Freescale Semiconductor
Application Note

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On-Grid Solar Microinverter on Freescale MC56F82xx/MC56F82xxx DSCs

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1 Introduction

In recent years, demand for renewable energy has increased significantly. The development of devices utilizing clean energy such as solar, wind, geothermal, and fuel cells attracts more and more attention. Solar energy harvesting is developing fast and will play a more important role as a global energy source. One of the ways to capture solar energy is via photovoltaic power generation systems, which are connected to the grid through power inverters. Therefore, many companies are focusing on development of photovoltaic grid-tie inverters. Freescale offers digital signal controllers, the MC56F8xxx family, that are well suited to on-grid solar inverter designs.

This application note describes the solar microinverter solution developed together with Future Electronics.

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2 Solar photovoltaic technology

Photovoltaics (PV) is a method of generating electrical power by converting solar radiation into direct current (DC) electricity using semiconductors that exhibit the photovoltaic effect. Power generated from a PV panel is influenced by irradiance and temperature (see Figure 1). Because of the volt-ampere characteristics of a PV panel, the maximum power point tracking (MPPT) algorithm was developed to get the maximum possible power from PV panel, in all conditions.

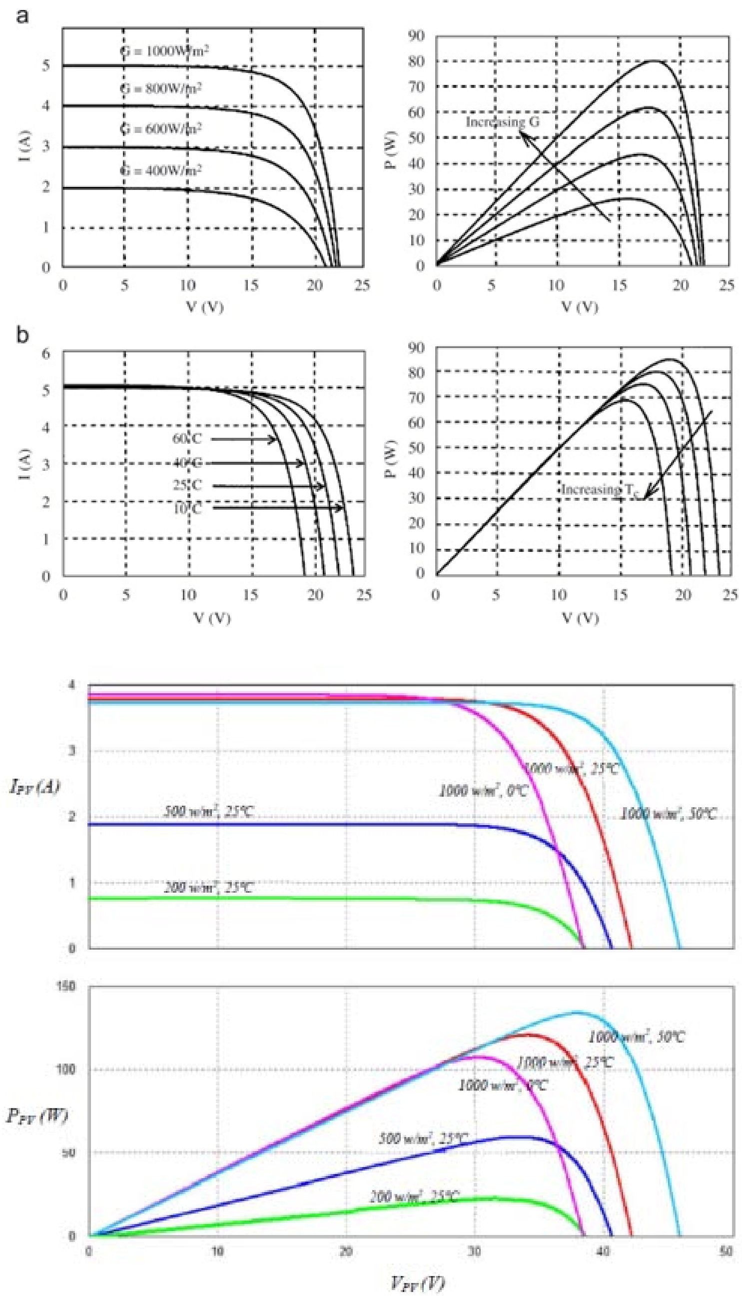

Figure 1. Solar panel characteristics

PV panel generates direct current and therefore a power electronic inverter is required to convert the DC power to AC power. Currently, PV systems are used in power plants as a residential source of electricity for remote areas, for lighting, and so on. The residential PV systems can be divided into two types:

- Standalone: In standalone systems, the power inverter is connected to local loads.
- Grid-tied systems: In these systems, the power inverter is connected to the AC grid.

There are several possible circuit topologies for PV systems.

- Centralized: PV panel outputs can be connected together and DC power is delivered to one converter. This circuit topology is called centralized.
- String: When several PV panels are connected in rows and each row has its own inverter, this topology is called a string.
- Modular: In this topology, each PV module is connected to one inverter.

Different circuit topologies are summarized in the following figure.

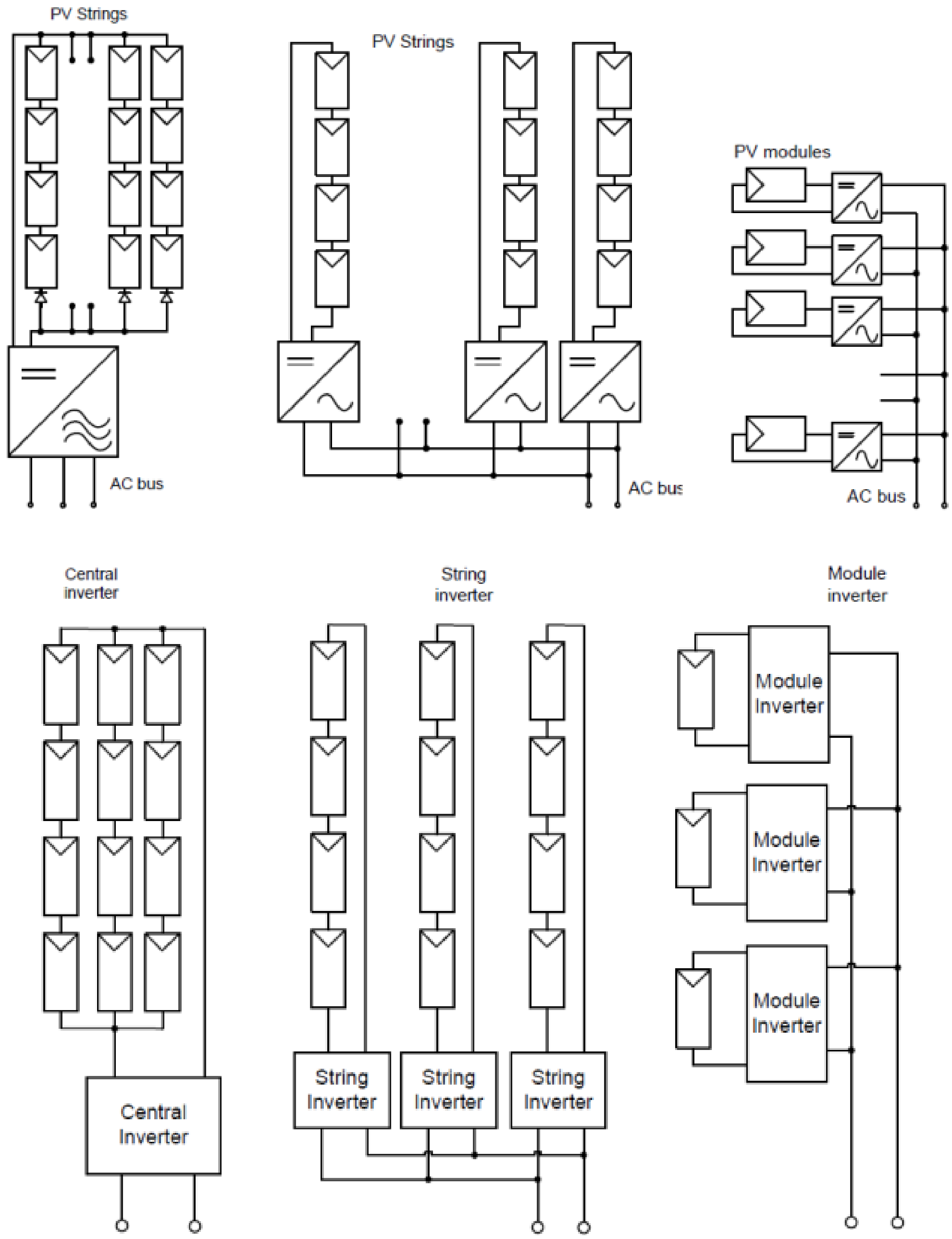

Figure 2. PV system circuit topologies

The module topology has some advantages over string or central topology. PV panels are typically manufactured to generate power up to 200 W and therefore, power inverters designed for module topologies have to meet this power range.

The inverters for module topologies are microinverters and can give 5-25% higher efficiency, because of the following advantages.

- One microinverter does not influence the performance of other microinverters connected to the same link.

- Shade, snow, and dust on any one solar panel, or a panel failure, do not disproportionately reduce the output of an entire array.
- Each microinverter obtains maximum power by performing the Maximum Power Point Tracking Algorithm (MPPT) algorithm for its connected panel. Thus, there is no need for big transformers or capacitors which can be replaced by more reliable film capacitors and no fan for cooling is required. All these significantly improve mean time between failures (MTBF), up to decades.

The module topology also has some disadvantages.

- The main disadvantage is the initial system cost per watt compared to the string or central inverter topology, but this is offset with higher efficiency.
- A second disadvantage is that the inverters are located near the PV panel and thus, are not easily accessible for maintenance. However, failure or damage of a microinverter can be easily located and quickly replaced, while in a string inverter topology, it is comparatively difficult to repair a central inverter or find a specific PV panel in a string of panels, which can degrade the overall system performance.

Grid-connected inverters need to meet the requirements for connection to the AC grid. In the U.S., standard IEE1547 deals with performance, operation, testing, safety, and maintenance of this connection. While in Great Britain, G83/1 and in Germany, the complex standard DIN VDE 0126 defines the requirements for an automatic AC disconnect interface. These standards define requirements for power quality, anti-islanding detection, DC current injection, earth current, etc. As a part of this, the International Electrotechnical Commission (IEC) is trying to establish IEC 61727 as a unified standard.

Besides the regulation requirements, maximum MPPT efficiency, or overall system efficiency and reliability, and key parameters for selecting a PV system, the other requirements for simple maintenance and remote monitoring are also important. For example, wireless (ZigBee®) or power line modem (PLM) communications can be used for communication with monitoring/controlling systems.

Long-term parameter warranty, monitoring requirements, and the strict parameter requirements placed on these systems can be met only by a digital solution because of the following advantages.

- A digital solution is free from the effects of component tolerance such as parametric drift or aging.
- Adaptive control can also significantly reduce the influence of changing operating conditions.
- Similarly, various communication protocols can be implemented in software and used to monitor and control the PV system.
- Firmware can also be easily changed to meet specific country standards. Digital systems also have high power density due to system integration.

Solar microinverter systems benefit from all these advantages of a digital solution.

3 System concept and control technique

The solar microinverter system presented meets the following performance criteria summarized in this table.

Table 1. Microinverter parameters table

Parameter	Value
PV panel nominal power	200 W
PV cells	72–96
Input voltage	32–65 V DC
DC bus voltage	400 V DC
Nominal output power	200 W
Boost switching frequency	50–300 kHz
Inverter switching frequency	16 kHz
Grid voltage range	220–240 V AC
Grid frequency range	49.5–50.5 Hz
Power factor	0.99
Peak efficiency	93 %
THD at full load	3%
MPPT tracking efficiency	99.5 %

Various solar inverter topologies or control strategies can be used for a solar microinverter. PV modules are typically rated up to 200 W and solar microinverters are therefore designed to meet this power range. The output voltage from solar panel can vary within a wide range due to changing irradiance and thus a DC/DC boost converter needs to be designed to step up the PV panel voltage to a required level of 400 V (for 230 V AC systems). A two-stage topology, where a DC/DC converter together with a DC/AC inverter stage creates a complete design, is often used in PV systems. The following figure shows a block diagram of such a two-stage system with filtering at the output.

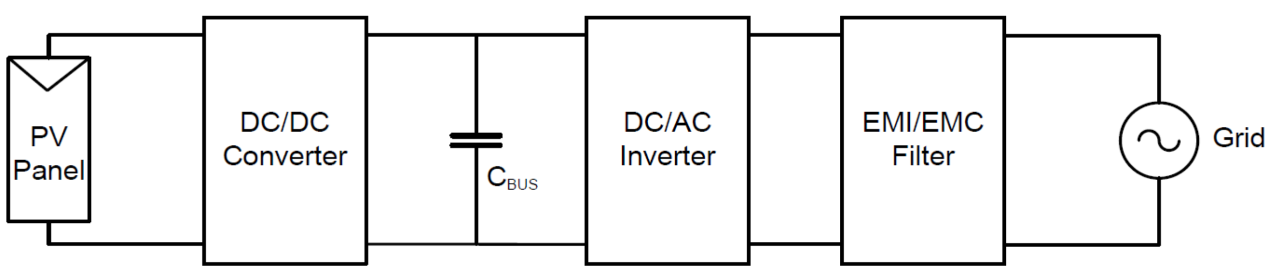

Figure 3. Generic solar microinverter system

Single stage boost, buck-boost, fly-back or other topologies are also possible. Some of these topologies are isolated and others are non-isolated. Recently, the U.S. regulation has changed to allow non-isolated topologies to be used. The topologies which use high-frequency transformers or transformers on the grid side have an overall efficiency lower than a transformerless design. However, in a transformerless topology, the DC current injected into the grid is a critical issue. DC current is caused by non-symmetrical half bridge legs of the inverter. As per the Great Britain regulation G83/1, the DC current must be below 20 mA. To optimize the efficiency of the inverter, unipolar switching is considered versus bipolar switching, to decrease switching losses.

In a single-phase PV system, power flowing to the grid varies over time, while the power of the PV panel must be constant to utilize the maximum energy from PV panel, otherwise this can result in an input power mismatch with the generated output power. Therefore, a decoupling or storage component must be placed in the system to balance this possible mismatch between the input and output power. In two stage topologies, a decoupling capacitor bank is placed between the DC/DC and DC/AC stages. Thin-film capacitors are used on the DC-bus to improve long-term system reliability. In order to have DC bus voltage that is higher than the peak of grid voltage during the whole sine period, the minimum capacitor value can be calculated. When a small capacitance is used, high-voltage ripples are present on the DC bus voltage. Therefore, a software control technique eliminating the influence of the DC bus voltage fluctuation needs to be implemented; otherwise the output current will be distorted. To decrease current ripples generated at the output from the inverter stage, a filter needs to be used. An LCL filter gives good harmonics reduction if well-designed, but care must be taken as bad filter design can cause critical instability of the control loop.

As mentioned earlier, a DC-DC converter is used for boosting the input voltage from the PV panel to the desired level. To maximize the energy from the PV panel, the maximum power point tracking (MPPT) algorithm is implemented. The boost converter is operating in Critical Conduction Mode (CrCM) and PWM signals are generated by the DSC controller based on the MPPT algorithm. The MPPT algorithm gives information about actual power generated from the solar panel and it is also used as a part of the current reference used for active current control.

This figure displays the hardware components of a solar microinverter.

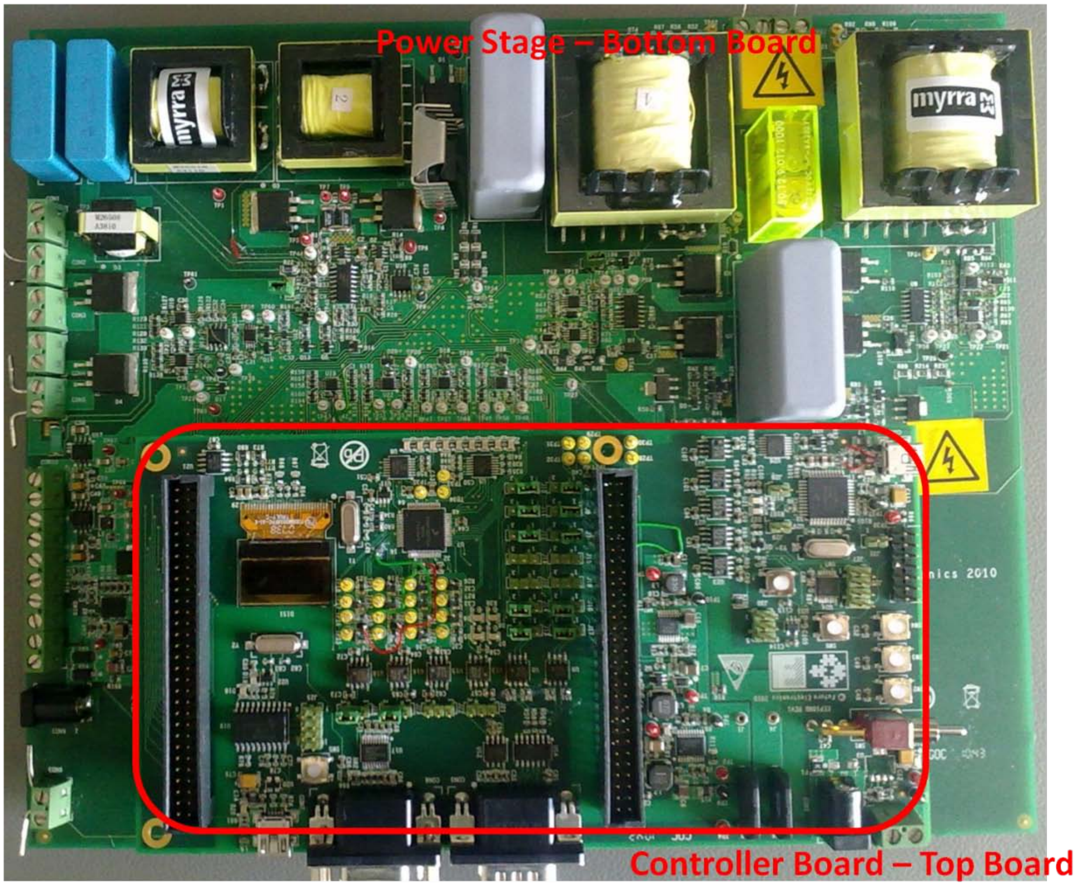

Figure 4. Generic solar microinverter system

4 MC56F82xx / MC56F82xxx DSC advantages and features for solar microinverter designs

The MC56F82xx /MC56F82xxx/MC56F84xxx digital signal controller family combines the processing power of a DSP engine and the functionality of a microcontroller with a flexible set of control peripherals on a single chip, to create a cost-effective system solution. Because of its low cost, configuration flexibility, compact program code, and dedicated control peripherals, the DSC family is very well-suited for power conversion applications.

Solar microinverter application benefits from control peripherals which include:

- Enhanced Flex Pulse Width Modulator (eFlexPWM)
- 16-bit Analog-to-Digital Converter (ADC)
- High-Speed Comparator (HSCMP)
- 5-bit Voltage Reference Digital-to-Analog Converter (VREF_DAC)
- Crossbar Switch (XBAR)

- Quad Timer (TMR)
- Inter-Integrated Circuit (I2C)
- Queued Serial Communications Interface (QSCI)
- Queued Serial Peripheral Interface (QSPI)
- Freescale's Scalable Controller Area Network Interface (MSCAN)

The application uses only the peripherals essential for the control techniques implemented in the application code and all other peripherals are disabled. The peripherals used are discussed as follows.

- **Enhanced Flex Pulse Width Modulator** (eFlexPWM): It offers the flexibility required for the generation of PWM signals used to drive the MOSFET transistors in the boost and inverter stages, with 15-bit resolution. Each eFlexPWM module can be synchronized to either external or internal signals which allows the boost converter to work in critical conduction mode. The external signals used in this case are the zero-crossing signals from the internal high-speed comparators (HSCMP). The inverter stages, in general, can benefit from the generation of complementary switching waveforms with automatic deadtime insertion. Fault inputs can also be assigned to control multiple PWM outputs in case of overcurrent in the boost or inverter stages, for example.
- **Analog-to-digital converter** (ADC): This module consists of two separate 12-bit analog-to-digital converters each with eight analog inputs and its own sample and hold circuit. Therefore, one ADC can be used for measuring quantities in the boost stage and another for measuring quantities in the inverter stage. Each ADC is then synchronized by a PWM trigger signal assigned to the inverter or boost converter.
- **High-speed comparators** (HSCMP): The comparators have been designed to operate across the full supply voltage range. The analog multiplexer provides a circuit for selecting an analog input signal. Internal voltage reference is connected to the comparators minus input and comparator is used for zero-crossing detection.
- **5-bit voltage reference digital-to-analog converter** (VREF_DAC): The DAC provides a selectable voltage reference for the zero-crossing comparators.
- **Crossbar switch module** (XBAR): XBAR implements an array of 30 outputs and 22 inputs of combinational digital multiplexes. All 30 multiplexes share the same 22 inputs in the same order, but each multiplex has its own independent select field. This module is designed to provide a flexible crossbar switching matrix that allows any input (typically from external GPIO or internal module outputs) to be connected to any output (typically to external GPIO or internal module inputs) under the user control. This allows user configuration of data paths between internal modules and between internal modules and GPIO. The XBAR module also provides interconnection of PWM synchronization signals from the comparators in boost converter, interconnection of fault input signals for the PWM modules, interconnection of the ADC converters with the PWM for the boost converter and inverter, and finally interconnection of the comparator output signal with the timer module.

- **Timer module** (TMR): Every DSC contains two timer modules, each with four timers. Each timer can operate as a timer, or as a counter. The counter provides the ability to count internal or external events. Two timers are used and operate in count mode counting the switching period of each leg in the boost converter.

The MC56Fxxxx family of DSCs also provides various communication interfaces such as QSCI, I2C, QSPI, and MSCAN, which can be used for communication with displays, user memory, user interfaces, or external modules allowing connection of WiFi or PLM (Power Line Modem) which are commonly used in solar inverter applications.

5 System / hardware description

A two-board solution from Future Electronics consists of a power board and a controller board. The hardware block diagram is shown in Figure 5. The two 60-pin DIL connectors provide the interface between these boards. Both these boards are described in details in the following subsections.

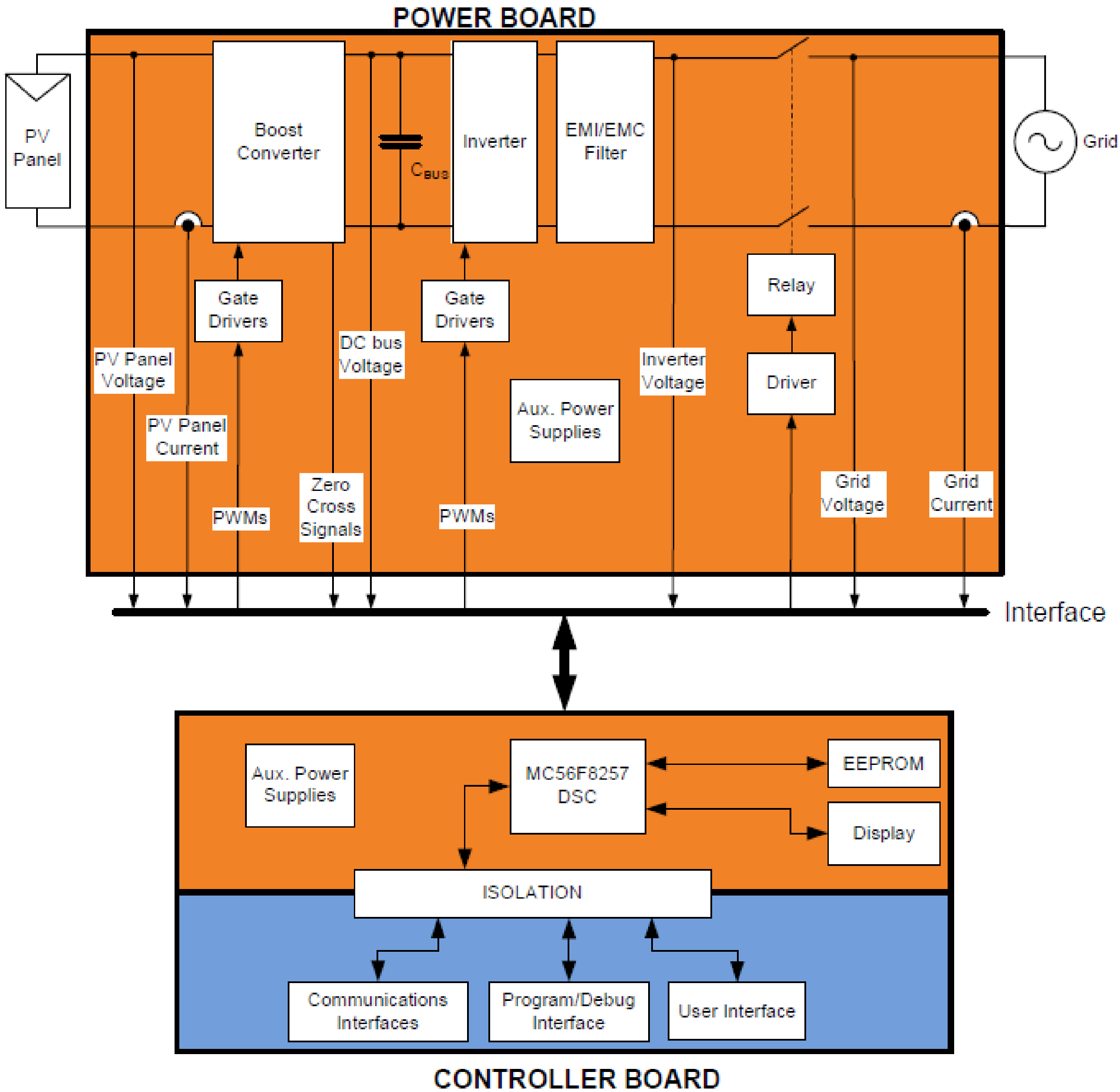

Figure 5. Generic solar microinverter system

5.1 Power stage board

An interleaved boost converter, two half-bridge inverters, and an output filter create the power stage board. It also incorporates all the necessary circuitry: drivers, auxiliary power supplies, protection circuitries, and conditioning circuitries required for sensing through a microcontroller (MC56F82xx DSC).

The boost converter works in critical conduction mode (CrCM) and therefore does not necessarily need input voltage and current sensing. But, it does need zero cross detection circuits for the restart of a new

PWM cycle. Zero-cross voltage signals are fed to the controller board where they are compared with the threshold value for the correct zero-cross detection point using the comparators of the microcontroller. One quantity necessary for successful boost converter operation is the DC bus rail voltage which is scaled signal that is fed to one of the ADC inputs of the microcontroller.

PV panel voltage and PV current are sensed and scaled in conditioning circuits to values that are acceptable to the microcontroller. Based on these two values, the implementation of the MPPT algorithm is simple using software running on the microcontroller and many different MPPT algorithms can be tried. The output from the MPPT algorithm are PWM driving signals generated by microcontroller and amplified in gate drivers for both MOSFET transistors of the boost converter.

Two half bridges create the inverter stage. One half bridge is used for generating a positive half-wave of sinusoidal output waveform and the other one for generating a negative half-wave. The PWMs driving signals for the inverter stage are generated on the basis of a control algorithm executed in the microcontroller and the signals are then amplified in gate drivers for all the four MOSFET transistors. Grid current and voltage are sensed after the relay and scaled in conditioning circuitry for the microcontroller to process.

The output LCL filter is used to reduce current ripples on the output waveform generated from inverter and to provide decoupling between the inverter stage and AC grid.

EMI/EMC filter suppresses the EMI/EMC noise generated by the switching of the MOSFET transistors.

The output relay is an important device in the system because mechanical disconnecting from the grid is a key requirement. The relay is closed and energy is delivered to the AC grid only when all the operating conditions are met. The relay needs to be switched off very quickly if these conditions are out of limits, or in case of any failure in the microinverter. The relay driving signal is generated by the microcontroller and is amplified by a driver circuit.

Various power supplies generated by an auxiliary power supply are required for the gate driver, conditioning circuits, and protection circuits.

5.2 Controller board

The controller board contains signal filtering for the sensed signals on the power stage board, the MC56F8257 DSC, auxiliary power supplies, an external EEPROM memory, an OLED display, a debug/programming interface, a user interface, various opto-isolated communication interfaces, and signal conditioning circuits. These are explained as follows.

- All sensed quantities are filtered by RC filters before being connected to the microcontroller. RC filters are positioned very close to the microcontroller to minimize noise and the effectiveness of the filters.
- The external EEPROM can store configuration parameters such as serial number, firmware version, and failure mode for the end users.
- A 64x132 dot matrix OLED display can be used to display key parameters of solar microinverter, that is, the actual input voltage or current, output voltage and current, and the actual generated power.

- Communication with a monitoring system is required in a solar microinverter. The microcontroller, with many communications interfaces and on-chip hardware support, can support various communication protocols and is used for monitoring or controlling the PV system. The controller board also contains various opto-isolated communication interfaces like CAN, RS232, RS485, and USB-to-SCI. The controller board also contains a power line modem/wireless module slot as an optional plug-in for the preferred communications module.

Various power rails are generated by the auxiliary power supply which serve to supply the microcontroller, communication interfaces, OLED display, and program/debug interface.

6 Software description

This section describes the software implementation of the solar microinverter. Current control is implemented in a synchronous rotating reference frame. This control method consists of a transformation from the stationary to synchronous rotating reference frame. Based on this transformation, AC quantities are changed to DC quantities and current can be controlled using a PI controller without steady stage error when controlling AC quantities. Separate control of active and reactive power is another benefit of this approach. A phase-locked loop (PLL) is used for the coordinate transformation and therefore in three-phase systems, the transformation is easy. For the transformation to work in a single-phase system, it is necessary to create a virtual phase in quadrature with the real one. Some of the known techniques like Transformation Delay Block, Inverse Park, and Hilbert Filter or SOGI (Second Order Generalized Integrator) can be used.

The system processing is interrupt-driven with the application state machine running in the background. The software is described in terms of the following:

- Main software flowchart
- Application Interrupts—PWM_ISR and FAULT_ISR

After a reset, the application performs the following routines—PeripheralCoreInit, AppInit, and archEnableInt in this sequence only and then enters an endless (main()) loop.

After a reset, the application also performs the following functions:

- Initializes the controller core, peripherals, and application variables.
- Enables all interrupts.
- Enters an endless main loop, which contains the application state machine running in the background, in between interrupts, and the clear watchdog timer function.

The application state machine incorporates the following seven operational states. See Figure 6.

- AppInit —this state initializes the core, peripheral, and application variables.
- AppLimitChecking—this state checks that all the measured quantities are within limits.
- AppMS_Identification—Master/Slave Identification is the state in which the interleaved boost converter legs are tested and one is selected as a Master and other as a Slave.

- AppBoostStart—the boost converter startup operates in a soft start mode increasing the required DC bus rail voltage by an increment value until it reaches the required DC bus voltage (400 V).
- AppNormal—when the required DC bus rail voltage is reached, the inverter stage starts generating a sinusoidal voltage which is synchronized with the AC grid voltage by the Phase Lock Loop (PLL) algorithm and has the same amplitude. Then, after a preset time, the relay is closed and energy is delivered to the AC grid.
- AppStandby—this state is executed when the power delivered from the PV panel drops below a threshold value.
- AppError—this state is executed if any measured quantities are out of operational limits, or an overcurrent state in the boost converter or inverter stage is triggered.

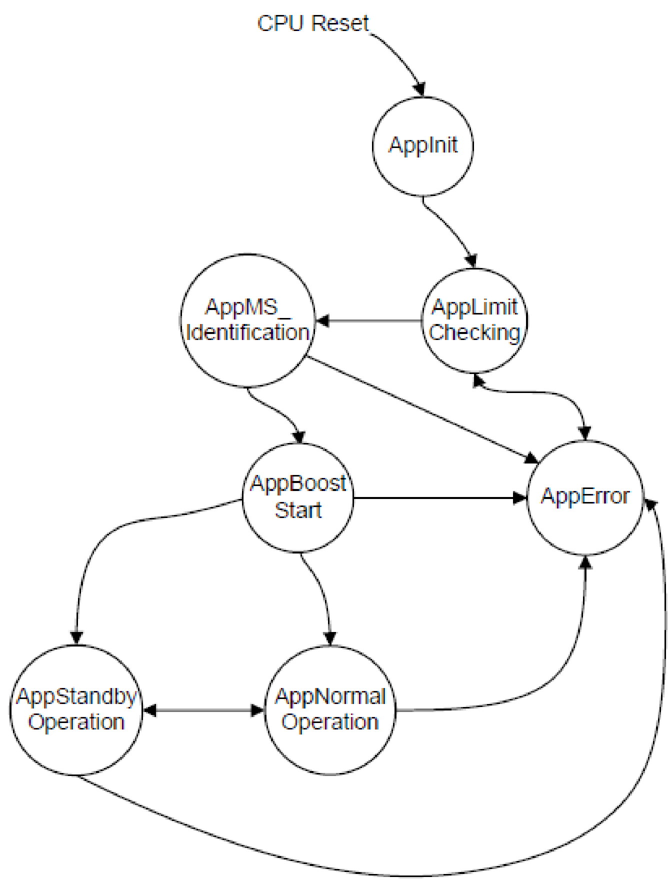

Figure 6. Software state machine

The Fault_ISR interrupt service routine is executed in case of an overcurrent in the boost converter or in the inverter stage, to protect the microinverter as a whole.

Graphical interpretation of control structure can be seen in the following figure.

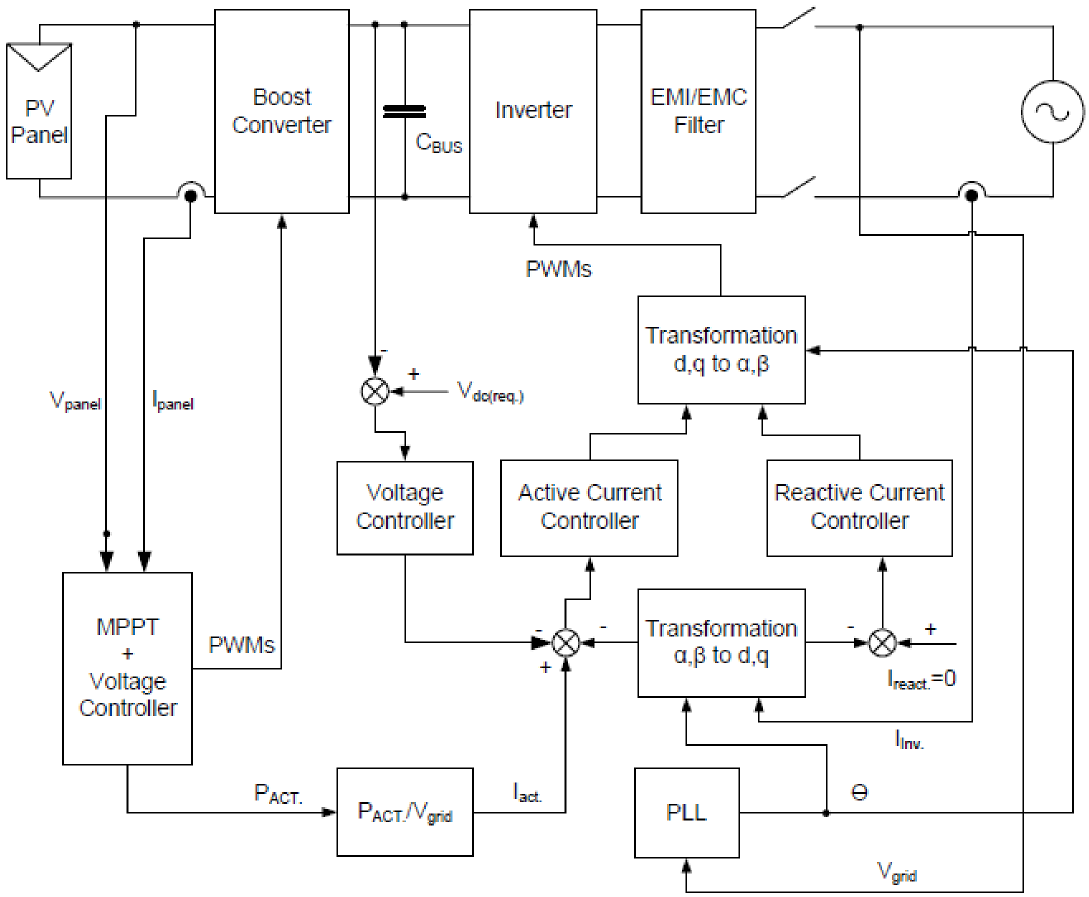

Figure 7. Solar microinverter software block diagram

The entire control algorithm is executed in the PWM interrupt service routine. The PWM_ISR interrupt service routine is executed regularly every 62.5 µs. All the tasks are executed in one interrupt service routine, PWM_ISR.

7 Conclusion

This reference solution was built in cooperation with Future Electronics which executed the hardware design of the microinverter with Freescale providing the operations software. The concept of a fully digitally-controlled transformerless grid-connected solar microinverter has proved to work very efficiently. As shown, using digital control, the solar microinverter system becomes very flexible and can also realize complex control algorithms which are either very complicated, or nearly impossible, for an analog control to perform. A solar microinverter based on digital signal controller integrates high-performance digital signal processing with efficient power electronics, providing a control environment for the design of highly efficient power electronics, and implementation of the typical high-level control and communication capability required in photovoltaic systems.

The MC56F8257 DSC meets all the requirements for the control of such a complex application. All the existing control algorithms consume 40 µs (75%) of the PWM ISR interrupt service routine, which is executed regularly every 62.5 µs; so there is space for communication software to monitor the system or for additional features. The software is written in the C language with the support of libraries of functions from the FSLESL (Freescale Embedded Software Libraries). Control algorithms for MPPT such as Fractional Voltage, Perturb and Observe, and Ripple Correlation Control were implemented and tested. Several PLL synchronization algorithms were implemented and finally, a PLL algorithm based on SOGI was selected which gives the best performance.

No electrolytic capacitors were used in the design, which significantly improves overall system reliability, lifetime efficiency, and life span of the system. The value of DC bus decoupling capacitance was calculated to be 30 µF and verified in the system as sufficient. If large voltage ripples are present on the DC link voltage, the shape of the output current waveform may be distorted. To eliminate these ripples, a DC bus ripple elimination algorithm was successfully implemented and tested.

The measurements made using this system gave excellent results:

- Total harmonic distortion (THD) is below 3%.
- MPP tracking efficiency reached 99.5%.
- Demo efficiency was found to be 93%, from a simple transformer-less CrCM boost converter and unipolar switching inverter controlled by the DSC.

In transformer-less inverter topologies, the DC current injected into the grid is an issue. The DC current injection limit specified in G83/1 20 mA was met. The measured peak value of DC current injected into the grid was 12 mA over the whole power range. Additional DC current elimination algorithms may improve this value further.

Freescale provides this reference design as a means to support fast development of digital solar inverter designs. With power management experts available to help, available development tools and embedded software libraries (FSLESL) development of such an application can be very fast and straightforward.

8 References

The following reference sources are available on freescale.com.

Documentations

- MC56F825x/MC56F824x Digital Signal Controller technical data sheet (document MC56F825X)
- MC56F825x/MC56F824x Reference Manual (document MC56F825XRM)
- MC56F847xx digital signal controller technical data sheet (document MC56F847XX)
- MC56F847xx Reference Manual, (document MC56F847XXRM)
- Digital Power Conversion, APLDIPOCON

Software and Tools:

- CodeWarrior for Microcontrollers 10.2
- FreeMASTER Run-Time Debugging Tool, FreeMASTER
- Embedded Software and Motor Control Libraries

- TWR-56F8257: DSC MC56F8257 Motor Control Tower System Module
- TWR-56F8400: DSC MC56F84789 Motor and Power Control Tower System Module

9 Revision history

Revision number	Date	Substantive changes
0	08/2013	Initial release

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