光伏應用與能量轉換探討

MICROCHIP

A Leading Provider of Smart, Connected and Secure Embedded Solutions

Microchip Power Team

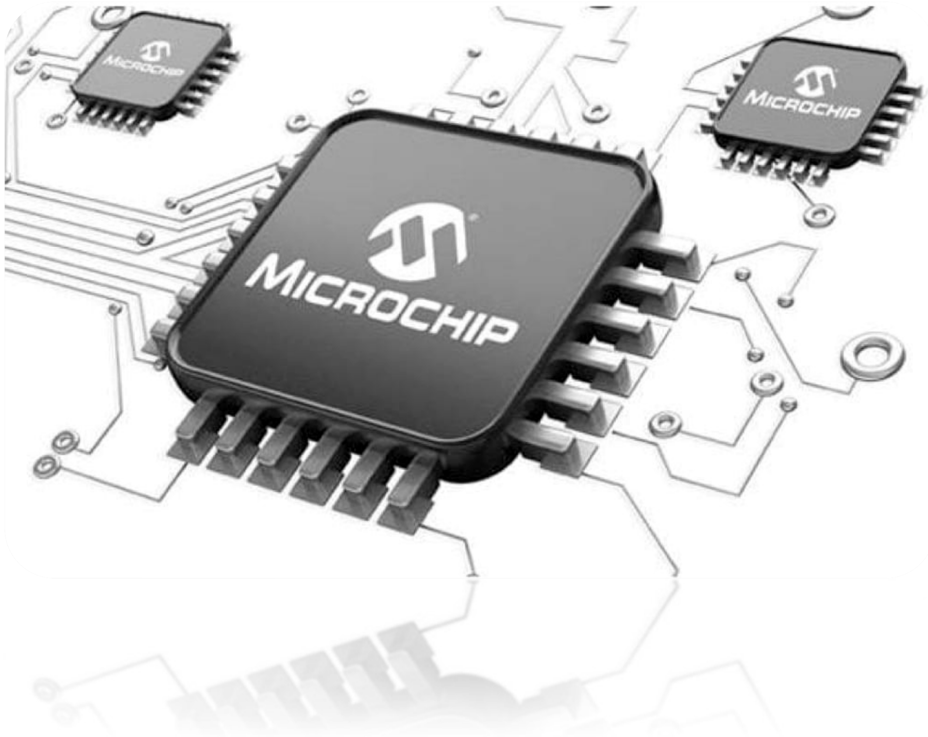
May 2023

SMART | CONNECTED | SECURE

Agenda

光伏應用與能量轉換探討

- **Background Information**
- **Solar Cell and Panel Characteristics**
- **Solutions**



Background Information

Solar Power Overview

Why Solar Power

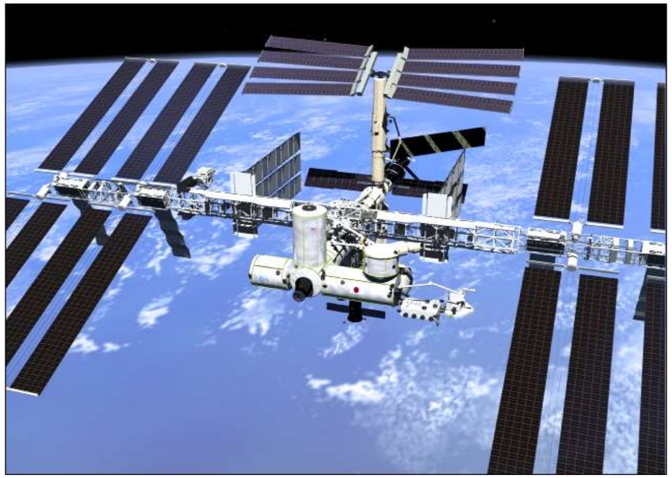
- PV systems produce clean and renewable electricity that replaces power produced by coal, oil, and nuclear power
- Costs for solar panels are declining
- Efficiency of Solar Cells has increased

Market Pain Points

- Higher Power Density for integration into a panel or more power in the same form factor
- Thermal Challenge
- > 20 years Lifetime

Solar Power Applications

- **Small Scale**
  - Watches, Calculators
  - Personal Electronic devices
- **Medium Scale**
  - Lighting, Battery Charger
  - Vehicles
- **Large Scale (kW)**
  - Commercial Buildings, Houses
  - Spacecrafts
- **Utility Scale (MW-GW)**

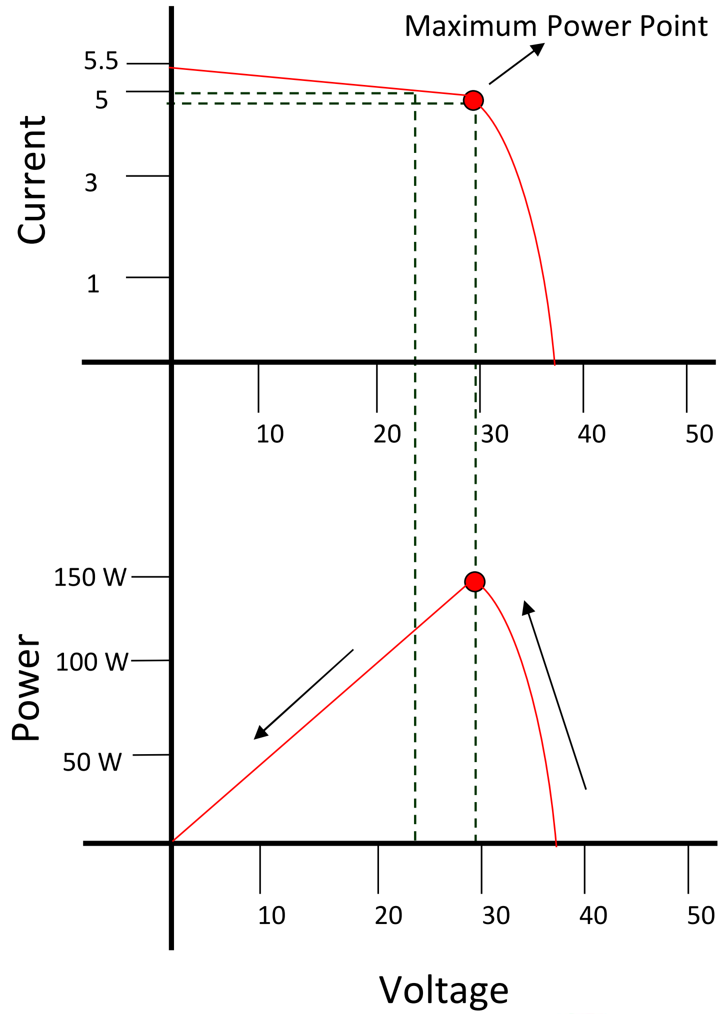


Common Solar Requirements

- **MPPT – Maximum Power Point Tracking algorithm required to optimize the power harvest from solar panels.**
- **System efficiency: 93% - 95+%**
- **Support a wide DC input voltage range**
- **Safety:**
  - Fault detection
  - Anti-islanding
- **Communication (PLM, Wireless)**
- **AC Quality (THD<5%) – meet IEEE 519**

Maximum Power Point Tracking

- **Because of the complex relationship between solar irradiation, temperature and total resistance a maximum power point tracking algorithm is required**
- **MPPT is a closed loop algorithm that continuously adjusts the output power in order to operate at maximum power as measured at the input**
- **Two common algorithms:**
  - Perturb and Observe
  - Incremental Conductance



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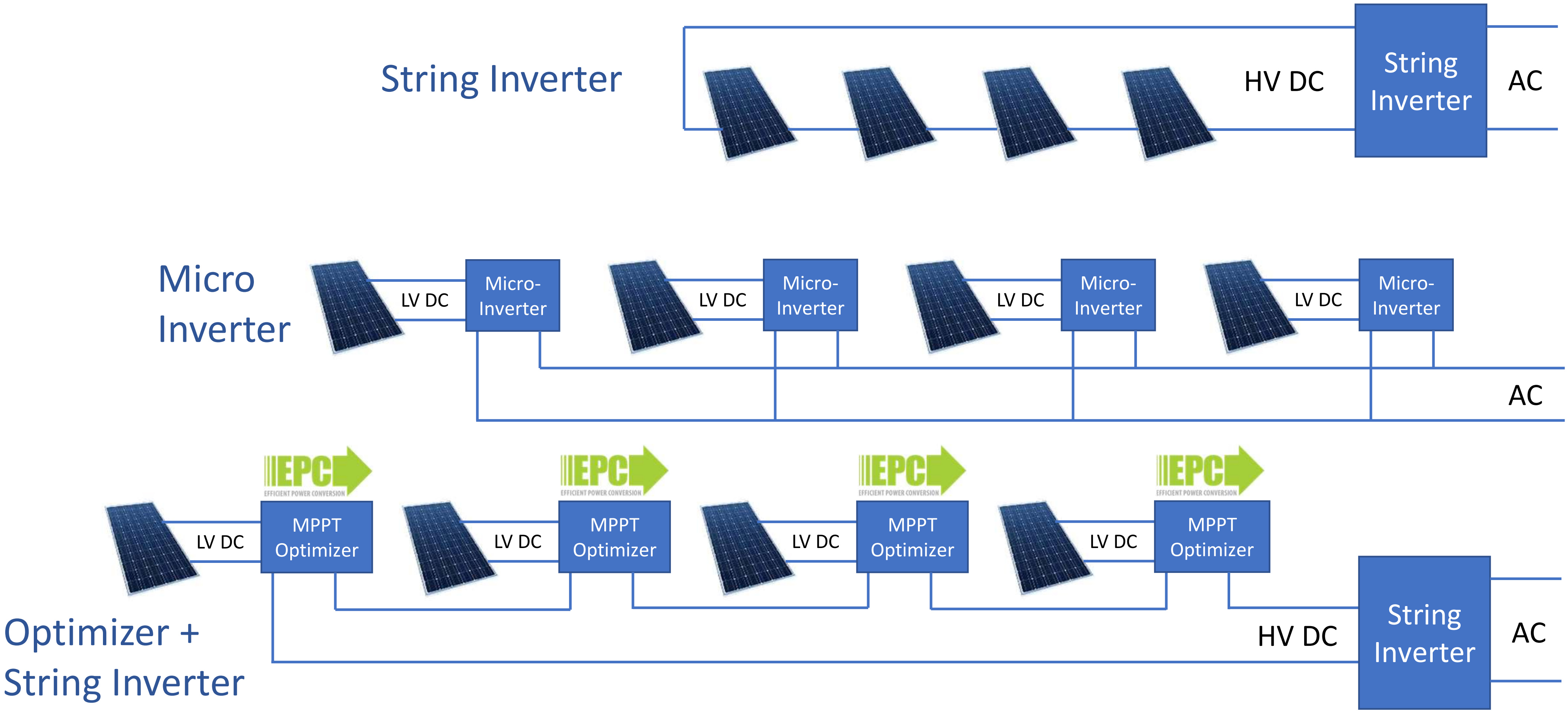
Solar Power Topologies



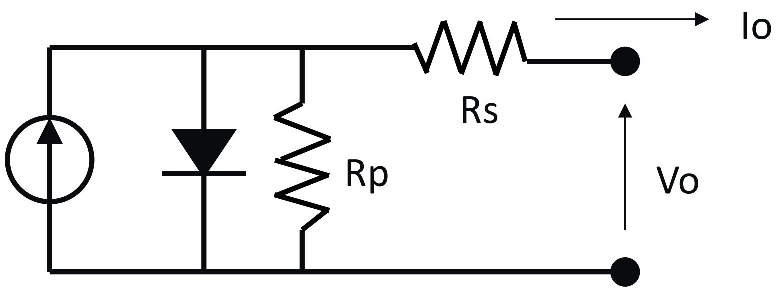
Trend:
MPPT/Optimizer or panels with built-in microinverter

String Inverter	Microinverter	MPPT Optimizer with String Inverter
Centralized system with single inverter connected to multiple solar panels. Power > 2,000 W.	Plug-and-play device that converts DC current by a single up to 6 panels to AC & harvest optimum power by MPPT. Typical power around 350 W for 1 panel (500 W max) to 2,200 W for 6 panels.	A power optimizer is a DCDC converter that maximizes the energy harvest from a solar panel true MPPT. Single or dual panel solutions, up to 800 W.
Lower initial equipment cost per peak watt.	Panels are electrically isolated, resulting in 5% - 25% higher output power. A panel failure does not affect the system. Longer lifespan (20 – 25 years). Does not need to be replaced during the lifespan of the solar panels. Fully Scalable & Monitoring capability. Other Benefits: simplicity, low amperage wires, safety, efficiency.	Same advantages as microinverters with lower initial equipment cost and about 2% higher efficiency. Easy to integrate to solar panel to simplify installation.
Shorter lifespan (5–12 yrs). It will need replacement during the lifespan of the solar panels. Lower performance: malfunctioning of 1 panel affects output power. No monitoring capability.	Each inverter needs to be installed adjacent to a panel (usually on a roof). This makes them harder to remove and replace. Some manufacturers have addressed these issues with panels with built-in microinverters.	Less scalable than microinverter as the size of the inverter is fixed.

Solar Cell Characteristics

Solar Cell Characteristics

- A solar cell is a current source, not a voltage source
- The amount of current depends on the illumination from the sun
- Rs and Rp are parasitic resistances that in an ideal world would be zero and infinite respectively

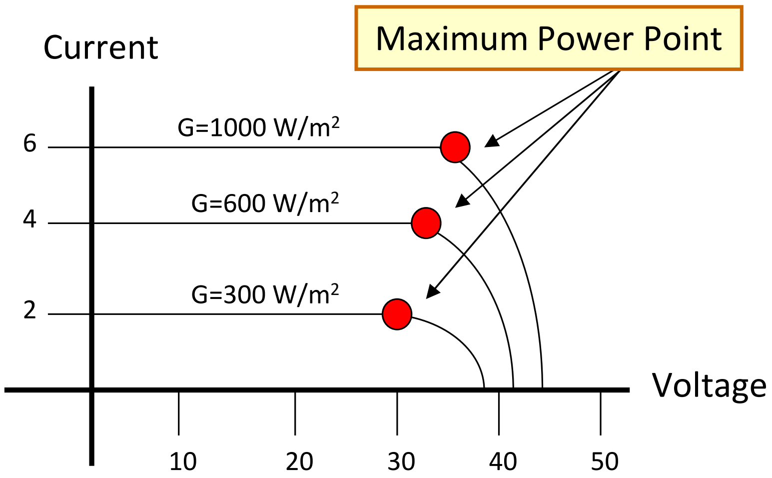


V_o ~ 0.5V

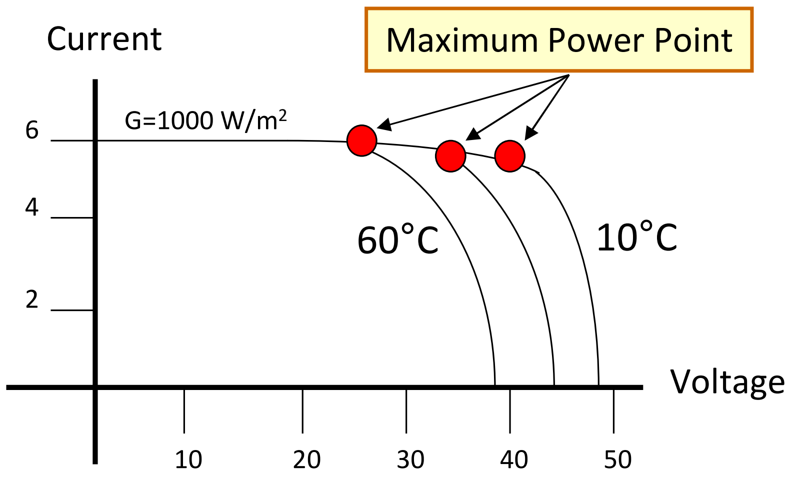
I_o ~ 1 - 3A

Simplified circuit model of a solar cell

Panel Operating Characteristics



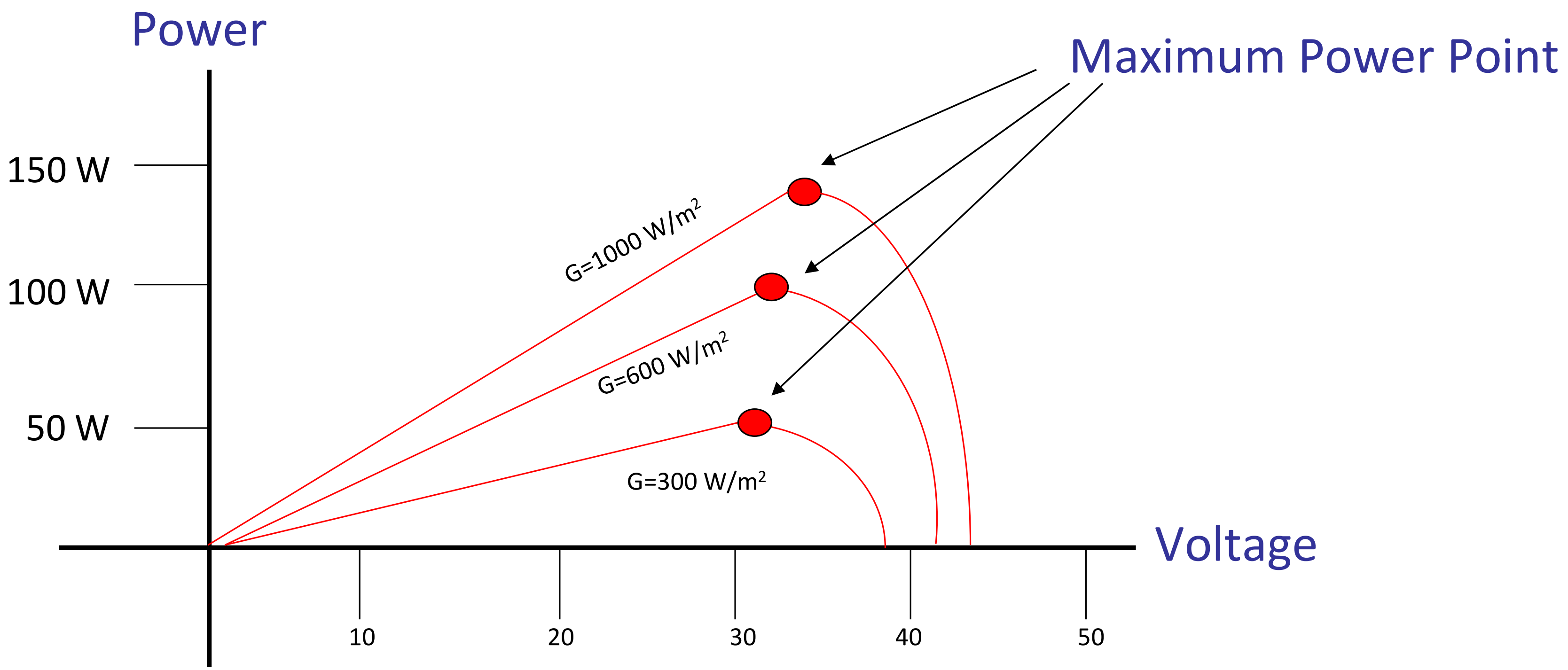
I-V versus Illumination (36 cell string)



I-V versus Temp (36 cell string)

Solar Panel output varies with LIGHT and TEMPERATURE

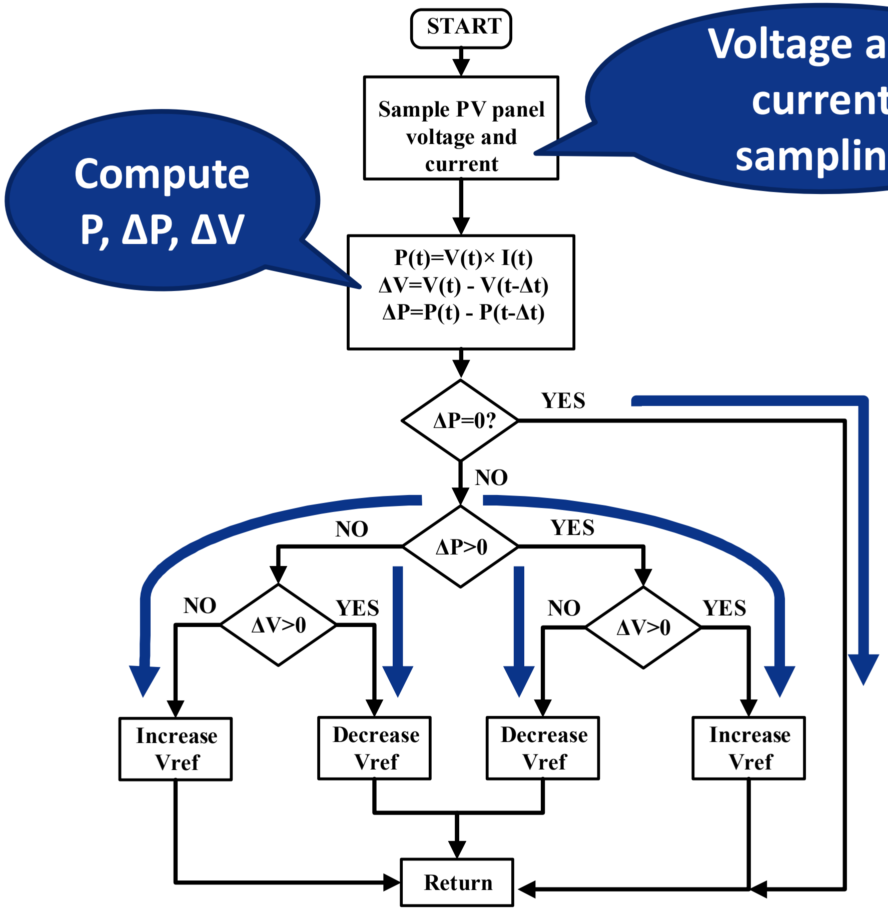
Panel Operating Characteristics

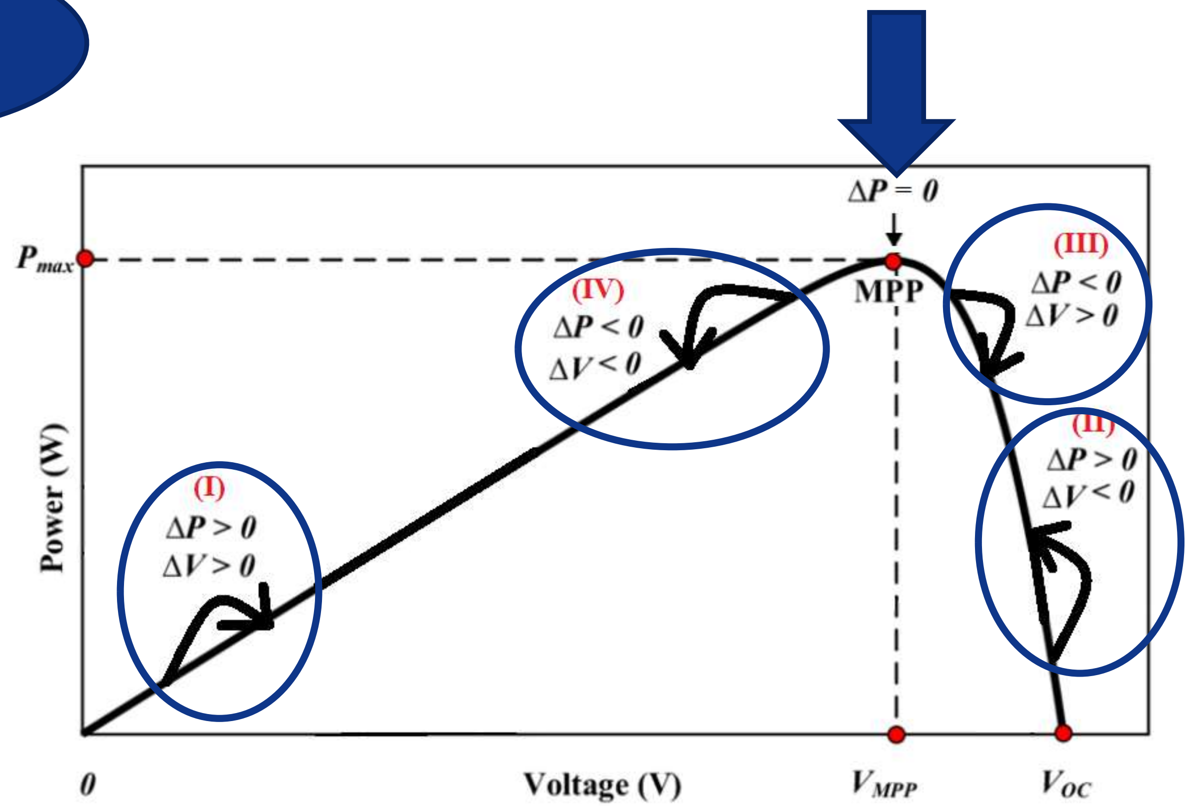


P-V versus Illumination
(36 cell string)

MPPT Algorithms

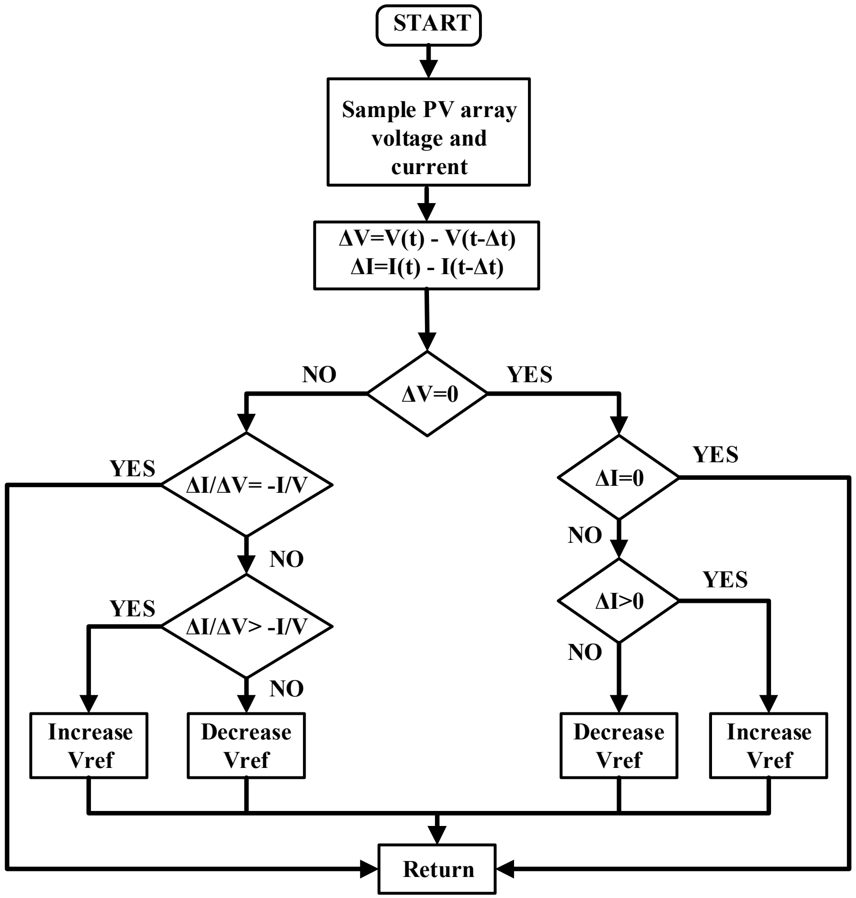
The perturb and observe algorithm

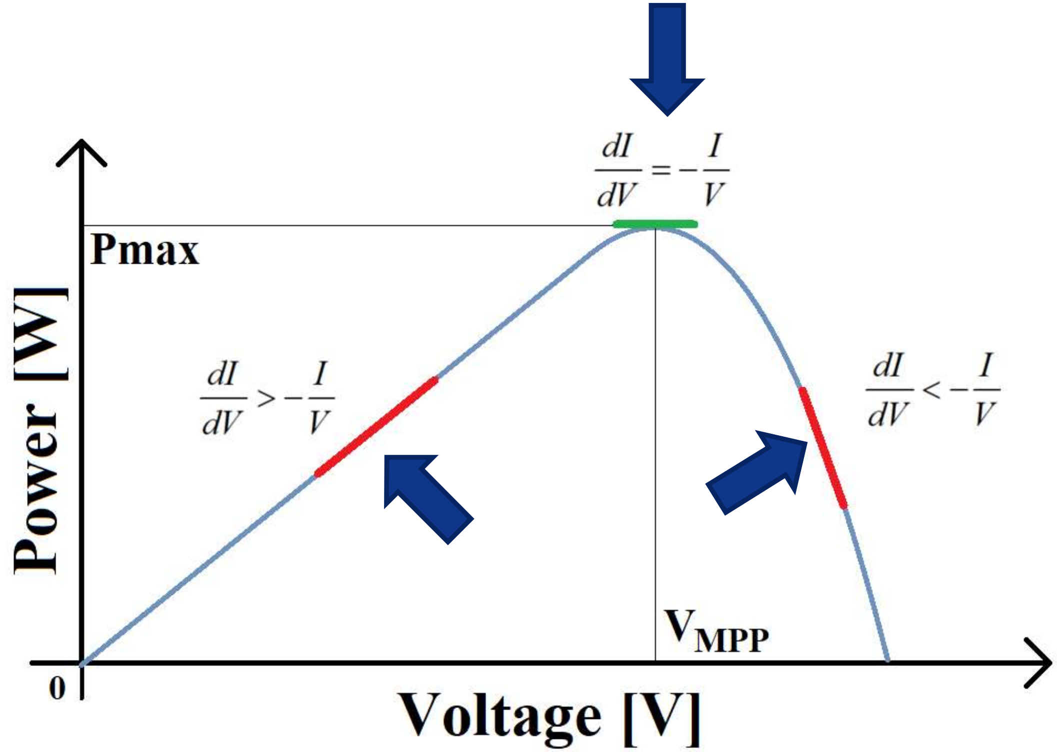




MPPT Algorithms

The incremental conductance (INC) algorithm

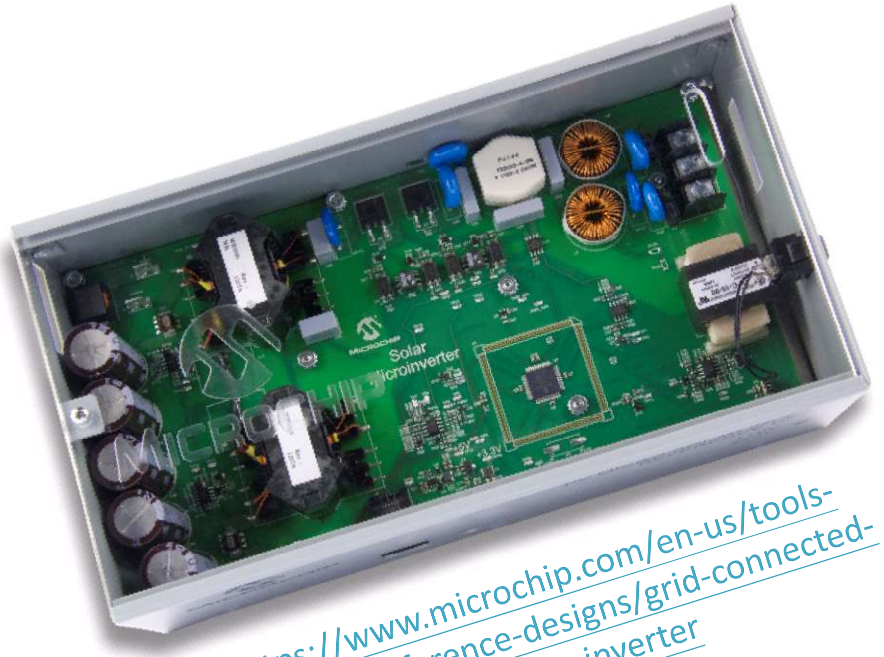




Solutions

Grid-Connected Solar Microinverter Ref. Design

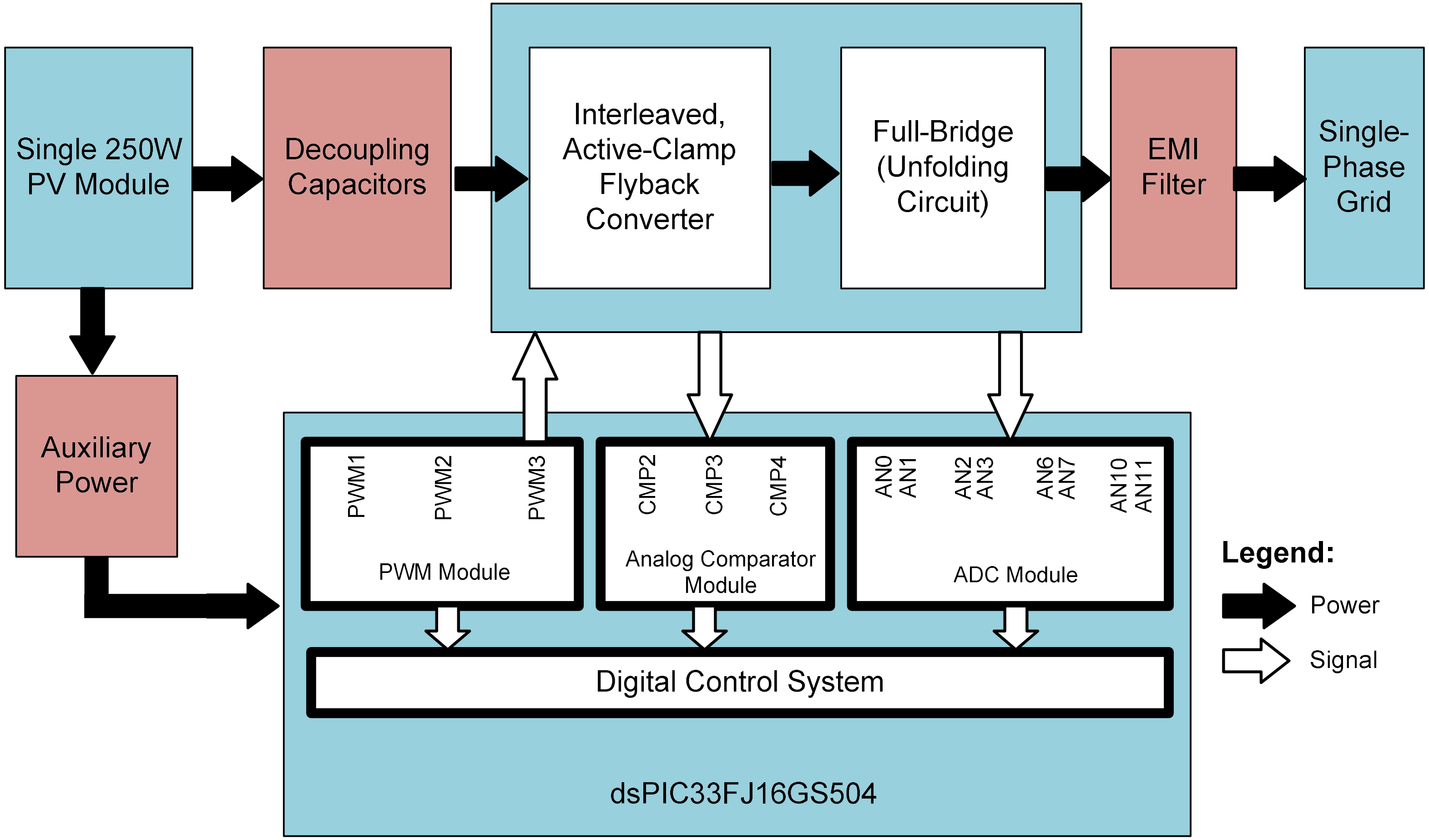
- **PV Input Power: 250W (max)**
- **Maximum Output Power: 215W**
- **Open Circuit PV Voltage: 53Vdc (max)**
- **Maximum Power Point Tracking: 99.5%**
- **MPPT Voltage: 20Vdc – 45Vdc**
  - Power de-rating: Vdc < 25Vdc
- **AC Output Voltage range (50/60 Hz)**
  - 210Vac – 264Vac
  - 90Vac – 140Vac
- **Total Demand Distortion: < 5%**
- **Output Power Factor: > 0.95**
- **Peak Efficiency: 94.5% (nominal conditions)**



https://www.microchip.com/en-us/tools-resources/reference-designs/grid-connected-solar-microinverter

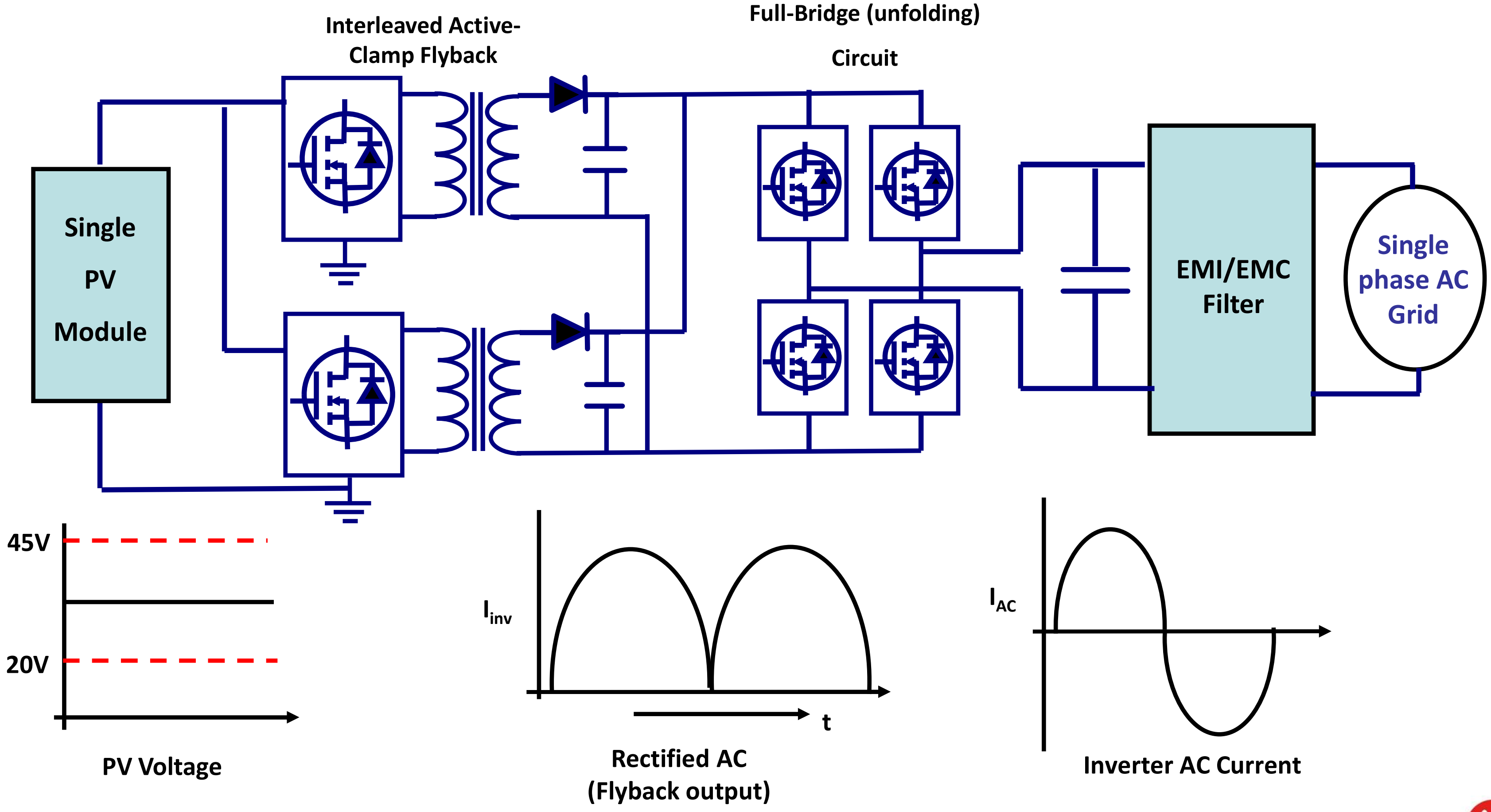
Grid-Connected Solar Microinverter Ref. Design

Solar Microinverter Block Diagram



Grid-Connected Solar Microinverter Ref. Design

Solar Microinverter Schematic



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Why Interleaved?

- **Interleaved Flyback shares the input and output current which results in lower copper and core losses**

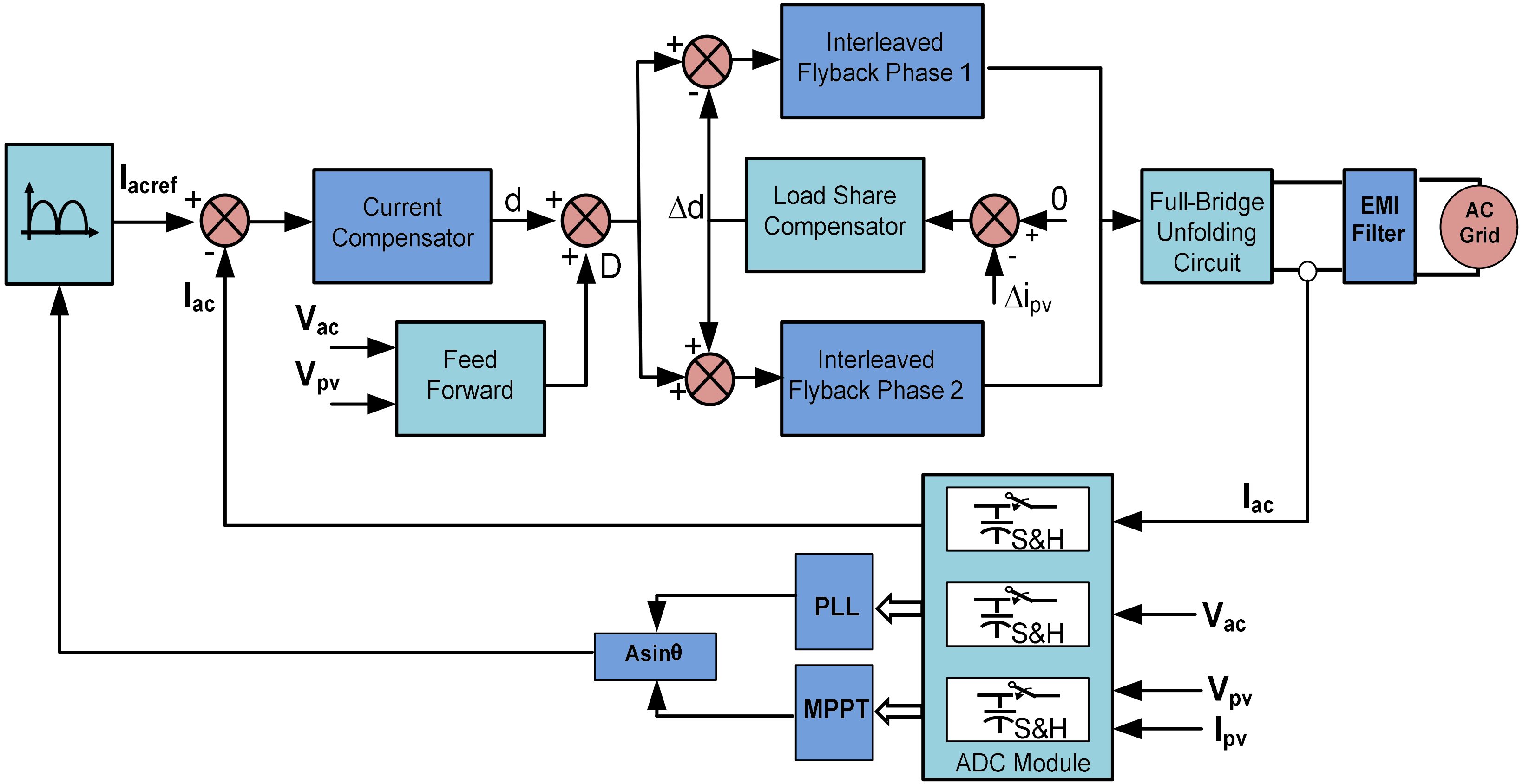
- **Interleaved Flyback reduces the output current ripple which results in lower ITHD**

- **Interleaved Flyback reduces the input current ripple which increases capacitor life**

Why Active-Clamp?

- Active clamp circuit utilizes the leakage energy that is typically transferred to heat (Snubber)
- Active clamp circuit clamps the leakage spike which reduces stress on Flyback MOSFETs
- If correctly implemented, active clamp circuit also allows ZVS on the Flyback MOSFETs which reduces switching losses
- With P-Channel MOSFET configuration no high-side gate drive required

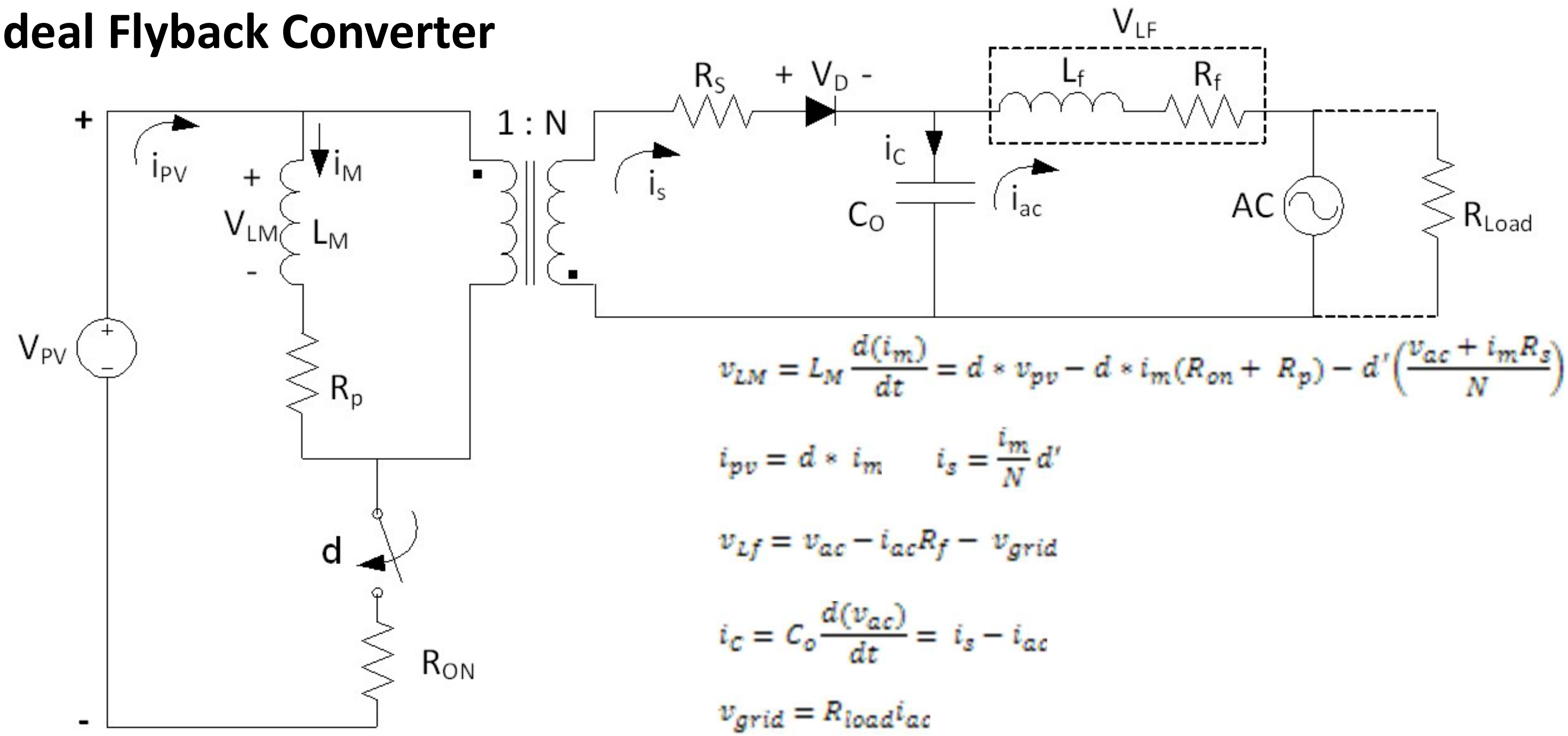
Control Loop – Block Diagram



- Current Compensator, Voltage Feed-forward, PLL (Execution Rate ~56 kHz)
- Maximum Power Point Tracker (Execution Rate – 3 x f_{ac})
- Load Share Compensator (Execution Rate – 5 kHz, ~1/10th current compensator)

Control Loop – Block Diagram

- **Non-ideal Flyback Converter**



$$v_{LM} = L_M \frac{d(i_m)}{dt} = d * v_{pv} - d * i_m(R_{on} + R_p) - d'\left(\frac{v_{ac} + i_m R_s}{N}\right)$$

$$i_{pv} = d * i_m \qquad i_s = \frac{i_m}{N} d'$$

$$v_{Lf} = v_{ac} - i_{ac} R_f - v_{grid}$$

$$i_c = C_o \frac{d(v_{ac})}{dt} = i_s - i_{ac}$$

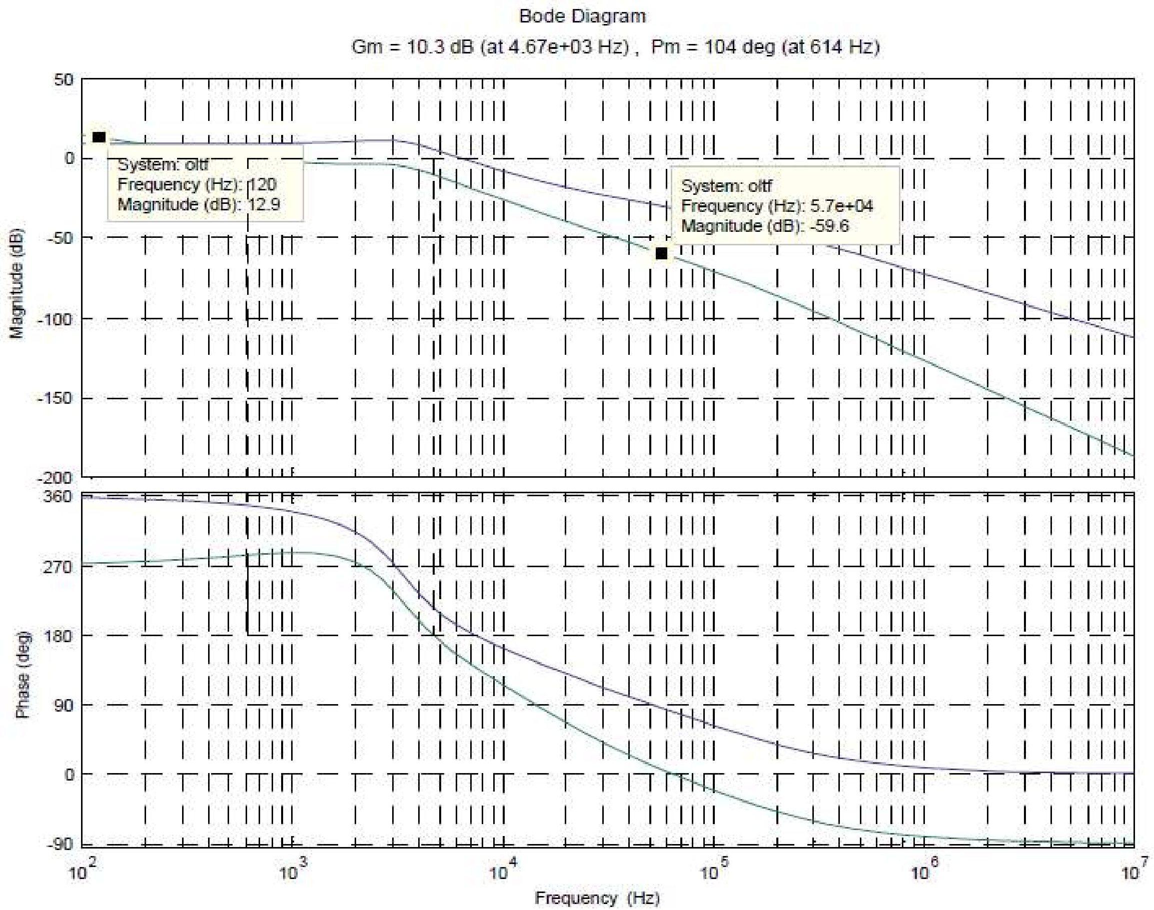
$$v_{grid} = R_{load} i_{ac}$$

The flyback converter has three states (storage elements)

- $I_m(s)$ – Flyback Inductor Current
- $V_{ac}(s)$ – Flyback Output Capacitor Voltage
- $I_{ac}(s)$ – Output Filter Inductor Current

Control Loop – Block Diagram

- **Using State Space Modeling the transfer function of the system can be obtained:**



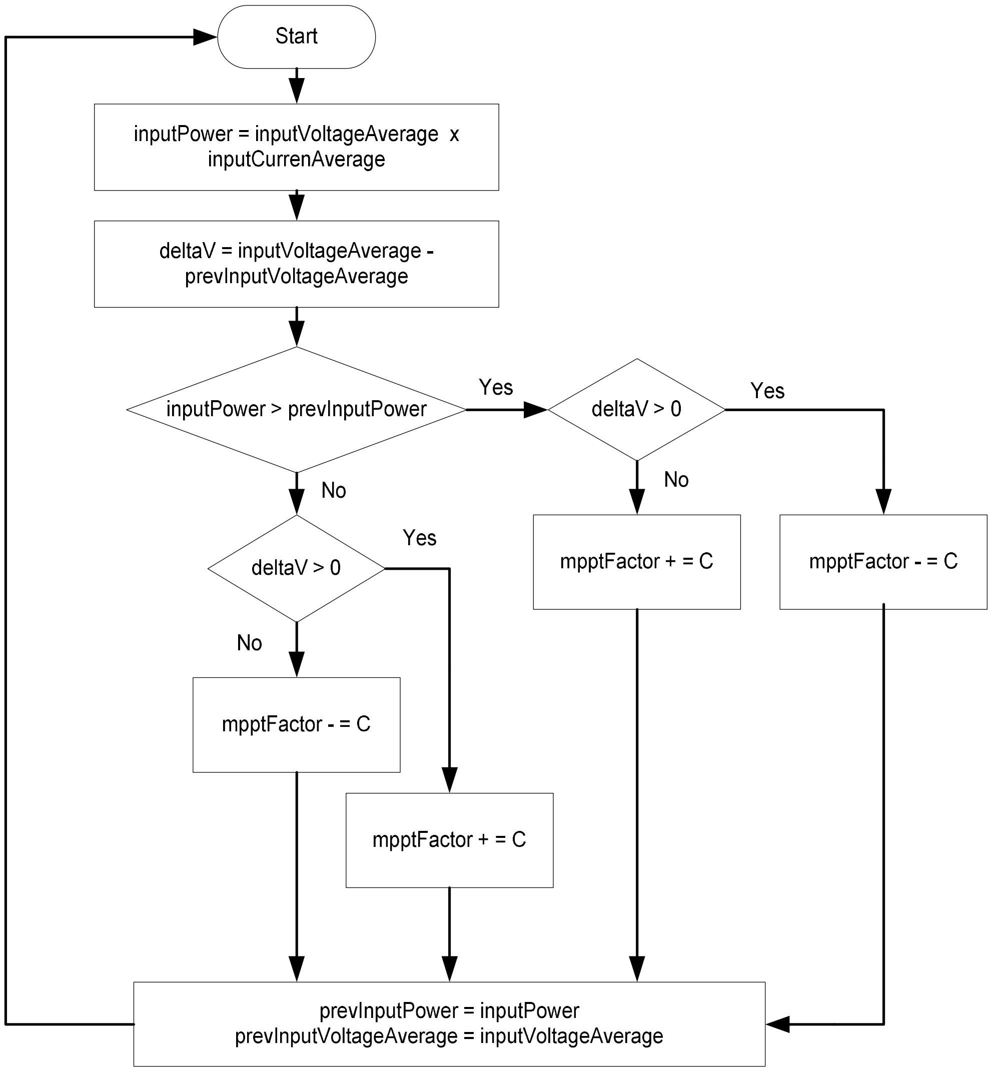
$$G_{id}(s) = \frac{\left(\frac{kD' - I_m R}{L_m N L_f C_o} - \frac{I_m s}{L_m c_o N}\right)}{s^3 + \left(\frac{R}{L_m} + \frac{R_f}{L_f}\right)s^2 + \left(\frac{RR_f}{L_m Lf} + \frac{1}{L_f C_o} + \frac{D'^2}{N^2 L_m Co}\right)s + \left(\frac{R}{L_m L_f C_o} + \frac{D'^2}{N^2 L_m C_o}\right)}$$

PI Compensator improves:

- Phase Margin (104 deg. vs. 10 deg.)
- Gain Margin (10.3 dB vs. 3 dB)
- Gain @ operating frequency

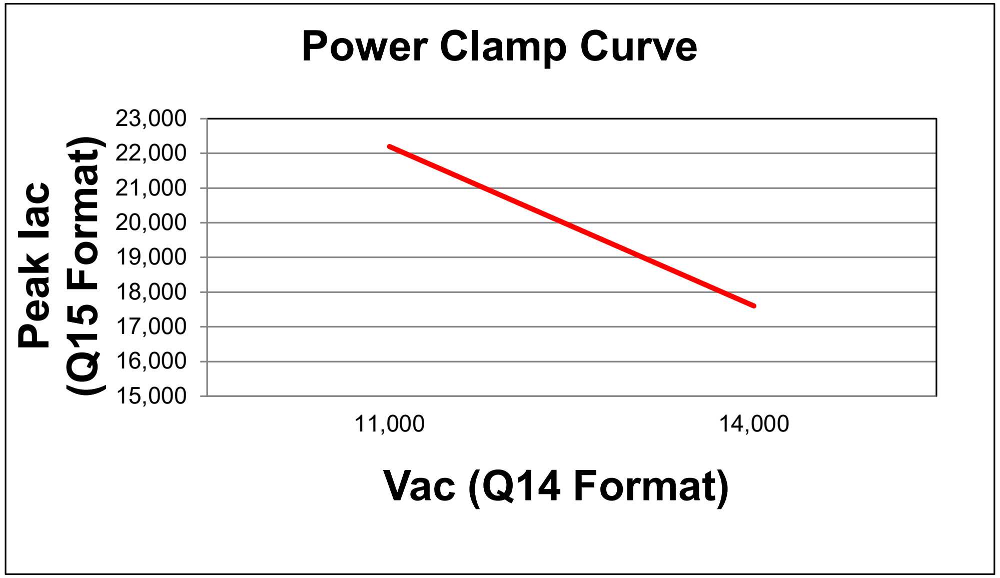
Control Loop MPPT (P&O)

- **Calculate average input power**
- **Determine change in input voltage/input power**
- **Add/subtract constant based on direction on power curve**
- **Executes every three AC cycles (average taken over 3 AC cycles)**



Output Power Clamp

- **Clamp output power to 215W across output voltage (controlled variable Iac)**
- **Determine peak inverter output current at min/max operating voltages**
- **Executes every zero crossing**
- **Software Implementation:**



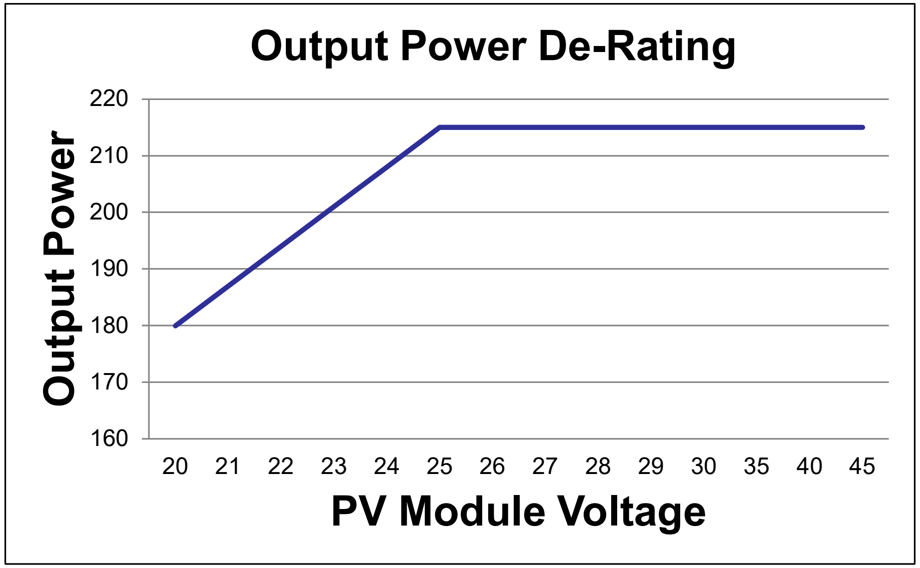
$y = -1.567x + 39530$

```
y = 39530 - ((_builtin_mulss(x, 25673)) >> 14);
```

- y = Maximum I_{ac}
- x = Measured V_{ac} in Q14
- 25673 = Q14 representation of 1.567

Output Power De-rating

- **When PV Panel voltage drops below 25Vdc**
  - De-rate the output power to prevent saturation of the flyback transformers
  - De-rating factor: ~7W per Volt
  - Clamping output current
- **Execute every zero crossing**
- **Software Implementation**
  - deratingFactor = ((_builtin_mulss(Vdiff, 18235)) >> 14);
    - Vdiff = 25V minus measured input voltage
    - 18235 = Q14 representation of I_{pk}(7W) / V_{pv}(1V)
  - maxCurrentReference -= deratingFactor



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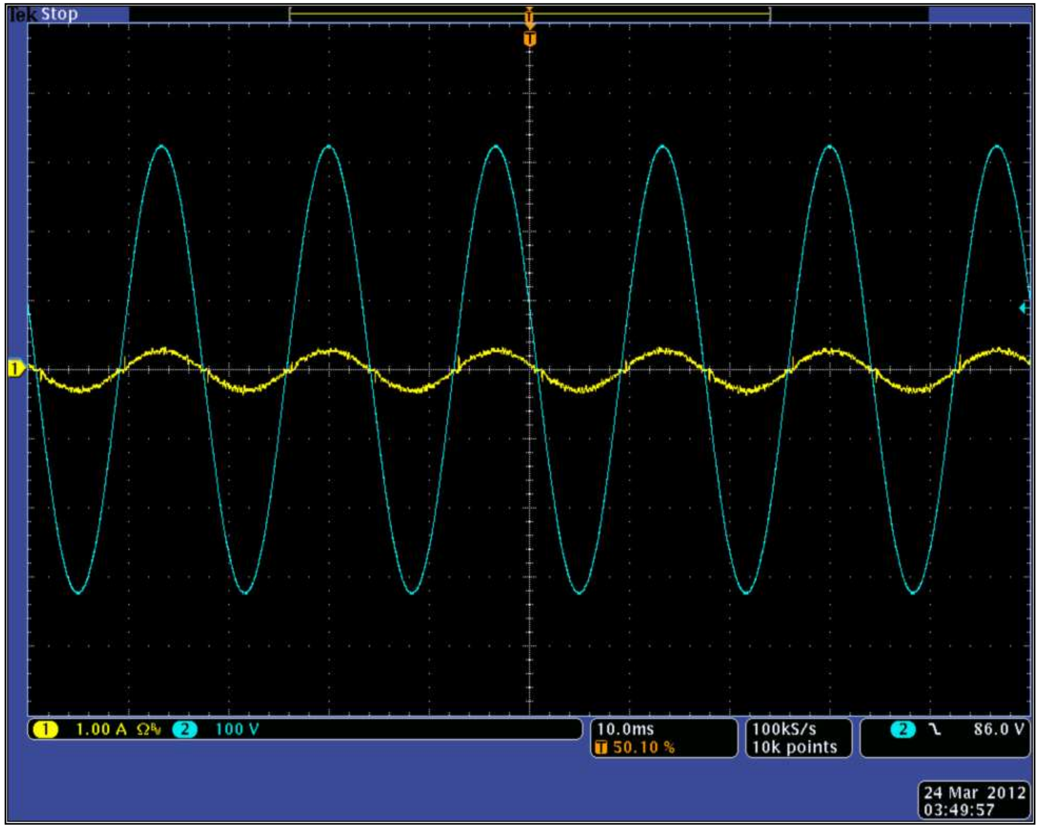
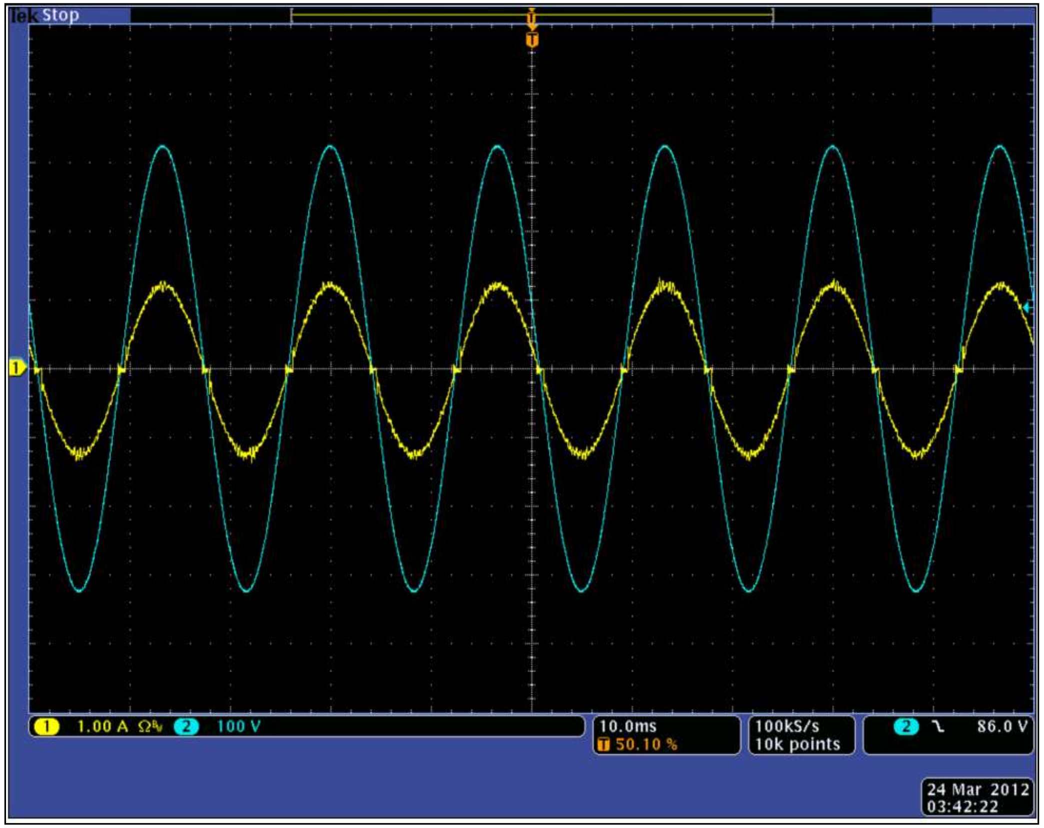
Output Current



Light Load: ~60W



Full Load: 215W

Active Clamp & ZVS

Clamp Voltage
drain-to source

Resonant current

ZVS at Flyback Turn-On

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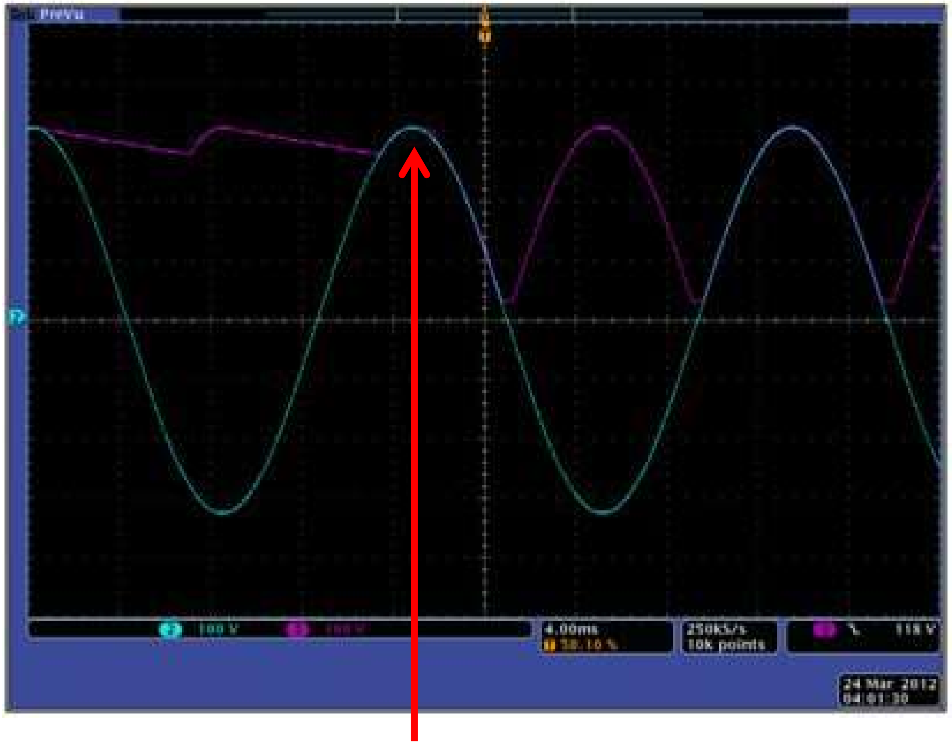
Full-Bridge Startup and Burst Mode



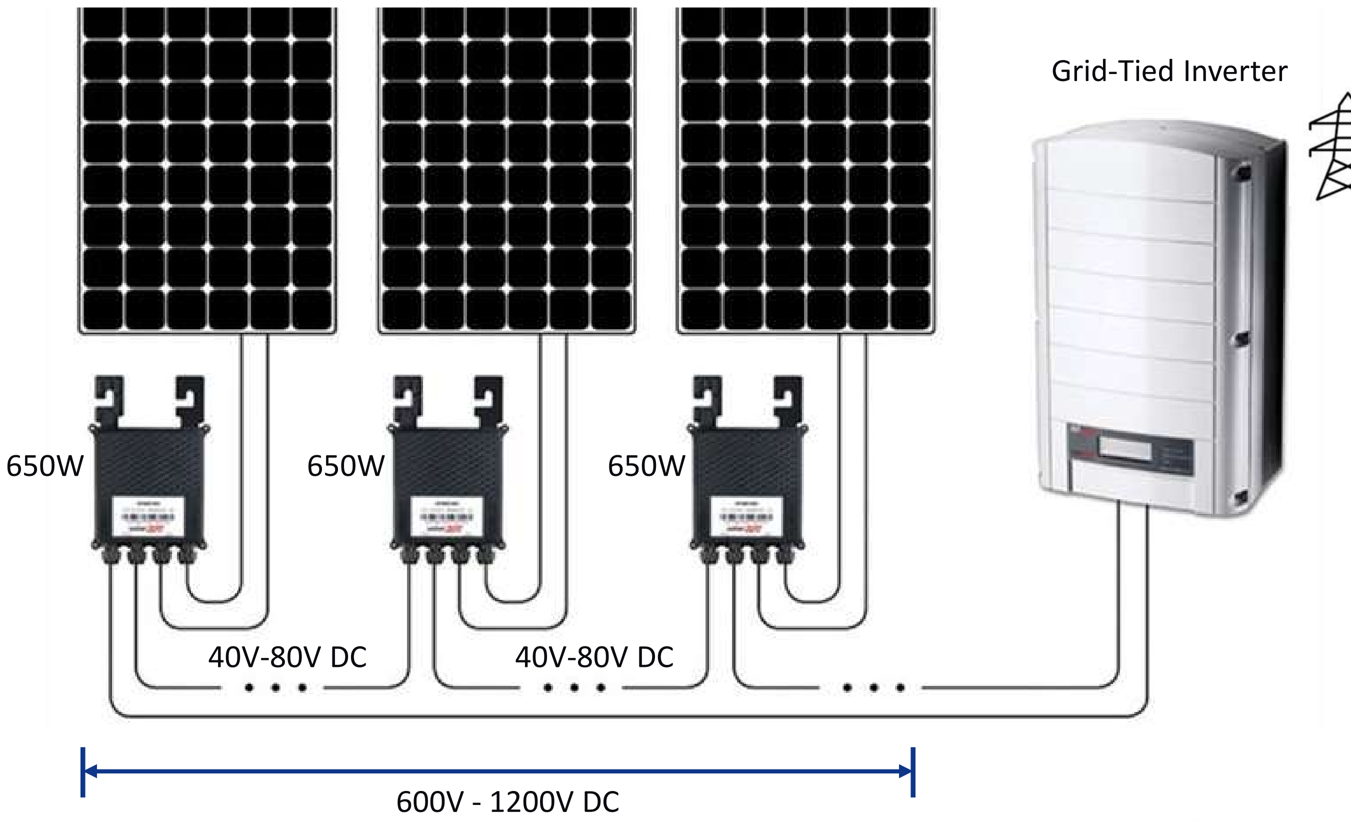
At Startup - enable full-bridge unfolding circuit at Peak of AC cycle as MOSFET body diodes will become forward biased and will charge the flyback output.

In Burst mode, deliver 3x the output power in one AC cycle and then shut down for two AC cycles allowing bulk capacitors to recharge.

PV Optimizer

Maximizing Single Panel Energy Harvest Efficiency

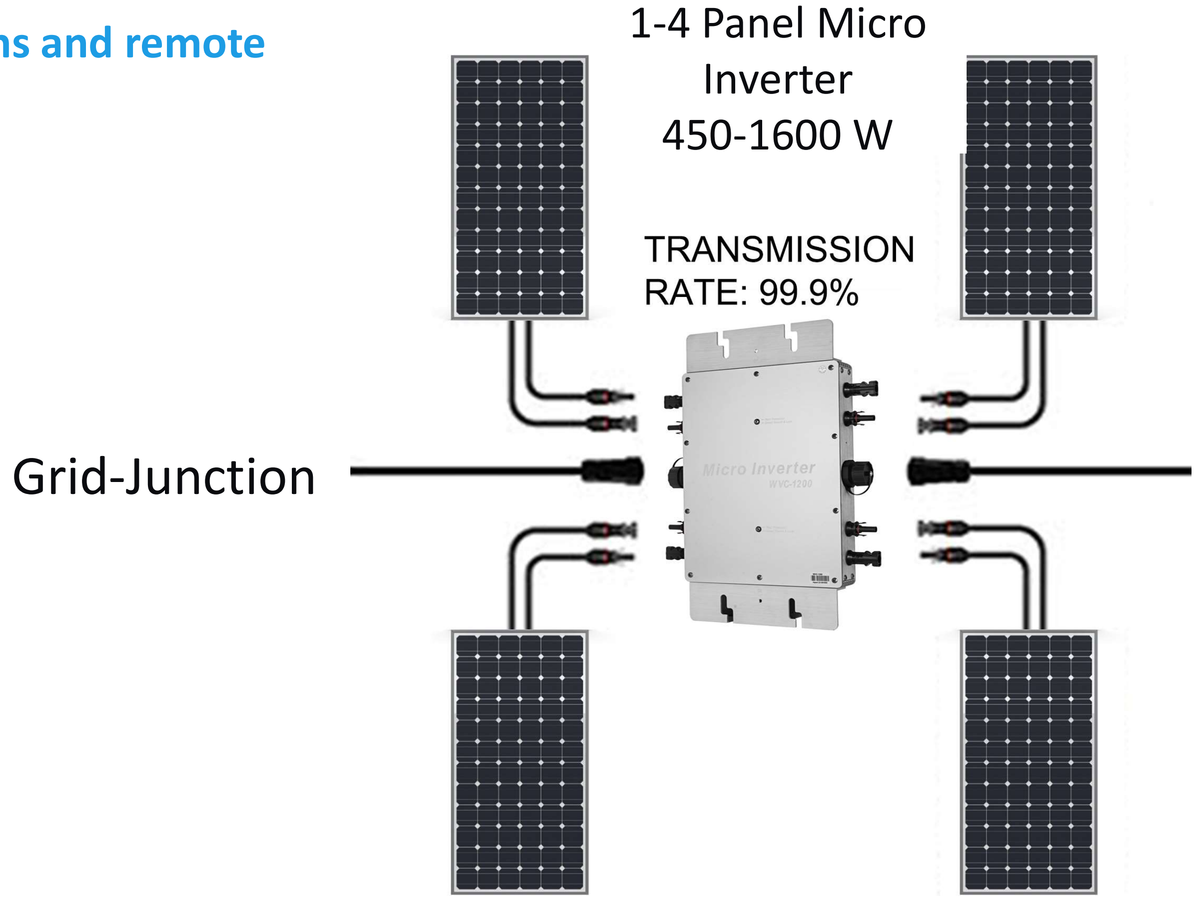
- **Solving partial shading power harvest limitations in series-connected PV panel installations**
- **Total power harvest improvements outweigh additional losses of each optimizer**
- **Most efficient in large scale installations, such as solar farms**
- **Specs:**
  - V_{IN} = 12,5-65 V DC
  - V_{OUT} = 40-80V DC (max.)
  - I_{OUT} = max. 20 A DC (P_{MAX} = 700W)
  - MPPT
  - Peak Efficiency >99%
  - -40° bis +85°C (IP68 – IP72)
  - EMC: FCC Class B (IEC61000-6-2, IEC61000-6-3)
  - Safety: IEC62109-1 (Class II), UL1741



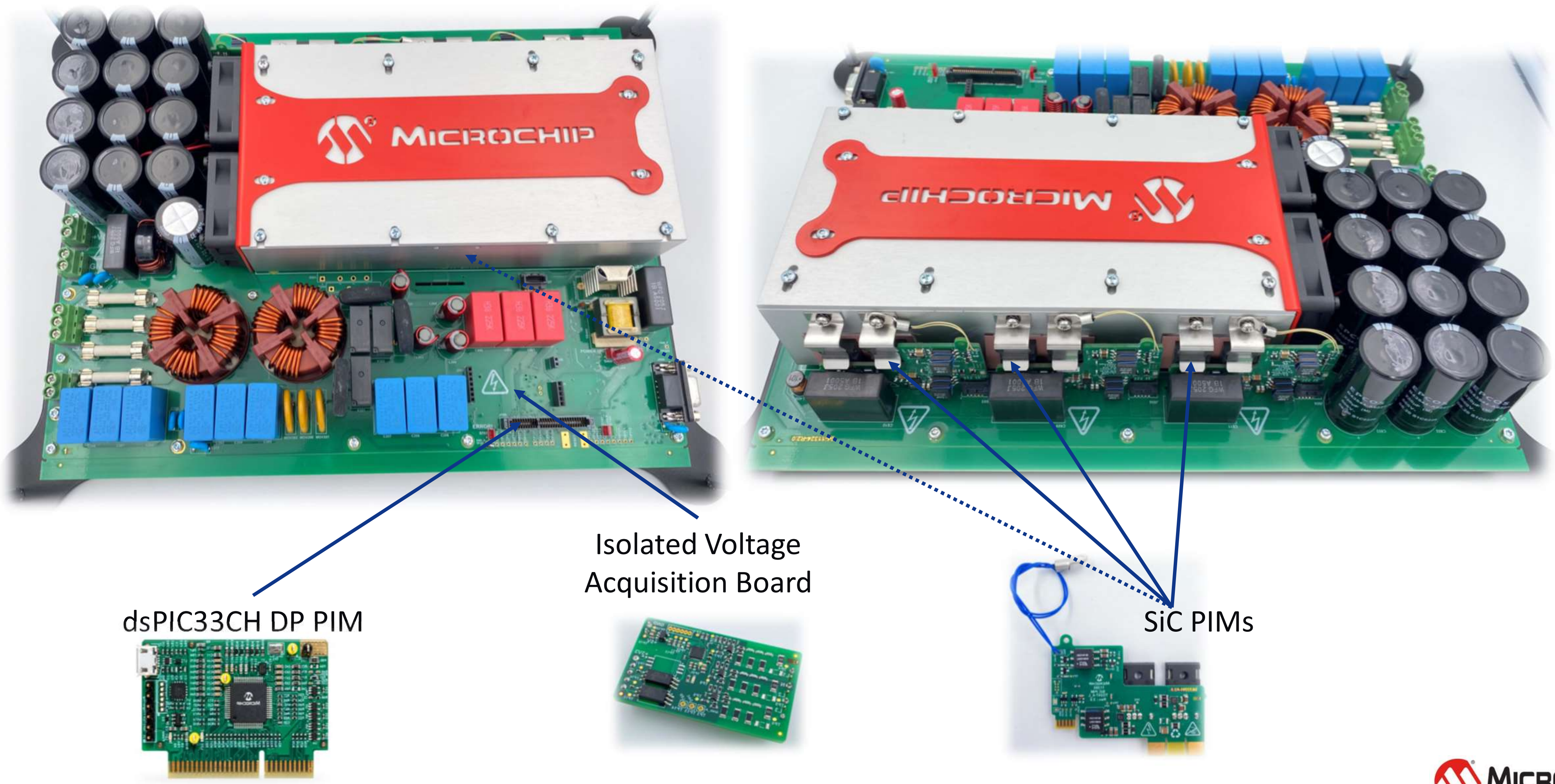
PV Micro Inverter

Enabling Small Scale Installations

- **Most efficient in small scale installations and remote island applications**
- **Two modes:**
  - Grid-tied inverter
  - Island inverter
  - Auto-Detection
- **Output options:**
  - 120V AC / 14A (max)
  - 240V AC / 7A (max)
- **Anti-Island Detection**
- **MPPT**
- **Wireless Metering / Status Monitoring**

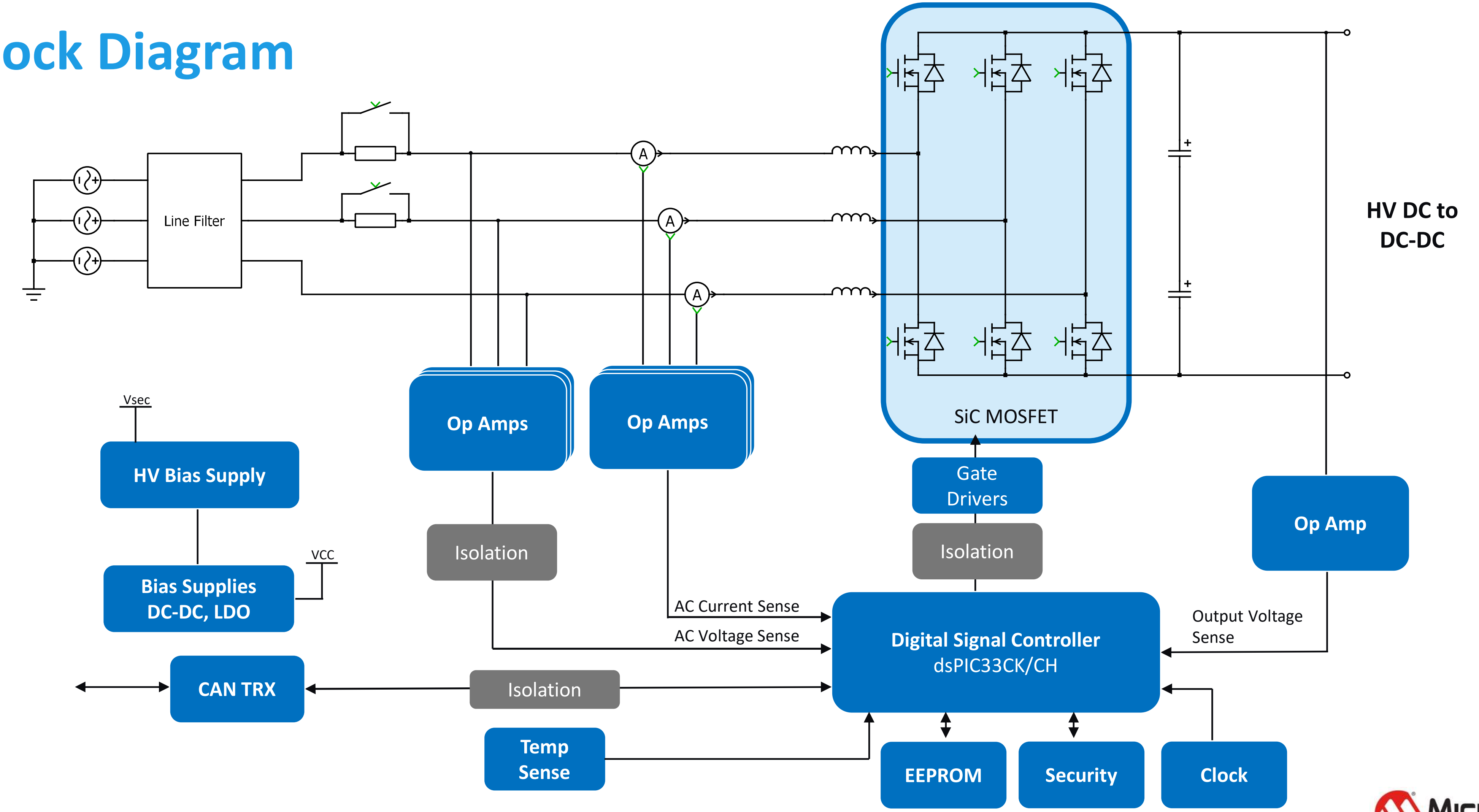


11 kW Bi-directional Totem Pole PFC Demo



11 kW Bi-directional Totem Pole PFC Demo

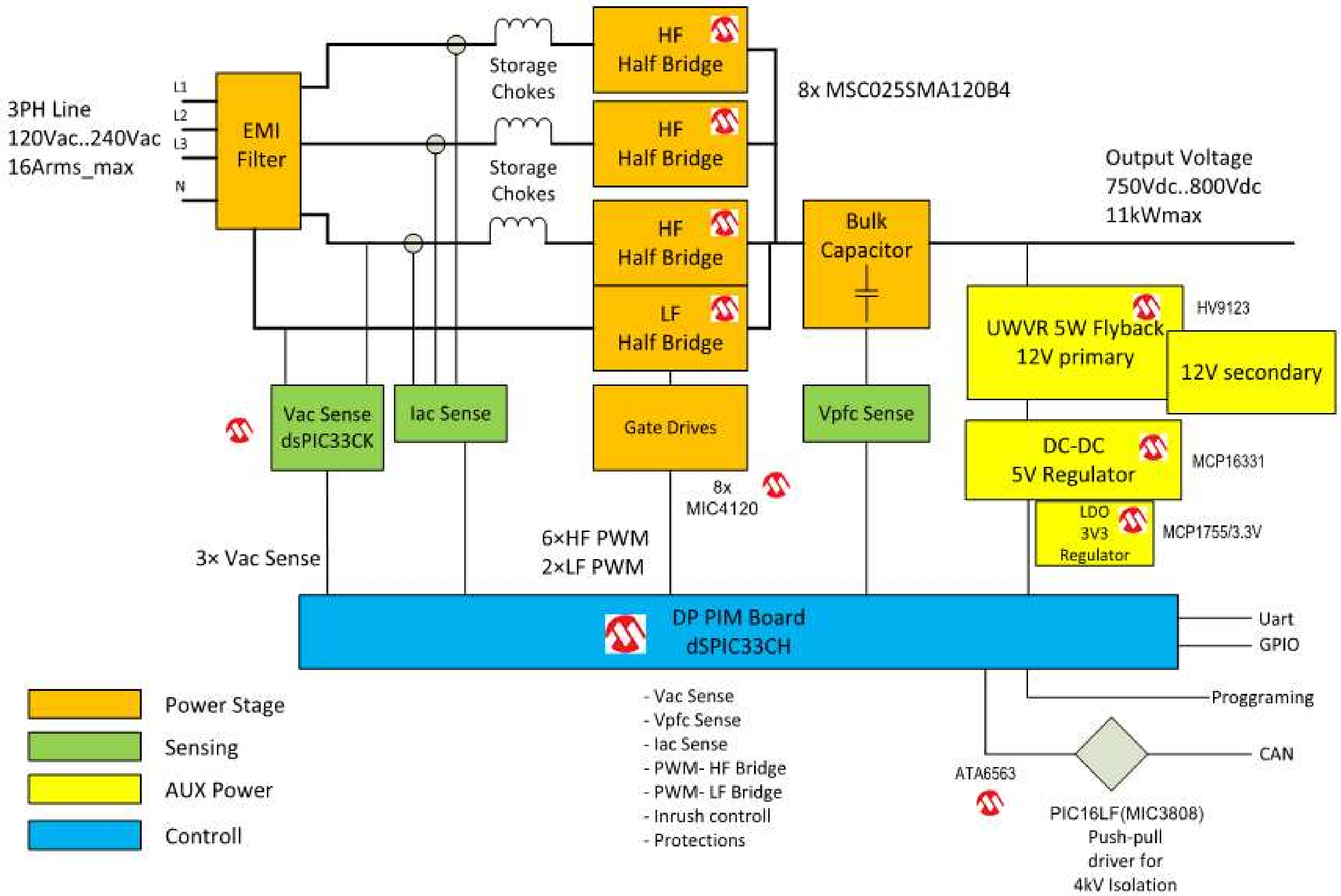
Block Diagram



11 kW Totem-pole PFC Development System

11 kW Totem-pole PFC Features:

- Single- or 3-phase AC source
  - Level 2: 11 kW from 3-phase source
  - Up to 3.6 kW from single-phase
  - Bidirectional operation
- Uses dsPIC33 DP PIMs and new FET PIMs for SiC power MOSFETs
- AEC-Q100 qual'ed components
- Forced-air cooled
- **Development Board available for evaluation**



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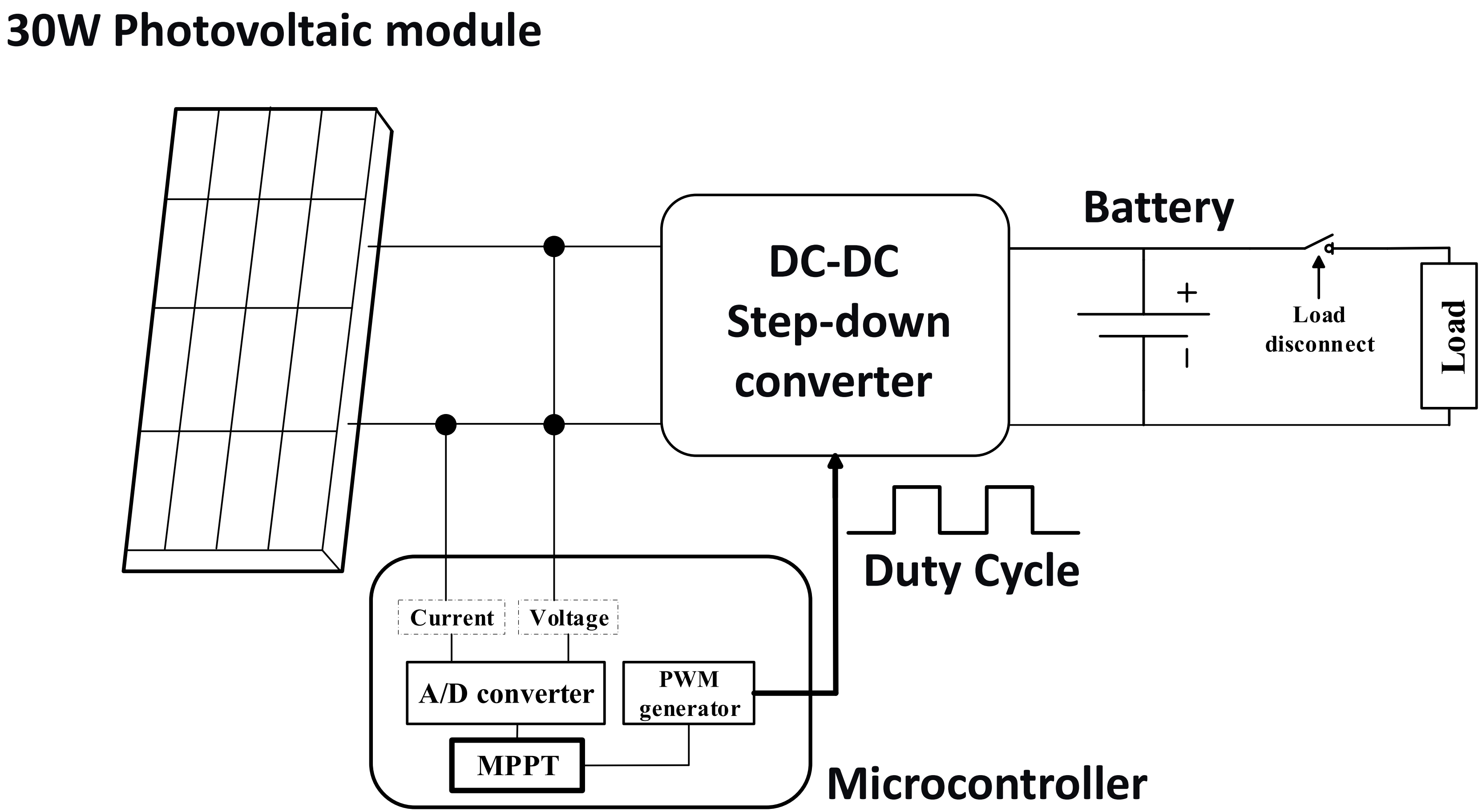
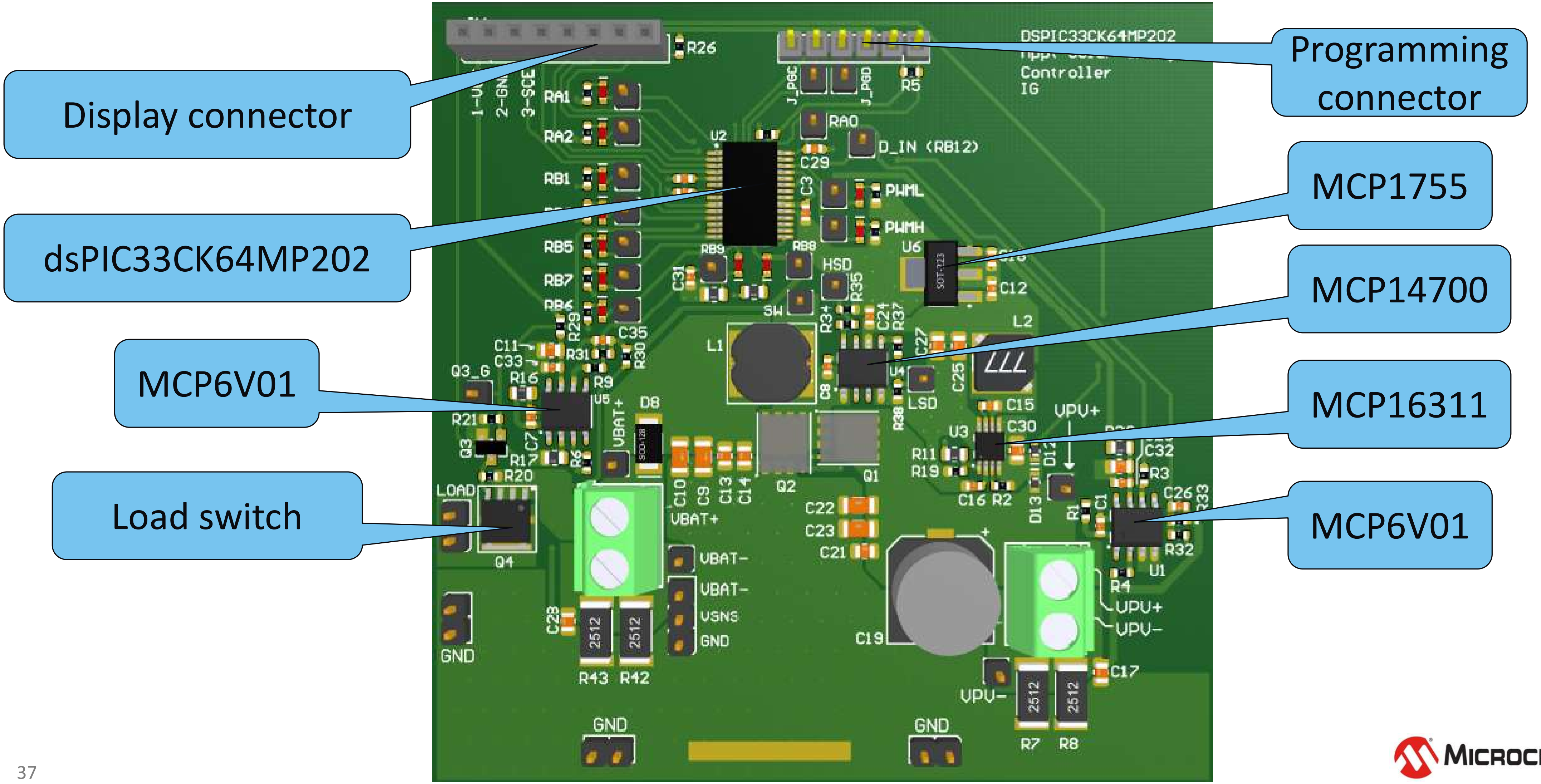
Solar MPPT Battery Charger Demo 1#

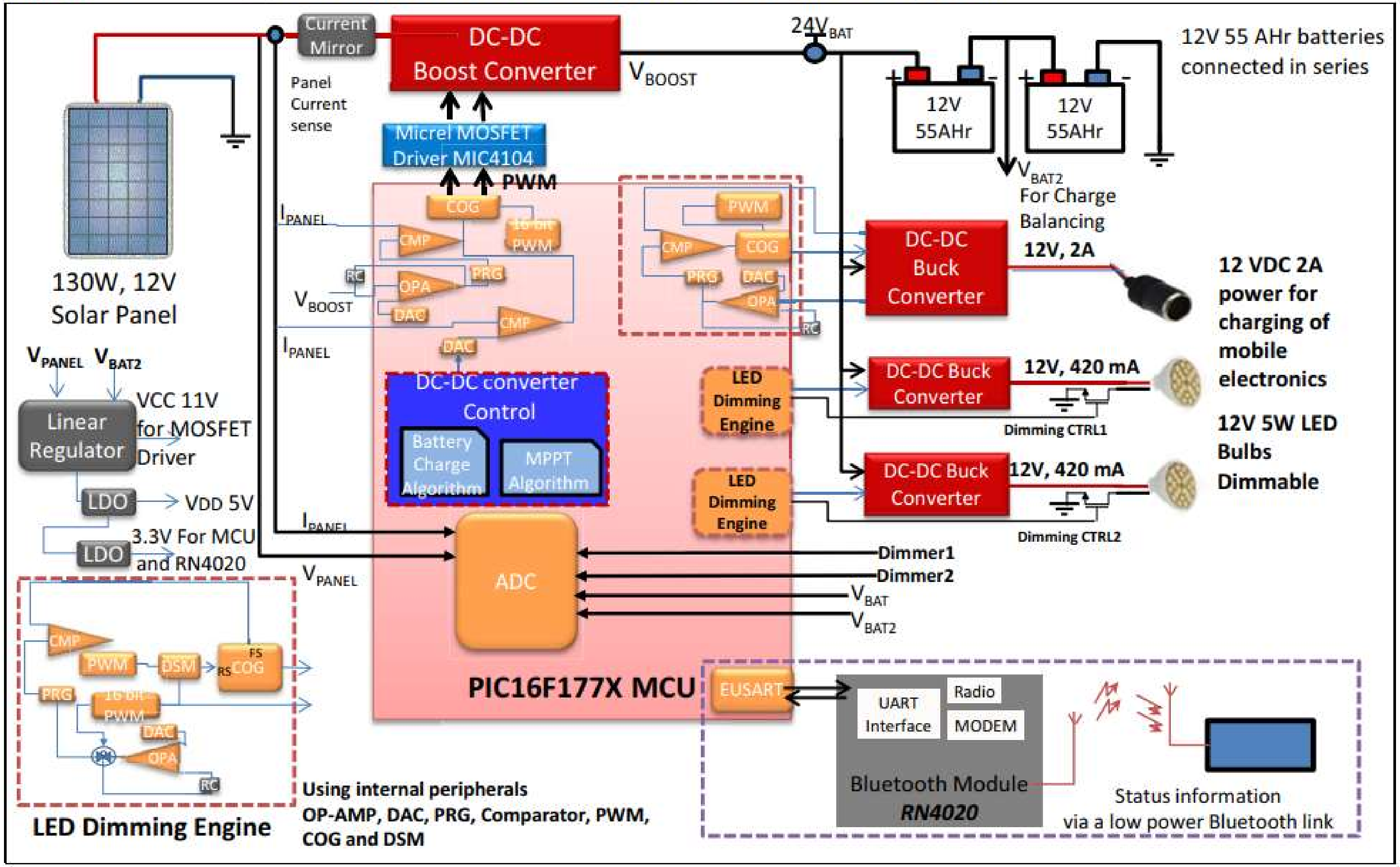


Solar MPPT Battery Charger Demo #1



Solar MPPT Battery Charger Demo #2

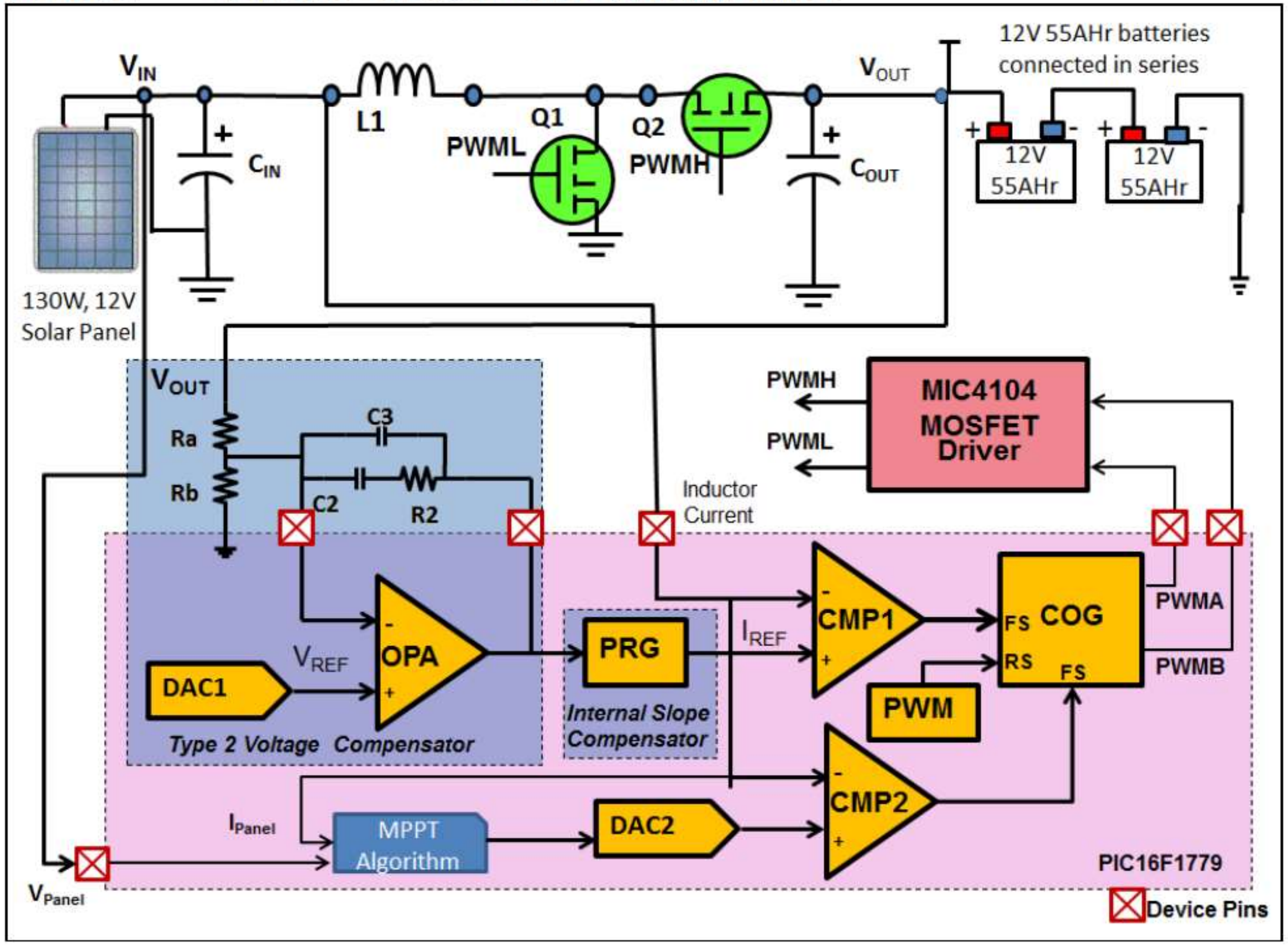
FIGURE 2: SOLAR MPPT BATTERY CHARGER BLOCK DIAGRAM **AN2321**



Solar MPPT Battery Charger Demo #2

AN2321

FIGURE 3: PCMC DC-DC BOOST CONVERTER WITH MPPT



Thank You!!