PV Energy Conversion and System Integration

Dr. Nasser Kutkut
University of Central Florida

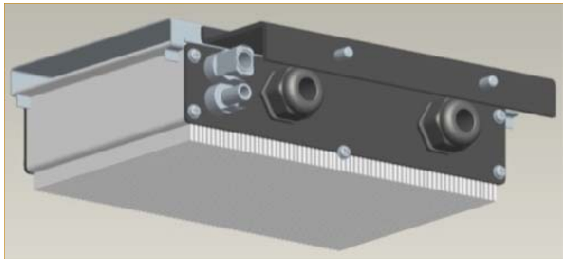
9/29/2009

PV Energy Conversion & Integration

- **Goal:**

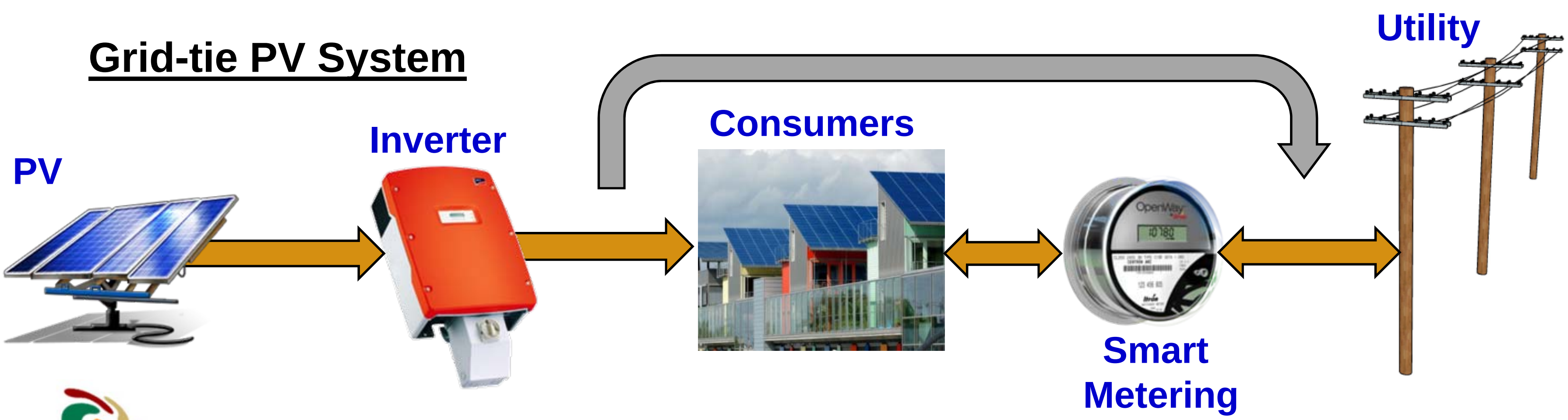
  Develop a ***Plug'N'Gen*** solar power architecture for decentralized, low-cost, mass-produced, PV panel-mounted micro-inverters

- **Tasks:**
  - Low cost and ultra-compact PV inverter packages
  - Advanced digital control algorithms
  - Novel inverter topology and control concepts
  - SmartTie interface with the utility grid
  - **Partners: Petra Solar**
  - **Lead Team: UCF (Florida PEC)**
  - **Budget: $1,267k**



PV Energy Conversion Systems

- **Grid-tie PV Systems**
  - Accounts for ~85% of PV market
  - Do not necessarily need backup energy storage
  - Prices:
    - Solar electricity costs: **21-38 ¢/kWhr**
    - Installation costs: **$5-$9 per peak Watt**



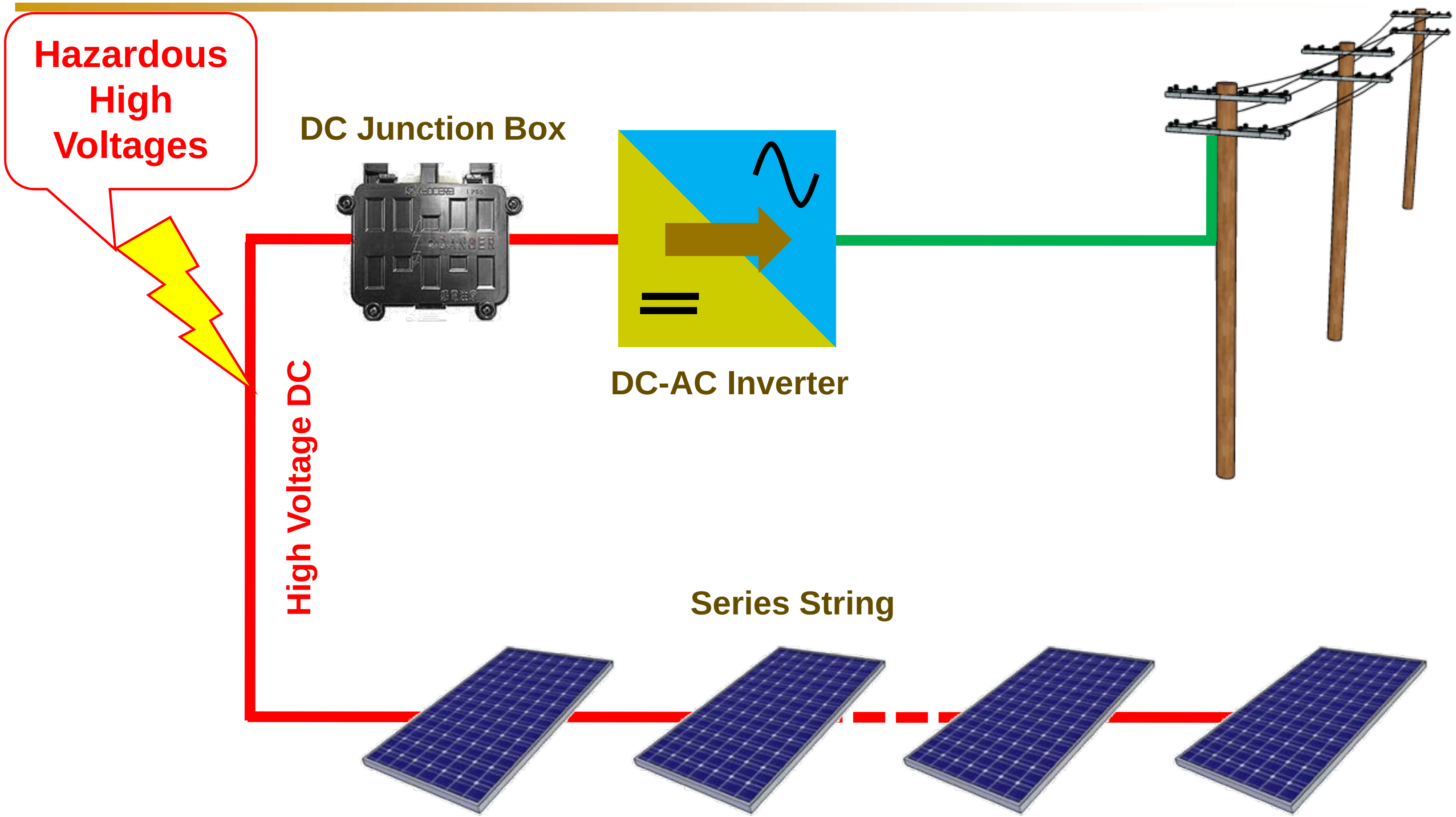
New PV System Architectures

- The inverter technology drives the PV power system architecture

- Presently, the market is dominated by:
  - **String inverter PV systems**
  - **Multi-string inverter systems**

- New PV system architectures can greatly impact overall PV system costs
  - **Micro inverters**
  - **AC PV modules (*Plug'N'Gen*)**

String Inverter PV Systems

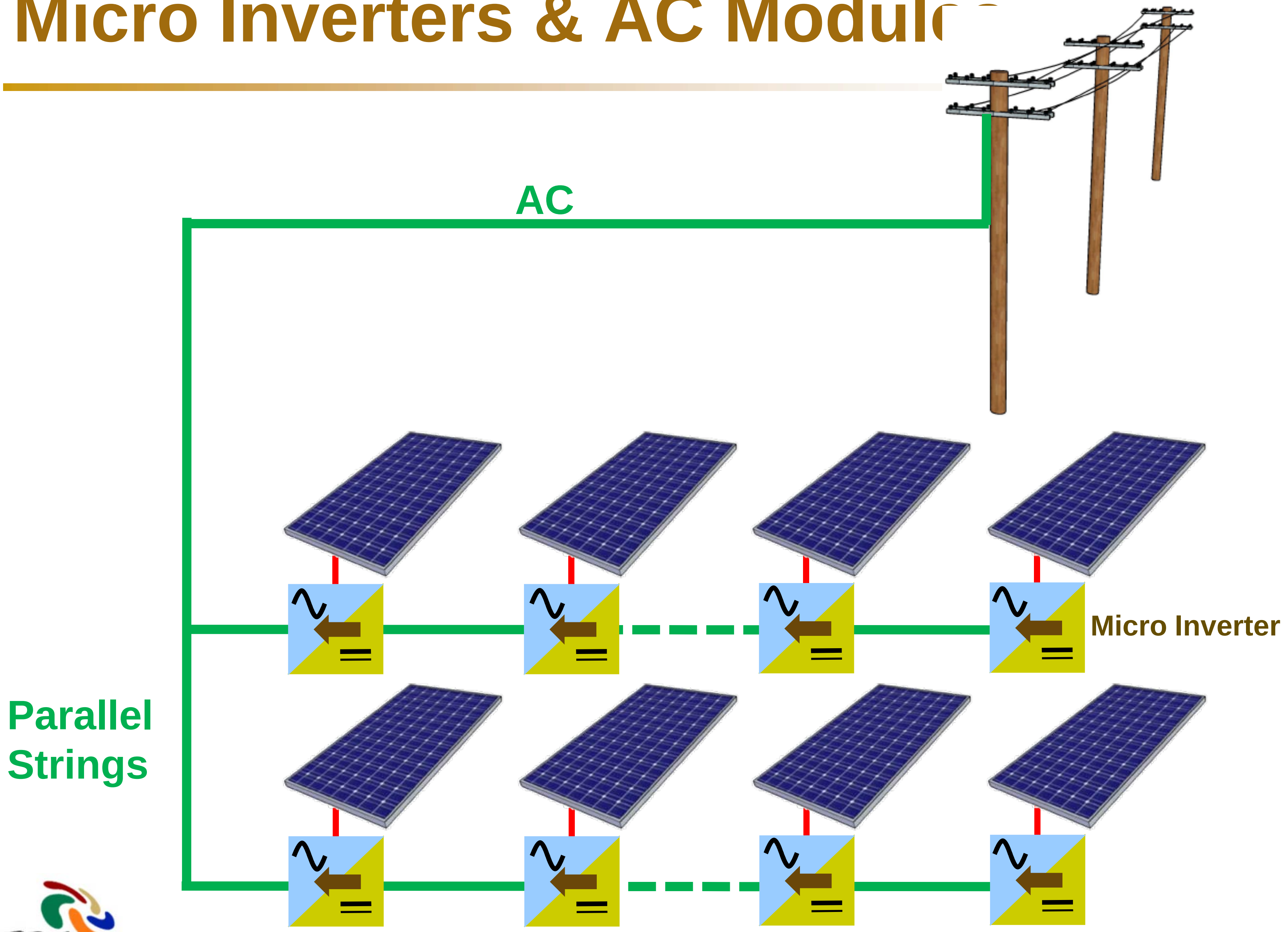


Limitations of String Inverter Systems

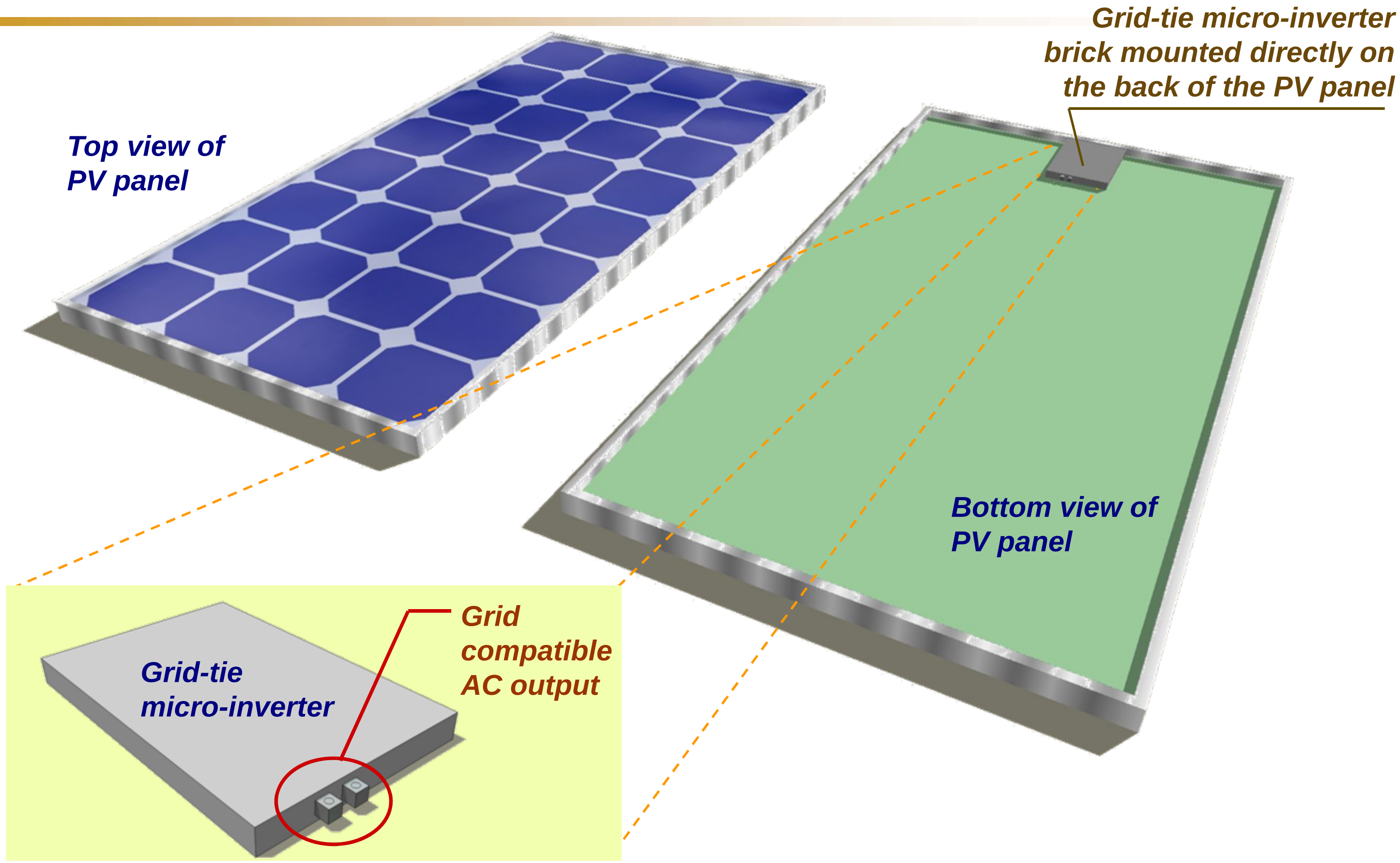
- **Non-flexible architecture**
  - Fixed size systems
  - Single point of failure (inverter)
- **Single MPPT process**
  - Susceptible to single panel damage / shading
- **Hazardous**
  - High-voltage strings → Arcing potential
- **Complex system design**
  - String sizing; module matching: direction, shading, ageing
- **Costly Installation**
  - Special installation codes and procedures; certified installers
  - DC disconnects and wiring conduit

FESC
Florida Energy Systems Consortium

Micro Inverters & AC Modules



AC PV Module



No DC wiring, disconnects, and bypass diodes
True plug-n-play system

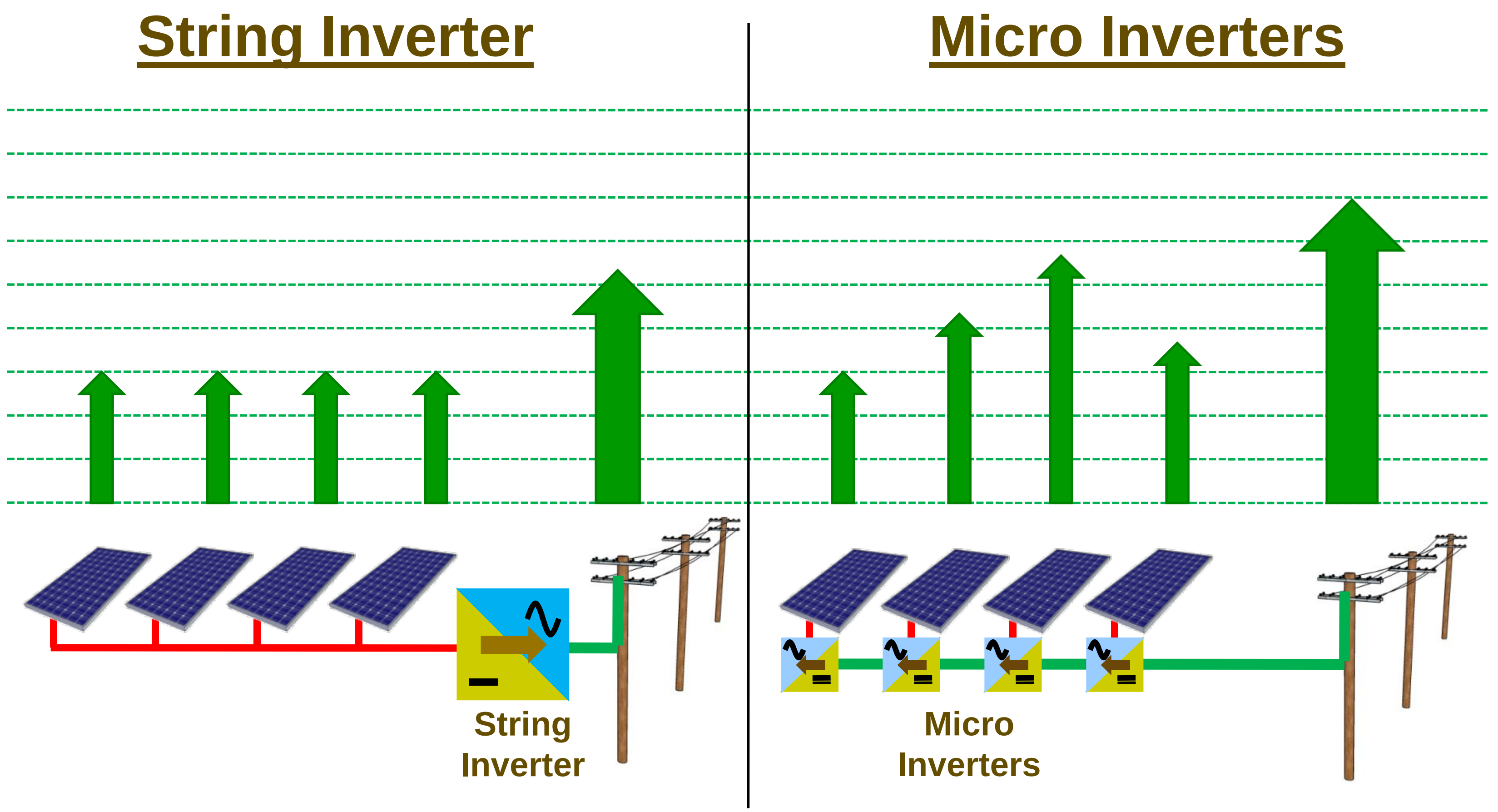
FESC
Florida Energy Systems Consortium

AC PV Module Features

- ***Plug'N'Gen* Installation & Operation**
    - Simple installation → Installable by any electrician / consumer - DIY
- **Lower Acquisition & Installation Costs**
    - No special wiring or installation procedures
    - No DC wiring, DC disconnects, DC fuses, bypass diodes, …
- **Single Panel MPPT process**
    - Optimal energy harness from each panel
- **Redundant Operation**
    - No Single Point Failure
- **Very Safe**
    - No high voltage DC → No accessible DC wiring
    - Automatically disconnects once the main power switch is turned off

Increased Energy Harvest

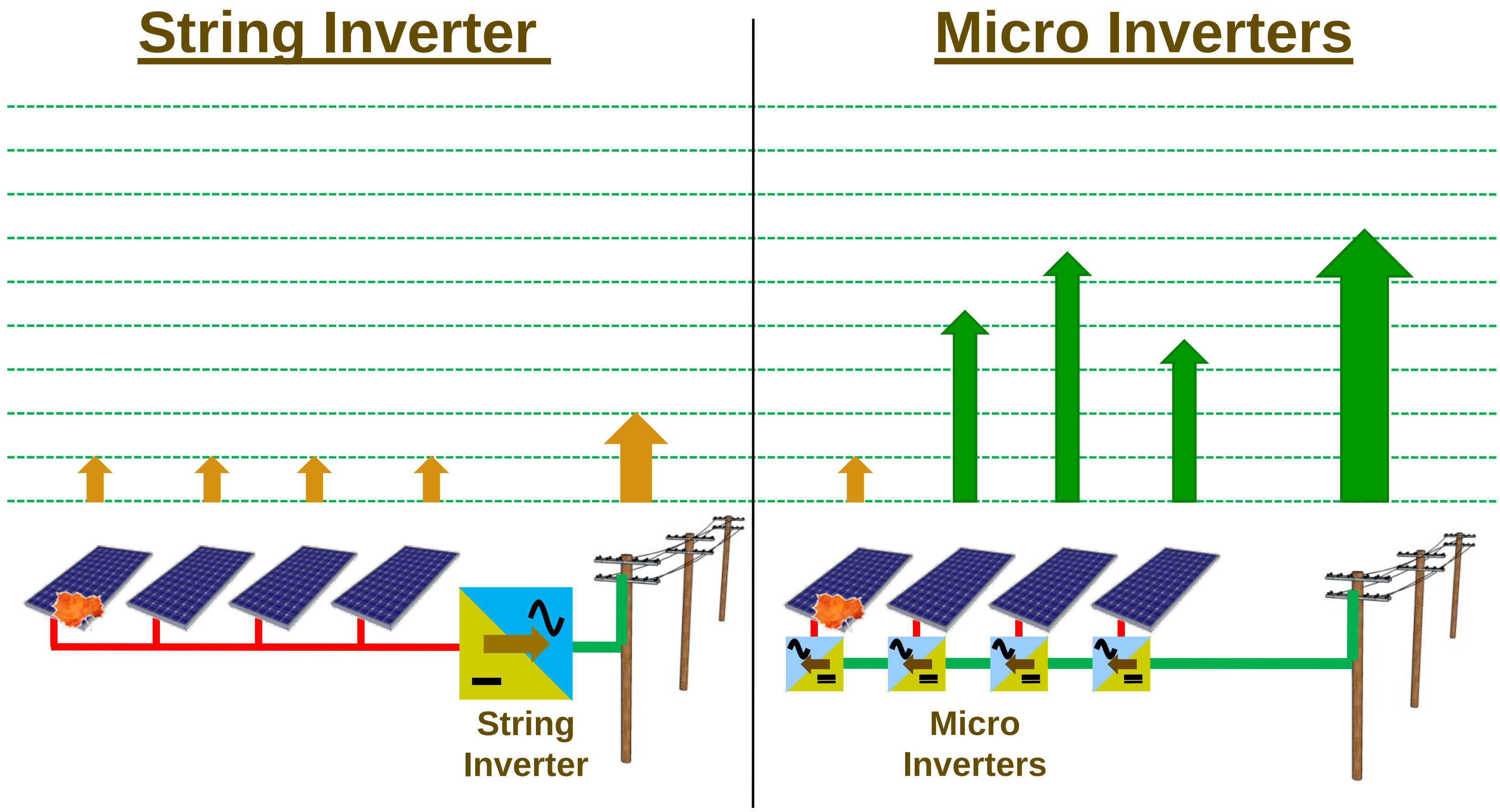
No Shading



Micro inverters can realize upwards of 20-25% increased energy harvest

Increased Energy Harvest

With Shading



With string inverters, shading can reduce string output by 10% to 50%

Project Tasks

I. **Advanced Digital Control**
   - Optimal pulse skipping control to improve light load efficiency

II. **System Integration**
   - Integration & packaging of DC/DC & Magnetics
   - Thermal modeling & design

FESC
Florida Energy Systems Consortium

Advanced Digital Control

- New advanced digital control techniques were developed to improve solar inverters' efficiency

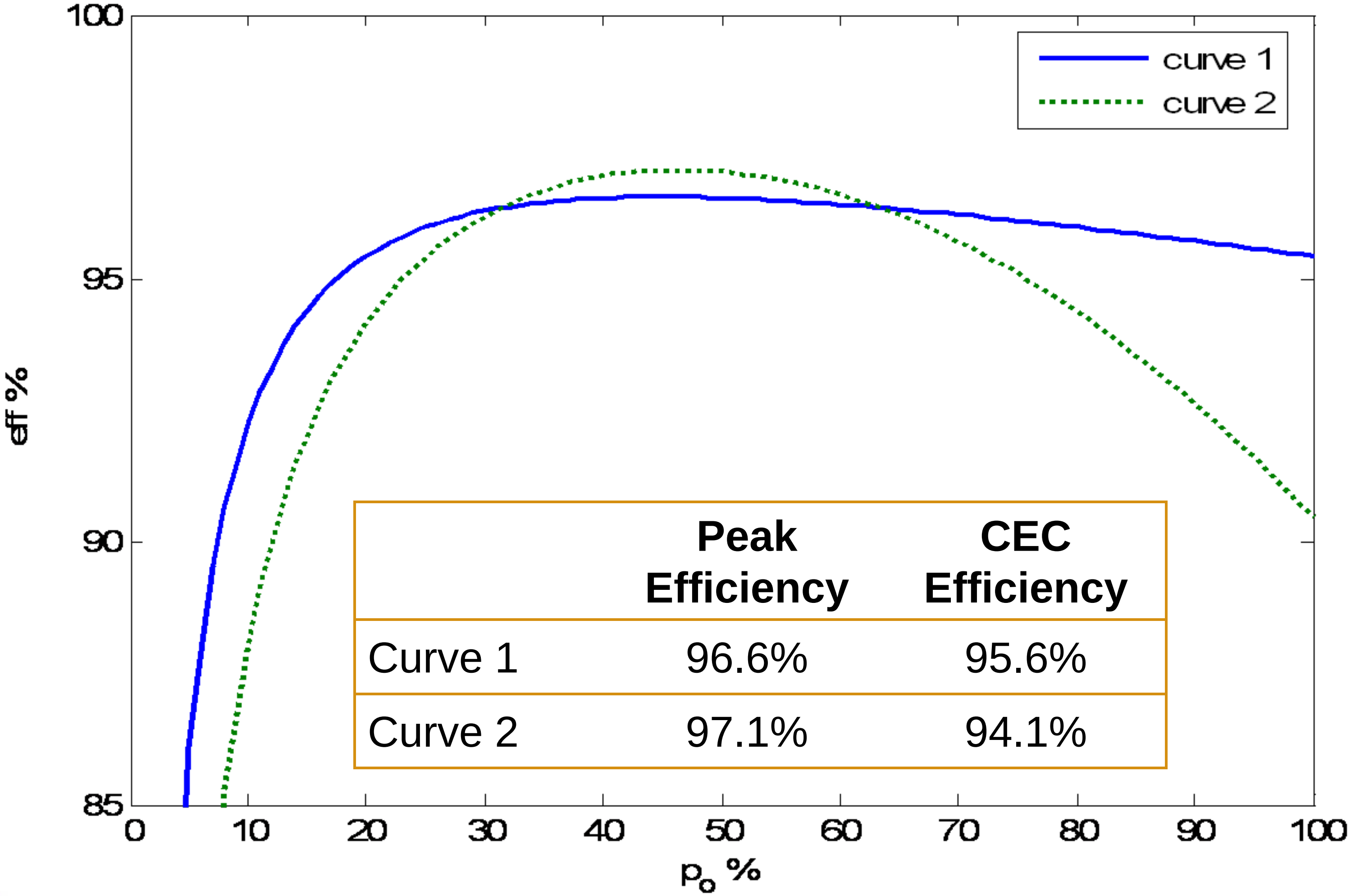
- **Background**
  - The California Energy Commission (CEC) efficiency is a weighted efficiency given by:

$$\eta_{CEC} = 0.04 \cdot \eta_{10\%} + 0.05 \cdot \eta_{20\%} + 0.12 \cdot \eta_{30\%} + 0.21 \cdot \eta_{50\%} + 0.53 \cdot \eta_{75\%} + 0.05 \cdot \eta_{100\%}$$

  - Maximizing the CEC efficiency necessitates a flat efficiency curve

FESC
Florida Energy Systems Consortium

Efficiency Optimization

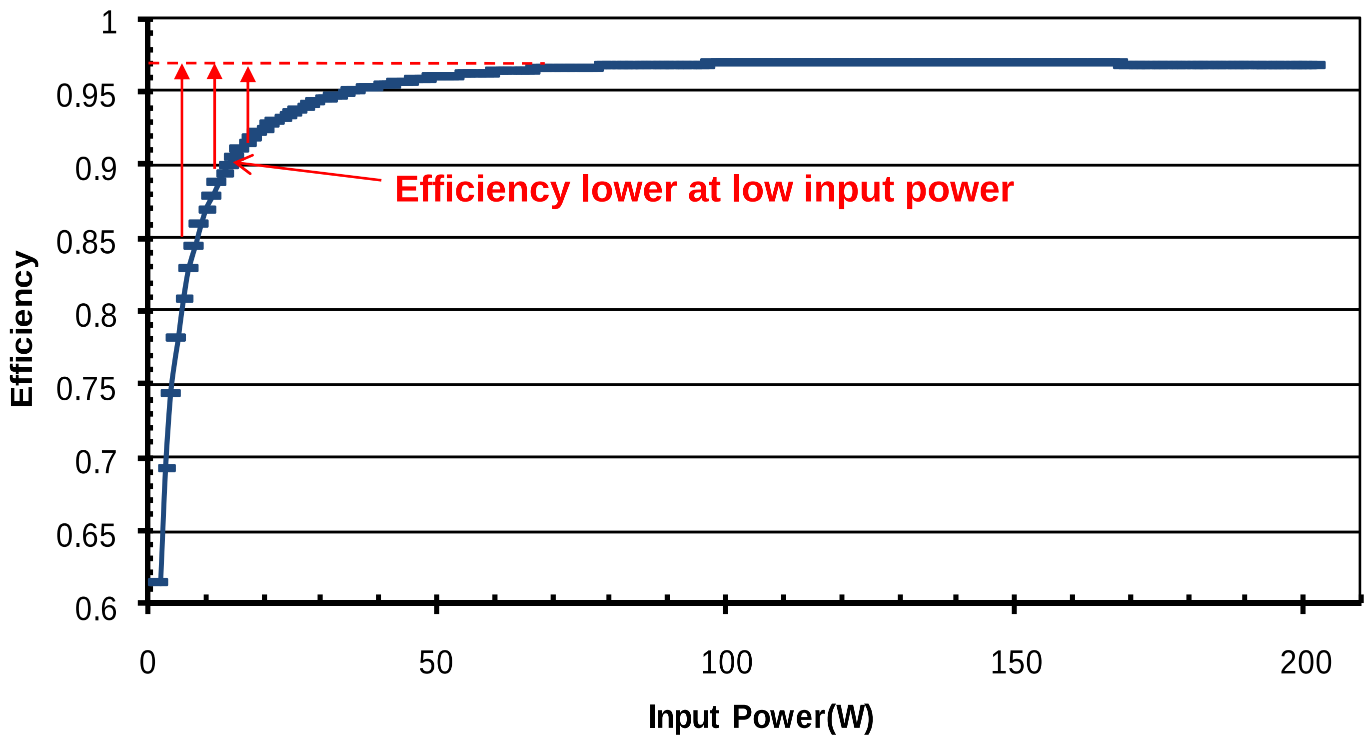


	Peak Efficiency	CEC Efficiency
Curve 1	96.6%	95.6%
Curve 2	97.1%	94.1%

FESC
Florida Energy Systems Consortium

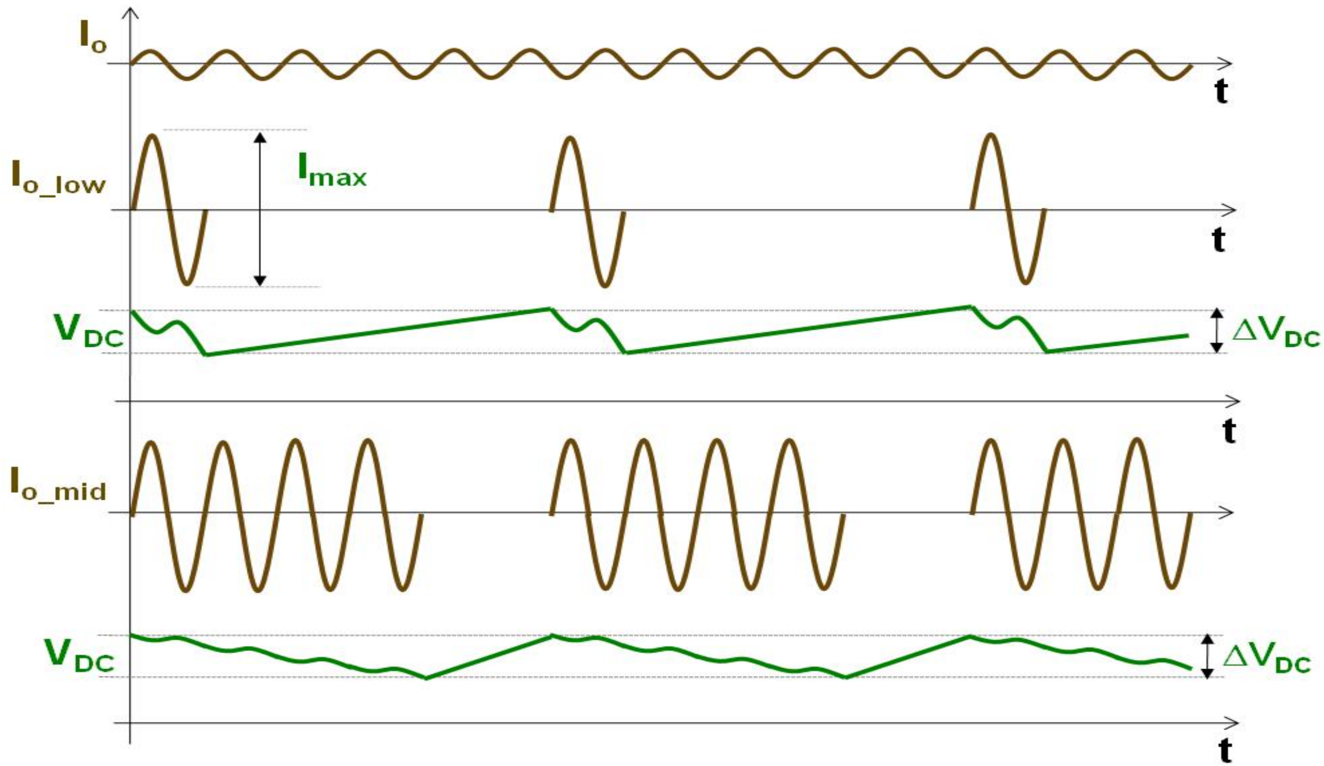
Efficiency Optimization

- For solar inverters, at low insolation levels (low input power) the inverter efficiency drops dramatically
  - **Reduces CEC efficiency**
  - **Need to improve the efficiency at low input power**



Pulse Skipping Strategy

- **Goal:** Improve light load & CEC efficiency
- **Approach:** Store energy from PV in DC bus capacitor then deliver it to the grid at the maximum efficiency point

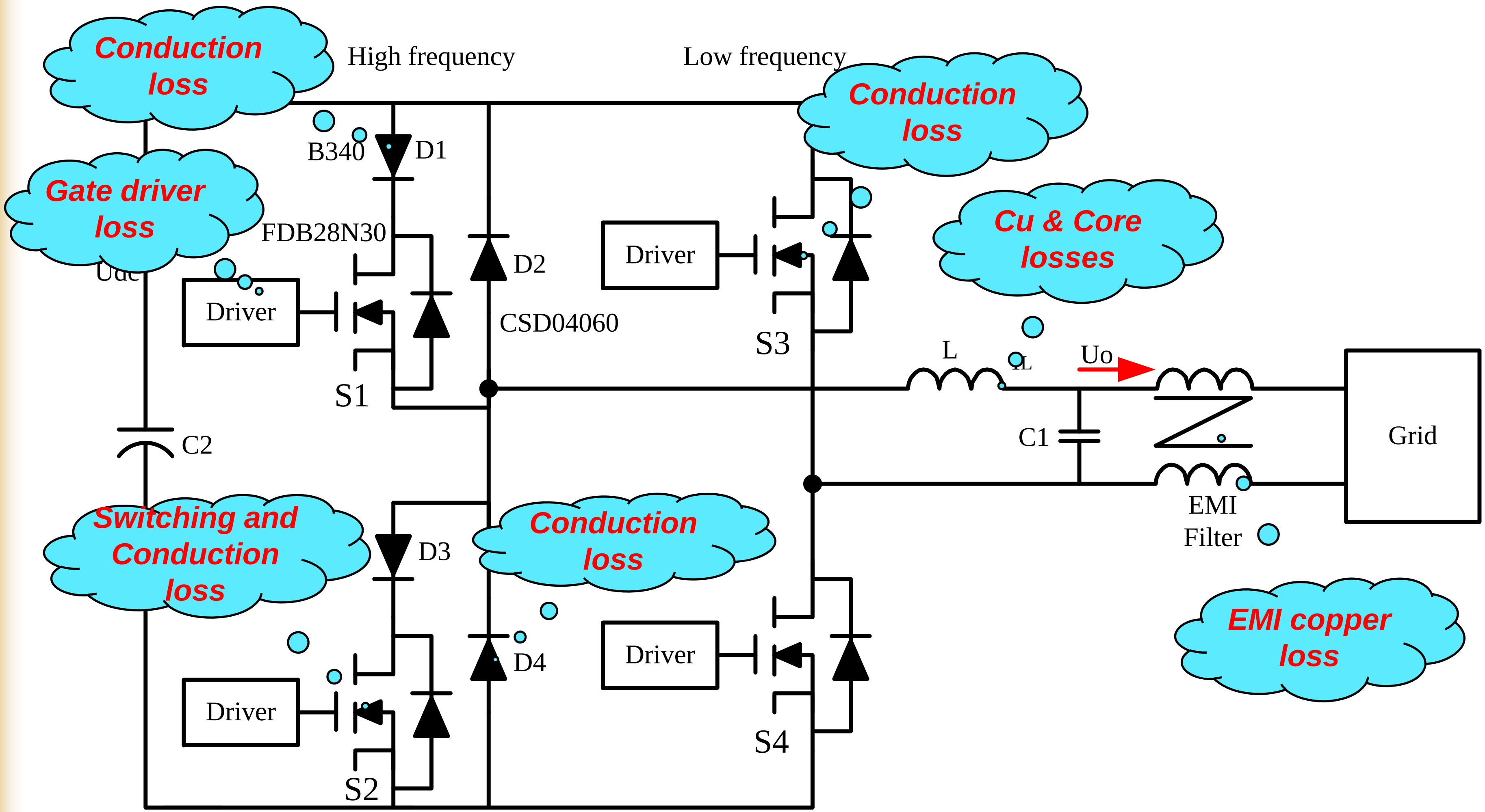


FESC
Florida Energy Systems Consortium

Optimal Pulse Skipping Control

- **Pulse skipping control strategy development**
  - Mathematical loss model
  - Model verification
  - Optimization for pulse skipping
  - Simulation results
  - Experimental verification

Loss Model Derivation



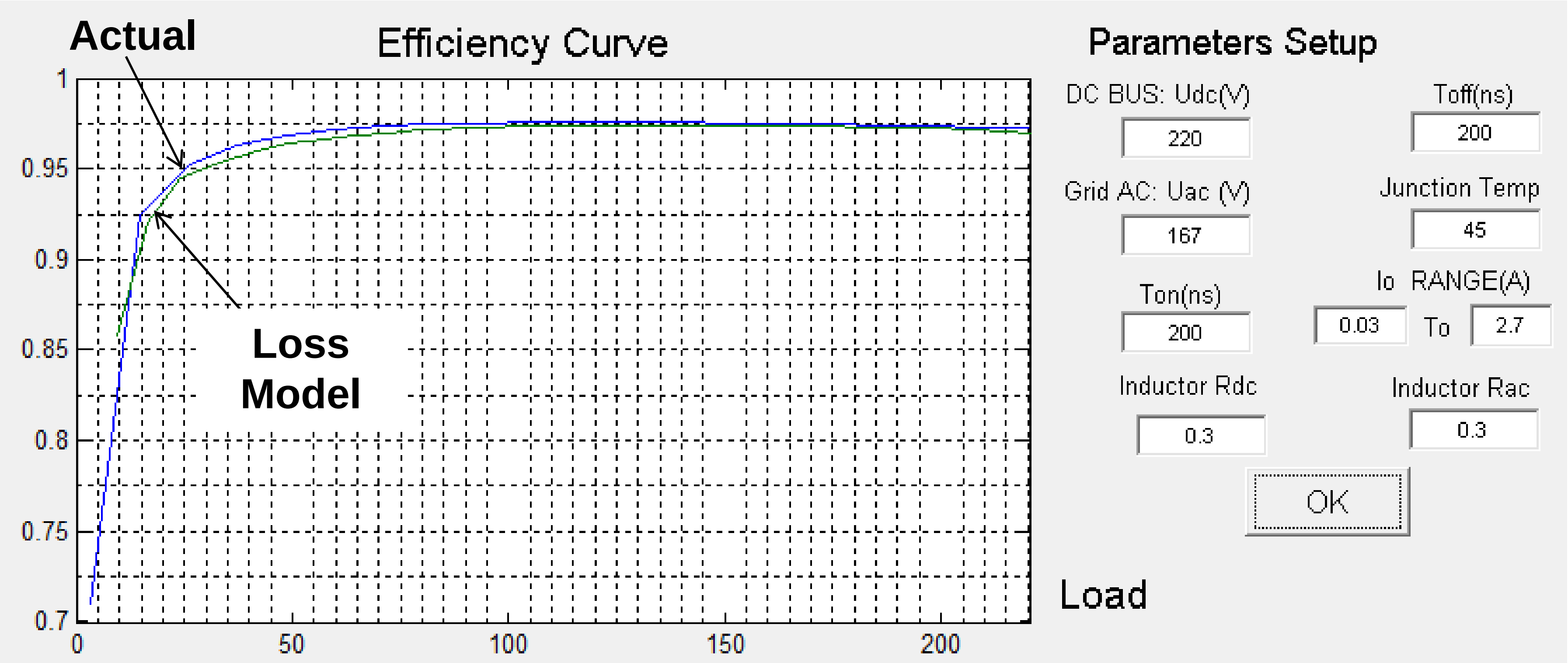
Loss Model Derivation

Component	*Items*	*Mathematical expression*
Mosfet	Conduction Loss	$P_{conduction\_loss} = R_{on} \times I_{RMS}^2$
	Switching loss	$P_{switch\_loss} = \frac{1}{2} C_{oss} U_{dc}^2 f_s + (C_{oss} + C_d) U_{dc}^2 f_s + \frac{1}{4} U_{dc} I_L t_{on} f_s$ when $I_L > I_s$ $P_{switch\_loss} = \frac{1}{2} C_{oss} U_{dc}^2 f_s + (C_{oss} + C_d) U_{dc}^2 f_s + \frac{1}{2}((C_{oss} + 2C_d)(U_{dc} - \frac{I_L t_{deadtime}}{(C_{oss} + 2C_d)})^2) f_s$ $+ \frac{1}{4} U_{dc} I_L t_{on} f_s$ when $I_L < I_S$
	Driving loss	$E_{charge} = \frac{1}{2} Q_g V_{gs}$ $P_{charge} = E_{charge} f$
Driver IC	Quiscent loss	$P_{driver\_loss} = I_{quiscent} U_{auxillary}$
Inductor losses	Core loss	$P_{core\_loss} = P_V \times core \quad volume(mm^3)$
	Rdc loss	$P_{Rdc} = R_{dc} I_{RMS}^2$
	Rac loss	$P_{Rdc} = R_{dc} I_{ac\_RMS}^2$
Sic diode	Forward conduction loss	$P_{Sic\_D} = \frac{1}{T_S} \int_{t0}^{t1} I_0 U_{Sic\_d} dt = D I_o U_{Sic\_d}$
	Reverse recovery loss	0
Diode	Forward conduction loss	$P_{Schoktty\_D} = \frac{1}{T_S} \int_{t1}^{t2} I_0 U_{Schoktty\_d} dt = (1-D) I_o U_{Schoktty\_d}$
EMI filter	Copper losses	$P_{EMI} = R_{EMI} I_{RMS}^2$

FESC
Florida Energy Systems Consortium

Model Verification

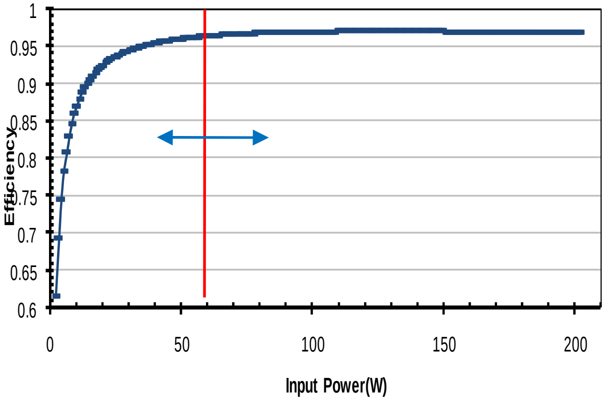
- Mathematical model was verified against an actual micro inverter

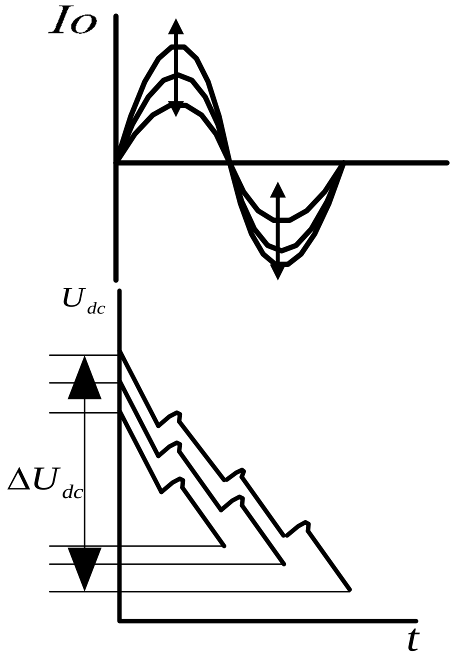


FESC Florida Energy Systems Consortium

Pulse Skipping Parameters

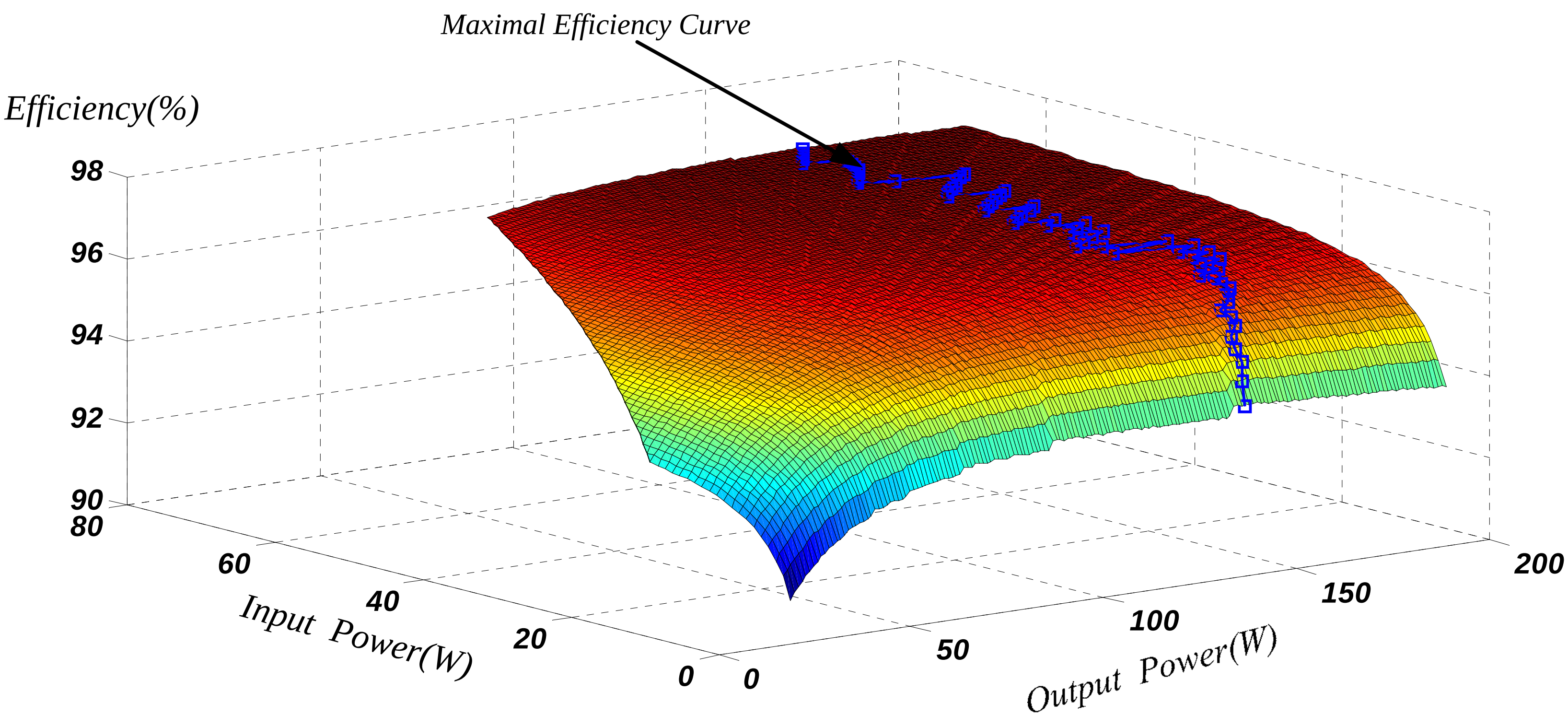
- **Power level to start pulse skipping**
- **Power level of pulse**
- **Optimal DC voltage ripple**





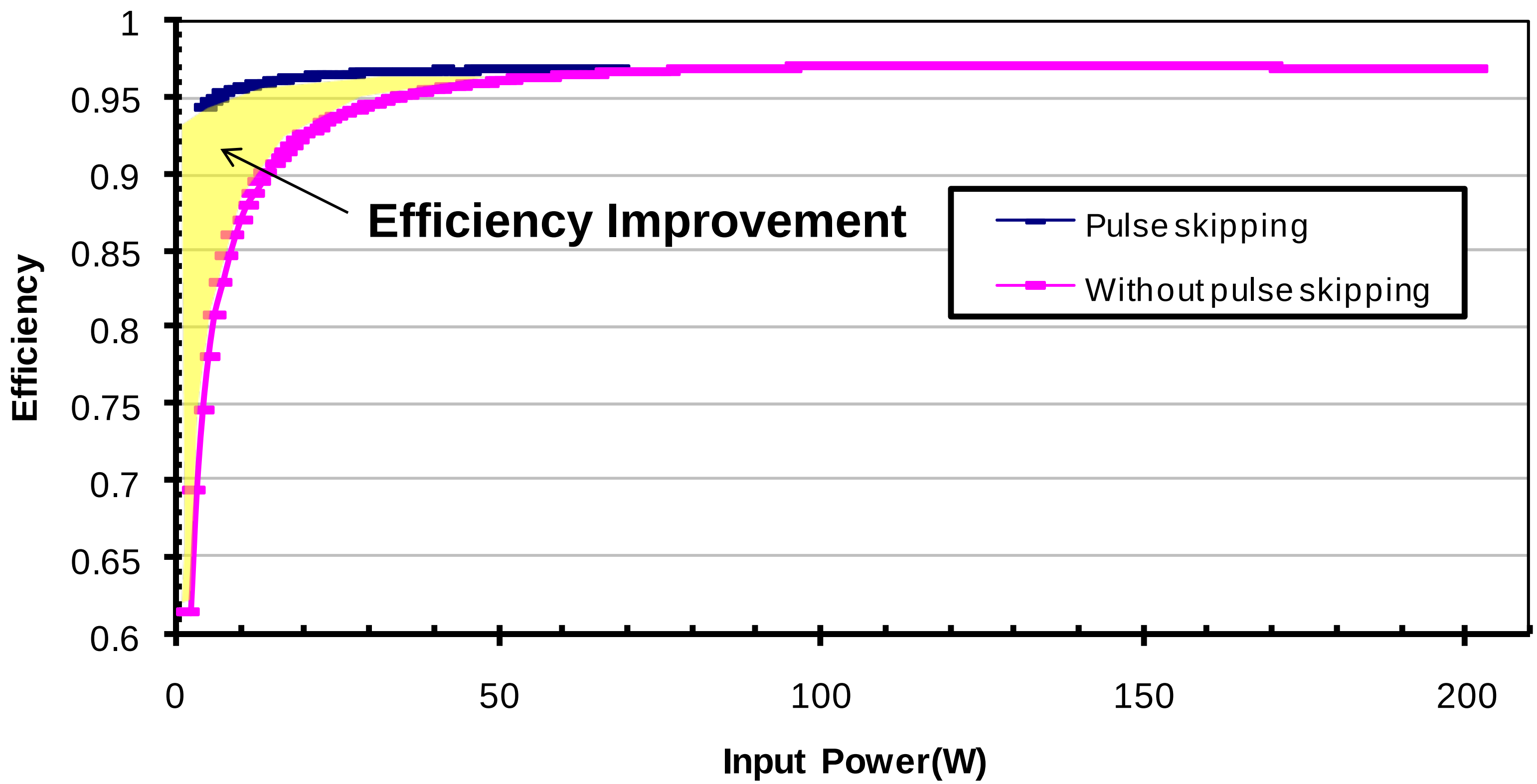
FESC
Florida Energy Systems Consortium

Optimization Results



- Optimum Power Level to Start Pulse Skipping: **70W**
- Optimum Pulse Power: **150W**
- Optimum DC Voltage Ripple: **Insignificant**

Efficiency Improvement



At a pulse power level of pulse 150W

FESC
Florida Energy Systems Consortium

Efficiency Improvement

- CEC efficiency can be improved by 0.5%-1% using newly develop digital control schemes
  - No cost impact on AC module
  - Maximized energy output at low insolation levels