Application Report

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TMS320C2000™ DSP Controllers: A Perfect Fit for Solar Power Inverters

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ABSTRACT

A worldwide concern for future access to affordable, sustainable energy is driving the development of more efficient solar power generation. In any photovoltaic (PV) based system, the inverter is a critical component responsible for the control of electricity flow between the module, battery, loads, and power grid. Inverters, which convert direct to alternating current, can be designed to be used with different voltage ranges and topologies for varying applications. They can also be designed with or without transformers. Besides DC/AC conversion, inverters provide additional functions such as maximizing power, battery charging, and protecting the circuit. All of these functions require optimized intelligent control that can occur in real time or near-real time. The wide variations in application and operational requirements mean that the system control has to be highly flexible. Digital signal processor (DSP) based controllers, such as the Texas Instruments TMS320C2000™ family of controllers, provide the high level of computational performance and programming flexibility needed for the real-time signal processing in solar power inverters. Highly integrated digital signal controllers help inverter manufacturers create more efficient, more cost-effective products that can support the growing demand for solar energy in upcoming years.

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1 The Need for Solar-generated Power

The continuing rise of oil prices is fueling a worldwide concern for future access to affordable, sustainable energy. According to the U.S. Department of Energy, alternative solutions such as wind, solar, biomass, geothermal, and small hydropower technologies now supply 160 Gigawatts of generating capacity, which is roughly four percent of the world's total capacity. Currently, the fastest growing alternative technology is solar power, growing at about 60 percent per year. The U.S., Germany, and Japan are leading markets for solar power and system development, with a number of companies focused on research, development and manufacturing activities for the delivery of photovoltaic (PV) based systems. Among these systems are battery-operated and remote-control products; multiple-interface data-loggers; and compact, high-performance solar inverters.

2 The Role of the Inverter

In any PV-based system, the inverter is a critical component, responsible for the control of electricity flow between the module, battery, and loads. The system performs the conversion of the variable DC voltage output from the solar cells into a clean sinusoidal 50- or 60-Hz current for use by appliances and for feeding back into the grid. In addition, inverters perform such functions as disconnecting the circuit to protect it from power surges, charging the battery, logging data on usage and performance, and maximum power point tracking (MPPT) to keep power generation as efficient as possible. Featuring nominal power between one and several hundred kilowatts peak (KWp), solar inverters can be designed around sophisticated topologies, either with or without transformers, and may integrate several control processors.

2.1 Inverter Topologies

Figure 1 shows where the inverter fits into an all-inclusive system that not only charges a battery and drives local AC loads from PV panels, but also ties to the grid and has an alternate power source in the form of an AC generator. A simpler system might just charge the battery for local use, or feed power back to the grid without local use, or leave out the generator.

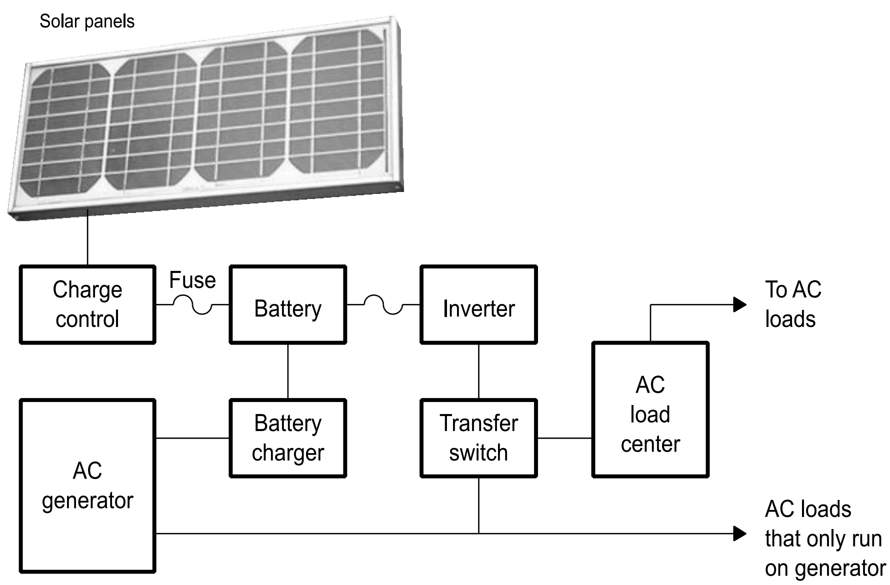

Figure 1. PV and Generator Hybrid System

Figure 2 shows an inverter topology in which several strings of PV panels are served individually by inverters whose outputs are fed in parallel to the grid, a configuration that yields medium nominal power up to about 10 KWp. Alternatives include:

- Each panel may be served by a small integrated inverter, yielding a few hundred watts peak (Wp).
- A single inverter may serve the parallel inputs of all the PV strings, yielding several KWp.
- Separate DC/DC conversion stages may be applied to each PV string, then the converted outputs fed in parallel to a single DC/AC inverter. This is the most efficient topology, yielding nominal power up to about 100 KWp.

Clearly, the topology will vary with the scale of the application, and higher yields are obtainable from installing multiple instances of a topology.

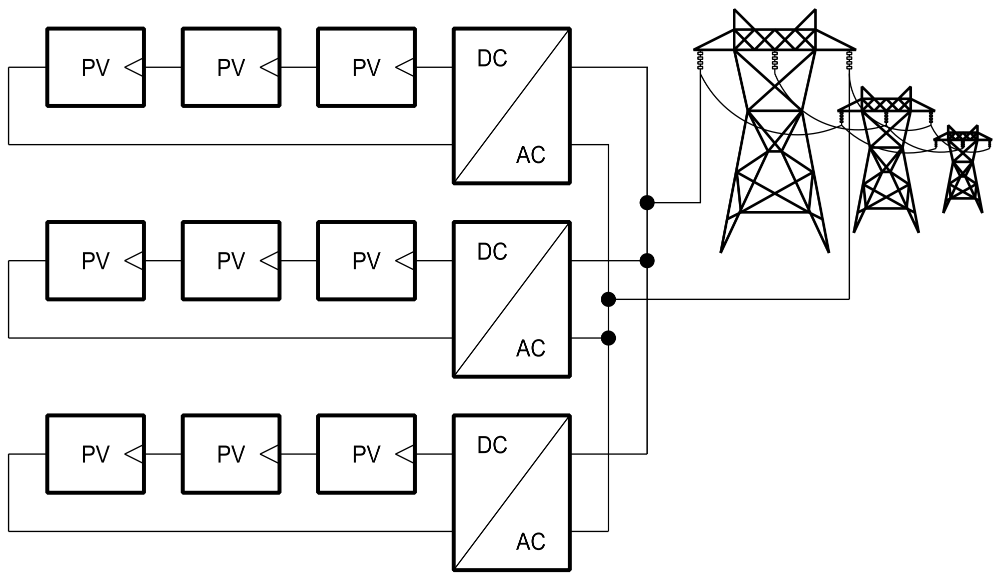

Figure 2. Modular Inverters Serving Multiple PV Panel Strings

2.2 *Inverter Stages and Functions*

The inverter's main function is to convert variable-voltage DC from the PV panels or battery storage to a specific AC voltage and frequency for use by appliances and feedback to the grid. The AC output varies by region, of course, with 60-Hz 115 VAC used in North America and 50-Hz 230 VAC in much of Europe. Applications also have different phase requirements, so one-, two- and three-phase inverters are available. Figure 3 shows the essential DC/AC conversion circuit, in which:

- DC/DC conversion raises or lowers the incoming PV voltage, adjusting its output for greatest efficiency in the DC/AC conversion stage,
- The capacitor provides further voltage buffering,
- The MOSFETs in the bridge use a switching frequency in the range of 20 kHz to create an AC voltage,
- The coils smooth the switched AC to a sinusoidal signal for use in generating a grid-frequency AC output.

Additional DC/DC conversion and regulation is required outside of the DC/AC conversion path for battery charging.

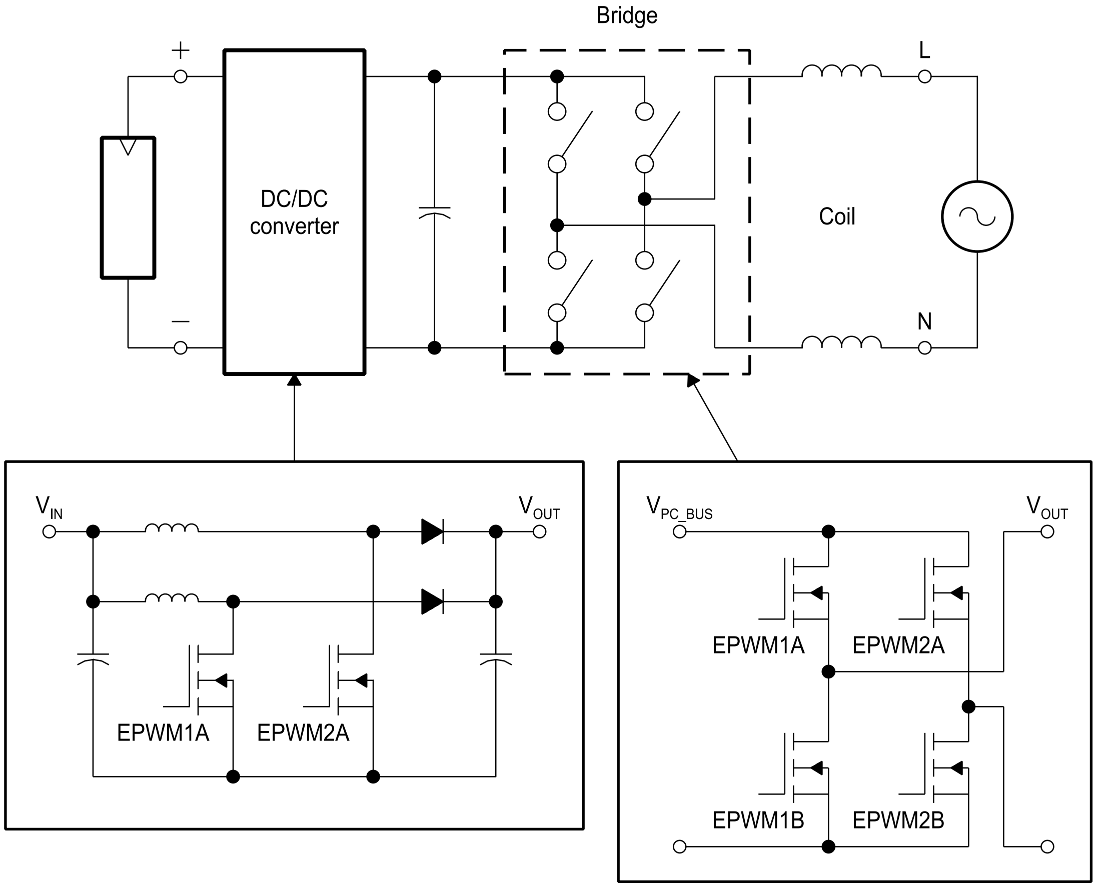

Figure 3. Transformerless DC/AC Conversion Circuit

At some point, the DC input has to be at a higher voltage level than the AC output. If the PV input is not high enough, the system can either step it up with a transformer on the AC side (after the coils in Figure 3) or boost it in the DC/DC conversion stage. The AC transformer inherently provides galvanic isolation, as does a phase-shifted full-bridge DC/DC converter with zero voltage switching (making it thus equivalently a transformer). Figure 4 shows the DC/AC circuit equivalent when either type of transformer is introduced. This circuit is equivalent either to the bridge in Figure 3 if the transformer is on the AC side, or to the DC/DC converter in Figure 3 if the transformer is on the DC side.

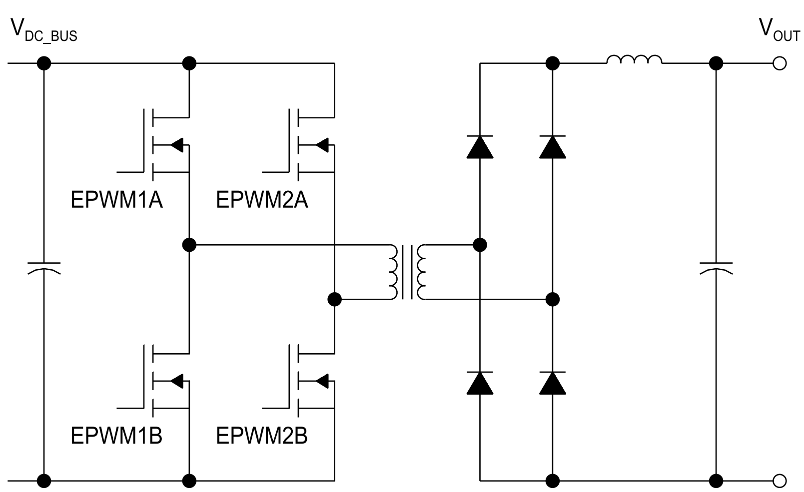

Figure 4. Equivalent Circuit with Transformer

The need to design in transformers varies by region. In the U.S., codes require the use of transformers, while Germany, the major European market, does not require them. Transformers add weight, bulk and cost, and they also cause a reduction in efficiency of about 2 percent. On the other hand, transformers increase circuit protection and human safety by isolating the two sides of the circuit electrically, preventing a DC fault from flowing to the AC side, and an AC leakage current from developing a potential between the PV panels and ground.

System protection mandates a relay to protect the conversion and charging circuitry against voltage surges and spikes on the grid. In addition, the design may include a residual current protection device (RCD) that monitors the currents of all phases, including neutral, then trips the relay if the current exceeds a certain value. Because of the risk of current leakage, RCDs are especially important in transformerless systems.

3 Obtaining Maximum Charging Power

Just as the efficiency of the DC/AC conversion depends on the input voltage, so does the battery charging. But the PV input voltage is variable, due to factors such as the weather, time of day and heat of the panels; and the battery conditions are different, too, depending on whether it is charged or discharged. Sometimes lowering the voltage while raising the current to the battery may increase the total power delivered and speed charging, while at other times sacrificing some current in order to achieve a higher voltage may be necessary to charge at all. Maximum power output to the battery occurs when the product of voltage × current is at its peak, the maximum power point (MPP). MPP tracking (MPPT) is designed to determine this point and adjust the DC/DC voltage conversion in order to maximize the charging output. MPPT can increase the overall efficiency of a solar system by a third or more during winter months, when power is most needed. Figure 5 shows how the determination of MPP can vary with different conditions.

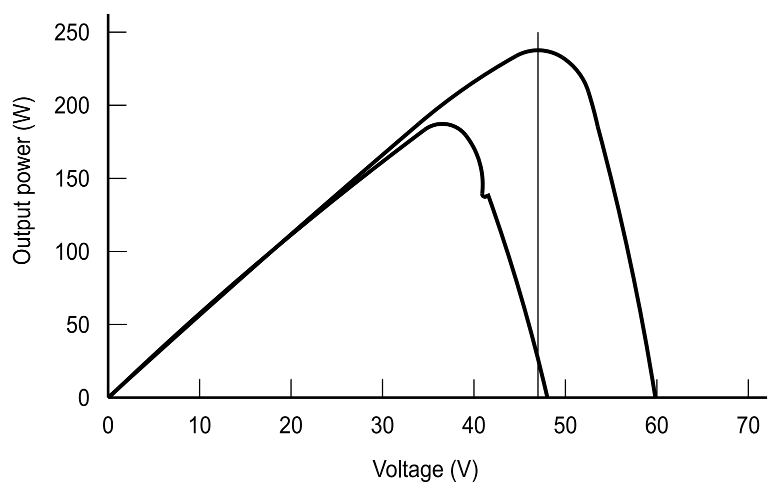

Figure 5. MPP for Different Conditions

The most common algorithm for determining MPP is for the controller to perturb the panel’s operating voltage with every MPPT cycle and observe the output. The algorithm continues oscillating around the MPP over a wide enough range to avoid local but misleading peaks in the power curve caused by, say, movement in cloud cover or some other condition that affects the curve. The perturb and observe algorithm is inefficient to the extent that it oscillates away from the MPP in each cycle. An alternative, the incremental inductance algorithm, solves the derivative of the power curve for 0, which is by definition a peak, then settles at the resolved voltage level. While this approach does not have the inefficiency caused by oscillation, it risks other inefficiencies because it may settle at a local peak instead of the MPP. A combined approach maintains the level determined by the incremental inductance algorithm, but scans at intervals over a wider range to avoid selecting local peaks. This approach, while the most efficient, also requires the greatest amount of performance on the part of the controller.

4 Digital Signal Controllers

By now it should be clear that an inverter is a critical component in the solar power system, and its design needs to be both flexible for use in different applications, and adaptable to changing conditions within an application. A control processor for an inverter has to meet a number of real-time processing challenges in order to effectively execute the precise algorithms required for efficient DC/AC conversion and circuit protection. MPPT and battery charge control, while only needing near-real time response, do involve algorithms with a high level of processing.

Digital signal controllers, combining high-performance DSPs and integrated control peripherals, offer an excellent solution for real-time control of the DC/AC converter bridge, MPPT and protection circuitry in solar power inverters. DSP controllers inherently support high-speed mathematical calculations for use in real-time control algorithms. Integrated peripherals such as analog to digital converters (ADCs) and pulse-width-modulated outputs (PWMs) make it possible to directly sense inputs and control power MOSFETs, saving system space and expense. On-chip flash memories aid in programming and data collection, and communication ports simplify design for networking with units such as meters and other inverters. The higher efficiency of DSP controllers in solar power inverters has already been demonstrated by designs reporting that conversion efficiency losses were cut by more than 50 percent, as well as achieving significant cost reductions.(1)

Example: TMS320F28x Digital Signal Processors

An example of such a processor is the Texas Instruments (TI) TMS320F28x ™digital signal controller, a 32-bit device that operates at frequencies up to 150 MHz and provides up to 150 MIPS in performance. Figure 6 shows the architecture of the F2808, a representative device in this DSP controller family. With its high level of performance, a single DSP controller can control multiple conversion stages in the same inverter and have overhead remaining for performing additional functions such as the MPPT algorithm, battery charge monitoring, surge protection, data logging and communications.

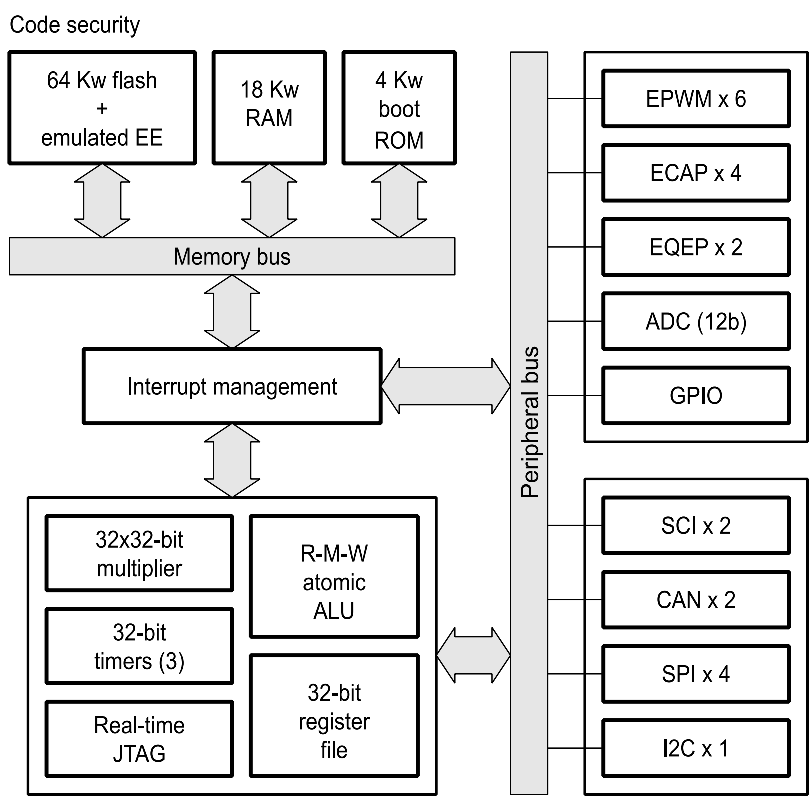

Figure 6. TMS320F2808 Architecture

Integrated functions keep costs efficient along with system operation. F28x controllers feature ultra-fast 12-bit ADCs that provide up to 16 input channels for performing the current and voltage sensing required to achieve a regular sinusoidal waveform. For safety, the ADCs also provide current sensing in the RCD.

Twelve individually controlled enhanced PWM (EPWM) channels provide variable duty cycles for high-speed switching in the converter bridge and battery charging circuits. Each of the EPWMs has its own timer and phase register, allowing phase delay to be programmed in, and all of the EPWMs can be synchronized to drive multiple stages at the same frequency. Multiple timers give access to multiple frequencies, and fast interrupt management is available to support additional control tasks. Multiple standard communication ports, including the CAN bus, provide simple interfaces to other components and systems.

With integrated flash memories, F28x controllers enable straightforward program development and updates while helping to protect intellectual property. Extensive third-party support is available for control algorithms, including software modules for solar power inverters that have been developed and are in development.

Figure 7 shows a multichannel buck converter driven by the independently timed EPWMs. All channels can be run at different frequencies, as shown in the example, or the same frequency can be chosen for all channels. For four channel frequencies, four EPWM modules are required. The choice of whether to run the modules as masters or slaves depends on the frequency and synchronization requirements of the system. If the channels are run as frequency multiples, it makes sense to synchronize, and a 1× master and 3× slave configuration is appropriate. If the channels cannot be fixed at multiples, then all the modules must be masters without synchronization, though resonance frequencies may be an issue. development.

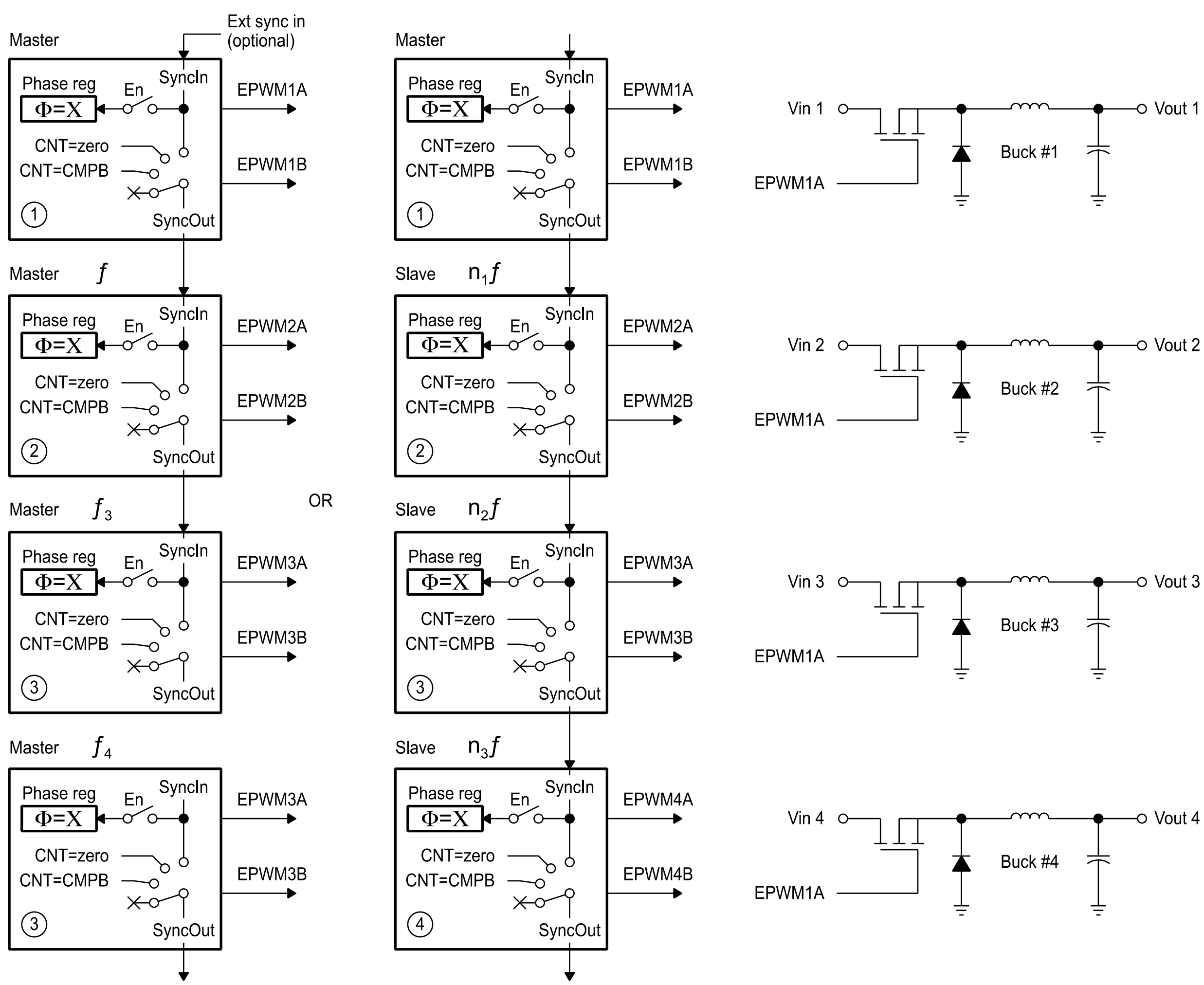

Figure 7. Design Example - Multichannel Buck Converter

5 A Key to Solar Power

Many parts of the solar power system are continually being improved in order to achieve greater efficiency that will lower the cost per kW of solar energy. While much attention is deservedly paid to improving the PV panels, the inverter can also contribute to making solar technology more feasible. Variability in regulatory and operational requirements make it important to select the right controller for the inverter, a controller that provides high performance, integration and flexibility. Digital signal controllers such as the F28x series have demonstrated their value in inverter systems and will continue to help improve the efficiency and lower the cost of solar power for greener solutions to the world's energy needs.

6 Reference

1. R. West. PV Inverter Products Manufacturing and Design Improvements For Cost Reduction and Performance Enhancements. NCPV and Solar Program Review Meeting 2003. NREL/CD-520-33586, p. 550.

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