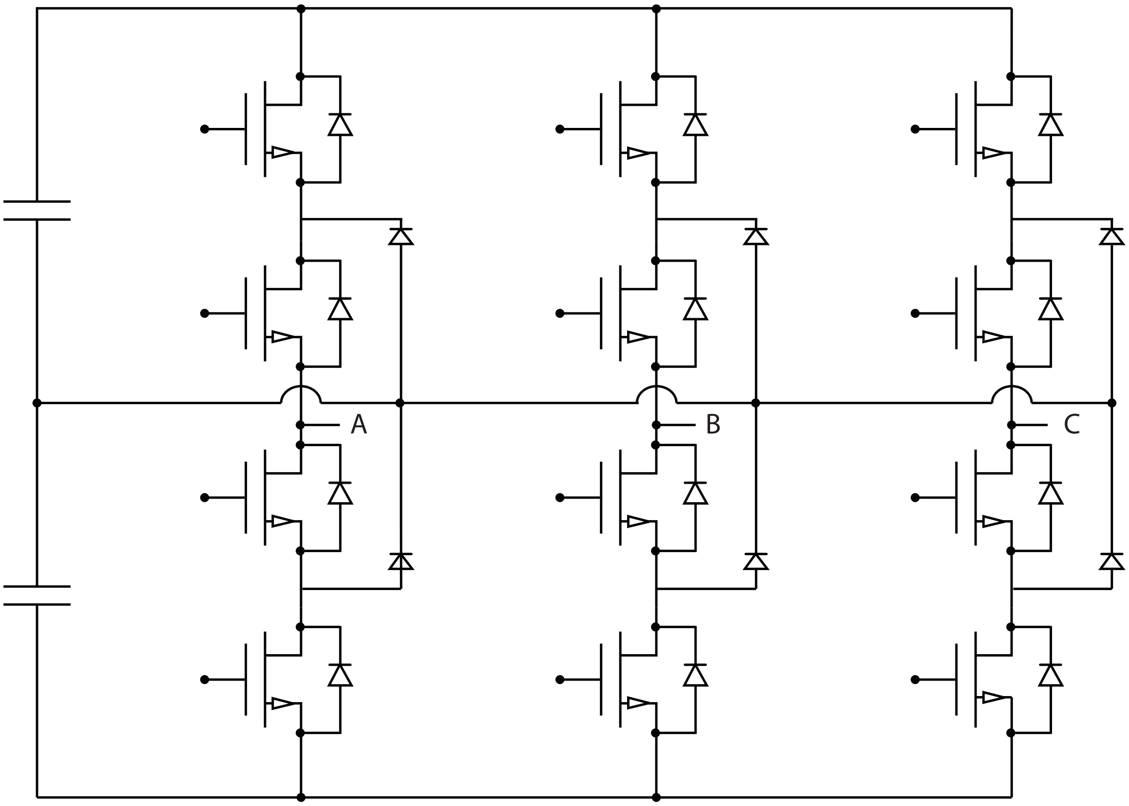

Figure 4: **Three-Level Central Inverter**

In addition to an inverter, a PV system can also have a DC-to-DC conversion stage. Although the DC-to-DC stage can be used to maintain the input voltage at the inverter at a constant and controlled level, as well as decouple the control of voltage and power, it can have a negative effect on system efficiency.

New Switching Technology

Recently, silicon carbide (SiC) power transistors have become a reality. SiC-based semiconductors offer several advantages over traditional silicon or even gallium arsenide (GaAs), allowing for much greater power handling and higher switching rates. Currently, there are projects to develop utility grade devices with an eye toward creating solid-state power transformers and high-power inverters for wind and solar farms.

Using SiC-based power transistors in power supplies has increased their efficiency from the high 80% range to the low 90% percent range. There are reports of SiC-based solar inverters achieving 99% efficiency.

The higher switching frequencies of SiC-based power transistors go beyond the capabilities of many microcontroller-based PWM circuits. FPGA-based PWM circuits, however, can handle the higher required frequencies and due to their programmable nature, allow the same control circuitry to be used for both Si and SiC-based power transistors. This flexibility helps future-proof control designs.

Maximum Power Point Tracking

A PV array's maximum output power varies over time due to many factors such as temperature, shading, soilage (dirt on the panel, for instance), cloud cover, light intensity, and the time of day. These effects impact the operation of the PV inverter and can dramatically lower its efficiency: The current in PV modules connected in series is determined by the lowest illuminated panel. As a result, the shaded module absorbs power (instead of generating power), causing a hot spot. The hot spot is eliminated by the bypass diodes but this also results in significant reduction at the output power generation and shifts the overall MPP, reducing the efficiency of the PV inverter.

Efficiency can be strongly influenced by the ability of the PV system to control the power inverter so that it can react to changes in the operating conditions. Maximum power point tracking (MPPT) algorithms are used to provide such functionality.

MPPT maintains the optimum operating point as the operating conditions change by regulating the PV output in order to guarantee that maximum power is delivered by the PV system. The algorithm also guarantees that the inverter does not draw more than the maximum PV array output power, thus preventing inverter collapse. An MPPT algorithm is typically deployed in the main controller; however, in certain cases where the operating conditions for individual PV modules differ significantly, it is more efficient to deploy the algorithm in the individual PV modules, allowing each to track independently. This finer control over power conversion can greatly enhance the efficiency of the conversion process in applications using a larger number of modules.

There are several possible algorithms for MPPT, each having its own advantages and disadvantages. The following are just two examples:

- **Perturb and observe:** The voltage or current is varied until the maximum power output is obtained. This technique has the advantage of being simple; however, it is susceptible to oscillations if the light intensity changes rapidly or if the step size is too large.
- **Incremental conductance:** The voltage and current are varied in small steps with the instantaneous and incremental conductance being constantly calculated and compared by a control loop that calculates and maintains the direction in which the power point should be moved. This technique has the advantage that it can reach and maintain the MPP without losing efficiency due to oscillations. Generally, this algorithm tracks more accurately than the perturb and observe method. The disadvantage of this method is increased computational requirement, resulting in longer reaction times to changing operating conditions if the algorithm is implemented in software (in a microcontroller, for example).

Pulse Width Modulation

PWM is a technique used to efficiently control power switching components in the inverter circuit when converting DC to AC power. A PWM algorithm controls the switching component's states in order to meet the time-average value of the voltage command. Such algorithms can reduce losses in the inverter while optimizing the voltage utilization of the DC bus. PWM techniques have the advantage of being well understood and easy to implement in either hardware or software.

Power Factor Correction

The power factor refers to the ratio of real power to reactive power where real power is useful and reactive power is wasted (the result of current and voltage being out of phase). Capacitive and inductive loads cause a poor power factor.

With a power factor of one, the voltage and current are in phase, providing maximum power. In effect, actively correcting the power factor improves system efficiency and is often required to meet certain energy efficiency standards.

Standards Impacting Solar Inverters

As with any industry, the solar industry has to contend with a number of regulations and standards, dealing with the design of the systems, how they interconnect to the grid, and the proper sizing and charging of lead-acid batteries.

IEEE 1547

The Standard for Interconnecting Distributed Resources with Electric Power Systems is a collection of multiple standards that cover the performance, operation, testing, maintenance and safety of the interconnection to the grid.

IEEE 1361

Guide for Selection, Charging, Test and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic Systems covers lead-acid battery charging requirements in PV systems as well as guidance in selecting batteries.

IEEE 1526

Recommended Practice for Testing the Performance of Stand Alone Photovoltaic Systems provides test methods and procedures for evaluating PV system performance.

IEEE 1561

Guide for Optimizing the Performance and Life of Lead-Acid Batteries in Remote Hybrid Power Systems provides methods regarding the use of lead-acid batteries.

Hardware Implementation of Inverter Systems—Why Programmable Logic?

PV inverters have traditionally been implemented using a variety of processors, including microcontrollers and digital signal processors (DSPs). With constant gains being made in FPGA technology, including cost improvements, higher performance, increased programming flexibility, and increased gate capacity, an FPGA-based customized controller can now outperform microcontrollers, DSPs and ASICs in the equivalent price range.

DSPs only have an advantage when implementing common DSP tasks. As a result, much of their space and power is wasted in the moving and decoding of instructions and data with only a small fraction of the silicon being used for actual computation. The end effect is that DSPs can be quite inefficient when implementing basic system control functions.

FPGAs give PV designers fine-grained control over the design’s implementation, resulting in a highly optimized solution and allowing them to create custom functions such as PWM, MPPT, and PFC algorithms, adapted to their specific application requirements. This is, in part, due to the fact that both hardware and software are customizable at a very low cost. Further, flash-based FPGAs can be reprogrammed at any time, not only reducing development costs but allowing for upgrades and bug fixes to be made in the field. Generally, the use of FPGAs provides increased reliability and robustness, increased flexibility through in-field upgrades and expansions, plus improved testability.

The design and performance of a PV inverter system can be further enhanced by the use of an cSoC platform—a platform which combines programmable logic with an embedded controller and configurable analog. The integration of board-level components into a single monolithic IC has many advantages, including reduced cost, reduced power dissipation, and shorter circuit delays due to the absence of board-level wiring. By avoiding the long wires needed to connect devices on the board, many other problems can avoided such as parasitic ringing and oscillations.

A cSoC allows a designer to chose where and how best to implement control functions—in hardware or software, or in a combination of the two.

The Evolution of Programmable Logic for PV Applications

Microsemi's SmartFusion cSoC is a new class of programmable logic ideally suited for PV applications. This third-generation device builds on Microsemi's long history of flash-based FPGAs. IGLOO® devices were the first generation, providing designers with a low-power, single-chip solution that could integrate custom PWM routines and provide hardware acceleration for custom control routines as well as I/O expansion.

Microsemi's solution offering was further expanded with the introduction of the second generation flash-based FPGAs: Fusion—the first mixed signal FPGA. Fusion added voltage, current and temperature monitoring to the capabilities of IGLOO devices, allowing designers to achieve greater levels of integration than were previously possible.

SmartFusion cSoCs represent the third generation in the line—the first platform to integrate a flash-based FPGA fabric, programmable analog, and a high-performance embedded processor, providing the world's first and only intelligent and fully programmable cSoC. This new family is proving to be a powerful platform for PV applications. Refer to the "Highly Efficient, Low Power SmartFusion cSoC for PV Inverter System Management" section on page 12 for more information.

Function	CPU	FPGA	Percentage Gain
256-point, 16-bit Radix-2 FFT	326 µs	11 µs	29×

Design Techniques Made Possible with cSoCs

Central to much of the control of advanced PV inverters is signal processing. With the programmable fabric within a cSoC, computational throughput can be increased by using hardware acceleration techniques to implement any needed DSP functions that cannot be feasibly implemented in the embedded microcontroller. In essence, arithmetic co-processing is accomplished through the highly parallel nature of an FPGA fabric.

Fast Fourier transforms (FFT) are a technique commonly used for filtering and cleaning the inverter output signal in a PV system, performing signal quality analysis based on total harmonic distortion (THD). Results are then compared to grid waveforms and adjusted accordingly. Implementing the FFT algorithm is possible using an embedded processor such as the ARM® Cortex™-M3 processor or using programmable logic. Refer to the "Using SmartFusion's Core as a Hardware Accelerator" section on page 13 for more information. Typically, the performance for a hardware implementation is measured in the tens of microseconds vs. hundreds of microseconds when executed within a microcontroller. In either case, the required performance is design-dependent; therefore, having the option of a hardware or software implementation is advantageous. Such flexibility can only be found in an cSoC, which incorporates both an embedded processor and programmable logic.

PWM is necessary to efficiently control power switching components such as IGBTs and MOSFETs. Alternative PWM implementations exist, so selection is dependent on system requirements. For example, in a system that requires a small footprint due to space constraints, a technique of resource sharing can be utilized whereby a high-performance PWM state machine operates at frequencies in the multi-MHz range—a technique ideally suited for implementation in programmable logic.

With resource sharing, the input of the PWM is controlled in a feedback loop from the analysis of the inverter output versus grid supply waveform. The high-frequency PWM output is then placed into FIFOs that control the multiple KHz range switching elements. This design technique is also applicable in applications where a single device controls multiple switching supplies, such as mini-inverters, when multiple microinverters are included within a single package. Conversely, in systems with tight power budget requirements, the approach is to integrate board-level PWM devices into multiple, on-chip low-frequency PWM channels. This method immediately reduces off-chip power supply requirements and allows designers to custom tailor the exact number PWM channels and switching characteristics as per the system specification. Again, the programmable fabric of the cSoC allows a designer to implement the exact number and configuration of PWM channels needed for the application.

A recent research paper titled *Flash FPGA-Based Numerical Pulse-Width Modulator*, illustrates the utilization of hardware resources for a PWM implementation in Microsemi's devices.

Microsemi—The Complete Solution Provider

Microsemi offers a range of products suitable for the various stages of the PV system to allow designers to create a low power, highly optimized, reliable, and cost-effective solution tailored for their particular application while meeting all standards and regulations.

Highly Efficient, Low Power SmartFusion cSoC for PV Inverter System Management

Microsemi takes the traditional advantages of FPGAs and SoCs to another level through its SmartFusion cSoC (Figure 5).

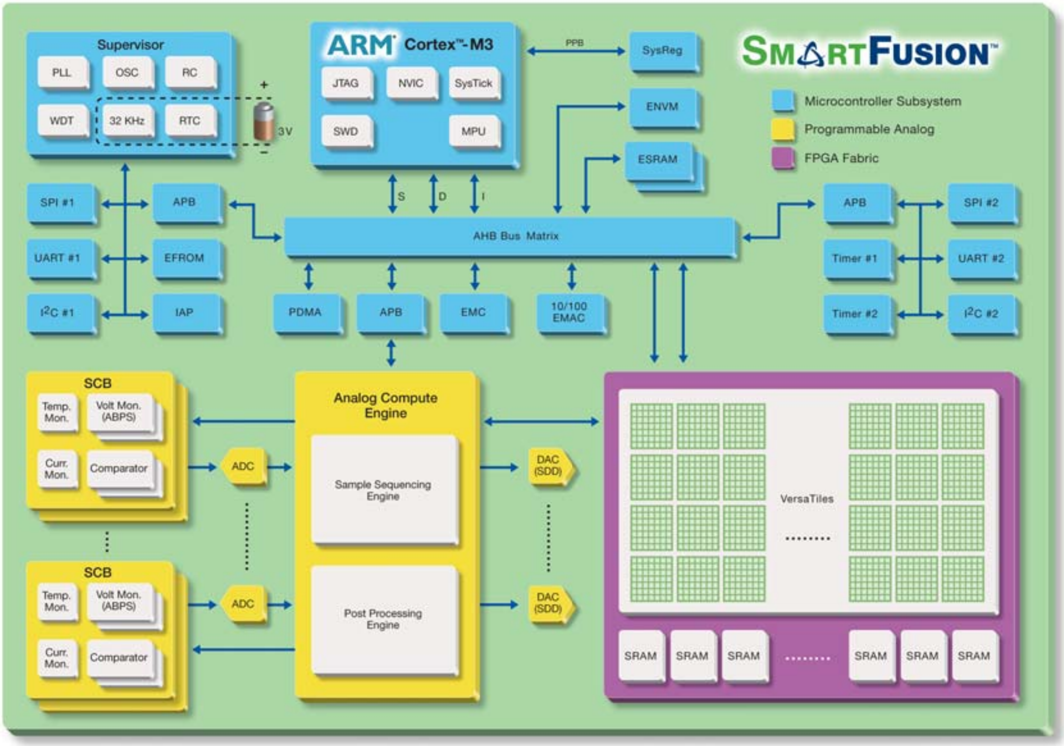

Figure 5: **SmartFusion Customizable System-on-Chip**

SmartFusion is the world's first customizable system-on-chip that combines a flash FPGA, hard ARM Cortex-M3 processor, and programmable analog allowing for the integration of control, sensing/power management, and communications functions into a single low-power device. Not only does Microsemi's cSoC reduce system cost, design time and effort; it also offers better IP protection and much more flexibility without the excessive cost of soft processor cores in traditional FPGAs. SmartFusion cSoCs offers up to half a million gates of programmable logic, 13.8 Kbytes of general-purpose FPGA RAM, and a wealth of system peripherals and programmable analog, combined with a microcontroller subsystem (MSS) consisting of a 100 MHz Cortex-M3 processor with 64 Kbytes of SRAM and 512 Kbytes of flash memory. In addition to providing IP security and live-at-power-up (LAPU) operation, Microsemi's proprietary flash technology also enables high-voltage analog to coexist with a reprogrammable FPGA fabric and a high performance processor with hard peripherals — all without any performance or noise issues. This means that the processor and the FPGA can function independently, allowing the PV designer to take full advantage of both components.

Because all major components (processor, FPGA, and analog block) in SmartFusion are programmable, PV designers can make hardware/software trade-offs as needed. Further, because of the easy-to-use SmartFusion design tools, a single designer can implement a complete design without a requirement for expertise in analog or software design.

Using SmartFusion’s Core as a Hardware Accelerator

A designer of PV controller applications could use a microcontroller along with a generic FPGA as his/her solution platform. However, in PV applications, DSP algorithms are needed to control power-factor correction and remove the total harmonic distortion out of the DC-to-AC conversion. A microcontroller could host the signal processing algorithm, but any need for performance will quickly outstrip the microprocessor's bandwidth; moreover, the signal processing algorithm will compete with the host application for processor resources.

Another approach is to implement the required DSP functionality in hardware, building a DSP coprocessor operating in tandem with the embedded microprocessor. In this alternative, the coprocessor is constructed in the programmable logic core of the cSoC. The embedded microprocessor makes calls to the coprocessor each time a signal processing function is needed, unburdening this task from the microprocessor while achieving the needed throughput.

For example, performing a total harmonic distortion analysis requires using a fast Fourier transform (FFT)—a block that can be easily implemented in programmable logic. Hosting this transform in programmable logic yields impressive increase in performance — a 256-point, 16-bit, radix-4 FFT takes only 11 µs to complete versus nearly 30 times as long in a typical microcontroller.

While designing a specialized function such as an FFT is a complex task, a number of off-the-shelf IP cores are available to greatly simplify the tasks of implementing the algorithm in hardware.

Taking Advantage of SmartFusion’s Programmable Analog

Monitoring and evaluating operating conditions are one of the critical tasks in a PV system to keep the system operating at its peak performance, giving end-users and utilities visibility into potential failures prior to their occurrence so that they can act accordingly. SmartFusion has a multitude of peripheral controllers as well as various analog monitors provided in the signal conditioning block (SCB) to implement such communication and control functions. Peripheral controllers include a 10/100 Ethernet MAC, two I^2C ports, two UARTs, two SPI interfaces, a pair of timers, and an 8-channel DMA controller. The SCB offers other analog components including prescalers, converters, sensors, analog/digital converters capable of reading 16 different analog inputs simultaneously with a sampling rate of 500-600 ksps, comparators, current monitors, temperature monitors and more. For example, monitoring battery charging temperature, a task that is important for optimizing battery performance and longevity, is available via the SCB with a 0.25°C resolution.

The SmartFusion analog compute engine (ACE) is provided to further optimize functionality. The ACE combines a sample-sequencing engine (SSE) with a post-processing engine (PPE) to offload the job of reading analog inputs from the Cortex-M3 processor. The SSE reads data from the analog inputs and passes it to the PPE to perform functions such as low-pass filtering to remove noise and data transforms to clean the signal.

Power Switching Devices with Minimum Power Loss

Microsemi offers a variety of power switching devices with minimum losses, enabling the design of switching systems to achieve new levels of efficiency and power density. Minimum power loss not only saves energy, but also enhances system reliability, making the system more compact and less costly. For example, the 600 V CoolMOS™ C6 devices feature high-voltage super-junction technology for extremely low conduction and switching losses. The super-junction MOSFETs have very low input capacitance and allow high-frequency operation in the range of several hundred kHz with acceptable conduction losses at high output power.

Microsemi's SiC diodes also offer excellent features with essentially zero forward and reverse recovery losses not only at room temperature but over a wide temperature range. This fast recovery results in much lower switching losses. Microsemi's low profile packaging gives the advantage of the full speed characteristics of these power semiconductors without introducing any parasitic elements into the power circuit.

Conclusion

With increasing market demands for highly efficient and reliable PV systems, designers are facing many challenges. SoC platforms help designers to deal with such challenges by reducing many of the board-level parasitics and by allowing for more compact, low cost, low power solutions. Microsemi takes SoC to a new level by introducing the world's first customizable SoC. Microsemi's SmartFusion cSoC combines a flash FPGA core, a hard ARM Cortex-M3 processor and programmable analog to give integration of control, sensing and power management and communications functions into a single highly-efficient, low power device. All three components are programmable through the convenience of user friendly tools, enabling a rapid design cycle. Microsemi's SmartFusion cSoCs and other highly efficient PV conversion components provide PV designers with state-of-the-art technology needed to meet today's market demands.

References

1. S. Bontemps, A. Calmels, S.D. Round, J.W. Kolar, "Low profile power module combined with state of the art MOSFET switches and SiC diodes allows high frequency and very compact three-phase sinusoidal input rectifiers." *Proc. Of the Conf for Power for Power Electronics, Intelligent Motion and Power Quality* (PCIM'07), 2007.
2. D. P. Hohm and M. E. Ropp, "Comparative study of maximum power point tracking algorithms using an experimental, programmable, maximum power point tracking test bed," *Proc. 28th IEEE Photovoltaic Specialists Conf*., 2000.
3. E. Koutroulis, F. Blaabjerg, "Techniques for the optimal design of photovoltaic inverters interconnected with the electric grid," *Proc.14th European Conf on Power Electronics and Applications* (EPE 2011), 2011.
4. S. Nema, R. K. Nema, and G. Agnihotri, "Inverter topologies and control structure in photovoltaic applications: A review", J. *Renewable Sustainable Energy*, 2011.
5. W.Choi and J. Choi, "High-Efficiency Power Conditioning System for Grid-Connected Photovoltaic Modules", *Journal of Power Electronics*, July 2011.
6. R. Arias, H. Mediote, and H. Tacca, "Flash FPGA-Based Numerical Pulse-Width Modulator," *Advances in Power Electronics,* 2011.
7. B.Burger, D. Kranzer, and O.Stalter, "Cost Reduction of PV-inverters with SiC-DMOSFETs", *Proc. of the 5th International Conference on Integrated Power Electronics Systems*, 2008.
8. P. J. M. Heskes and J. H. R. Enslin, "Power quality behaviour of different photovoltaic inverter topologies", *Proc. Of the 24th PCIM Conf*. (PCIM'03), 2003.
9. A. Hansen, P. Lars, H. Hansen and H. Bindner. "Models for a Stand-Alone PV System", National Laboratory, Roskilde, December 2000, ISBN 87-550-2776-8. [Online]. Available: http://www.risoe.dk/rispubl/VEA/ris-r-1219.htm

Microsemi Corporate Headquarters
One Enterprise, Aliso Viejo CA 92656 USA
Within the USA: +1 (949) 380-6100
Sales: +1 (949) 380-6136
Fax: +1 (949) 215-4996

Microsemi Corporation (NASDAQ: MSCC) offers a comprehensive portfolio of semiconductor solutions for: aerospace, defense and security; enterprise and communications; and industrial and alternative energy markets. Products include high-performance, high-reliability analog and RF devices, mixed signal and RF integrated circuits, customizable SoCs, FPGAs, and complete subsystems. Microsemi is headquartered in Aliso Viejo, Calif. Learn more at **www.microsemi.com**.