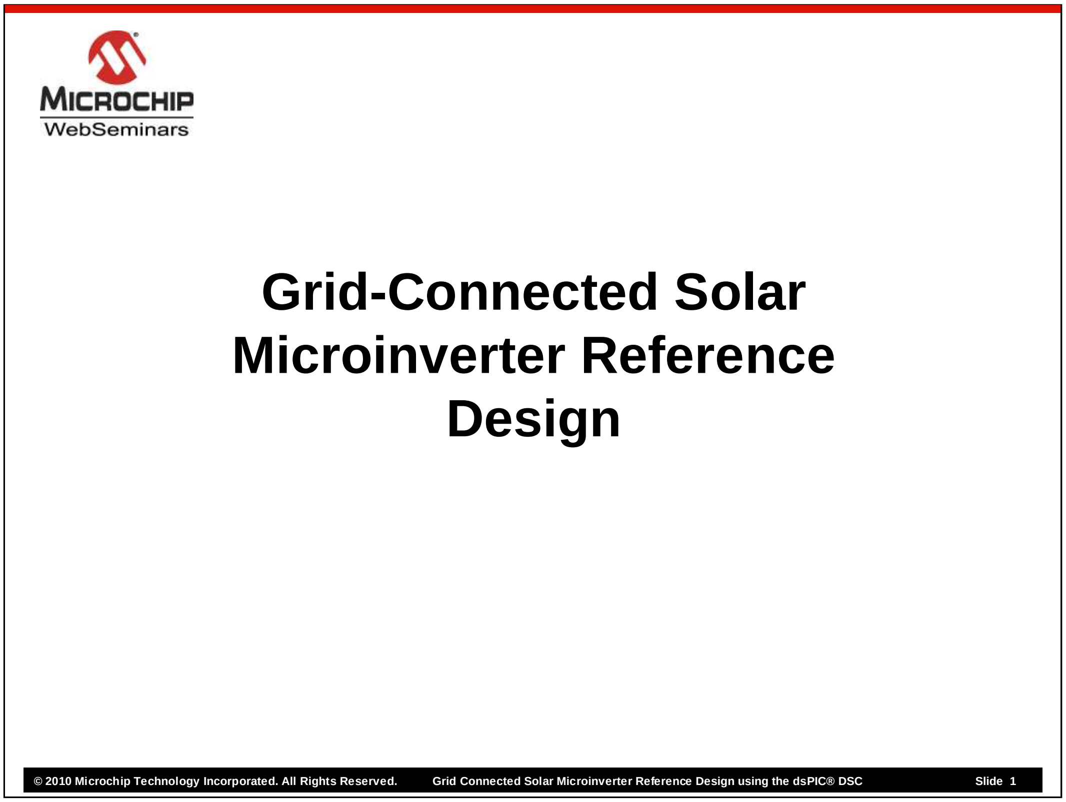


Hello, and welcome to this web seminar on Microchip's Grid Connected Solar Microinverter Reference Design.

My name is Mike Curran, and I am an Applications Engineer in the High Performance Microcontroller Division of Microchip.

MICROCHIP WebSeminars

Session Agenda

- Solar Microinverter Overview
  - Photovoltaic Cell Characteristics
  - Solar Microinverter Configurations
- Grid-Connected Solar Microinverter Reference Design
- Software Integration
- Summary

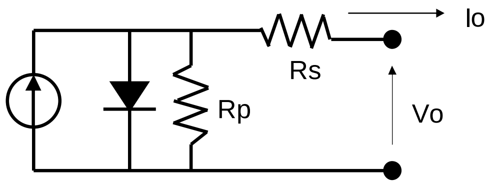
 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 2

In this webinar, we will go through the design of Microchip's Grid-Connected Solar Microinverter Reference Design, including hardware details and the system software.

So let's get started with some photovoltaic cell characteristics and background information of the Solar Inverter system.

Photovoltaic (PV) Cell

A PV cell is a current source, not a voltage source!



Vo ~ 0.5 Volts

Io ~ 1 to 3 Amps

Simplified circuit model of a solar cell

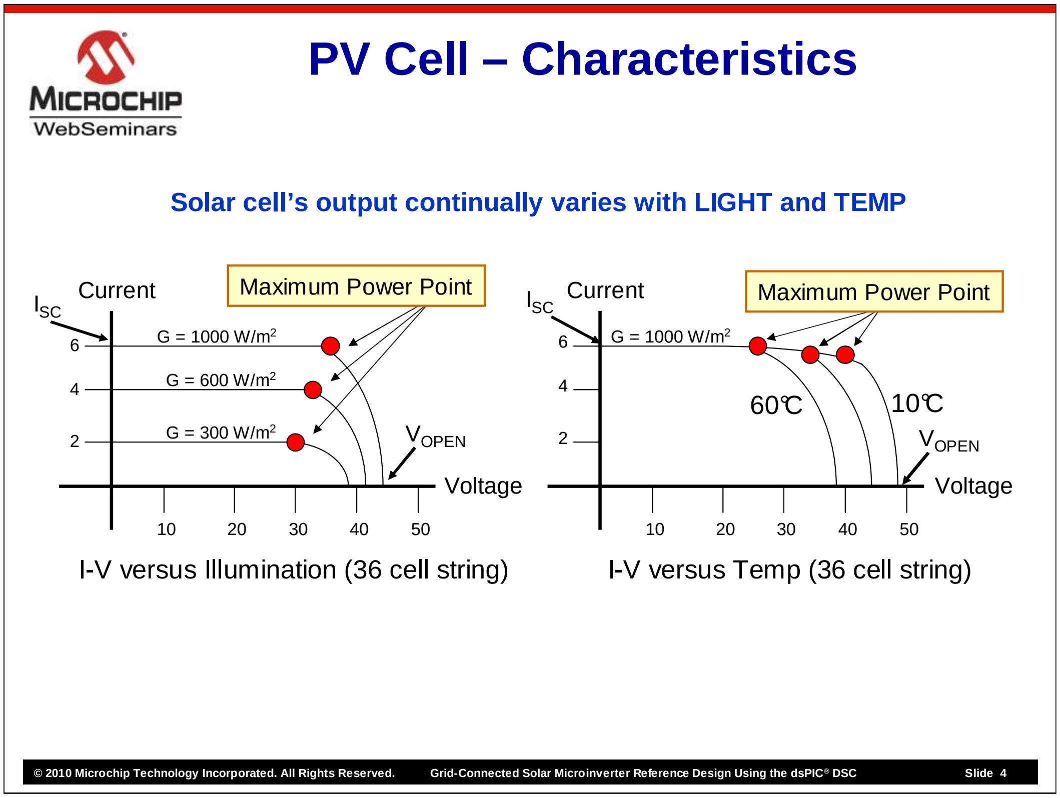
Effective use of series connected solar cells depends on identical currents being generated by each cell.

 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 3

PV cells are semiconductor devices, with electrical characteristics similar to a diode; however, a PV cell is a source of electricity, rather than an electrical load, and operates as a current source when light energy, such as sunlight makes contact with it.

The circuit shown is an equivalent model of a PV cell.

Next, we will look at more details of a PV cell and its characteristics.



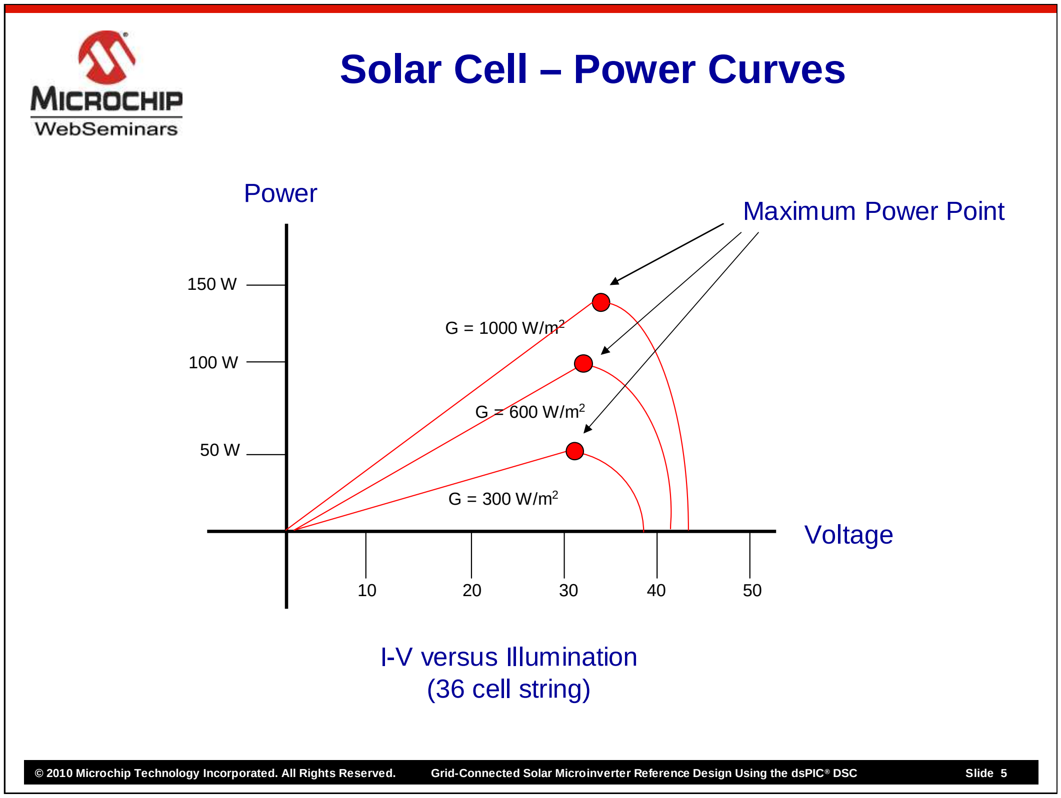
Light intensity as well as temperature affect PV cell characteristics. Current generated by a PV cell is directly proportional to light intensity.

Voltage also changes with fluctuating light levels, but by much less. Voltage is more affected by changes in the temperature of the PV cell rather than the current.

An increase in the cell temperature decreases the voltage and increases the current by a very small amount.

The short-circuit current (I_{SC}) from a cell is nearly proportional to the illumination, while the open-circuit voltage (V_{OPEN}) may drop only 10% with an 80% drop in illumination.

The important result of these two effects is that the power of a PV cell decreases when light intensity decreases and/or temperature increases.



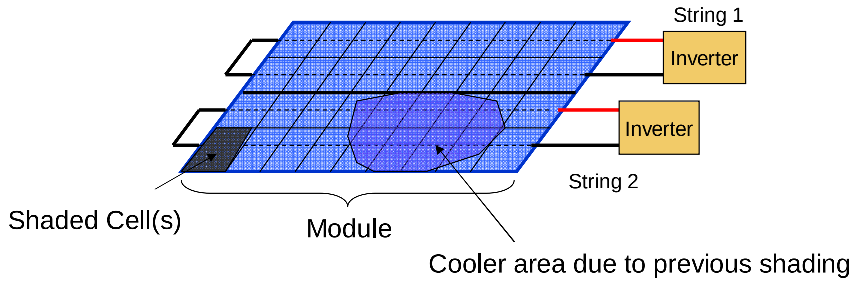
An increase in the output current after the Maximum Power Point will rapidly drop its output voltage and could produce power only 1 half of the open-circuit voltage *and* 1 half of the short-circuit current . The usable power output could thus drop from 70% of the open-circuit voltage times the short-circuit current (V_{OPEN} X I_{SC}) to 50% or even as little as 25%.

The amount of power generated by a PV cell depends on the operating voltage of the PV cell array.

Its V-I and V-P characteristic curves specify a unique operating point at which maximum possible power is delivered.

At the Maximum Power Point, the PV operates at its highest efficiency

PV Cell Shading



 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 6

PV manufacturer processes produce cells with relatively large variance in their power output capability.

They seek to reduce their variance by using advanced manufacturing technology. Regardless, panel models on the market today still have ±3 to 5% variance in their output.

Highest voltage strings or unshaded stings provide the bulk of power, and lower voltage strings due to shading or lower temperatures contribute little power.

Session Agenda

- Solar Microinverter overview
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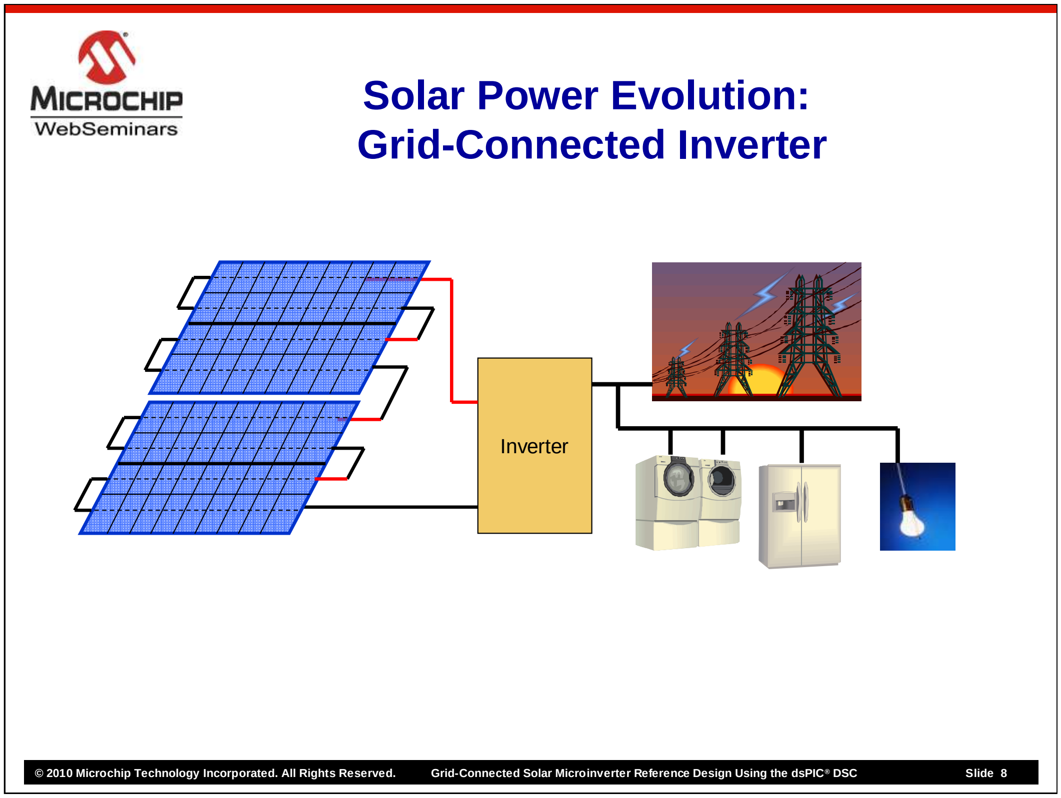
  - Solar Microinverter Configurations
- Grid-Connected Solar Microinverter Reference Design
- Software Integration
- Summary

Next, we will take a closer look at different solar inverter configurations.



Multiple solar modules connected in series and parallel provide 200 - 400 volts output and 10 to 50 Amps.

Combinations of these panels are then connected to a single centralized inverter to yield 120/240 VAC at medium power levels (2 - 10KW)

This system is connected to the AC power lines, hence known as Grid-Tied system.

The customer sells power to the power company during the day, and buys power from the power company during the night.

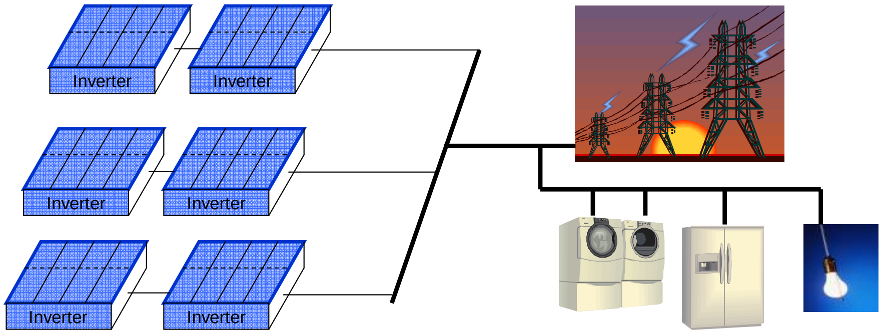
The Grid-Tied approach eliminates expensive and short lived batteries.

The inverter has the potential for a single point failure and has a non-optimal power harvest from the solar panel, especially in partial shading conditions.

In the case of multiple inverter systems – each string regardless of the output voltage will contribute the maximum

power it can because each inverter is optimizing the power output of its string. Tests indicate 20 – 34% additional energy harvest.

Solar Power Evolution: Grid-Connected Module Incorporated Inverters (MIC)



Module Incorporated Inverters (MIC) – Each solar panel module incorporates its own inverter. An MIC is also known as a “Microinverter”.

The incorporation of inverters into the solar panels greatly reduces installation labor costs, improves safety, and maximizes the solar energy harvest.

 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 9

Here is an example of a **Module Incorporated Inverter** (MIC) – Each solar panel module incorporates its own inverter.

An M-I-C inverter is also known as a “Microinverter”.

The incorporation of inverters into solar panels greatly reduces installation labor costs, improves safety, and maximizes the solar energy harvest.

Objective

- Solar Microinverter Overview
  - Photovoltaic Cell Characteristics
  - Solar Microinverter Configurations
- **Grid-Connected Solar Microinverter Reference Design**
- Software Integration
- Summary

We can now take a closer look at Microchip's Grid-Connected Solar Microinverter Reference Design and its operation,

starting with a high-level overview.

Microchip's Grid-Connected Solar Microinverter

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- 220 Watt, single PV cell module (36V) microinverter
- Maximum Power Point Tracking = 99.5%
- Maximum Power Point Tracking voltage
  - 25 VDC – 45 VDC
- DC short circuit current:
  - 10A
- AC output voltage range:
  - 180 VAC – 264 VAC
    - 45 Hz – 55 Hz
  - 90 VAC – 140 VAC
    - 55 Hz – 65 Hz
- Output Current THD
  - <5%
- High efficiency
- System islanding

 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 11

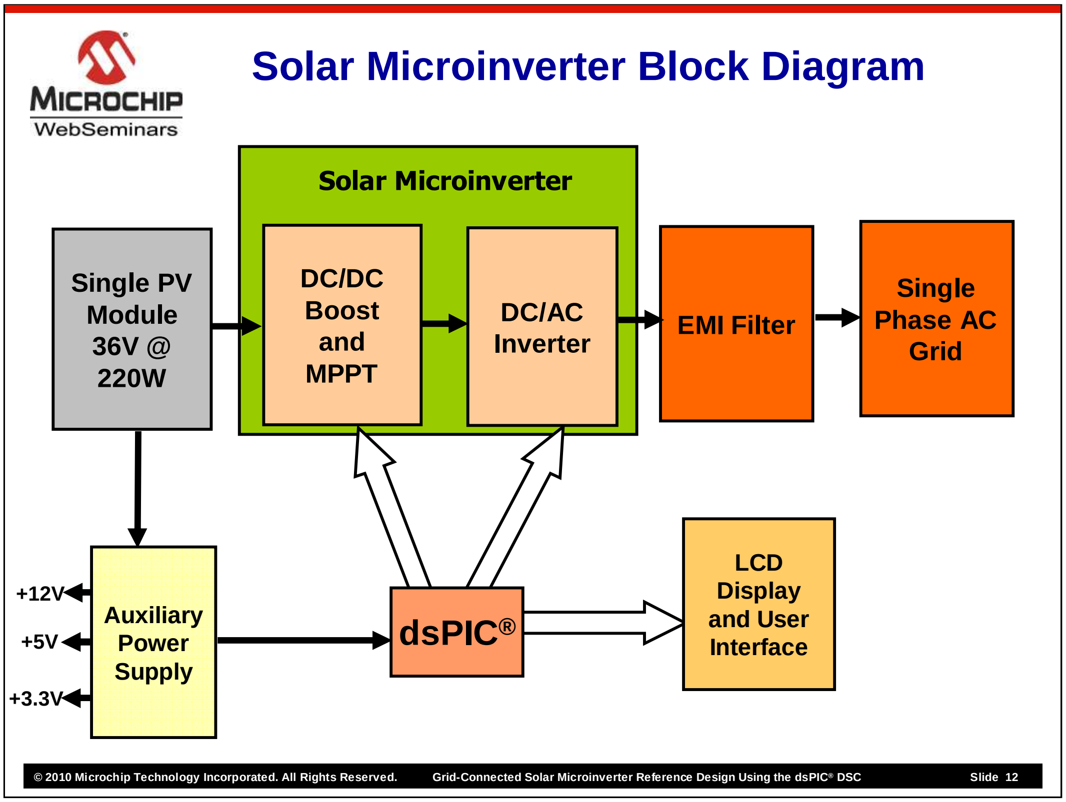
The Grid-Connected Solar Microinverter Reference Design is available in two versions. One version for 110V single-phase grid and one version for 220V single-phase grid.

Both versions are rated for a 220 Watt PV panel. The system feeds a pure sine wave output current to the grid with a current Total Harmonic Distortion (THD) less than 5%.

This reference design uses a dsPIC33F "GS" series digital signal controller for complete digital control of all power stages.

Use of the reference design is Royalty Free, and complete documentation, software, and hardware design information is available on the Microchip web site.

Demonstration units are also available from worldwide Microchip sales offices.

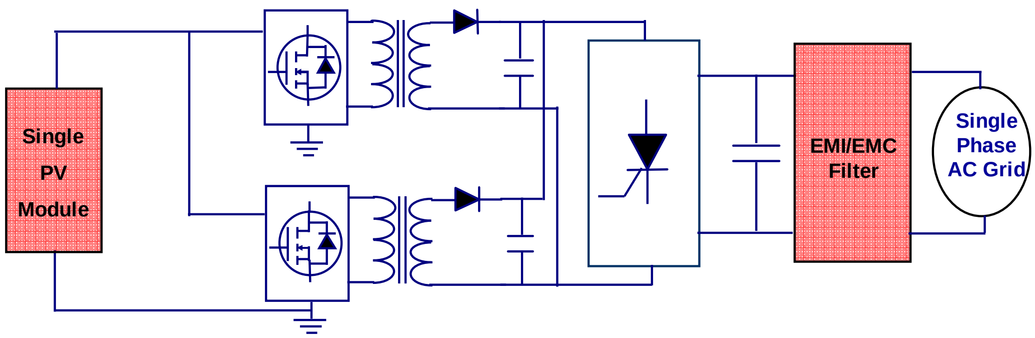


This slide shows a system-level block diagram of the Solar Microinverter. A single dsPIC33F "GS" series digital signal controller, shown in the center of the block diagram is used to control all of the important functions.

The system is primarily divided into two sub-sections:

1) DC-to-DC boost converter with Maximum Power Point Tracking and,
2) DC-to-AC inverter, synchronized with the grid.

Solar Microinverter Reference Design Schematic

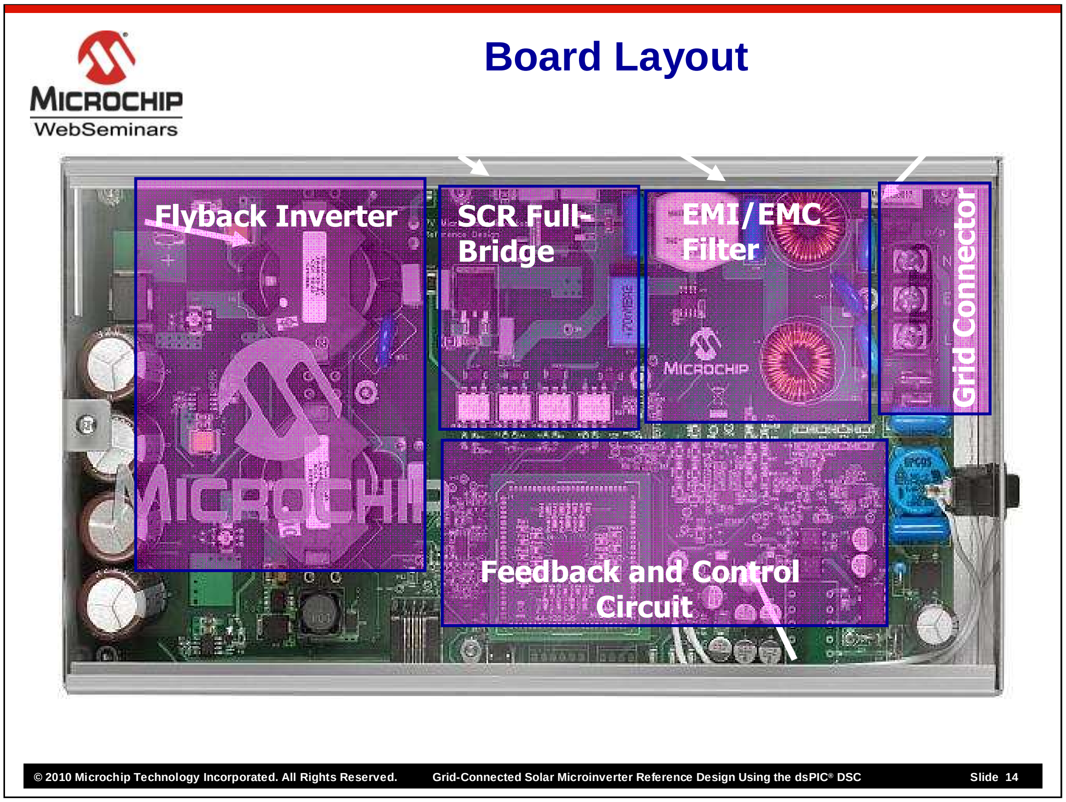


 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 13

A novel single-stage topology is used for this reference design. An interleaved active clamp Flyback inverter boosts the low-voltage DC from the PV panel to the high rectified AC voltage that is synchronized with the grid voltage.

The rectified AC output voltage is higher then the grid voltage.

The magnitude of the Flyback inverter output varies to ensure that the inverter operates at the Maximum Power Point of the PV module characteristics.



Now that we have seen a functional overview of the Solar Microinverter system, we can physically locate each section on a photograph of the system.

This is a top view of the Grid-Connected Solar Microinverter Reference Design.

The locations of each system block are highlighted as follows:

1. The dsPIC Digital Signal Controller is located at the bottom with all of its feedback circuitry.

2. The interleaved Flyback Inverter power circuitry is located on the left side of the board.

3. The SCR full-bridge is located in the middle top area of the board

4. The EMI/EMC filter is located at the top right.

5. The output connector to connect to the grid is located at the top right corner of the board.

Interleaved Flyback Converter

- Interleaved solution cancels the input current ripple, extending the capacitor life
- Interleaved Flyback Converter shares the input and output current, resulting in low copper and core losses
- Active clamp reduces switching losses
- Rectifier diode conduction losses are reduced
- Interleaved solution cancels the output current ripple, resulting in lower THD

 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 15

The Interleaved Flyback Converter has the following advantages over other commonly used topologies for solar microinverter applications.

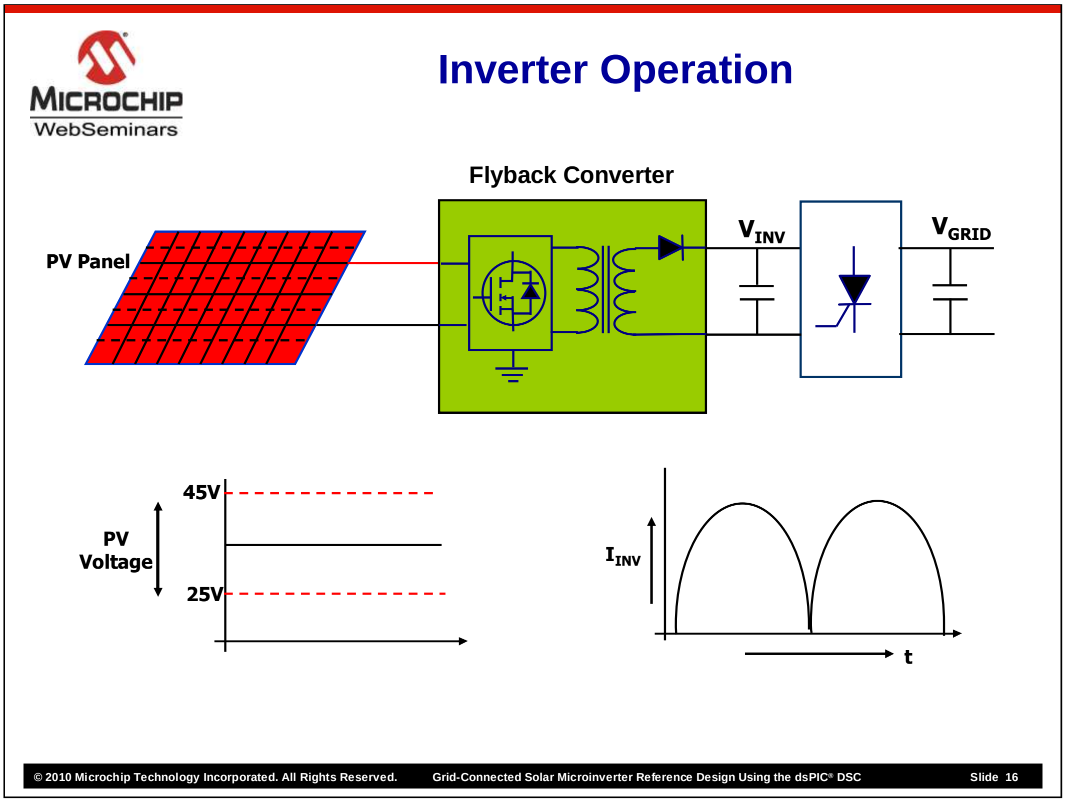
•The interleaved solution cancels the input current ripple, providing a longer capacitor life

•The Interleaved Flyback Converter shares the input and output current, resulting in low copper and core losses

•The active clamp reduces switching losses

•The rectifier diode conduction losses are reduced

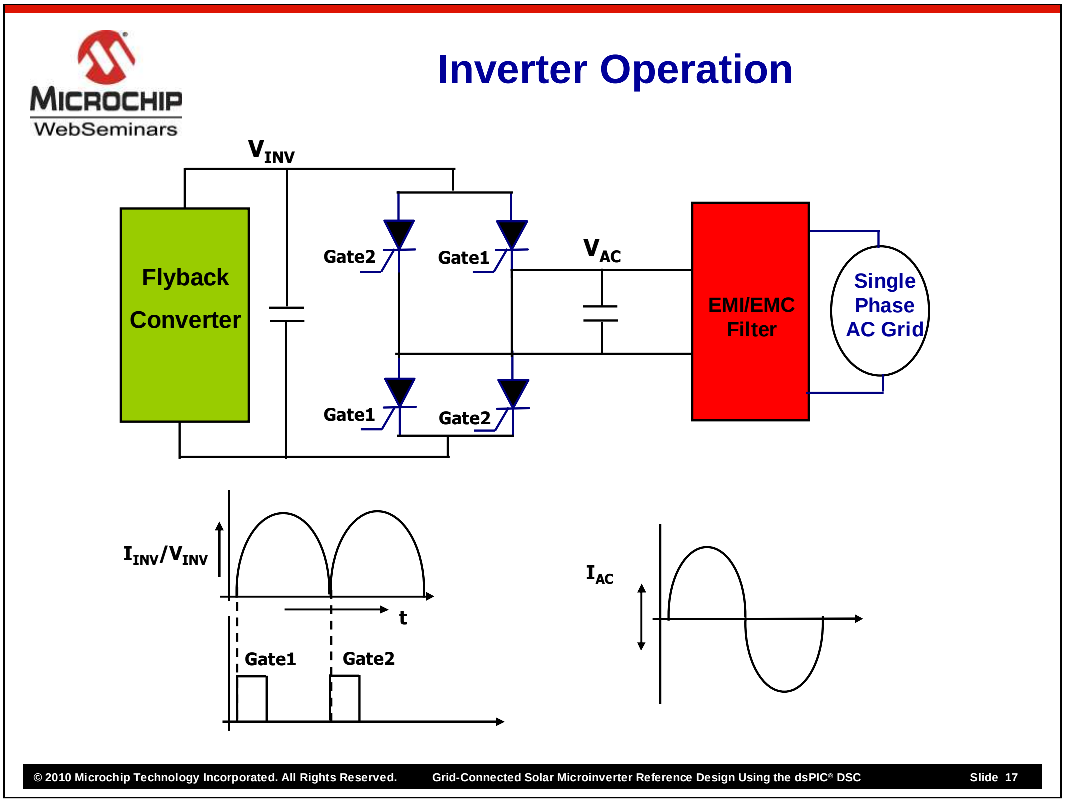
•The interleaved solution cancels the output current ripple resulting in lower Total Harmonic Distortion (THD)



The DC input from the PV module is fed to the Flyback primary. A modulated high-frequency sine PWM is used for the Flyback MOSFETs to generate the rectified sine output voltage and current across the Flyback output capacitor.

The average of the sine modulated secondary diode current, produces a rectified sine voltage and current across the output capacitor.

The two Flyback converters are operated 180 degrees out-of-phase to accomplish interleaved operation.



The SCR full-bridge is used to convert the rectified output voltage and current to sinusoidal voltage and current.

Therefore, the SCR is switched at line frequency. The output of the inverter is synchronized with the grid by a Digital Phase-Locked Loop.

The Maximum Power Point Tracker controls the magnitude (RMS) of the output current.

The shape of the output current is controlled by the current control loop.

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Objective

- Solar Inverter Overview
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- Grid-Connected Solar Microinverter Reference Design
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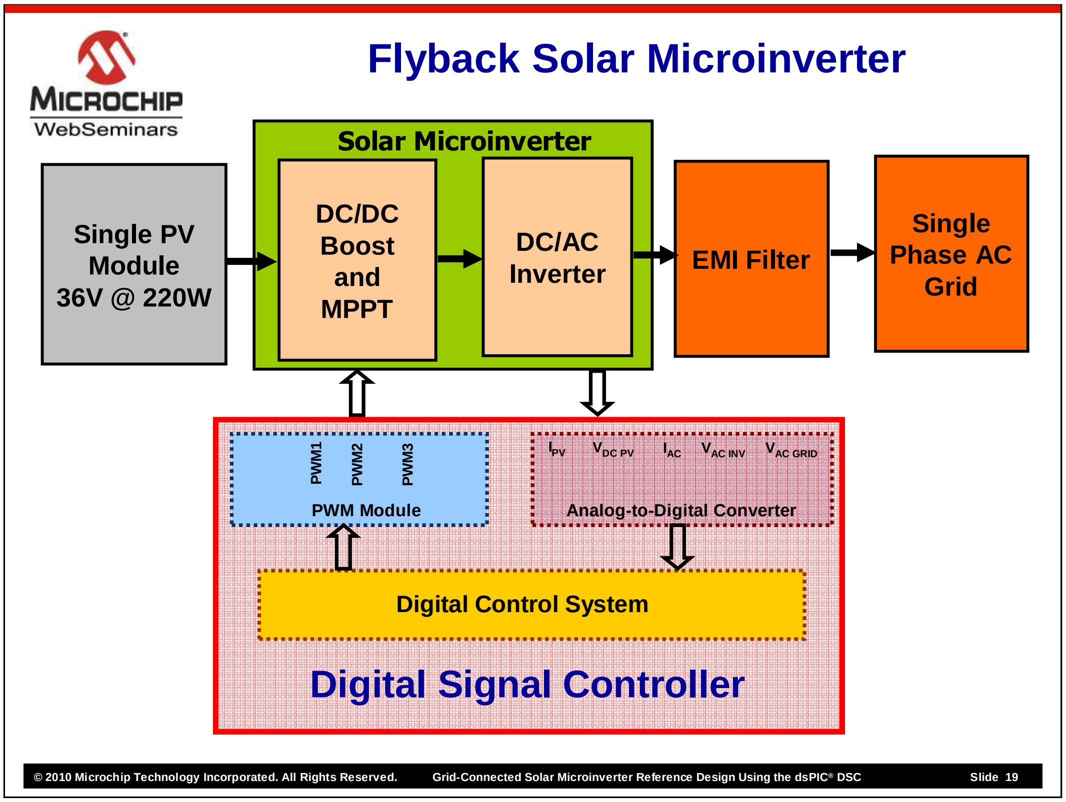
 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 18

We can now take a closer look at the software implementation of Microchip's Grid-Connected Solar Microinverter Reference Design.



The dsPIC DSC device is the heart of the Solar Microinverter design and controls all critical operations of the system as well as the housekeeping operations.

The functions of the dsPIC DSC can be broadly classified into the following categories:

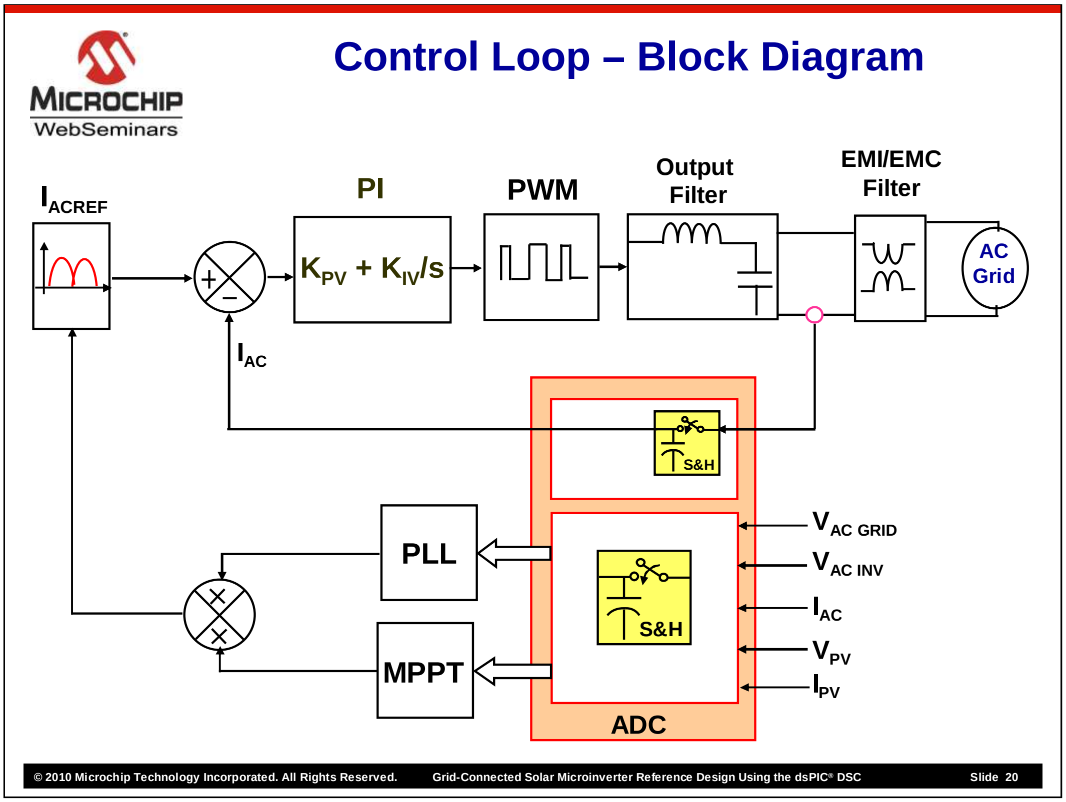
•All power conversion algorithms

•Inverter state machine for the different modes of operation

•Maximum Power Point Tracking

•Digital Phase-Locked Loop

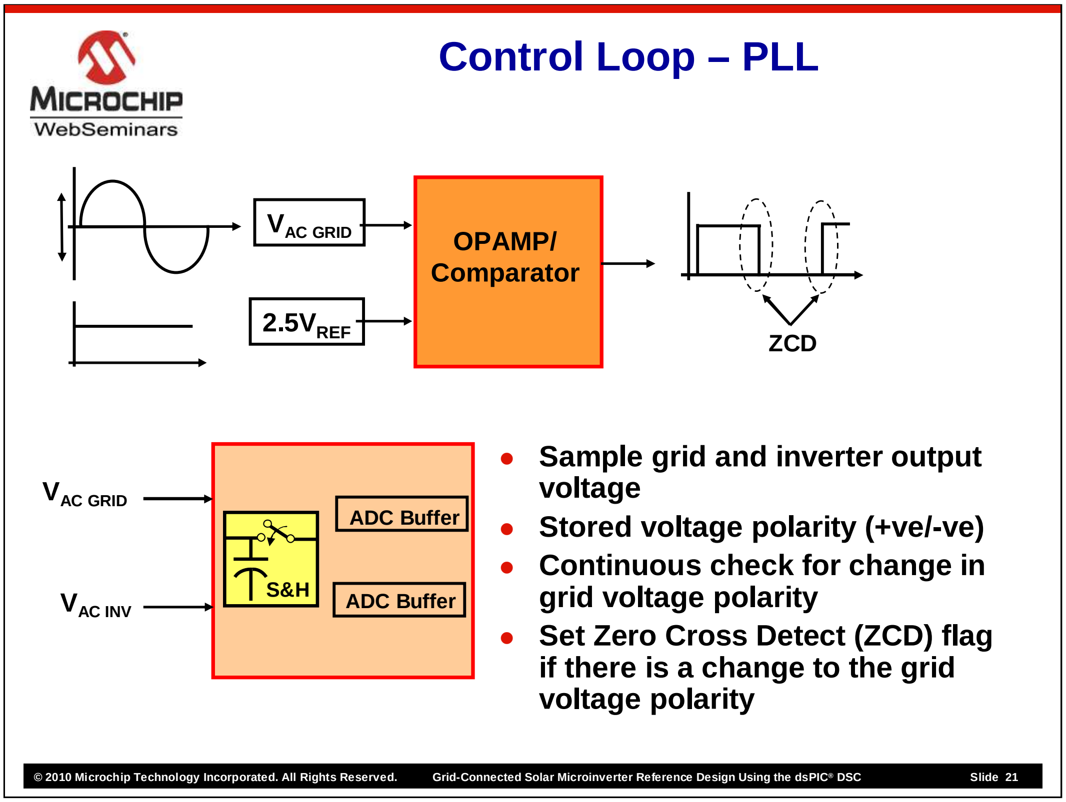
•System islanding and Fault handling



The Solar Microinverter feeds sinusoidal current to the grid; therefore, grid current is being sensed for the control loop. A sine wave reference is generated from the sine table and is synchronized with the grid with the help of a Digital Phase-Locked Loop.

PV voltage and its output current is sensed to calculate the magnitude of the current reference required for Maximum Power Point operation.

A PI-type compensator is used for the control loop, and is implemented as a difference equation in software. The result of the control loop computation modifies the duty cycle, and therefore, maintains a clean sinusoidal current to be fed to the grid.



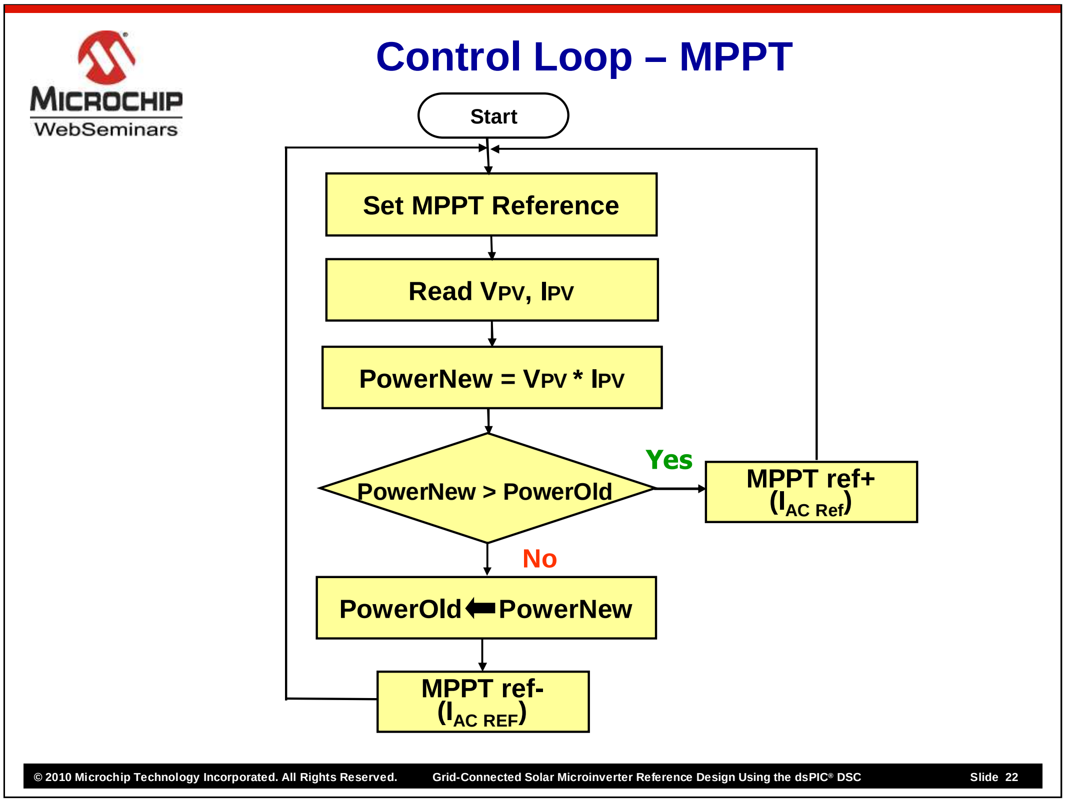
In a grid-connected system, a critical component of the converter's control is the Phase-Locked Loop that generates the frequency and phase angle for the reference to synchronize the output to the grid.

Hardware zero-crossing detection is done with the help of a differential amplifier and comparator.

The comparator output changes its state with a change in grid voltage polarity.

Grid voltage is sampled at every ADC trigger and the polarity of the grid voltage is stored in a register.

In every sample, the grid voltage polarity has been checked. If there is a change in grid voltage polarity, the software sets the zero cross detect flag.

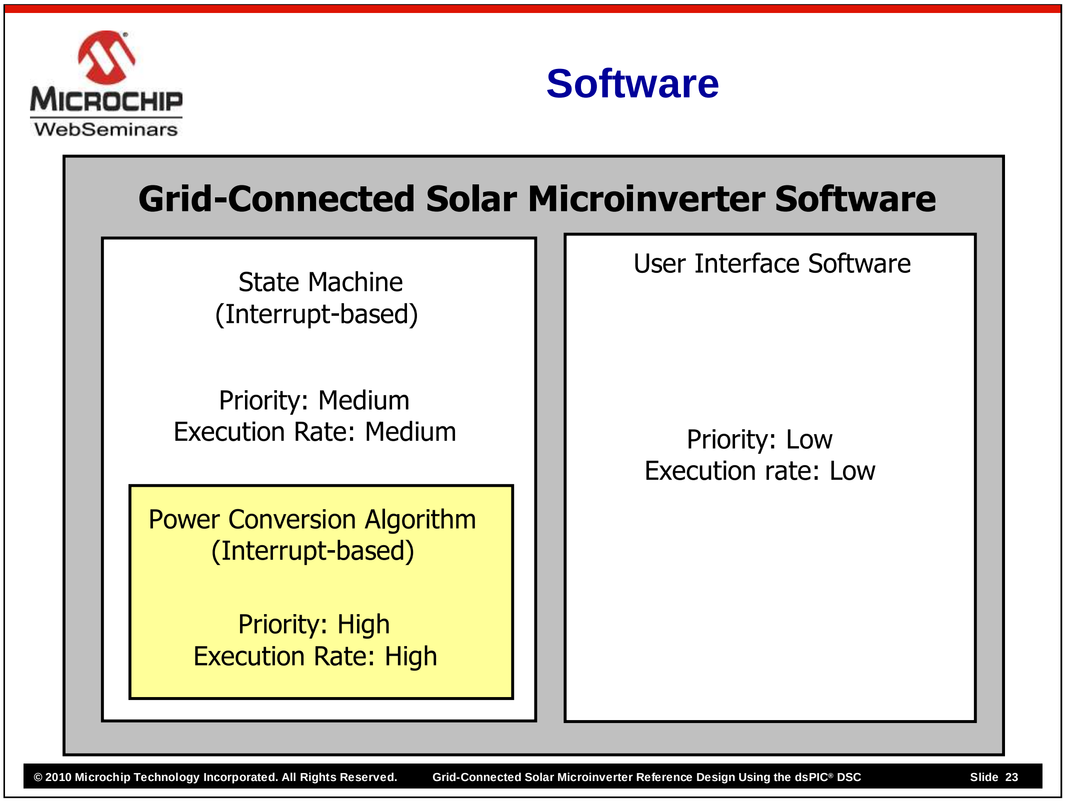


The Grid-Connected Solar Microinverter Reference Design uses the P&O method for Maximum Power Point Tracking.

The Maximum Power Point tracker operates by periodically incrementing or decrementing the solar array voltage. If a given agitation leads to an increase or decrease of the output power of the PV,the subsequent agitation is generated in the same or in opposite direction.

Set MPPT reference denotes the agitation of the solar array voltage, and *MPPT ref+* and

MPPT ref- represent the subsequent agitation in the same or opposite direction, respectively.



This diagram shows the high-level partitions for the PV Inverter software.

Each block represents a functional piece of software that pertains to one of the sub-sections of the inverter system.

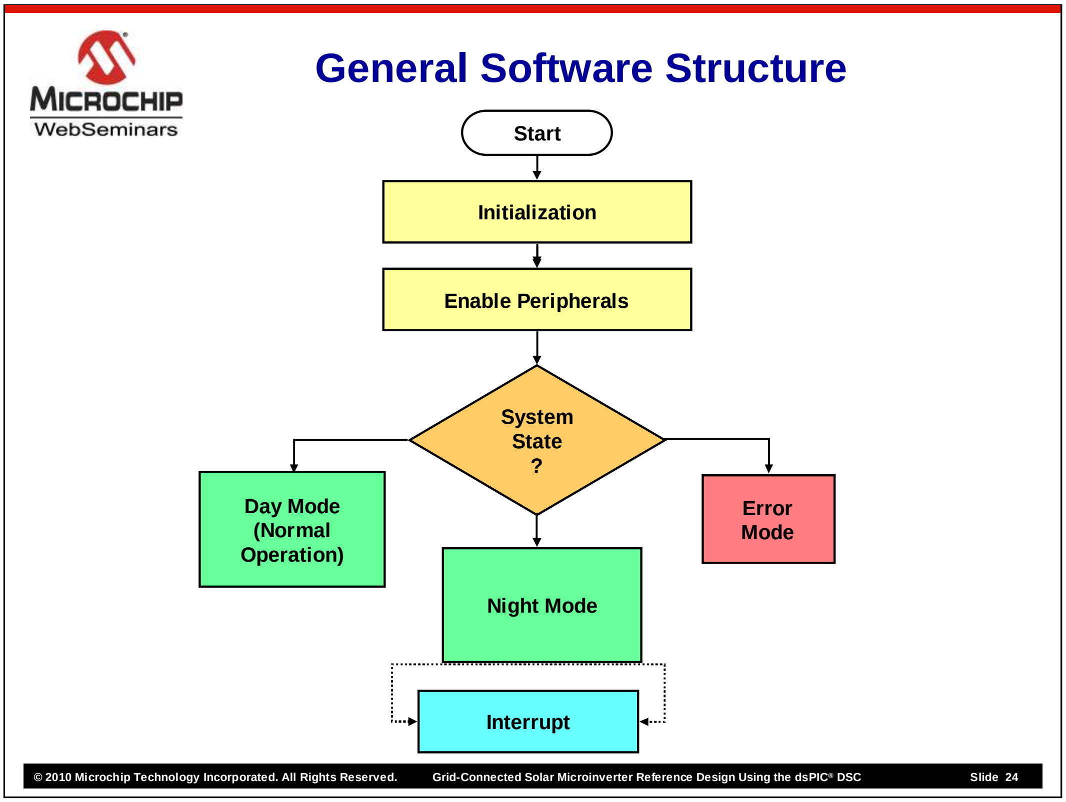
As seen from the diagram, software is first split into the State machine and the User Interface Software.

The State Machine software determines the mode of operation for the Inverter system,

detects the presence or failure of the PV module and grid , and also executes all of the power conversion algorithms.

Within the state machine, the power conversion algorithms are assigned the highest priority.

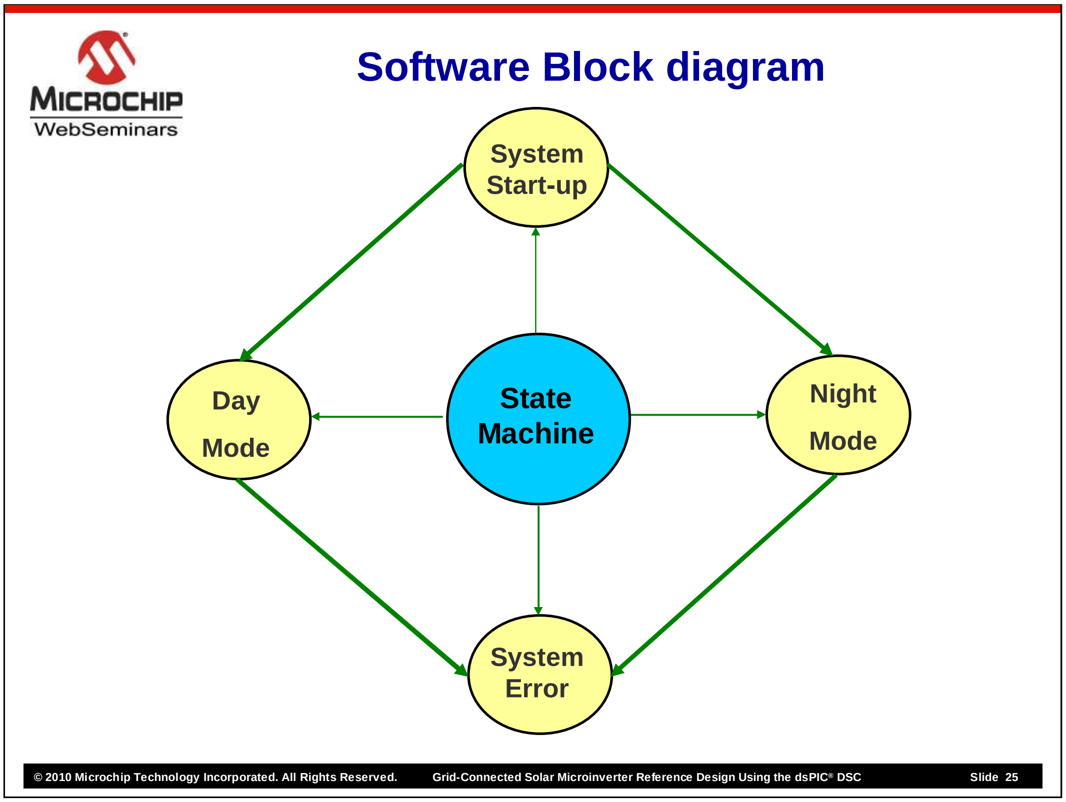
The other state machine code forms the next level, or medium priority.



When the Solar Microinverter is turned ON, the system goes into initialization routing and initializes all of its peripherals, variables and constants. The state of the system will initialize with the system start-up state. The state machine first monitors all system variables and the input and output state. If there is no fault, the state machine switches to the system state start-up.

Inside the ADC interrupt, the most recent voltage and currents are measured and used for the control loops. The control loops are executed inside the ADC interrupt routine and the PWM output is modified accordingly.

This structure ensures the fastest performance, and the highest execution priority.



The Solar Microinverter State machine consists of four main operating modes:

1. System Startup: the state machine will first calculate the input PV voltage and the output grid voltage and its frequency before setting the systemStartFlag to start the system in normal operation.

It reinitializes all of the mandatory control loop variables to ensure reliable operation during initial switching of the PWMs.

After initializing all mandatory control loop variables, the system state switches to DAY_MODE operation.

2. DAY_MODE: DAY_MODE is the normal mode of operation. The state machine configures the system peripherals to execute the correct power conversion algorithms as determined by the system state.

In this mode, the Solar Microinverter delivers the maximum available energy from the PV panel to the single-phase grid.

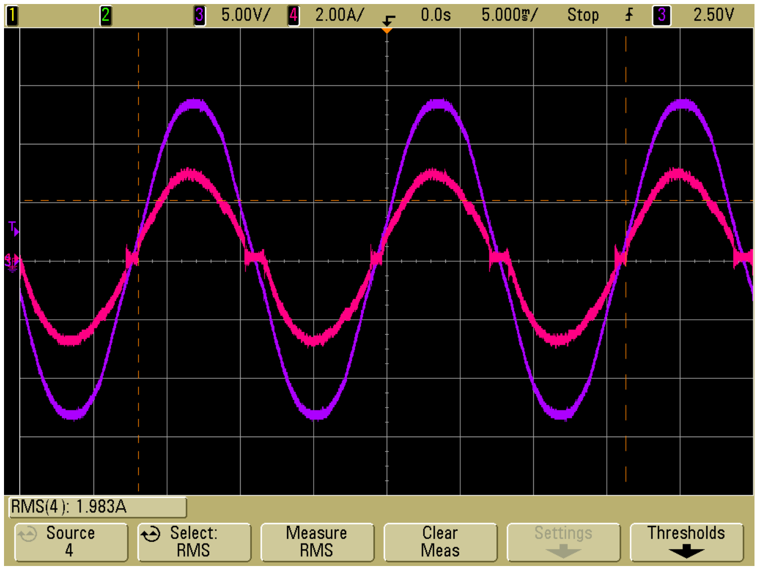
3. NIGHT_MODE: The system state switches to NIGHT_MODE when there is not sufficient energy available from the connected PV panel (power <25W) or the PV panel voltage is not within the specified limit.

All feedback signals are being continuously monitored and checked for fault and input/output current condition.

4. SYSTEM_ERROR: If grid voltage or input and output current is not within the specified limit, the state machine initiates system error mode. In this mode, all of the power conversion blocks are turned OFF and the input/output voltage condition and faults are monitored to recover the system in the normal operation state if faults were removed.

Test Result Waveform

Grid Voltage and Grid Current

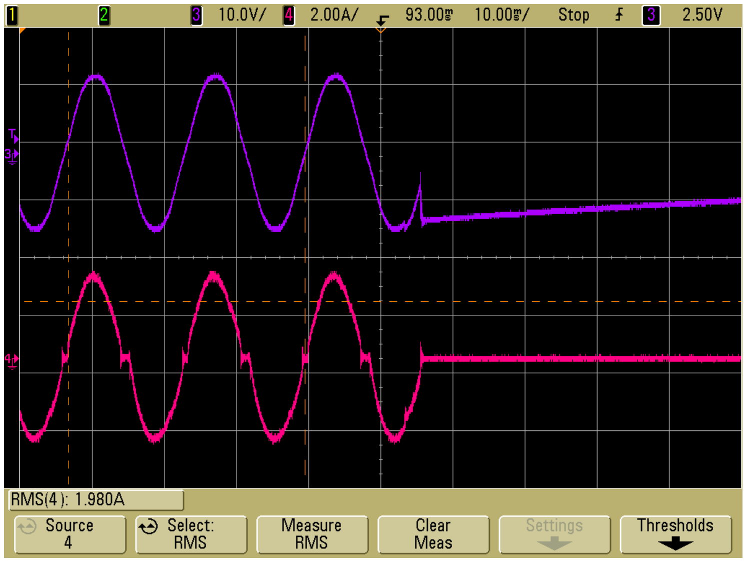


 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 26

The violet colored waveform is the grid voltage and the magenta colored waveform is the current being fed to the grid. From the captured waveform we can see that the output current is in phase with the grid voltage.

Test Result Waveform

System Islanding: System Turned OFF When Grid Fails

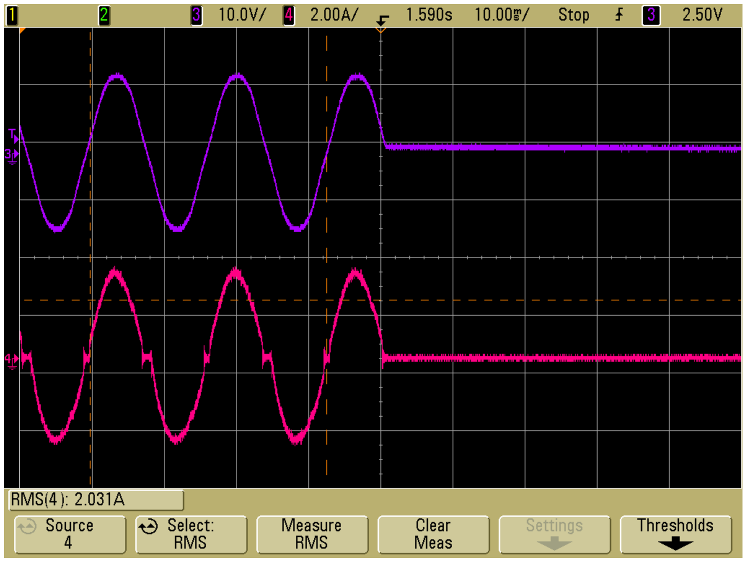


This waveform demonstrates islanding:

From the waveform, we can see that when the grid is turned OFF near its peak, the inverter stops feeding power to the grid.

Test Result Waveform

System Islanding: System Turned OFF When Grid Fails



From this waveform, we can see that when the grid is turned OFF near its zero crossing, the inverter stops feeding power to the grid.

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Objective

- Solar Microinverter Overview
  - Photovoltaic Cell Characteristics
  - Solar Microinverter Configurations
- Grid-Connected Solar Microinverter Reference Design
- Software Integration
- Summary

Next, lets recap what we discussed regarding Microchip's Grid-Connected Solar Microinverter Reference Design.

Summary

- Overview of Solar Microinverter
- Photovoltaic Cell Characteristics
- Solar Microinverter configurations
- Microchip Grid-Connoted Solar Microinverter Reference Solution Hardware and Circuit Operation
- Software Architecture

 Grid-Connected Solar Microinverter Reference Design Using the dsPIC® DSC Slide 30

In this webinar, we discussed the photovoltaic cell characteristics, different solar microinverter configurations, and Microchip's 220W Grid-Connected Solar Microinverter Reference Design.

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Thank You

- Visit www.microchip.com/smps for more design resources
- Available for Free Download:
  - Application Note
  - Complete Source code
  - PCB Design files
  - MATLAB Simulation files

Thank you for joining me in this web seminar on Microchip's Grid-Connected Solar Microinverter Reference Design using the dsPIC Digital Signal Controller.

Please visit the link on this page for more design details on the Grid-Connected Solar Microinverter as well as other Switch-Mode Power Supply Reference Designs.