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A New Concept in the Electronics Processing of the Photovoltaic Solar Energy

Federal University of Santa Catarina
Power Electronics Institute - INEP

Denizar Cruz Martins

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A Single-Phase Grid-Connected PV System with Active and Reactive Power Control
(Optimization of the Ferrite Core Volume)

Federal University of Santa Catarina
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Introduction

- Method to minimize losses and magnetic cores volume in a Single-Phase Grid-Connected PV System.

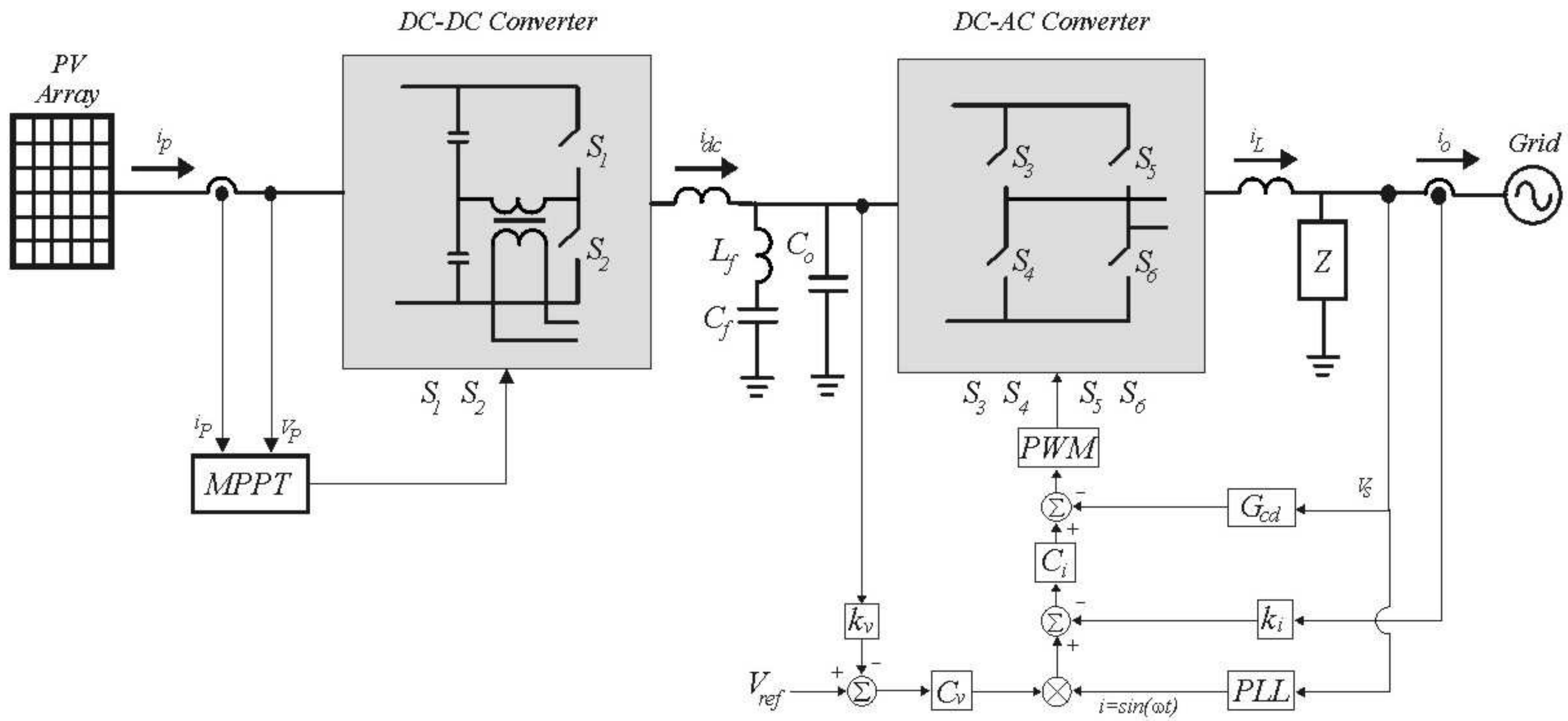
- The circuit injects PV generated power into the Utility, and acts as an Active Filter to Compensate Reactive Power;

- Independently of the Solar Radiation and the type of the Load Connected.

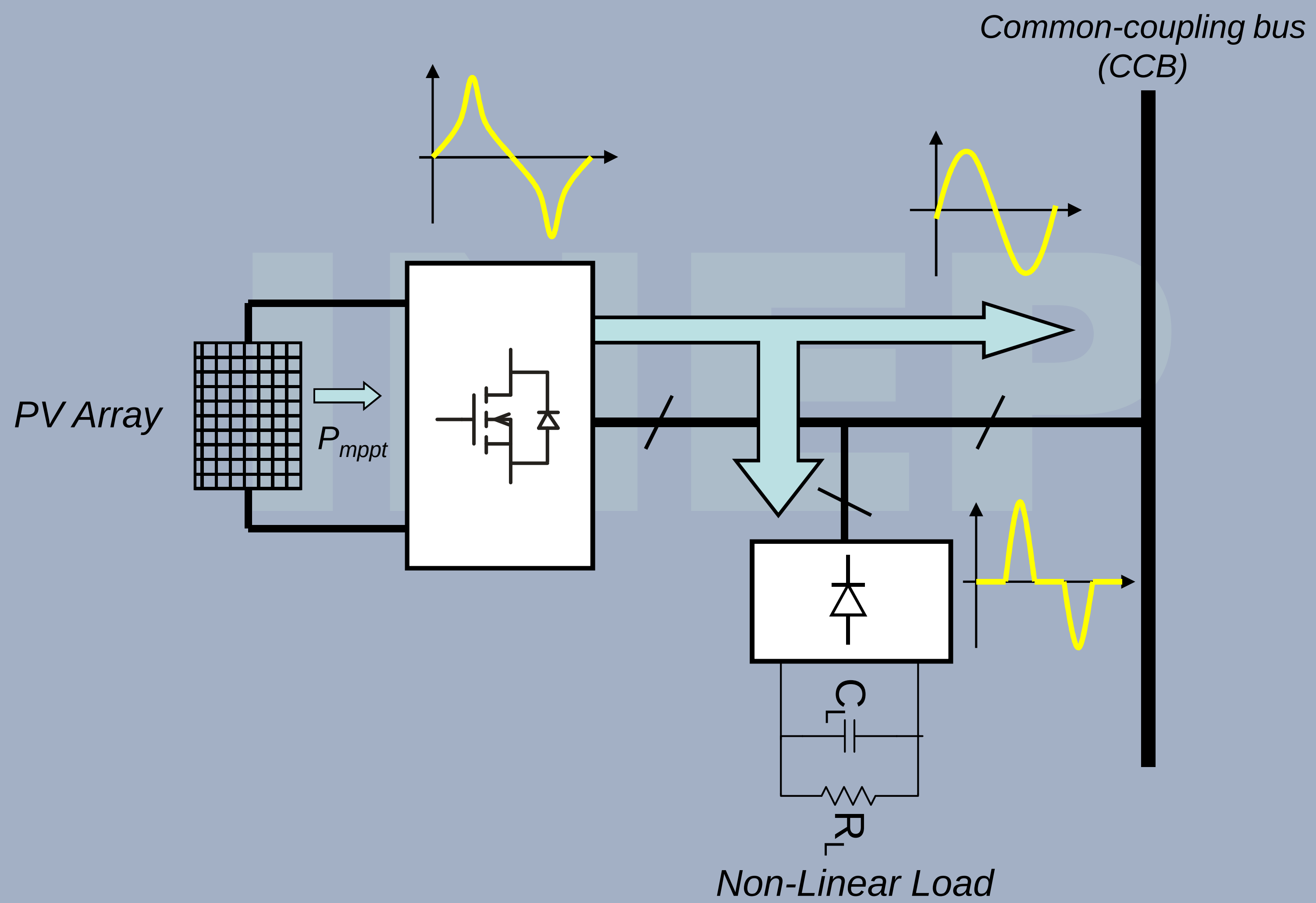
Introduction

- The PV energy conversion system is controlled so as to supply power to the load and supply power with a unity power factor to the utility line;
- The structure is a two stages power system;
- The efforts in the study of the structures used in the first stage were focused in characteristics like high efficiency, galvanic isolation, robustness, facility to control and MPPT.

System configuration



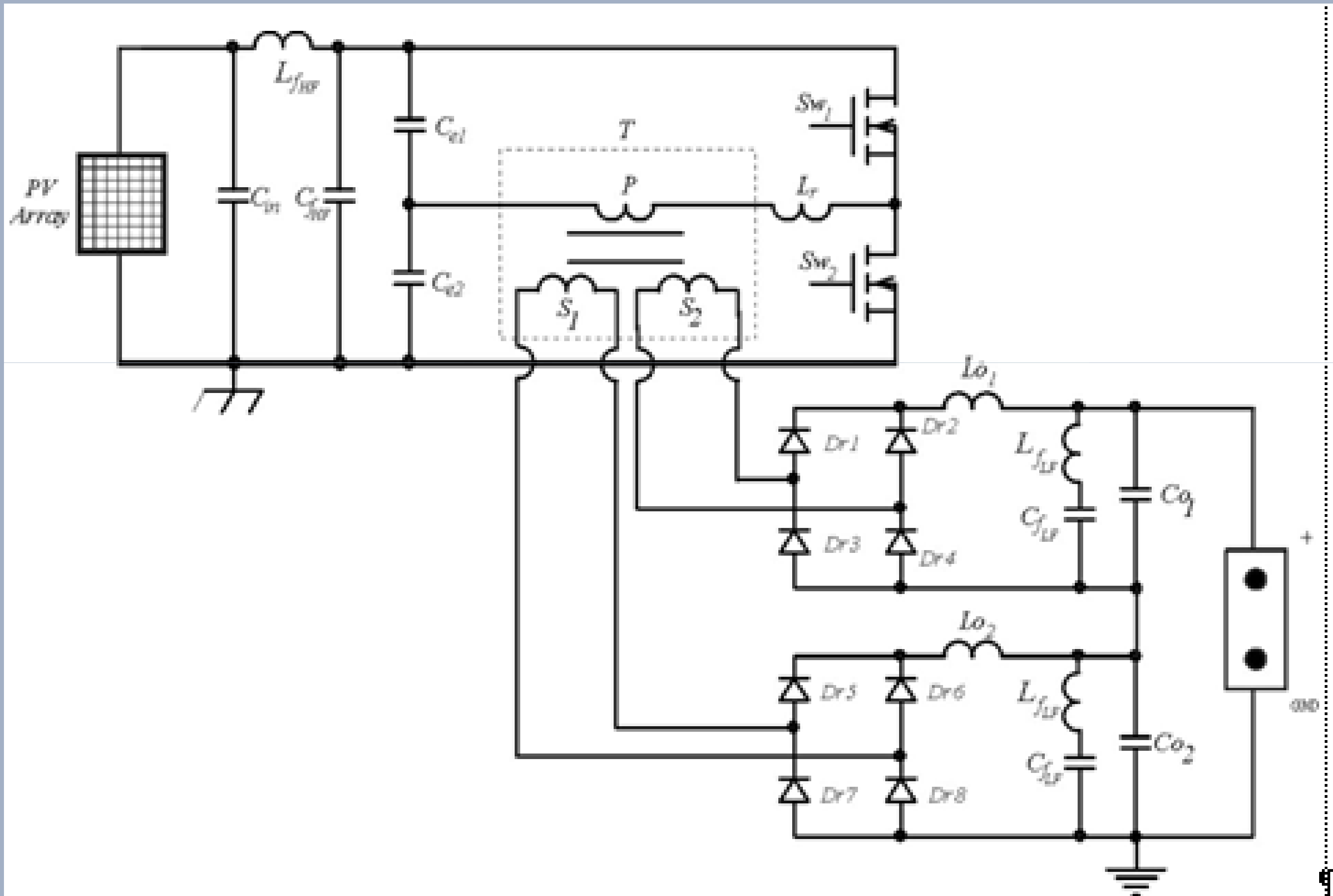
Power Flow of the System with Nolinear Load



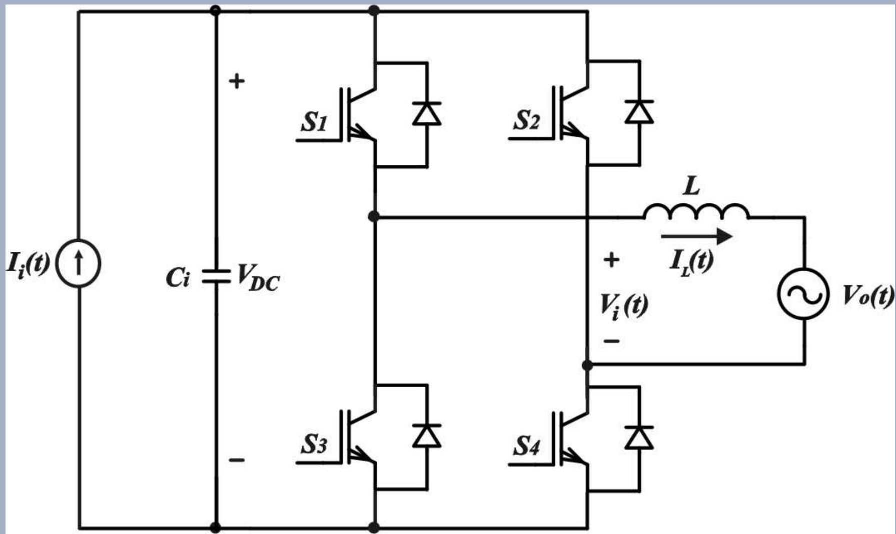
Design Procedures of the DC-DC Converter

- The DC-DC converter is a HB ZVS-PWM asymmetrically driven;
- The resonant stage occurs through a "*Lr*" and the intrinsic capacitors of the switches;
- The HB ZVS-PWM converter has been designed considering the reduction of losses and the volume of the magnetic cores.

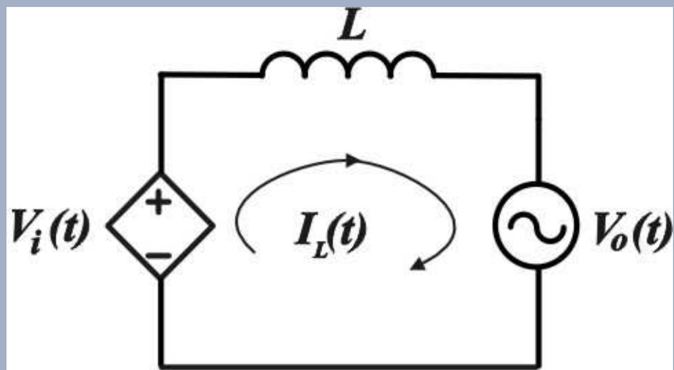
HB ZVS-PWM Converter



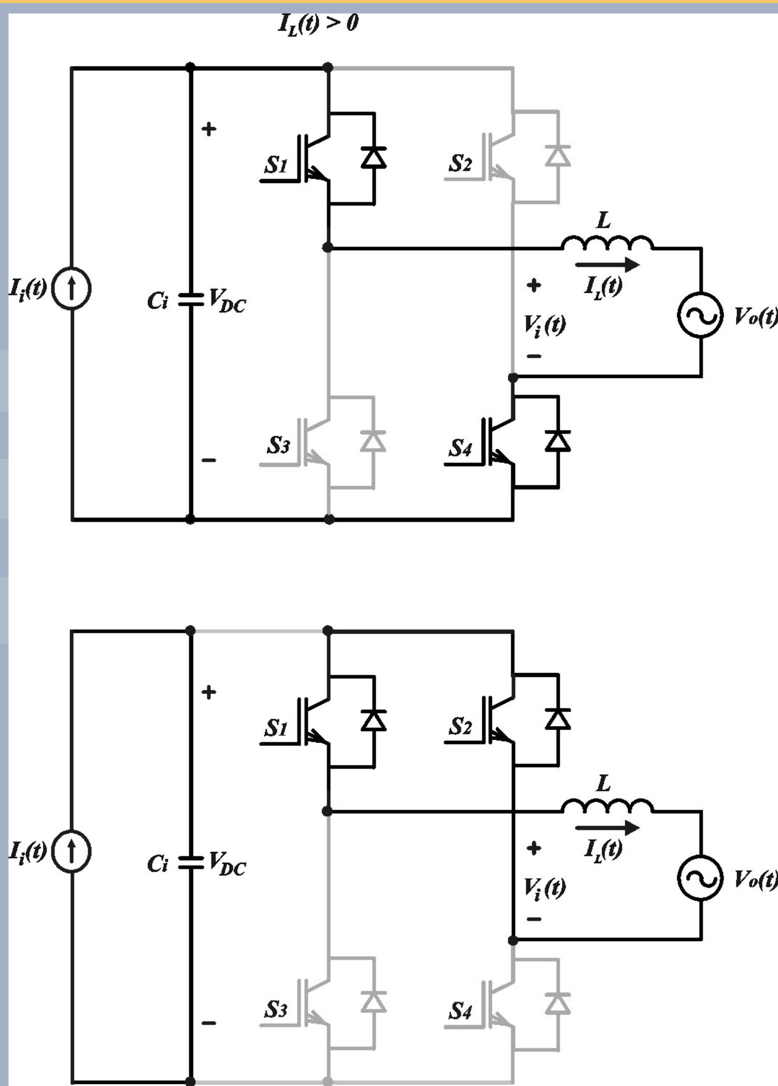
System configuration and Control Strategy of the DC-AC Converter



Single-phase PV system

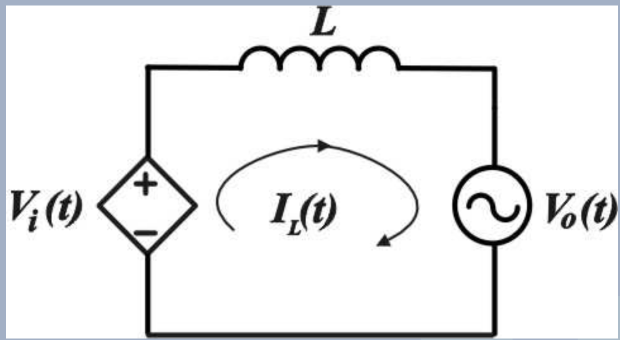


Simplified equivalent circuit

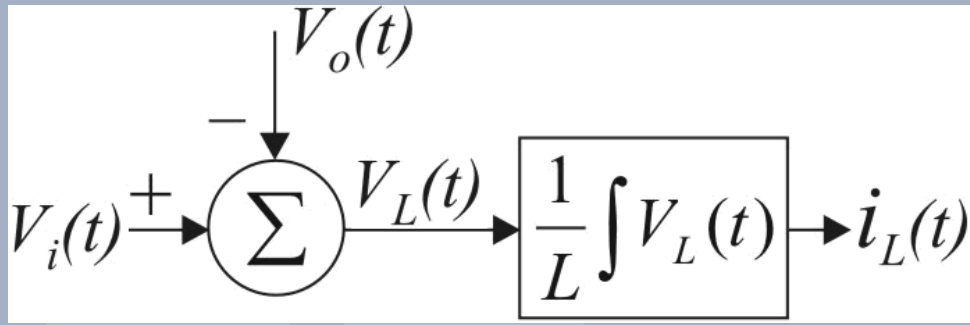


Simplified equivalent circuits of the switching modes

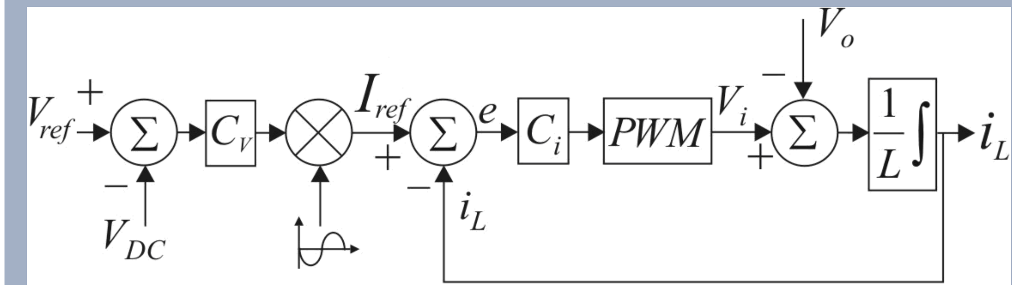
Control Strategy



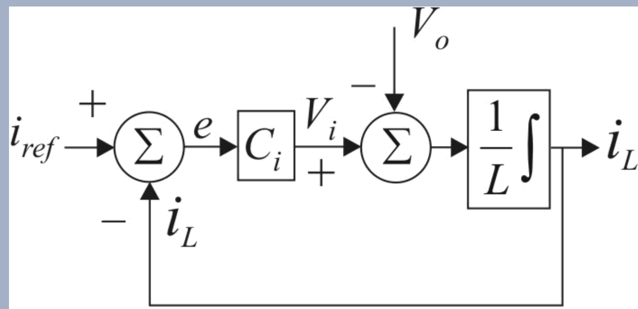
Simplified equivalent circuit



Block diagram of the simplified equivalent circuit

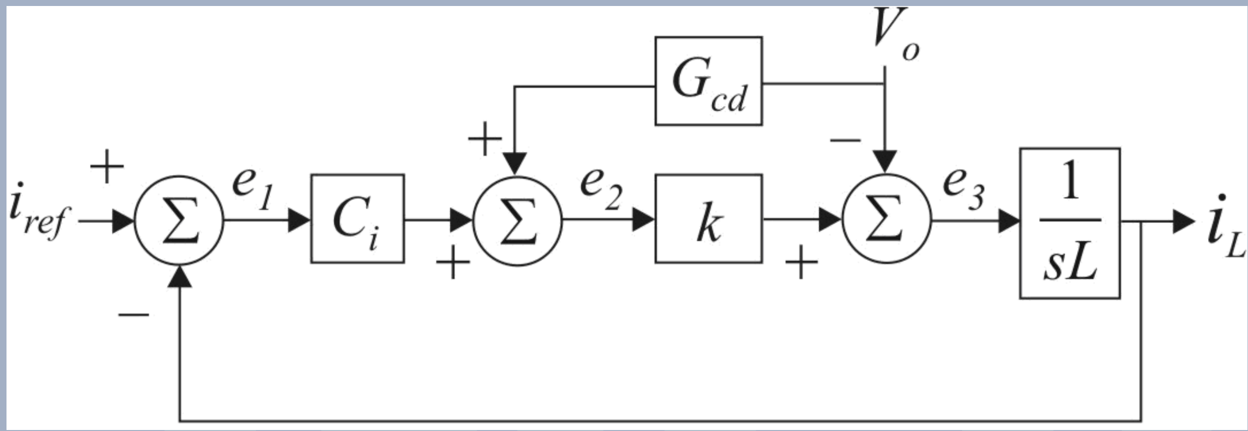


Block diagram of classical control strategy current loop



Simplified block diagram of classical control strategy current loop.

Control Strategy

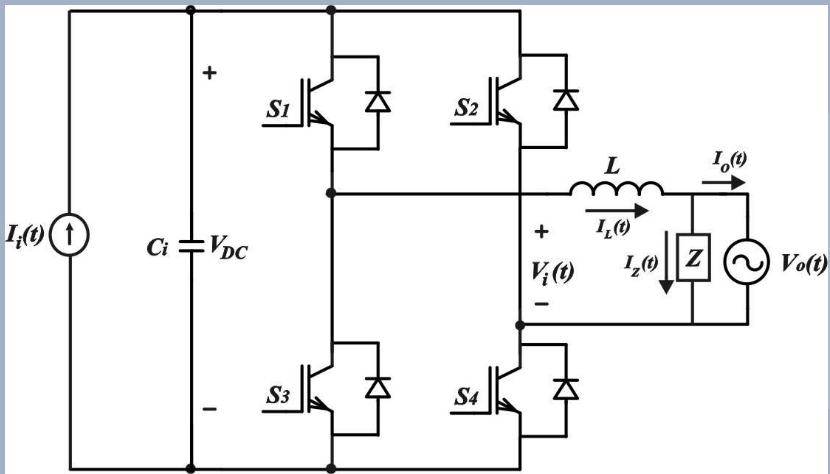


Block diagram containing the feed-forward controller

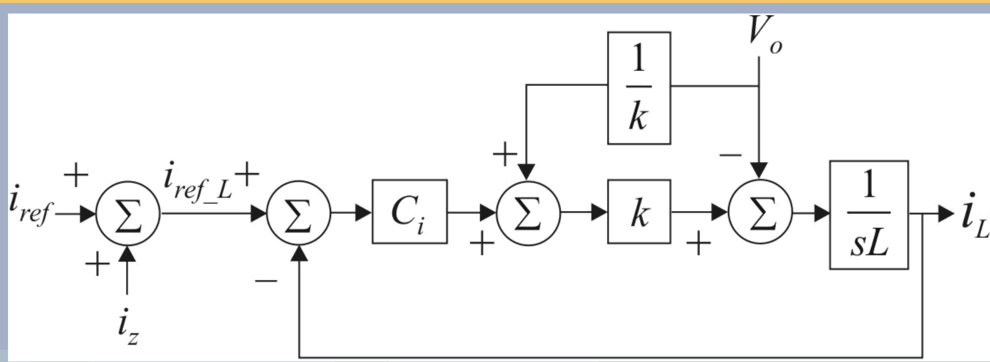
$$i_L = \frac{k \cdot C_I}{sL + k \cdot C_I} \cdot I_{Lref} + \frac{k \cdot \left(G_{cd} - 1/k \right)}{sL + k \cdot C_I} \cdot V_o$$

$$k = \frac{V_{DC}}{V_{tri}} \qquad G_{cd} = \frac{1}{k}$$

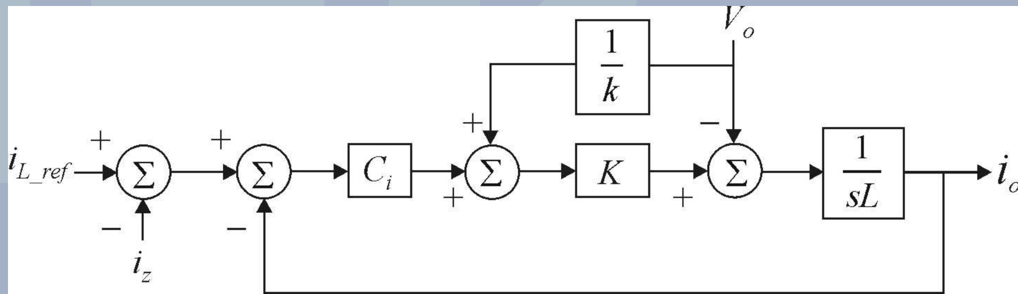
Control Strategy for any load connected



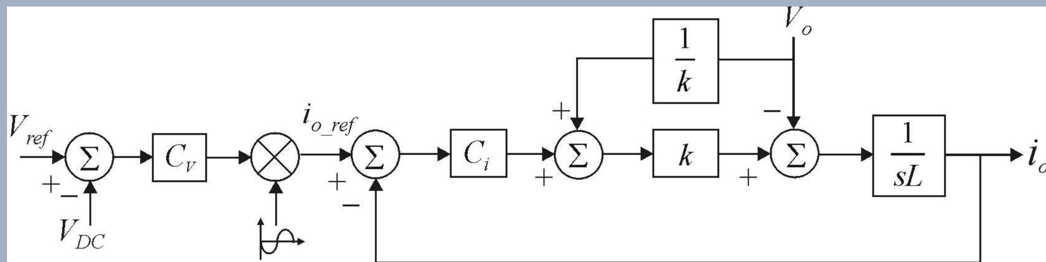
PV system with a load connected



New block diagram of the inductor current loop

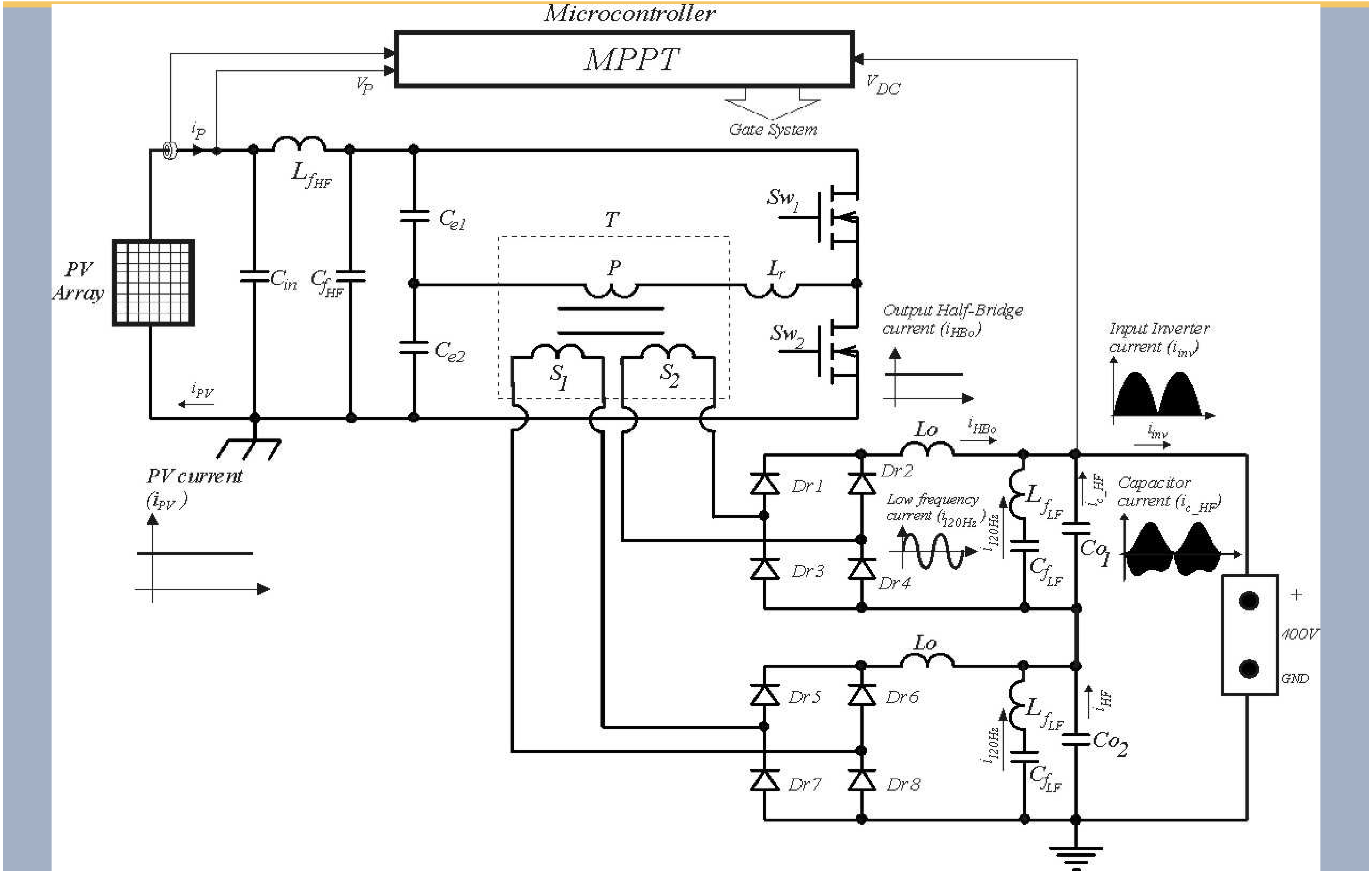


Block diagram of the utility current loop

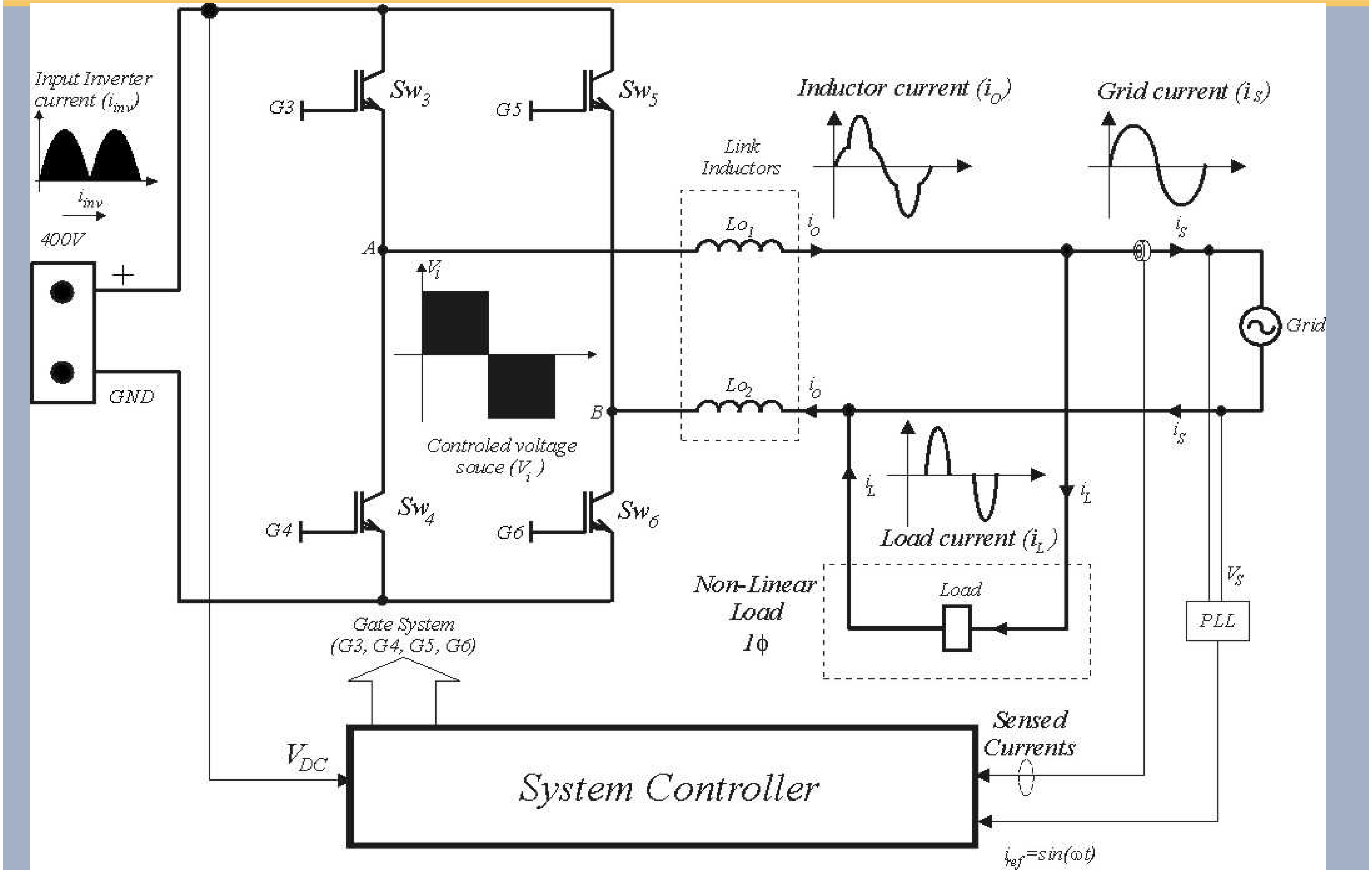


Utility current control diagram

DC/DC Converter



Inverter



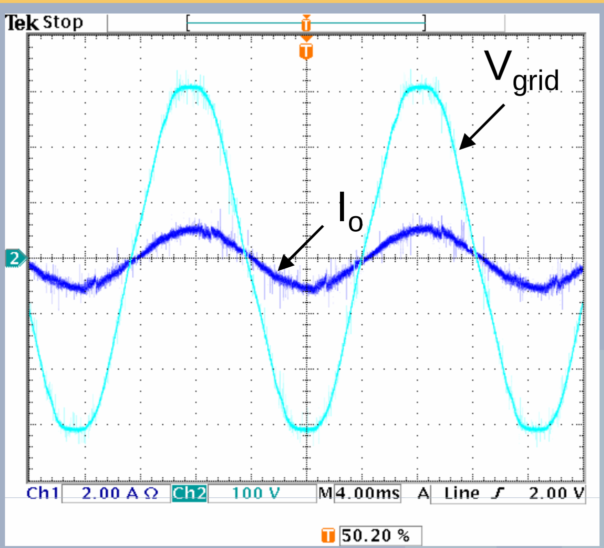
Input Inverter current (i_{inv})
i_{inv}
400V
+
GND
G3
Sw_3
G5
Sw_5
A
V_i
Controled voltage souce (V_i)
B
G4
Sw_4
G6
Sw_6
Link Inductors
Lo_1
Lo_2
i_o
Inductor current (i_o)
Grid current (i_S)
i_S
Grid
i_L
Load current (i_L)
Non-Linear Load 1ϕ
Load
V_S
PLL
Gate System (G3, G4, G5, G6)
V_{DC}
System Controller
Sensed Currents
$i_{ref}=sin(\omega t)$

Experimental Results

- Main Specifications of the System

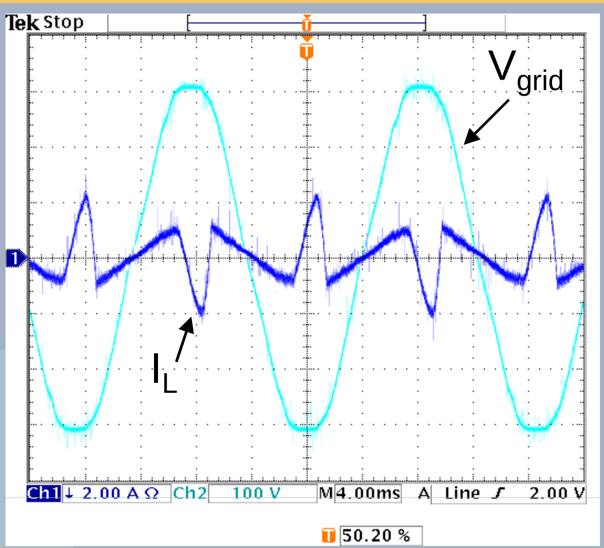
  - Number of PV Modules: 20
  - Rated Power: 1.0kW
  - DC Bus Voltage: 400V
  - Switching Frequency: 20kHz
  - Grid Voltage and Frequency: 220V; 60Hz
  - Load Power: 400W

Experimental Results

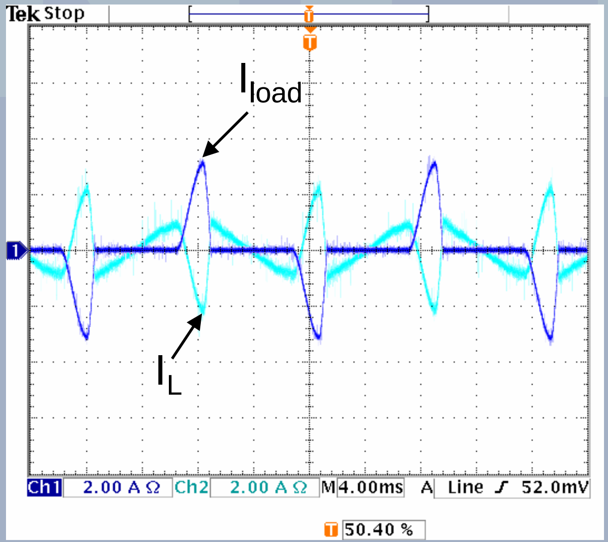


Output current and grid voltage
(THD of I_O= 4% - Crest factor = 3.09

Active power operation
(cloudy day or night)

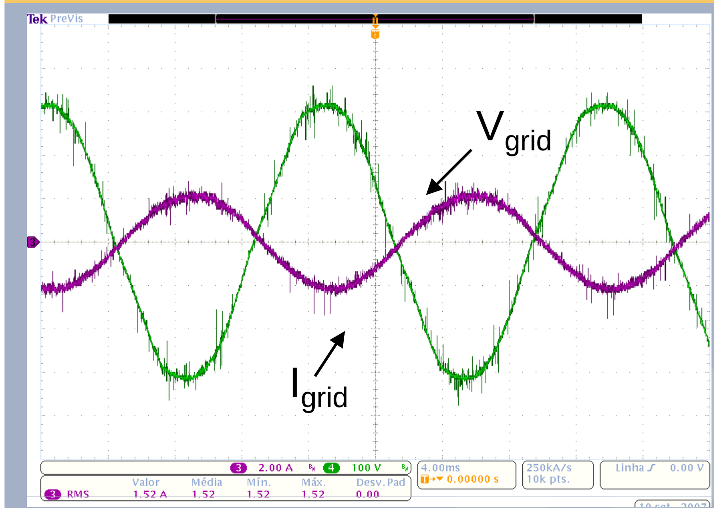


Inductor current and grid voltage



Inductor current and load current

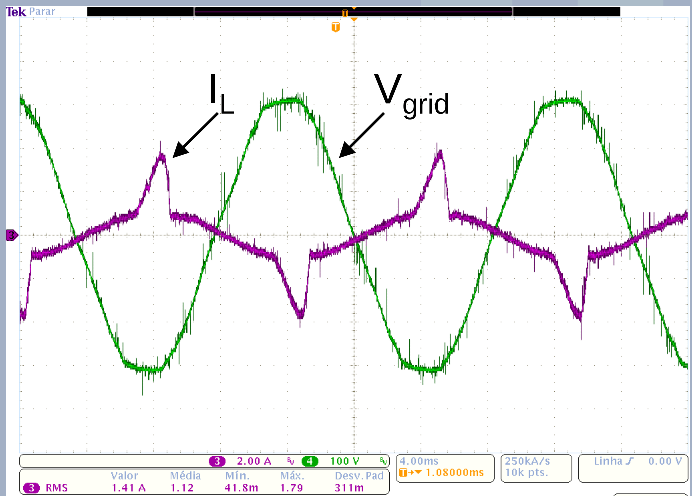
Experimental Results



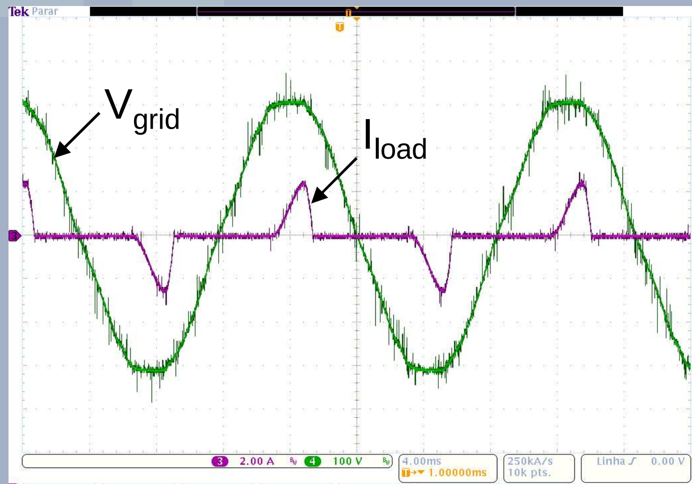
Output current and grid voltage

In this case the system supply the load and Inject 150W in the grid

THD I_{grid} = 3.67%

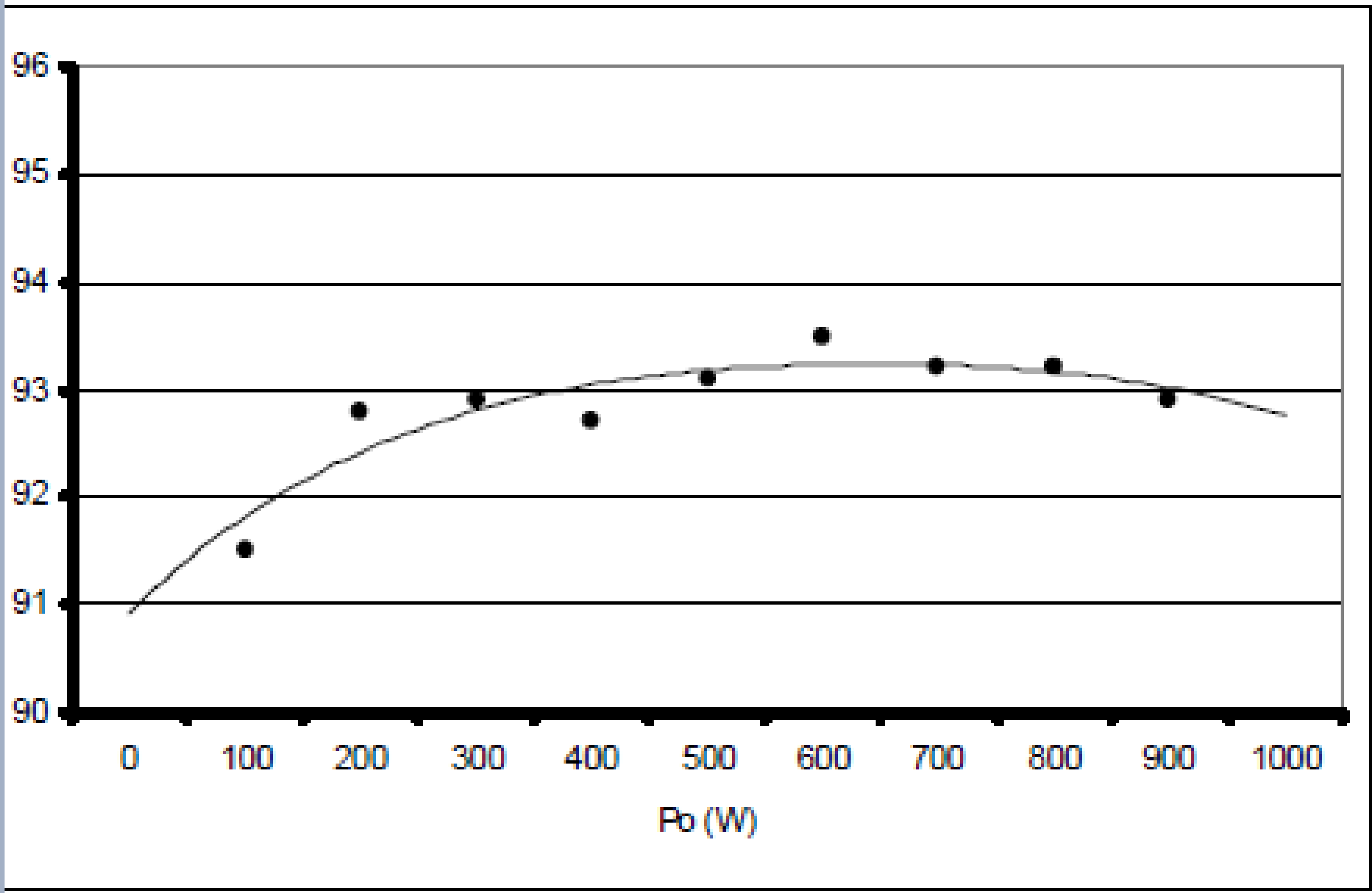


Inductor current and grid voltage



Load current and grid voltage

Experimental Results



Efficiency of de whole system

Conclusion

- The proposed Single-Phase PV system provides Active Power to the Grid and can act as Active Power Filter to compensate the load harmonics;
- The PF is very high, even for Non-Linear Load;
- The simplicity in the Output Current Control Strategy is another advantage of the System, because besides doing use of just one sensor, it is of easy practical implementation.

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Three-Phase Grid-Connected PV System With Active and Reactive Power Control

Power Electronic Institute - INEP

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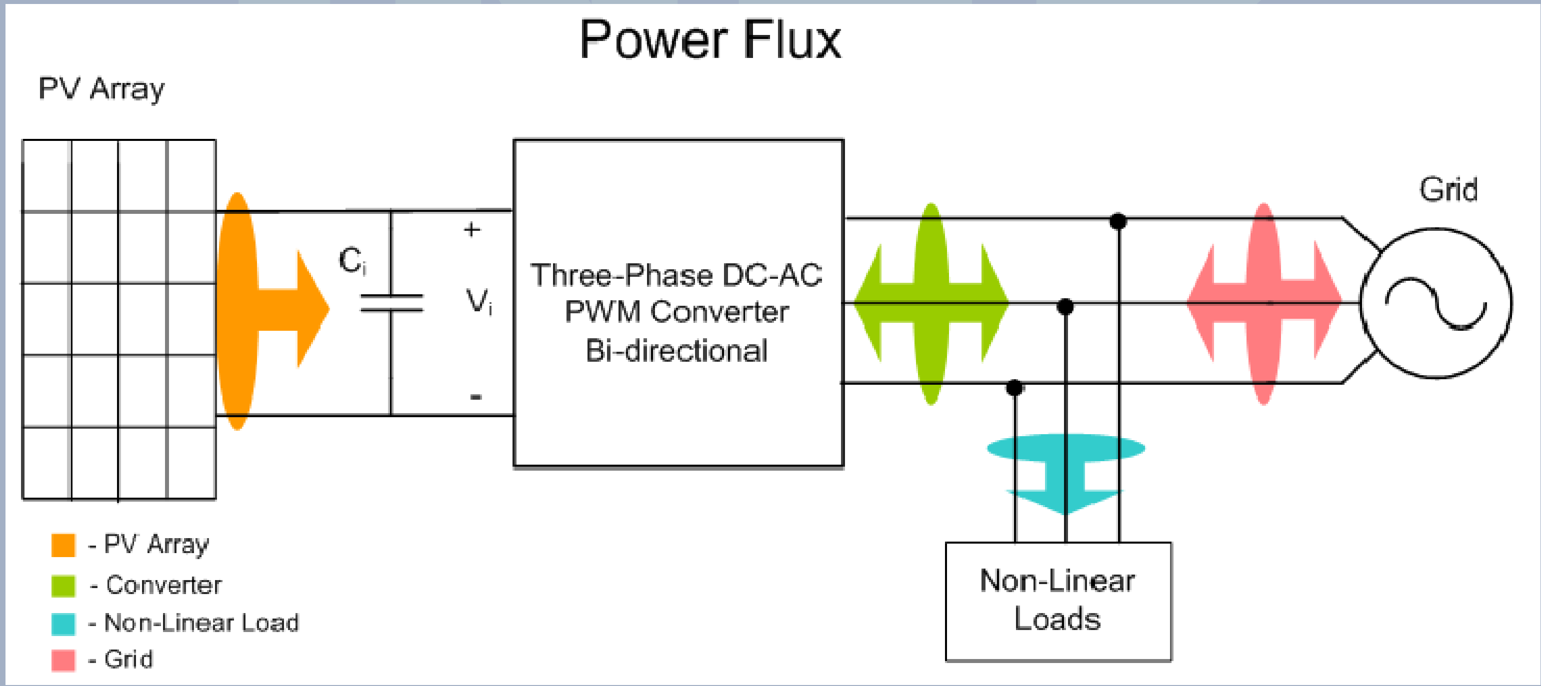
Denizar Cruz Martins

Proposed Three-Phase PV System

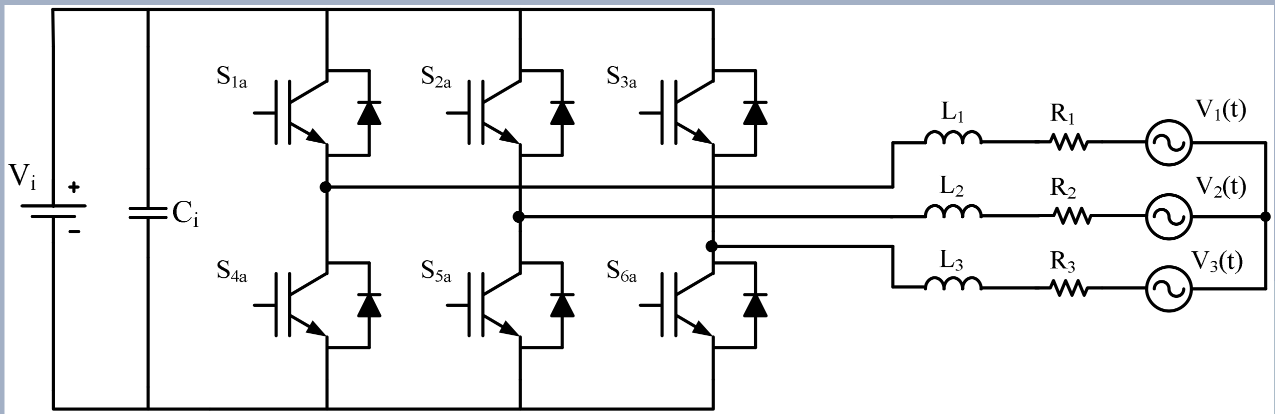
◇The modelling and the control strategy are implemented through Park transformation. The following characteristics are obtained:

1. Electric power generation to supply the load and to deliver the excess of the energy into the grid (Distributed Generation);
2. Operate as an Active Power Filter;
3. Capacity to operate in the MPP.



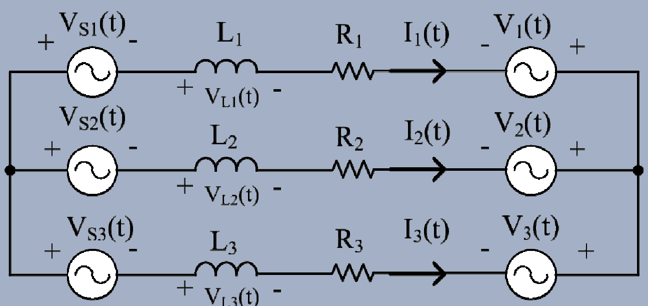
Modelling of the Converter

Proposed Converter



Bi-directional DC-AC PWM Converter

Current Control Modelling



Simplified circuit to output AC

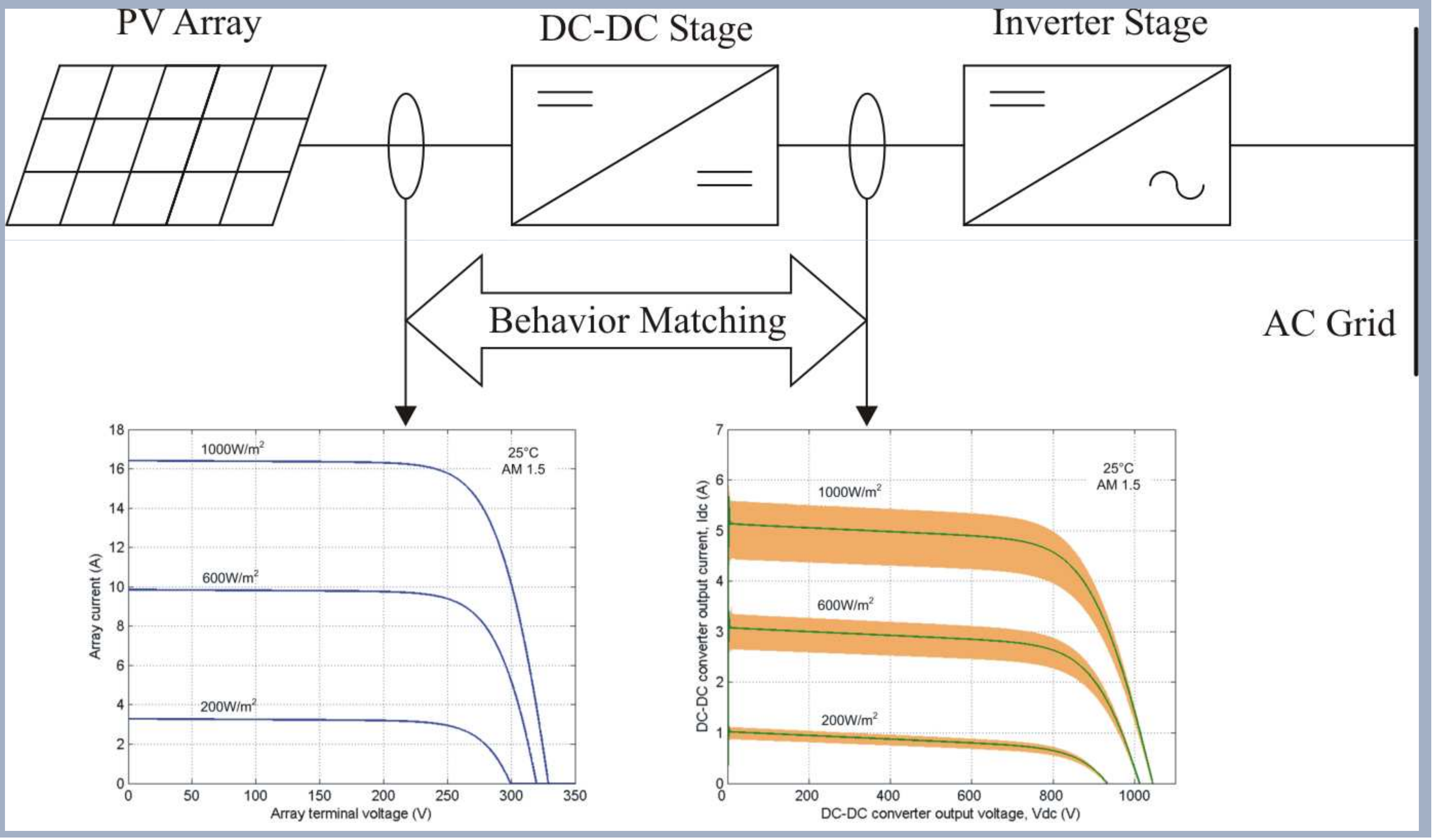
$$\begin{cases} V_{12}(t) = L\,\dfrac{dI_{12}(t)}{dt} + D_{12}(t)\,V_i + R\,I_{12}(t) \\ V_{23}(t) = L\,\dfrac{dI_{23}(t)}{dt} + D_{23}(t)\,V_i + R\,I_{23}(t) \\ V_{31}(t) = L\,\dfrac{dI_{31}(t)}{dt} + D_{31}(t)\,V_i + R\,I_{31}(t) \end{cases}$$

Transfer Functions used in the design of the current controllers ⇒

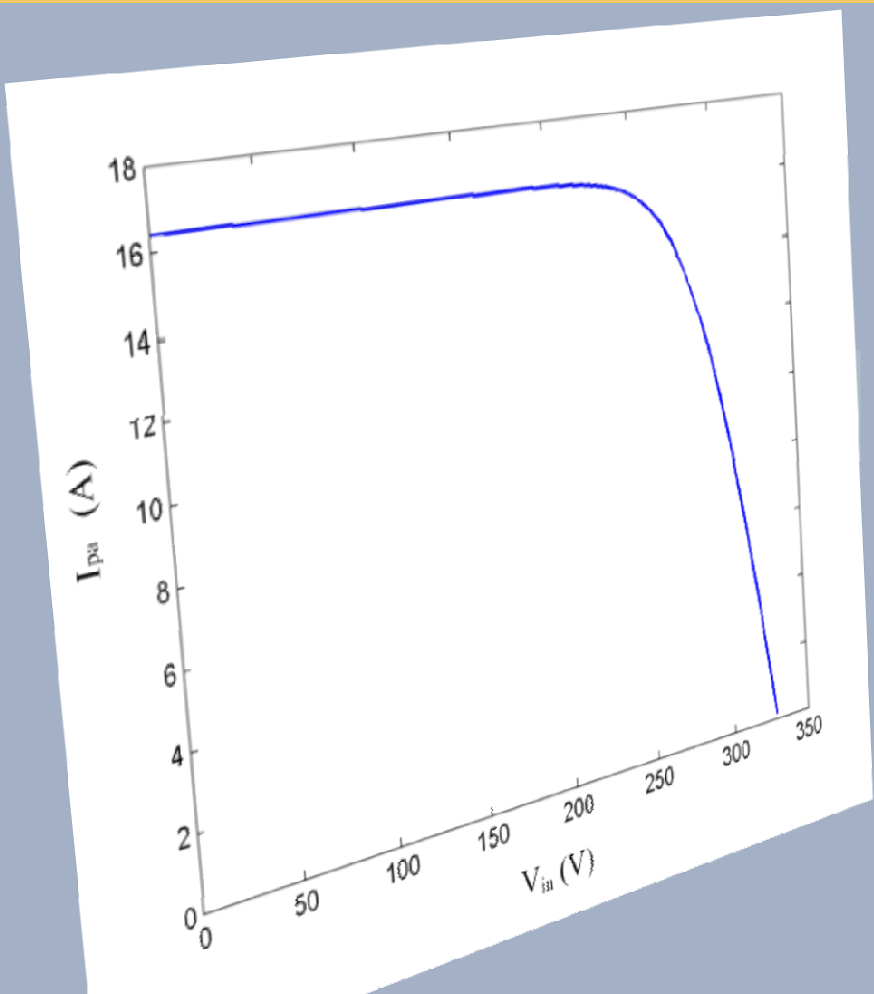
$$\begin{cases} \dfrac{i_d(s)}{d'_d(s)} = -\dfrac{V_i}{S\,L + R_{eq}} \\ \dfrac{i_q(s)}{d'_q(s)} = -\dfrac{V_i}{S\,L + R_{eq}} \end{cases}$$

Behavior Matching

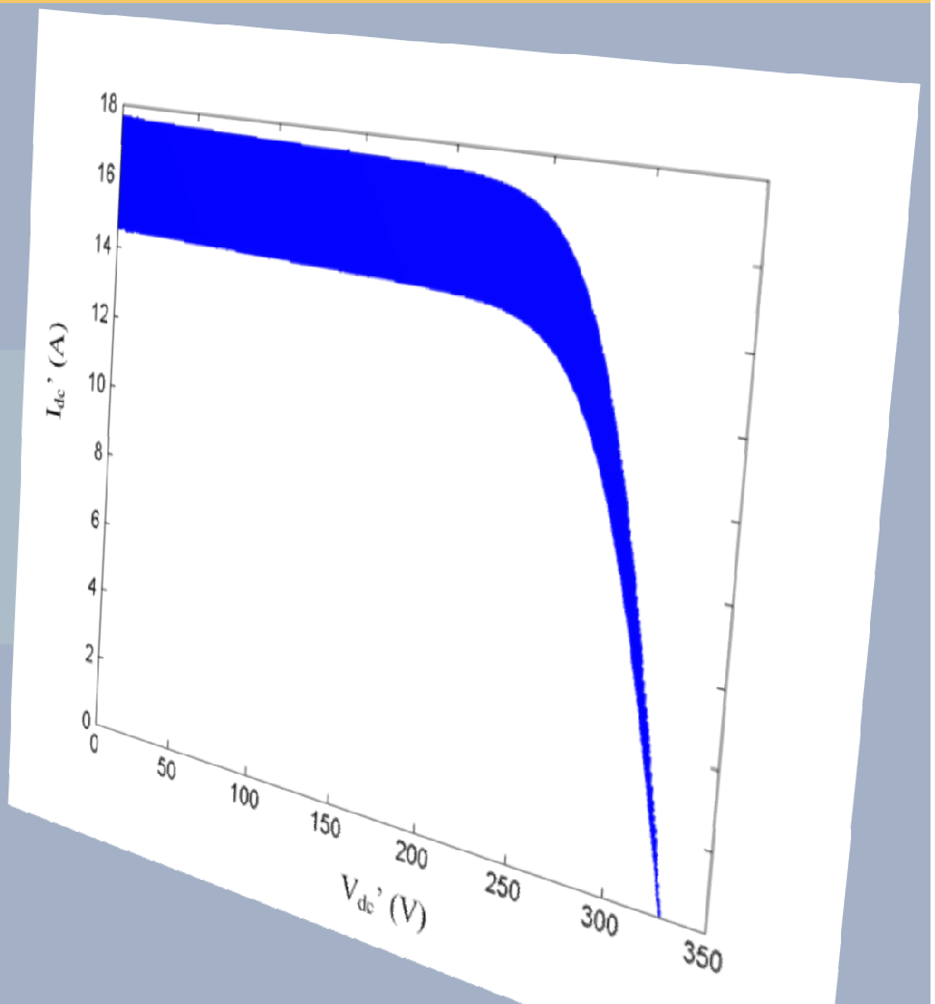
- The behavior of the PV array is reproduced in the DC-DC converter's output terminals.



MPPT – Behavior Matching

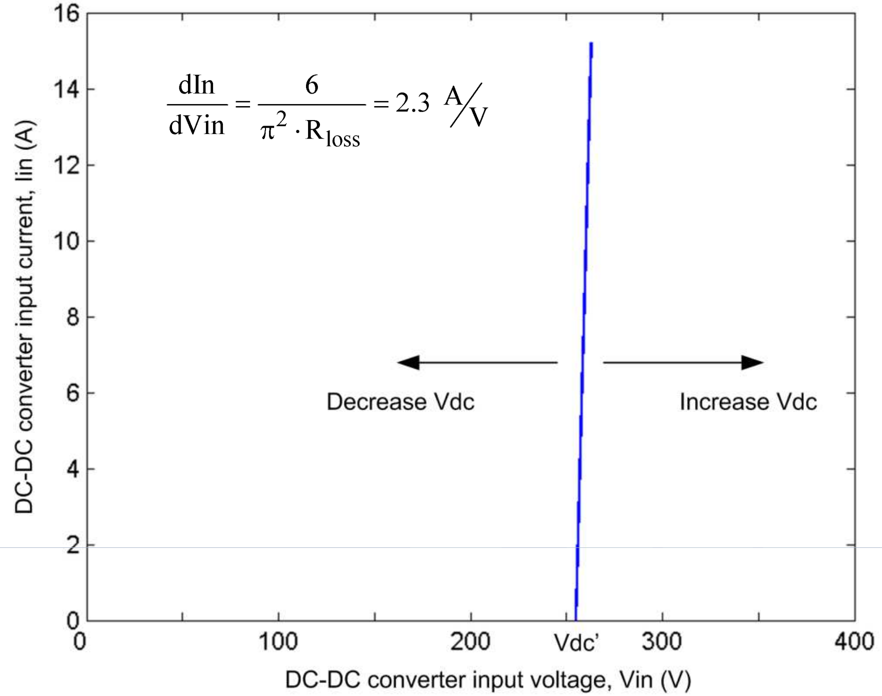


PV array output



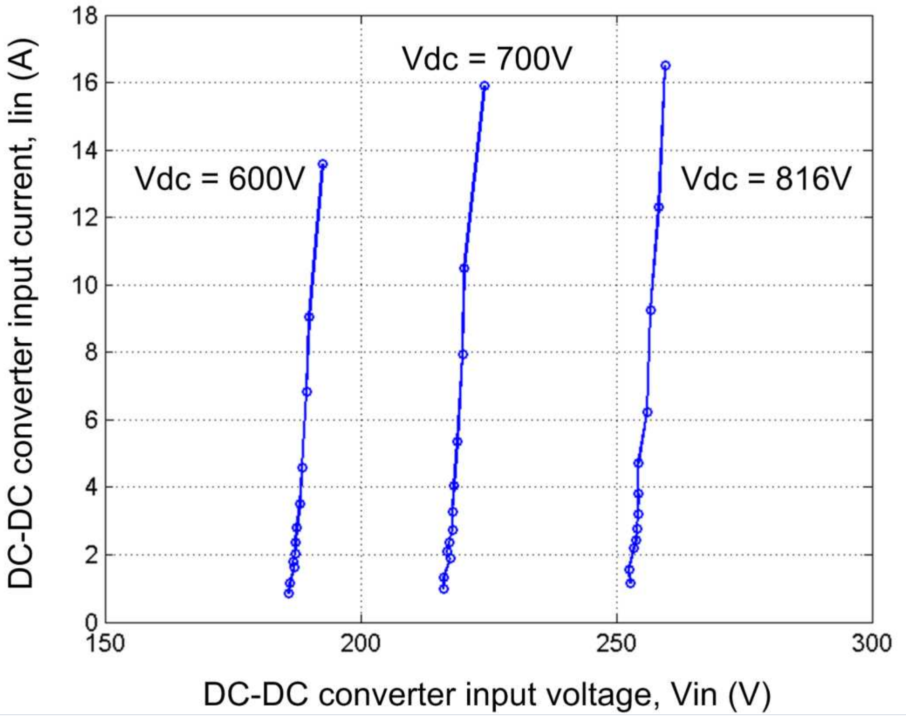
Converter output

Explanation

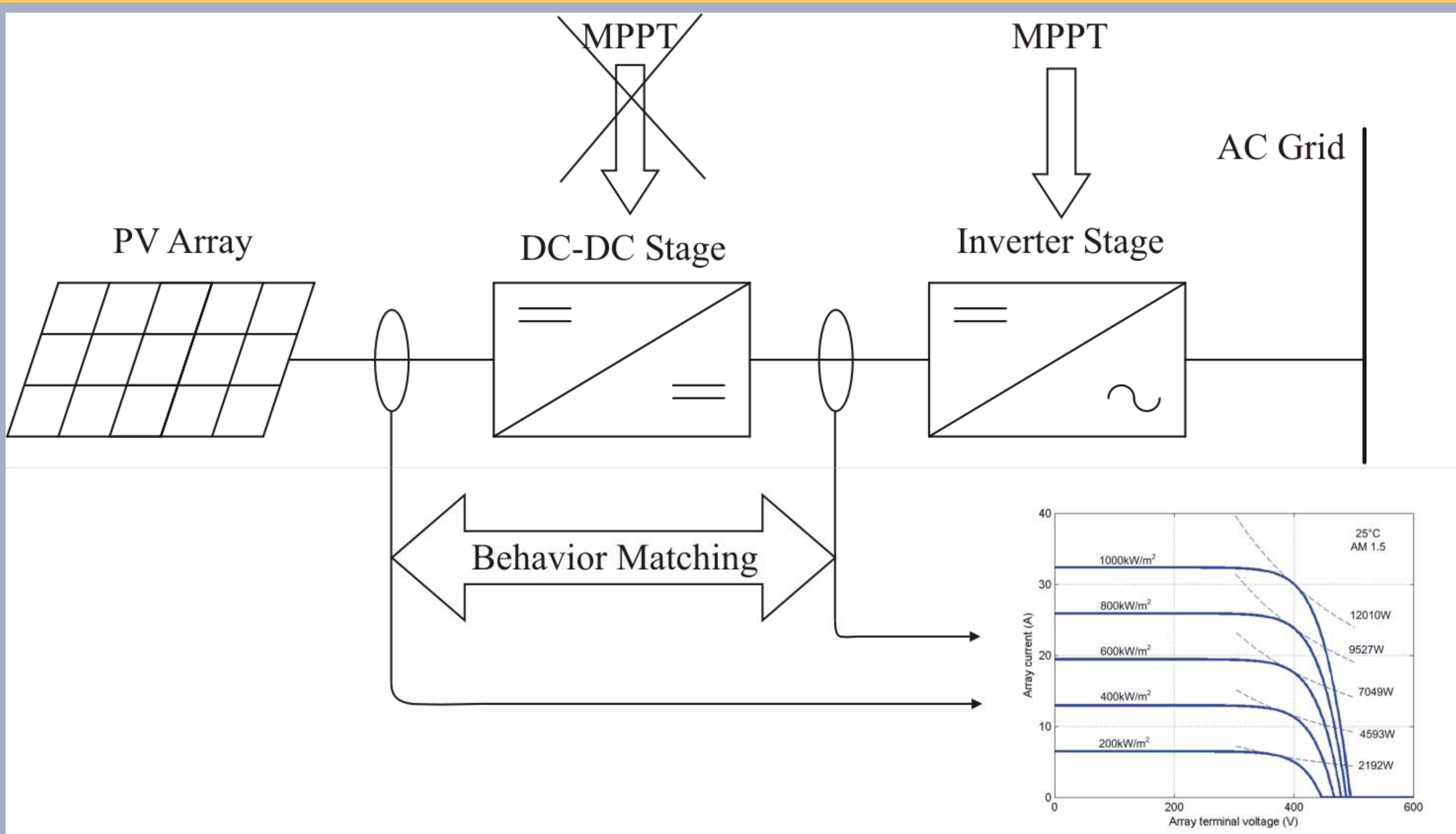


Theoretical

Experimental

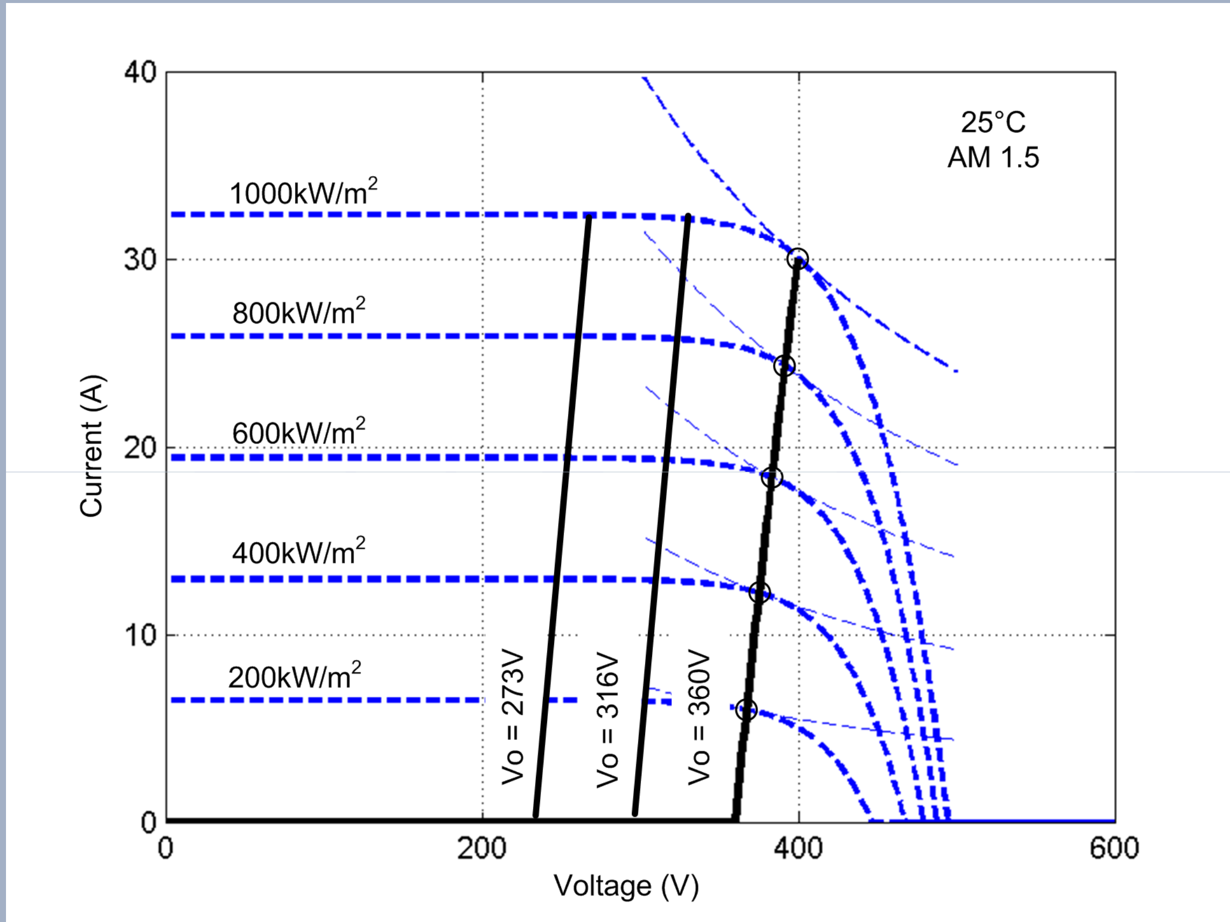


Indirect MPPT



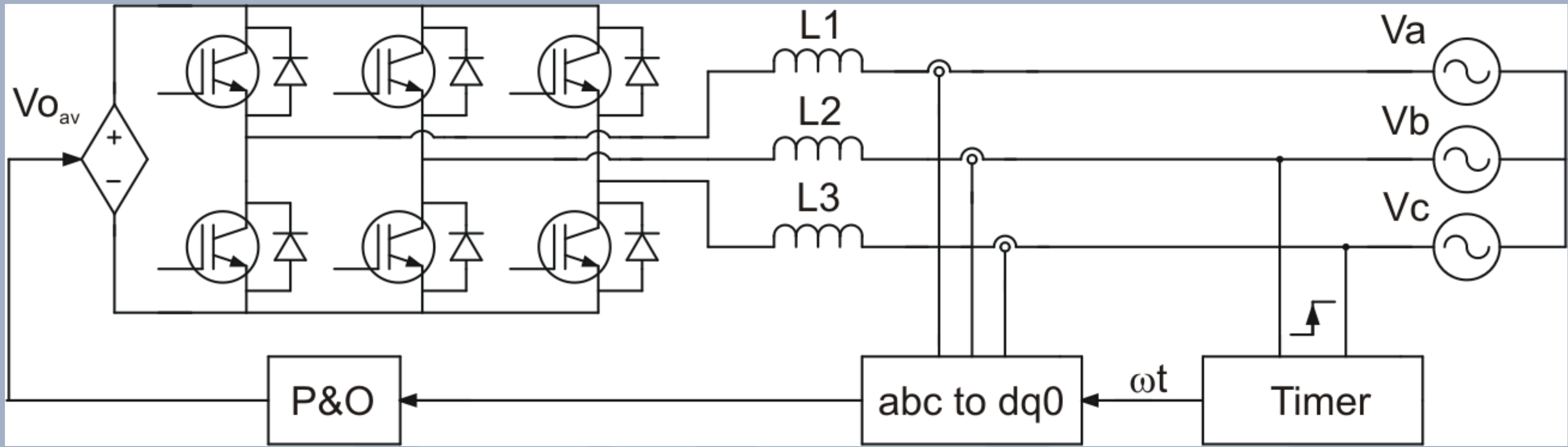
Inverter Stage → Vo_{av} → DC-DC Converter's Input Characteristic → PV Array Operating Point → Conclusion: P&O Algorithm in the Inverter Stage

Behavior Matching



$$Iin = \frac{6 \cdot (Vin - Vo)}{\pi^2 \cdot R_{loss}} @ fs = fr$$

MPPT Performed by Maximization of the Inverter's Output Power

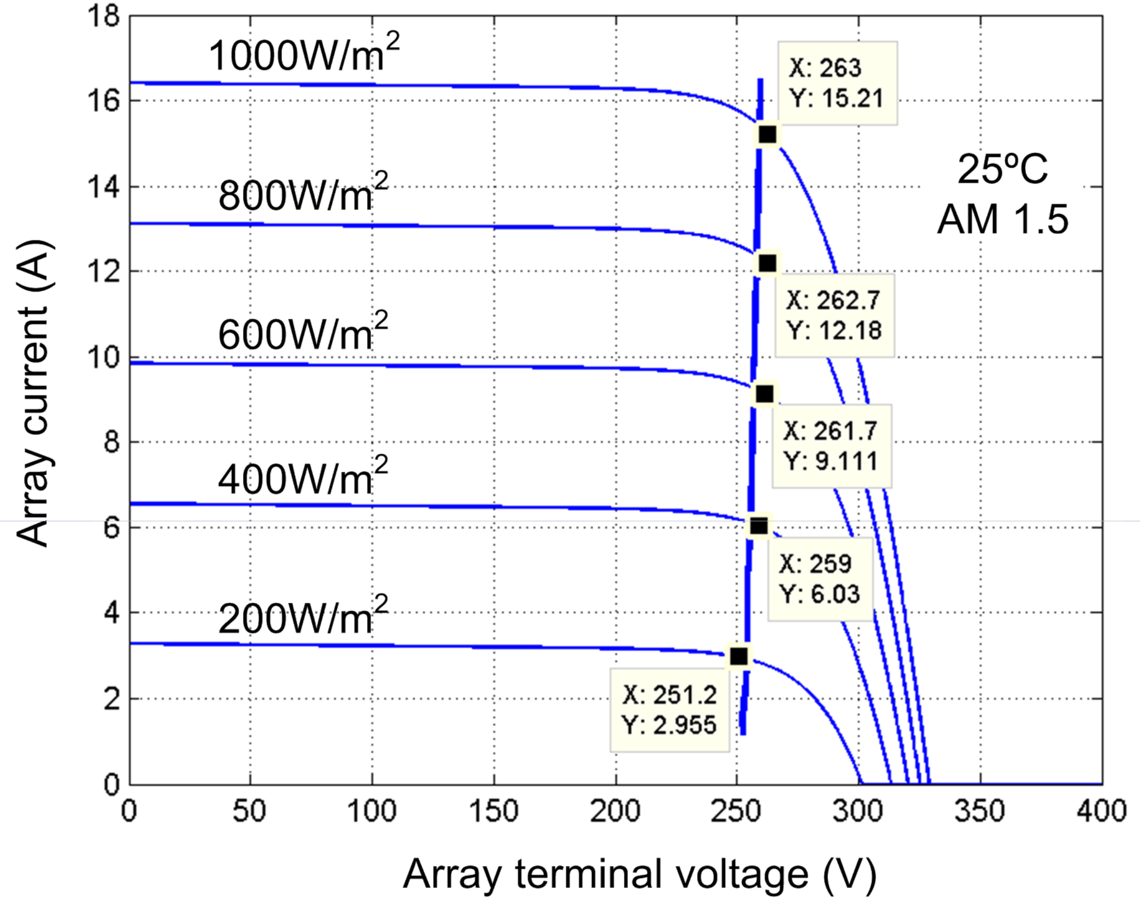


$$Vo((k+1)\cdot Ta) = Vo(k\cdot Ta) \pm \Delta V =$$
$$= Vo(k\cdot Ta) + \left[Vo(k\cdot Ta) - Vo((k-1)\cdot Ta)\right]\cdot$$
$$\cdot sign\left[Pg(k\cdot Ta) - Pg((k-1)\cdot Ta)\right]$$

$$Pg = Vd \cdot Id$$

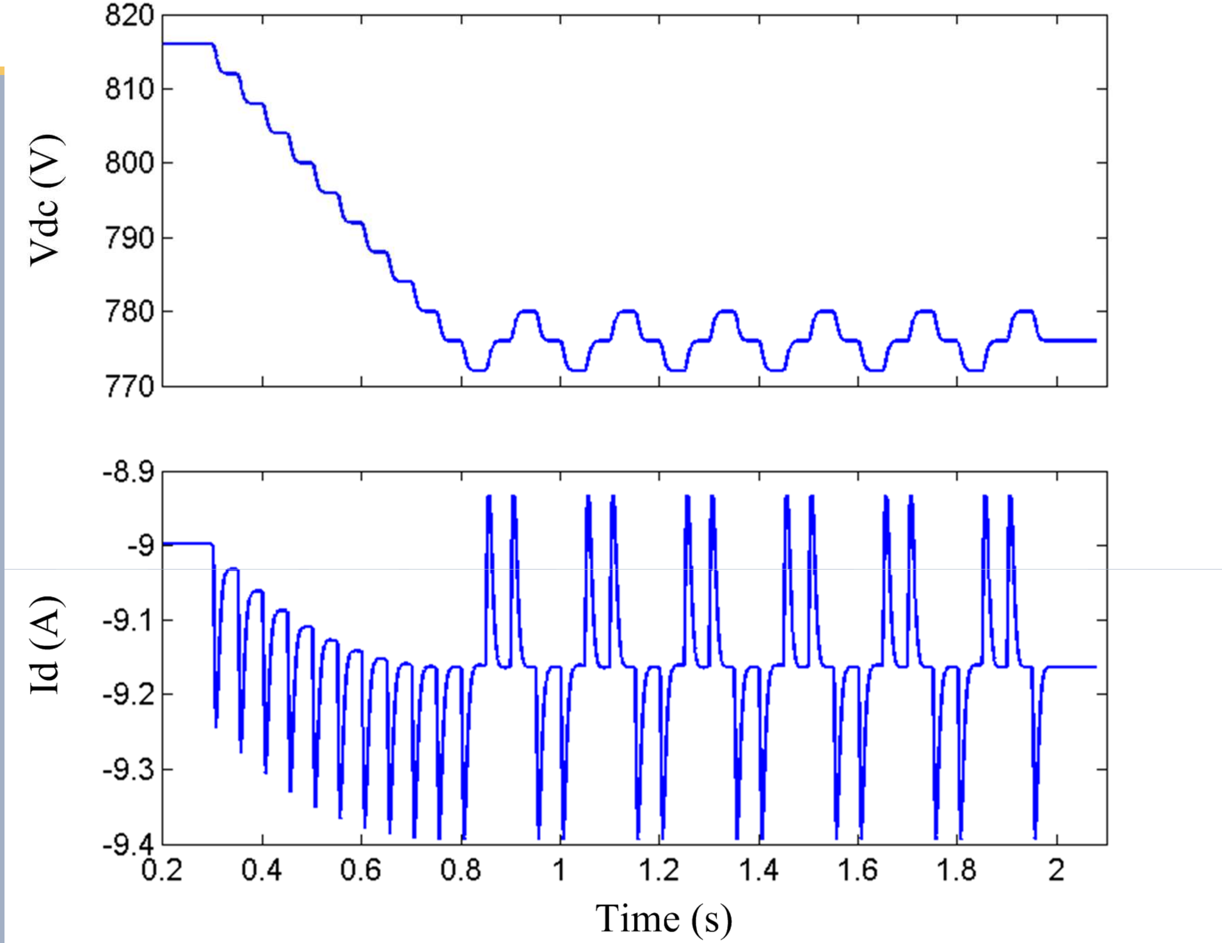
$$\dot{I}d = \frac{Vd}{L} + \omega\cdot Iq - \frac{R}{L}\cdot Id - \frac{Vo_{av}}{L}\cdot Dd$$
$$\dot{I}q = -\omega\cdot Id - \frac{R}{L}\cdot Iq - \frac{Vo_{av}}{L}\cdot Dq$$
$$\dot{V}o_{av} = -\frac{Io}{Cf2} + \frac{Id}{Cf2}\cdot Dd + \frac{Iq}{Cf2}\cdot Dq$$

6. I-V Characteristics



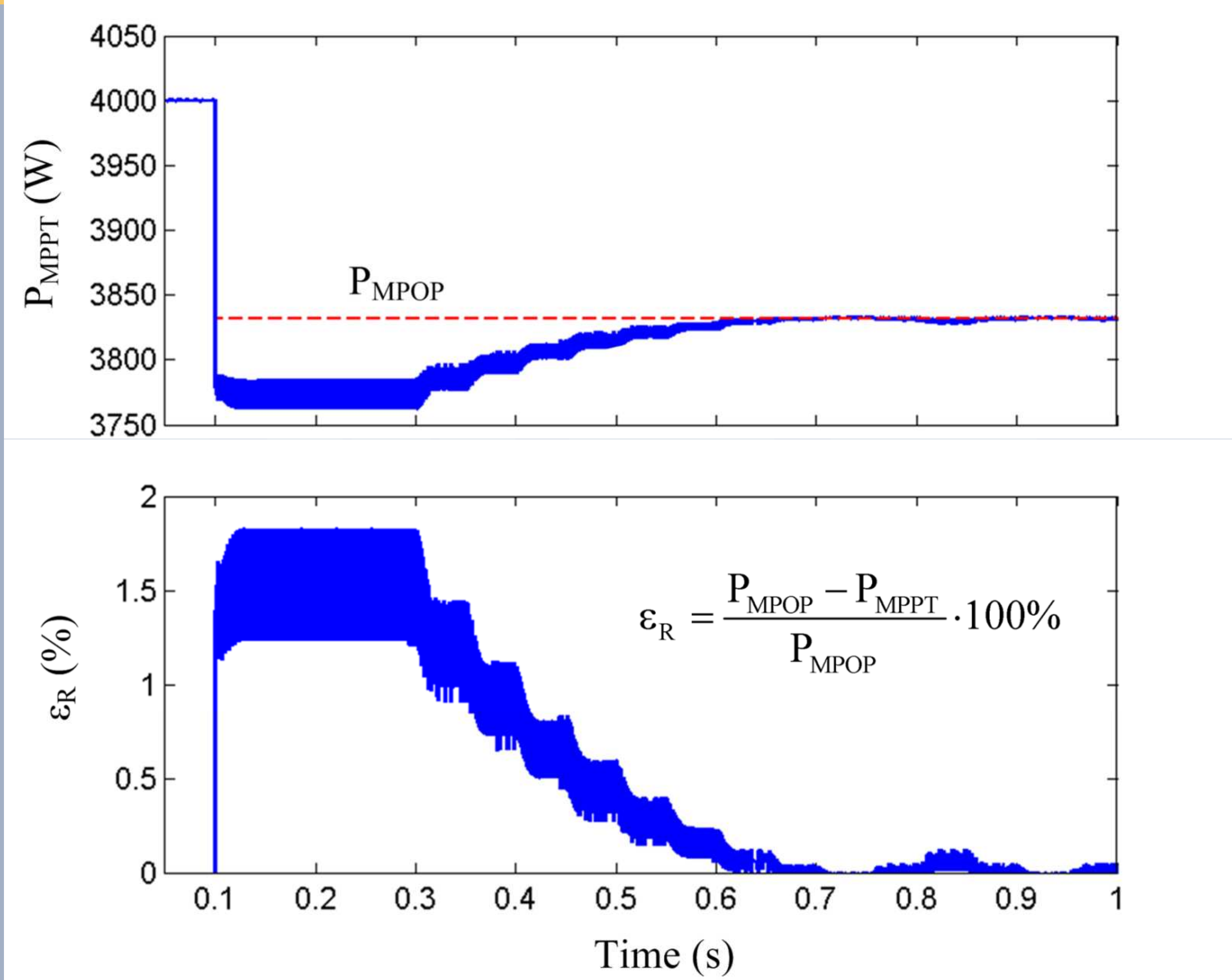
- DC-DC converter input I-V characteristic (Vdc = 816V) on the PV array I-V characteristic curves. The crossing points coincide with MPP.
- The inclination of the SRC3 input I-V characteristic improves the MPPT for fast changes in atmospheric conditions.

7. MPPT

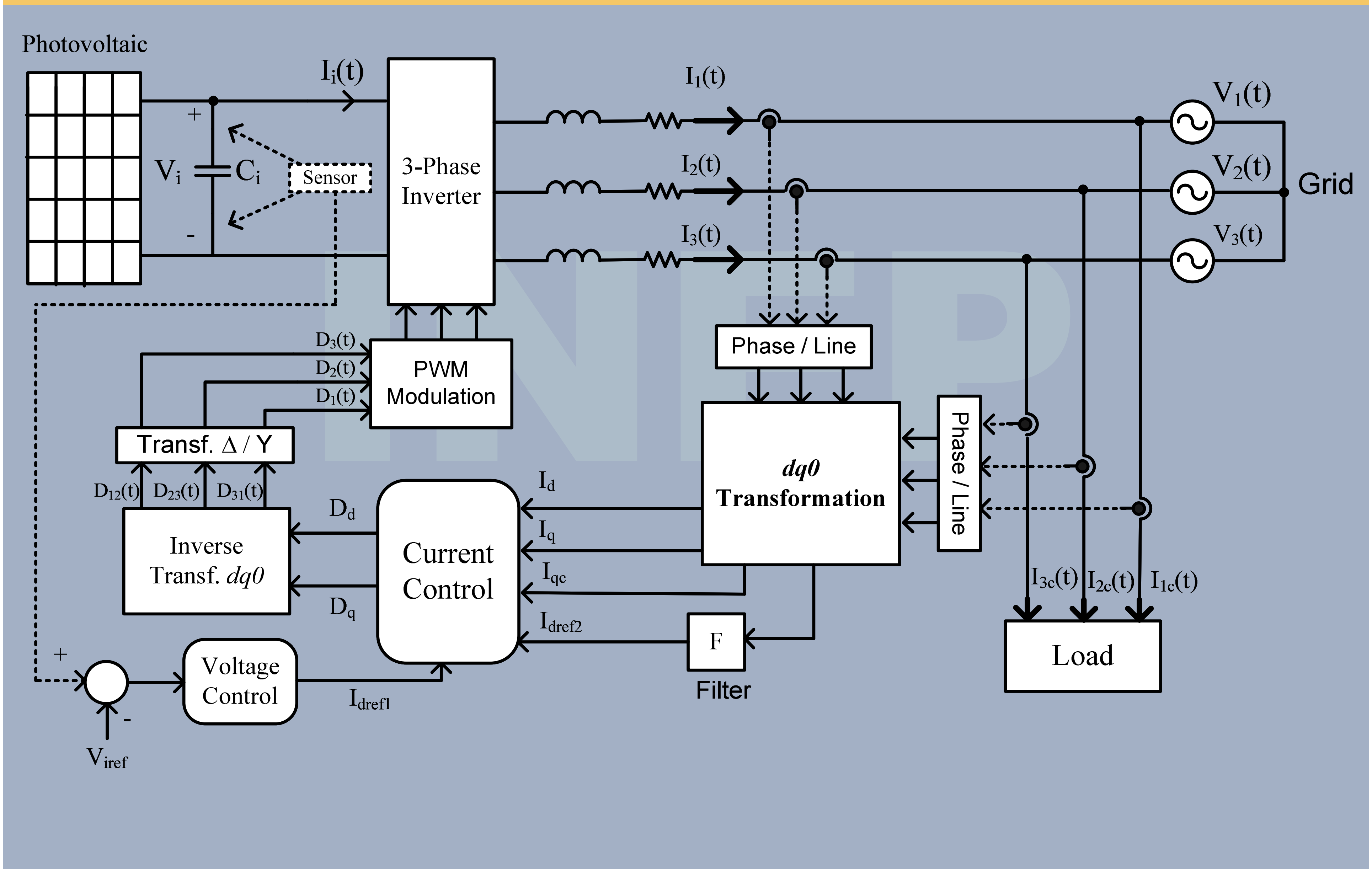


- The MPP is found by maximizing the direct axis current, using P&O.
- Additional hardware to realize the MPPT is not needed:
  - Variables used in the grid-current control: Id, Iq and Vdc.
  - Variables used in the MPPT: Id and Vdc.

8. Performance

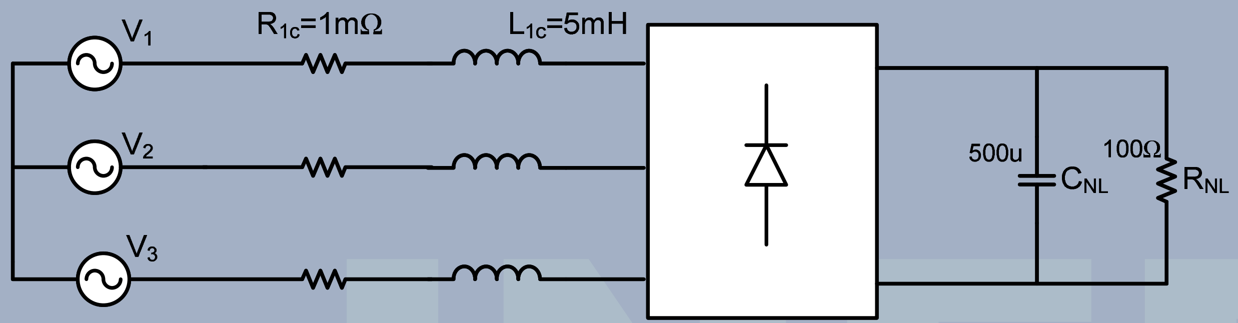


CONTROL STRATEGY



EXPERIMENTAL RESULTS

Non-linear loads



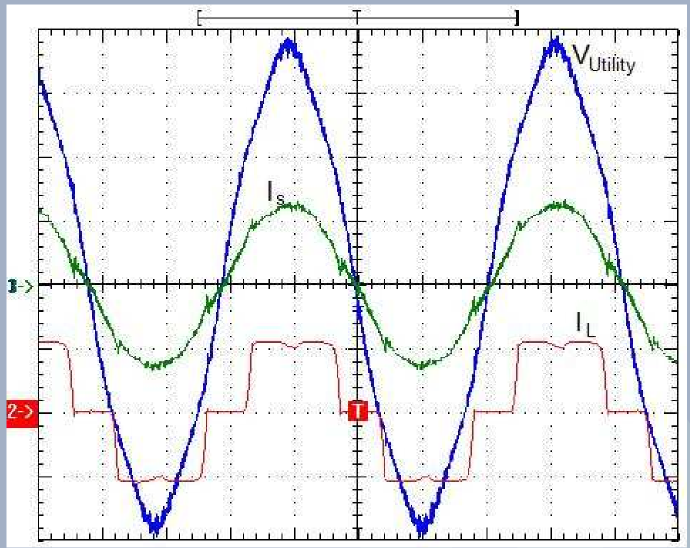
Specification of the System

Simulation parameters

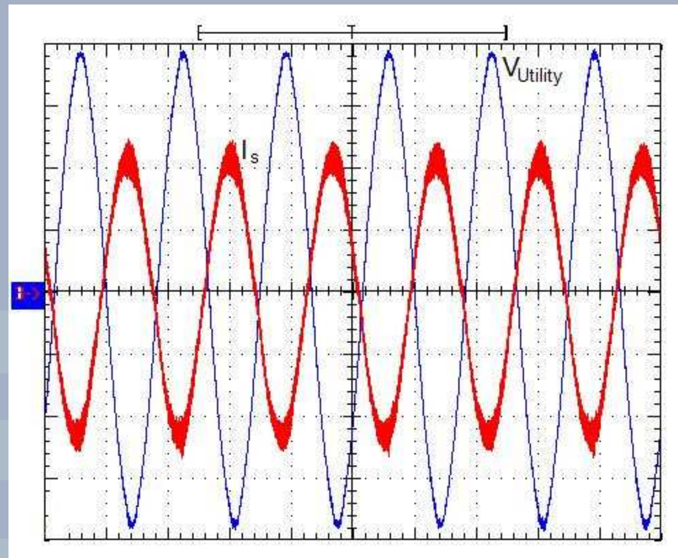
Parameter	Description
P = 12 kVA	- Converter Power
V_i= 700 V	- Input Voltage (DC)
V_{out}= 220 V	- Output voltage rms (grid)
L = 1,92 mH	- Output inverter inductance
C_i= 2,7 mF	- Input Inverter capacitor
R = 0,57 Ω	- Output inverter equivalent resistor
f_r= 60 Hz	- Grid Frequency
f_s = 20 kHz	- Commutation Frequency

EXPERIMENTAL RESULTS

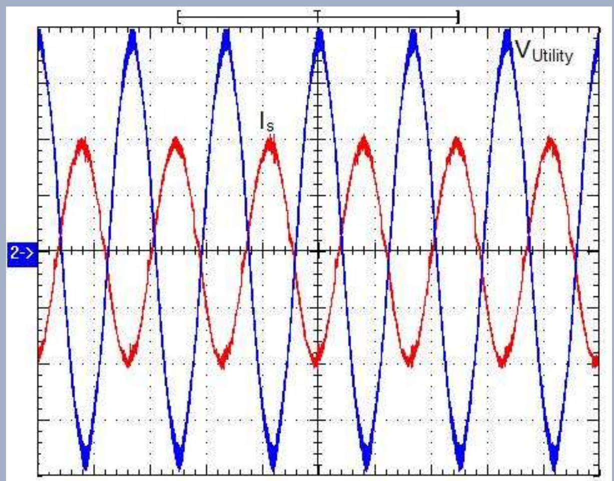
Non-Linear loads



Utility current (IS), Load current and utility voltage (VUtility) (Ch1 and Ch2 20A/div and Ch2 50V/div)

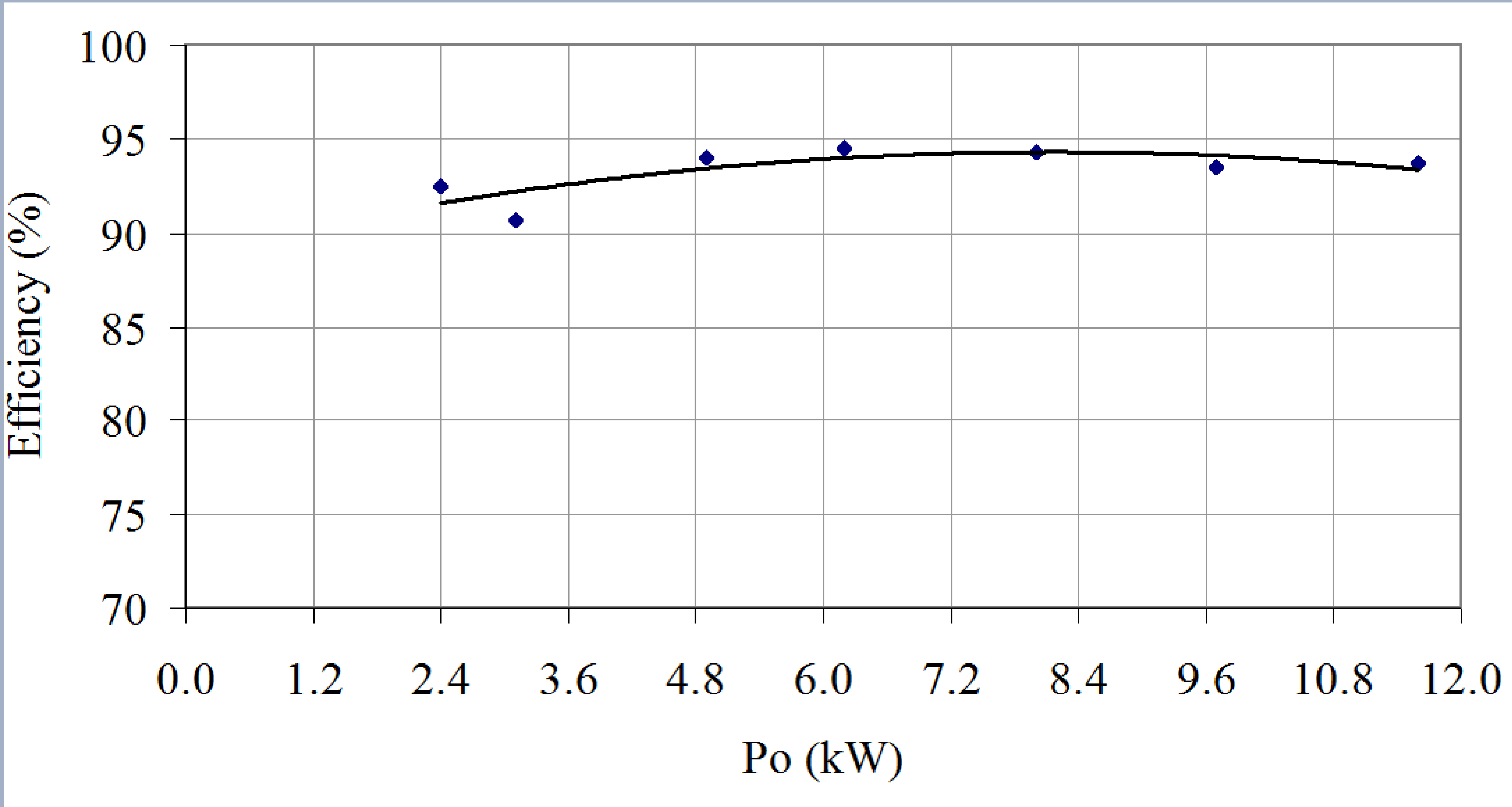


Utility current (IS) and utility voltage (VUtility) with no load. (Ch1 10A/div and Ch2 50V/div).



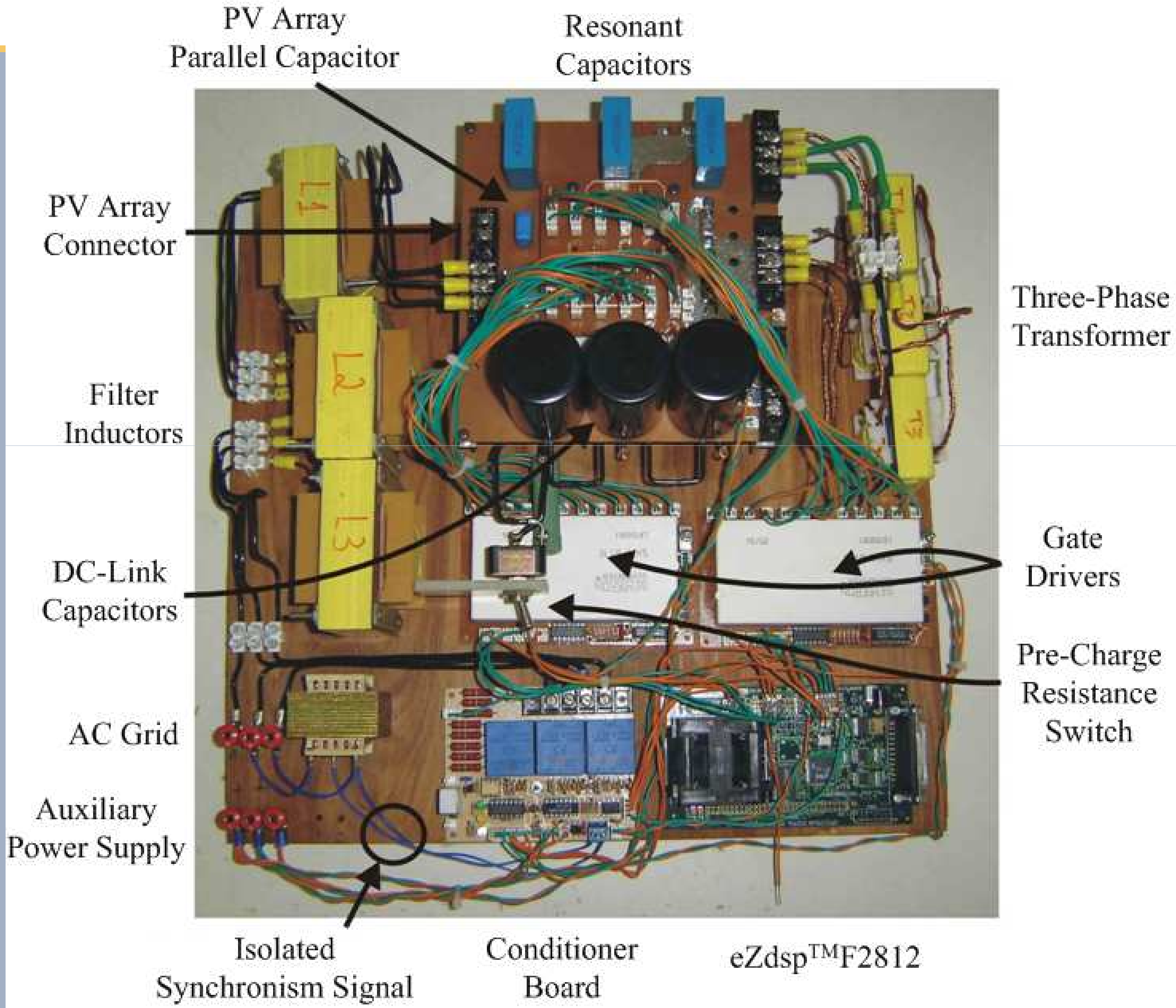
Utility current (IS) and utility voltage (VUtility) with 50% of non-linear load. (Ch1 5A/div and Ch2 50V/div).

Experimental Results



Efficiency of de whole system

9. Prototype


PV Array
Parallel Capacitor
Resonant
Capacitors
PV Array
Connector
Three-Phase
Transformer
Filter
Inductors
DC-Link
Capacitors
Gate
Drivers
Pre-Charge
Resistance
Switch
AC Grid
Auxiliary
Power Supply
Isolated
Synchronism Signal
Conditioner
Board
eZdsp™F2812

CONCLUSIONS

- This work presented in a simple way the modelling and the control strategy of a three-phase PWM inverter to be employed in a grid connected PV generation system using Park transformation.

- The proposed system realize dual function:
  - Solar generation;
  - Active Filter: Harmonic and reactive compensation.

- A concept of behavior matching is introduced to assure the Maximum Power Point (MPP) of the PV array.

- For any situations the Power Factor is always high and the currents present low harmonic distortion.

Contact

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