This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

goPV

Oct. 28th

PV grid-connected Inverter Design & Performance

(14:30-16:30)

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

Antoine DIZIER – INES

PV grid-connected inverters – INES

Agenda of the session

1. Inverter Objectives & Operation
2. Efficiency of grid-connected inverters
3. Types of inverters & Market
4. Inverter sizing and design
5. Inputs on GoPV project

PV grid-connected inverters – INES

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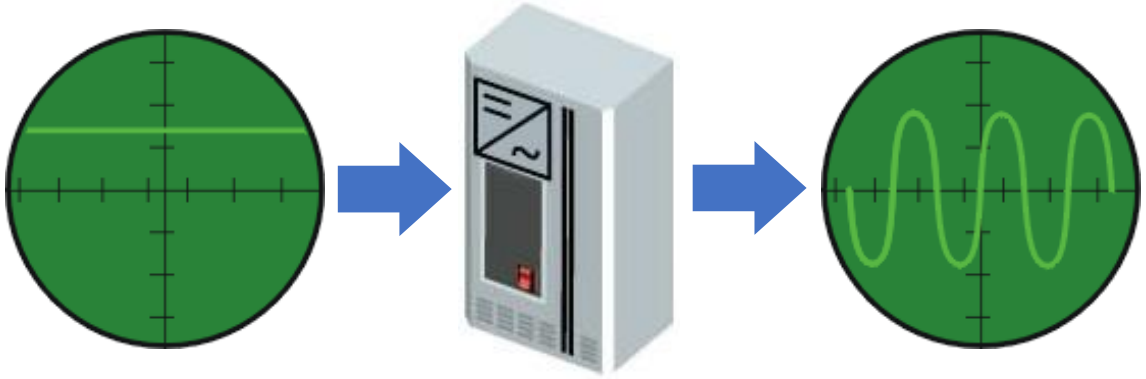
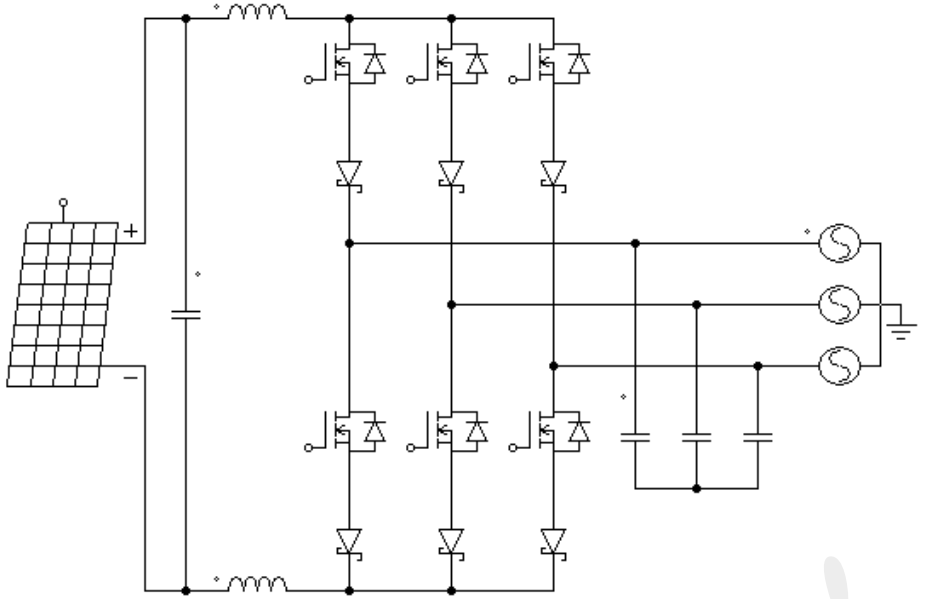
PV inverters – Operation

Converting DC into AC

- Using switch operation to convert DC into AC

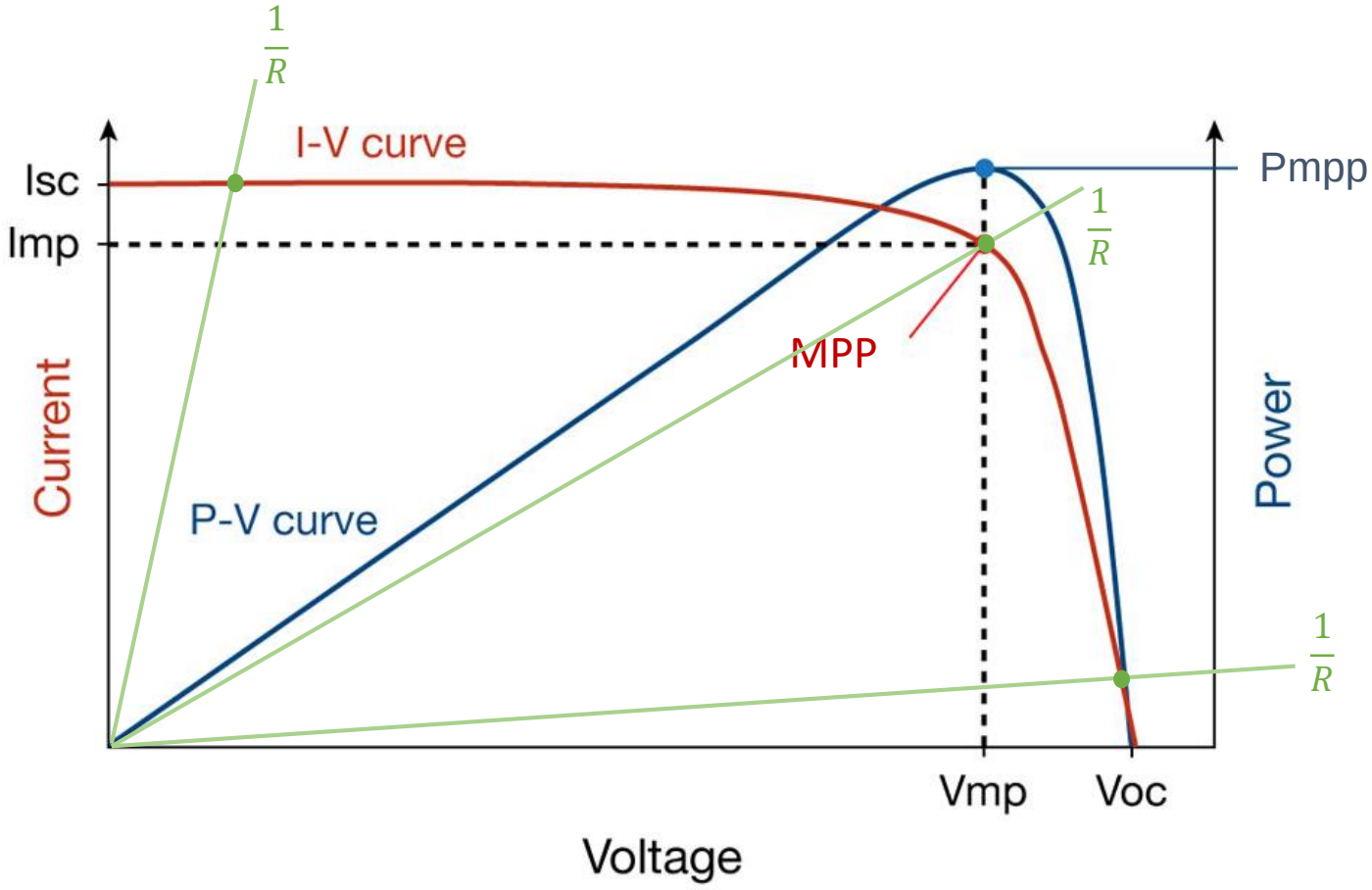




PV inverters – Operation

Finding MPP

1. Indirect Methods
2. Perturb & Observe
3. Incremental Conductance



MPPT Objective → Find Vmpp while decoupling Vpv and Vload

PV inverters – Operation

1. Finding MPP – Indirect Methods

- Constant Voltage Method

Using the specs of the PV array, apply the STC voltage that gets the MPP

- Fractional Open Voltage Method

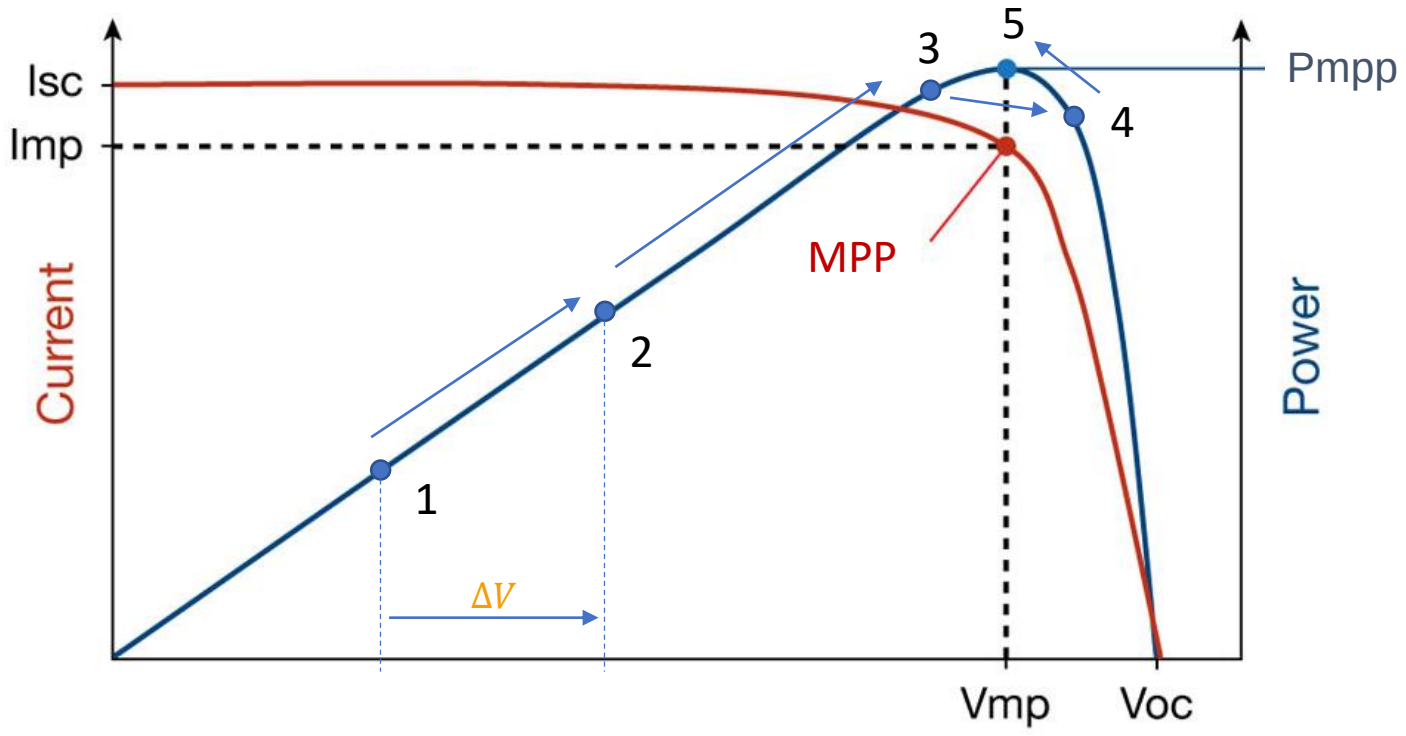
Considering Vmpp is a distinct fraction of Voc, apply a 70-80% fraction to find Vmpp

- Short Current Pulse Method

Considering Impp is a distinct fraction of Isc, apply around 90% fraction to find Impp

2. Finding MPP – Perturb & Observe

- Make incremental changes in the voltage and monitor the power



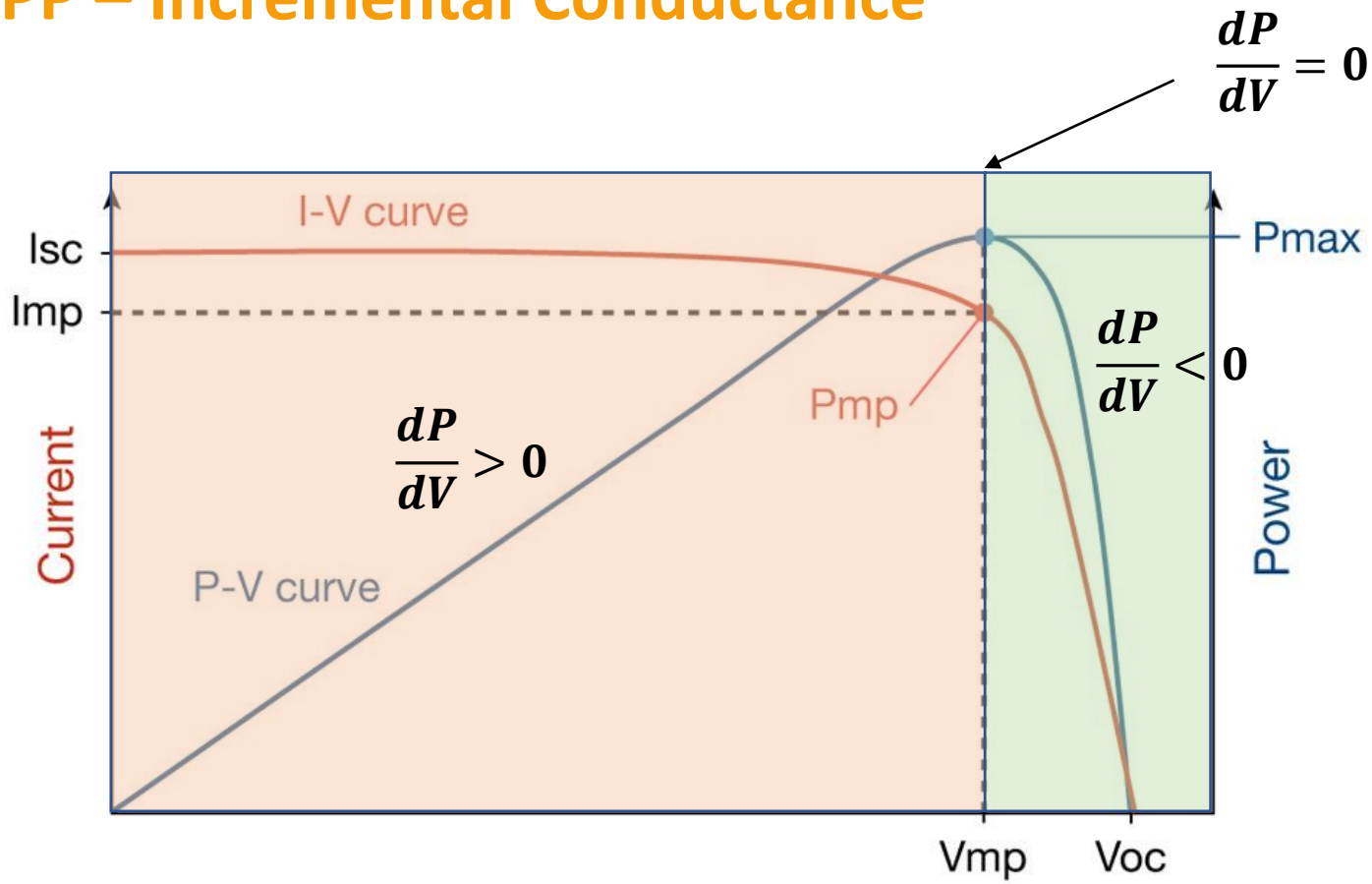
PV inverters – Operation

2. Finding MPP – Perturb & Observe

- Make incremental changes in the voltage and monitor the power

Prior Perturbation	Change in Power	Next Perturbation
Positive	Positive	**Positive**
Positive	Negative	**Negative**
Negative	Positive	**Negative**
Negative	Negative	**Positive**

3. Finding MPP – Incremental Conductance



3. Finding MPP – Incremental Conductance

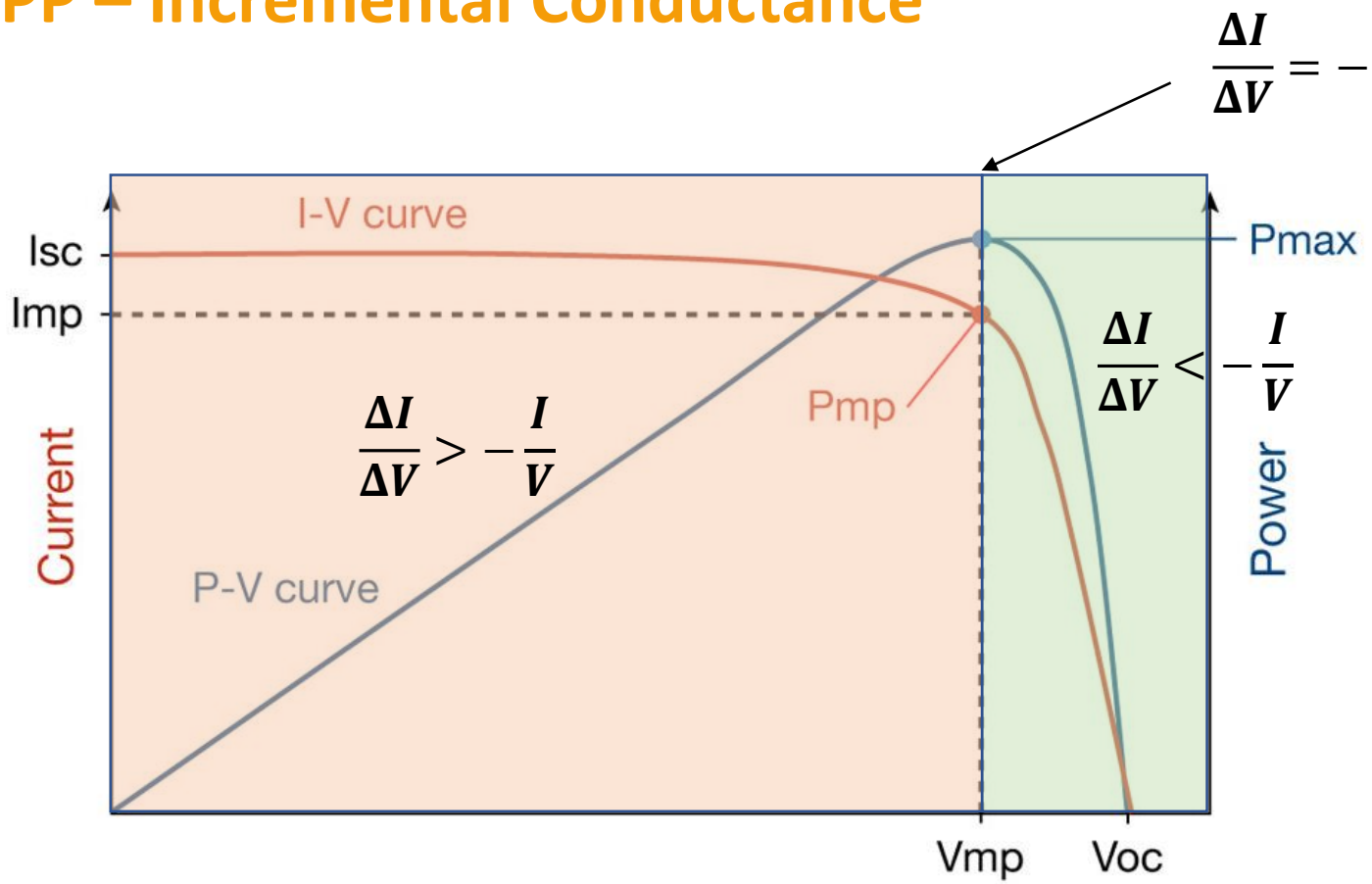
$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} \approx I + V\frac{\boldsymbol{\Delta I}}{\boldsymbol{\Delta V}}$$

Incremental conductance

- Increasing voltage to find Vmpp: $\frac{dP}{dV} > 0 \quad \rightarrow \quad \frac{\boldsymbol{\Delta I}}{\boldsymbol{\Delta V}} > -\frac{\boldsymbol{I}}{\boldsymbol{V}}$
- Decreasing voltage to find Vmpp: $\frac{dP}{dV} < 0 \quad \rightarrow \quad \frac{\boldsymbol{\Delta I}}{\boldsymbol{\Delta V}} < -\frac{\boldsymbol{I}}{\boldsymbol{V}}$
- Finding the right voltage Vmpp: $\frac{dP}{dV} = 0 \quad \rightarrow \quad \frac{\boldsymbol{\Delta I}}{\boldsymbol{\Delta V}} = -\frac{\boldsymbol{I}}{\boldsymbol{V}}$

PV inverters – Operation

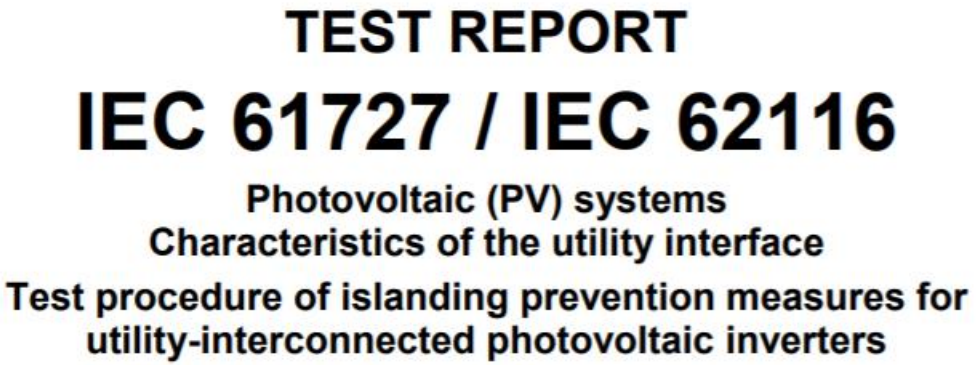
3. Finding MPP – Incremental Conductance



PV inverters – Operation

Standards Compliance

- Automatic isolation → CEI 61727 / IEC 62116
- Electromagnetism compliance → EN 55014
- Harmonics → CEI 61000-3-2
- Security → EN 60950 / CEI 62109



PV grid-connected inverters – INES

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1. Inverter objectives & Operation
2. **Efficiency of grid-connected inverters**
3. Types of inverters & Market
4. Inverter sizing and design
5. Inputs on GoPV project

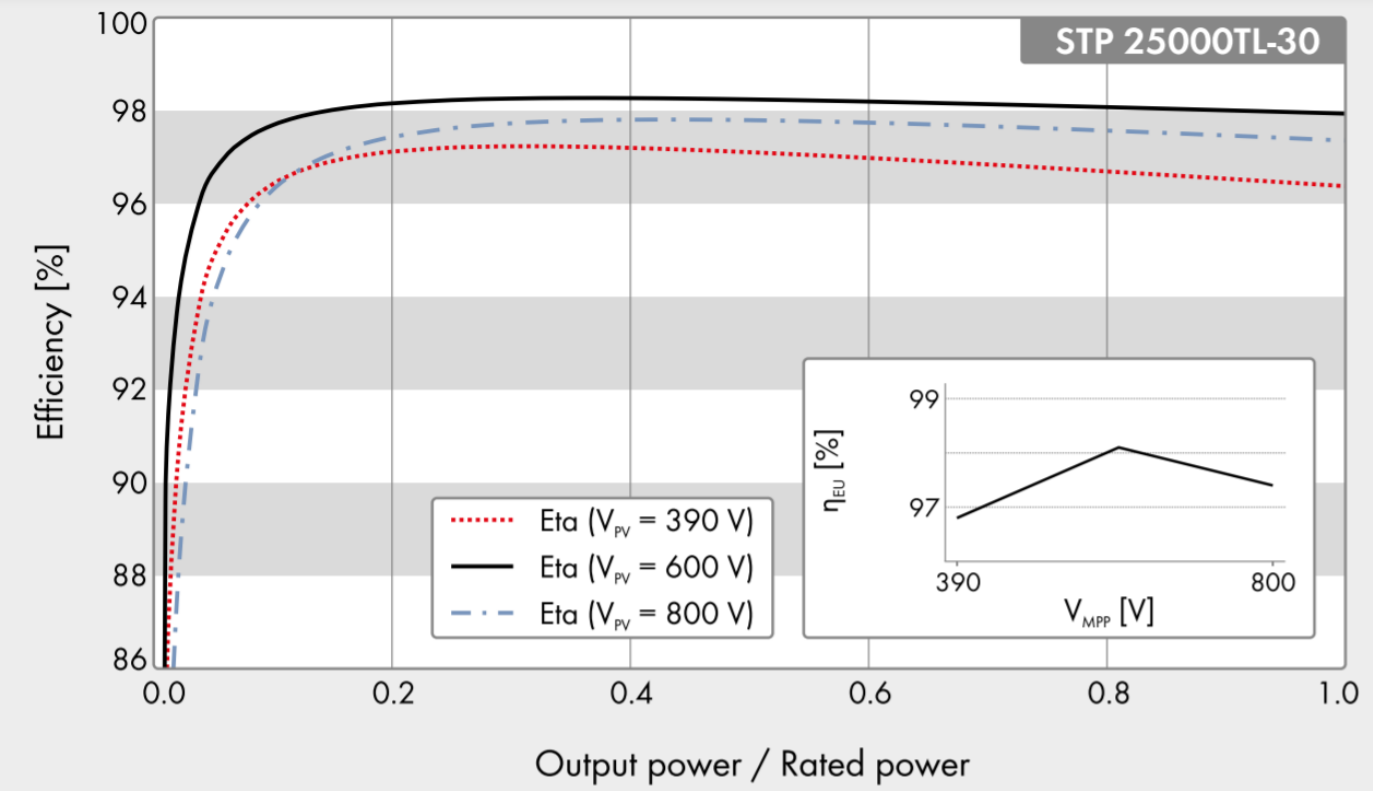
PV inverters – Efficiency

Maximum Efficiency

Efficiency is dependent on:

- Voltage DC range
- Performance of MPPT method
- Output power
- Types of inverter

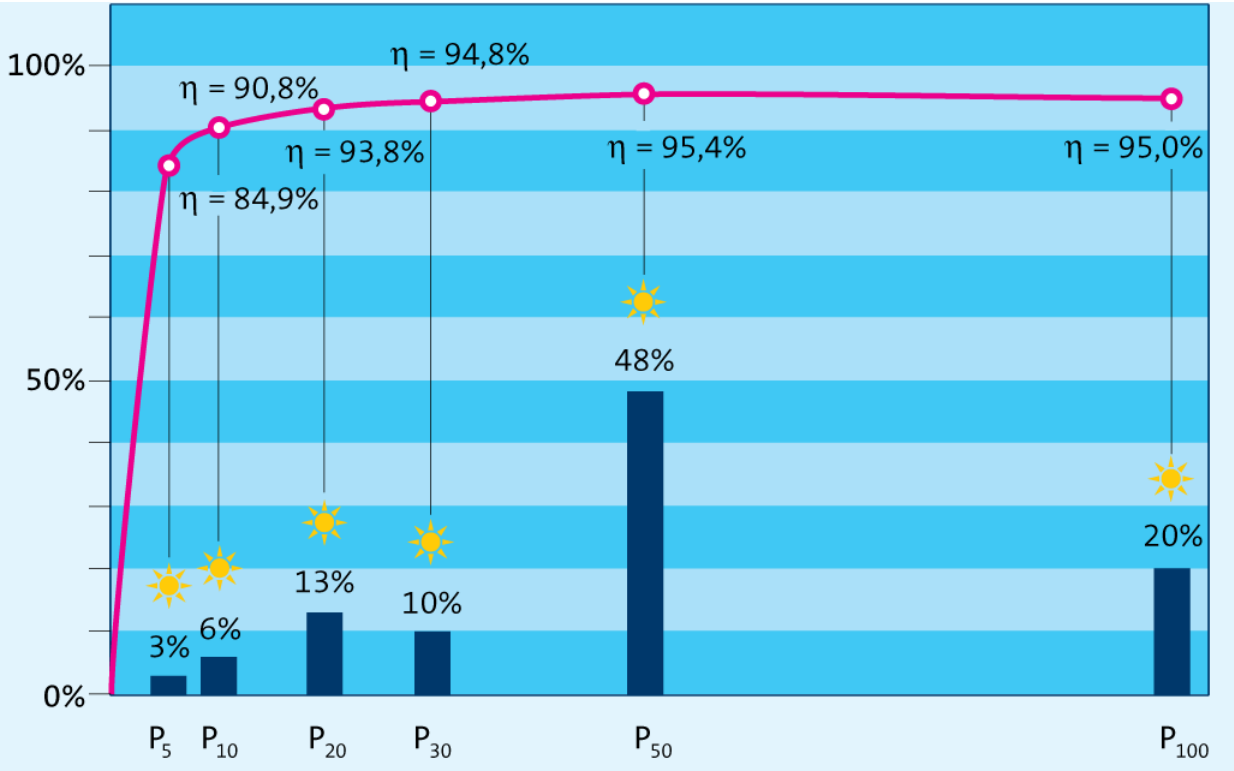
$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \approx 95 - 99\%$$



PV inverters – Efficiency

European & CEC Efficiencies

- Weighted efficiencies – Performance across the range of inverter's capacity



PV inverters – Efficiency

European & CEC Efficiencies

- Weighted efficiencies – Performance across the range of inverter's capacity

European Weighted Efficiency

$$\eta_{\text{euro}} = 0.03 * \eta_{5\%} + 0.06 * \eta_{10\%} + 0.13 * \eta_{20\%} + 0.10 * \eta_{30\%} + 0.48 * \eta_{50\%} + 0.20 * \eta_{100\%}$$

California Energy Commission (CEC) Weighted Efficiency

$$\eta_{\text{CEC}} = 0.04 * \eta_{5\%} + 0.05 * \eta_{10\%} + 0.12 * \eta_{20\%} + 0.21 * \eta_{30\%} + 0.53 * \eta_{50\%} + 0.05 * \eta_{100\%}$$

PV grid-connected inverters – INES

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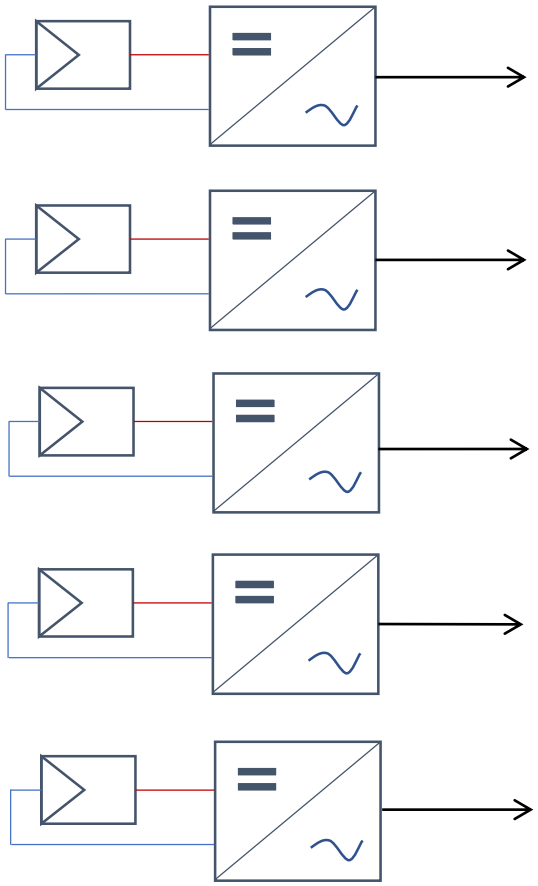
PV inverters – Micro-inverters



ENPHASE

solaredge

APsystems
ALTENERGY POWER

- Interesting flexibility (one MPPT / module) → improving PR
- Few DC wiring
- Individual power monitoring

- High cost in USD / Wp
- Less efficient
- Operating on rear-side (thermal exposition)

PV inverters – Micro-inverter

ENPHASE

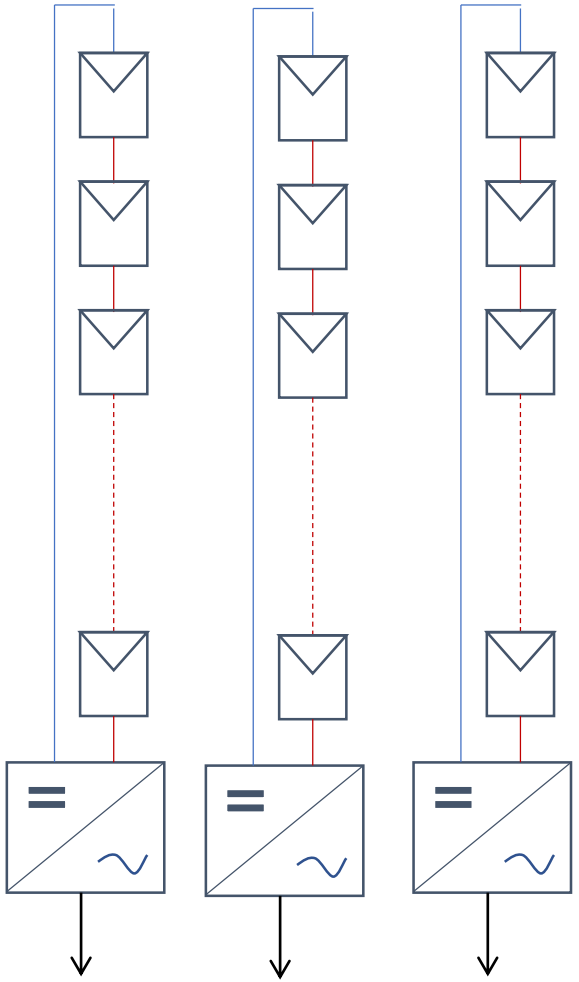
Enphase M250 Microinverter

INPUT DATA (DC)	MODELS: M250-60-2LL-S22, M250-60-2LL-S25	MODELS: M250-72-2LL-S22, M250-72-2LL-S25
Commonly used module pairings[1]	210 - 350+ W	210 - 350+ W
Compatibility	60-cell PV modules	60-cell and 72-cell PV modules
Maximum input DC voltage	48 V	62 V
Peak power tracking voltage	27 V - 39 V	27 V - 48 V
Operating range	16 V - 48 V	16 V - 60V
Min/Max start voltage	22 V / 48 V	22 V / 48 V
Max DC short circuit current	15 A	15 A
OUTPUT DATA (AC)		
Peak output power	250 W	
Maximum continuous output power	240 W	
Nominal output current	1.15 A @ 208 VAC 1.0 A @ 240 VAC	
Nominal voltage/range	208 V / 183-229 V @ 208 VAC 240 V / 211-264 V @ 240 VAC	
Nominal frequency/range	60.0 / 57-61 Hz	
Extended frequency range[2]	57-62.5 Hz	
Power factor	>0.95	
Maximum units per 20 A branch circuit	24 (three-phase 208 VAC) 16 (single phase 240 VAC)	
Maximum output fault current	850 mA rms for 6 cycles	
EFFICIENCY		
CEC weighted efficiency	96.5%	
Peak inverter efficiency	96.5%	
Static MPPT efficiency (weighted, reference EN50530)	99.4%	
Night time power consumption	65 mW max	

DC electrical data

AC electrical data

PV inverters – String Inverters



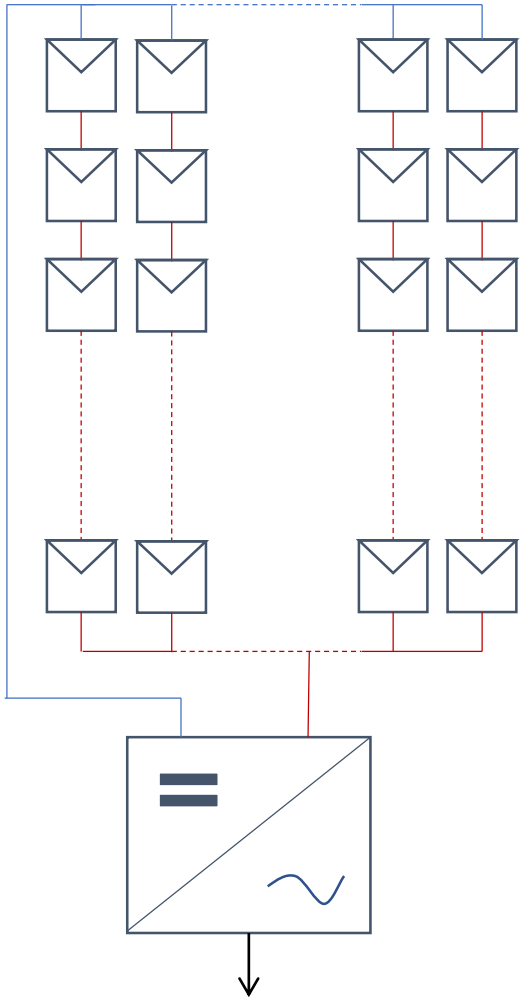
- Interesting with heterogeneous PV arrays
- Multi-MPPT configuration are possible
- Individual replacement & easy access

- Medium cost in USD / Wp
- Concerns about DC wiring (sometimes important on roof-top)

PV inverters – String Inverters

Technical Data	Sunny Boy 4000TL	Sunny Boy 5000TL
Input (DC)		
Max. DC power (at cos φ = 1)	4200 W	5250 W[3]
Max. input voltage	750 V	750 V
MPP voltage range / rated input voltage	175 V to 500 V / 400 V	175 V to 500 V / 400 V
Min. input voltage / initial input voltage	125 V / 150 V	125 V / 150 V
Max. input current input A / input B	15 A / 15 A	15 A / 15 A
Max. input current per string input A / input B	15 A / 15 A	15 A / 15 A
Number of independent MPP inputs / strings per MPP input	2 / A:2; B:2	2 / A:2; B:2
Output (AC)		
Rated power (at 230 V, 50 Hz)	4000 W	4600 W
Max. AC apparent power	4000 VA	5000 VA[2]
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V to 280 V	220 V, 230 V, 240 V / 180 V to 280 V
AC power frequency / range	50 Hz, 60 Hz / −5 Hz to +5 Hz	50 Hz, 60 Hz / −5 Hz to +5 Hz
Rated power frequency / rated grid voltage	50 Hz / 230 V	50 Hz / 230 V
Max. output current	22 A	22 A
Power factor at rated power	1	1
Adjustable displacement power factor	0.8 lagging to 0.8 leading	0.8 lagging to 0.8 leading
Feed-in phases / connection phases	1 / 1	1 / 1
Efficiency		
Max. efficiency / European Efficiency	97 % / 96.4 %	97 % / 96.5 %

PV inverters – Central Inverters



Ingeteam

HUAWEI

SUNGROW
Clean power for all

- High efficiency
- Low cost in USD / Wp
- Interesting and easy installation for homogenous PV field

- Some important mismatch losses can occur
- Lot of space required

PV inverters – Central Inverters

SUNGROW
Clean power for all

Type designation	SG5000UD	SG5000UD-20
Input (DC)		
Max. PV input voltage	1500 V	
Min. PV input voltage / Start-up input voltage	900 V / 915 V	960 V / 990 V
MPP voltage range for nominal power	900 – 1300 V	960 – 1300 V
No. of independent MPP inputs	1	
No. of DC inputs	28 (optional: 36)	28(optional: 36 inputs)
Max. PV input current	5669 A	6112 A
Max. DC short-circuit current	10000 A	
Output (AC)		
AC output power	5000 kVA @ 45 ℃	5750 kVA @ 25 ℃ / 5500 kVA @ 45 ℃ / 5000 kVA @ 50 ℃
Max. AC output current	4812 A	5030 A
Nominal AC voltage	600 V	660 V
AC voltage range	510 – 660 V	561 – 726 V
Nominal grid frequency / Grid frequency range	50 Hz / 45 – 55 Hz, 60 Hz / 55 – 65 Hz	
THD	< 3 % (at nominal power)	
DC current injection	< 0.5 % In	
Power factor at nominal power / Adjustable power factor	> 0.99 / 0.8 leading – 0.8 lagging	
Feed-in phases / connection phases	3 / 3	
Efficiency		
Max. efficiency	99.0%	
European efficiency	98.7 %	

PV inverters – Market

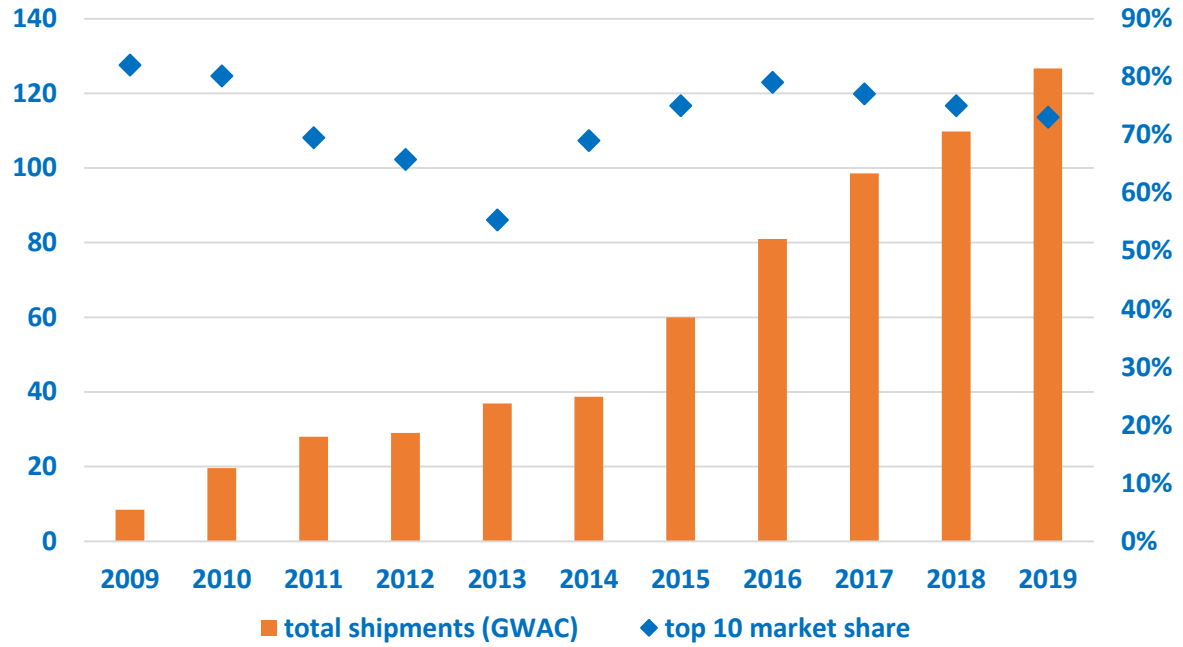
Global PV inverter shipments, 2019 (MW)

Top 10		
	Huawei	CN
	Sungrow Power Supply	CN
	SMA*	DE
	Power Electronics	US
	Fimer	IT
	Sineng	CN
	SolarEdge Technologies	US/IL
	Growatt	CN
	TMEIC*	JPN
	Ginlong Solis	CN
	GoodWe	
	Fronius*	
	Ingeteam	
	TBEA Sunoasis*	
	KSTAR*	
	Chint Power Systems	
	All Others	

* Estimate

Source: Wood Mackenzie

Annual Inverter Shipments and Top 10 Market Share



PV inverters – Market

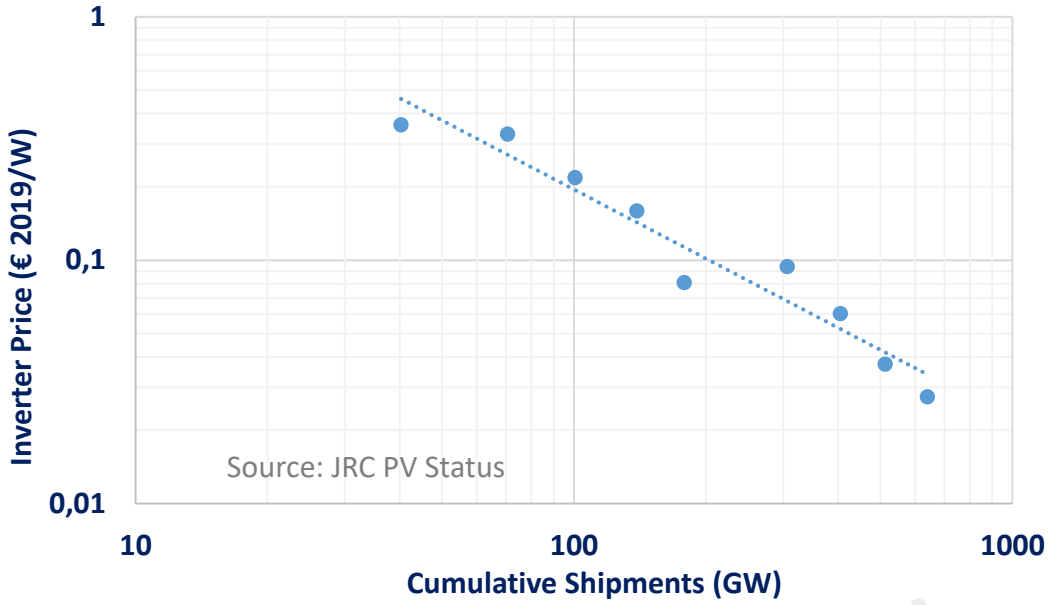
Inverter / Converter	Power	Efficiency	Market Share (Estimated)	Remarks
String Inverters	up to 80 kWp	up to 98%	~ 52%	• 6 - 17 €-cents /Wp • Easy to replace
Central Inverters	More than 80 kWp	up to 98.5%	~ 44%	• ~ 5 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-95%	~ 1%	• ~ 28 €-cents /Wp • Ease-of-replacement concerns
DC / DC Converters (Power Optimizer)	Module Power Range	up to 98.8%	~ 3%	• ~ 9 €-cents /Wp • Ease-of-replacement concerns • Output is DC with optimized current • Still a DC / AC inverter is needed • ~ 3 GWp installed in 2017

Data: IHS 2016. Remarks: Fraunhofer ISE 2018. Design: PSE GmbH 2018

37

Fraunhofer

Evolution of Central Inverter Price (€ 2019) vs Cumulative Shipments (GW)



PV grid-connected inverters – INES

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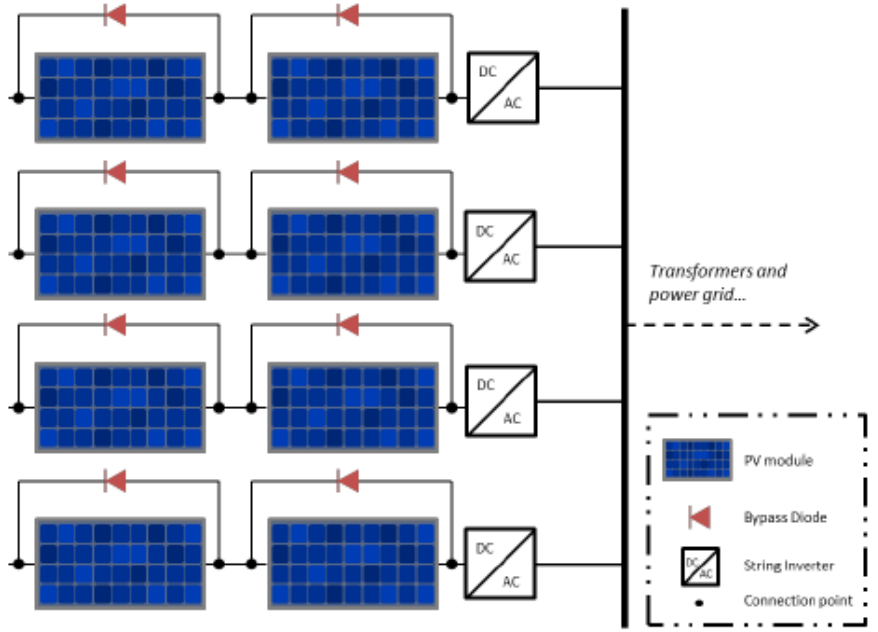
PV inverters – Sizing

Sizing criteria for inverter selection

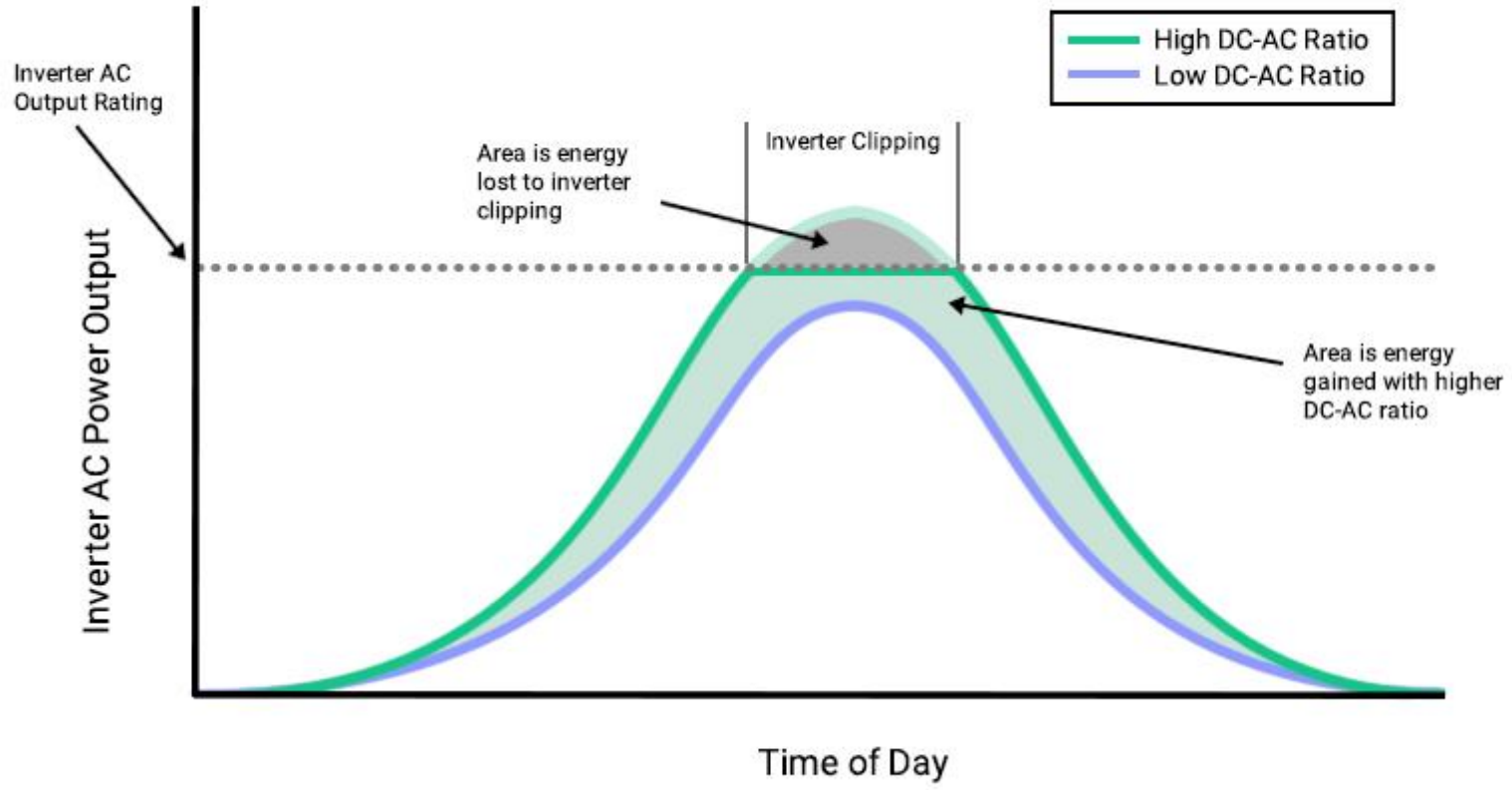
- Quality and performance of MPPT method
- Number of MPPT inputs
- Maximum input voltage (typically 1000V or 1500V)
- Large MPP voltage range
- High weighted efficiency (EURO or CEC)
- Output AC power



PV inverters – Power Sizing

Using DC/AC ratio to undersize inverter

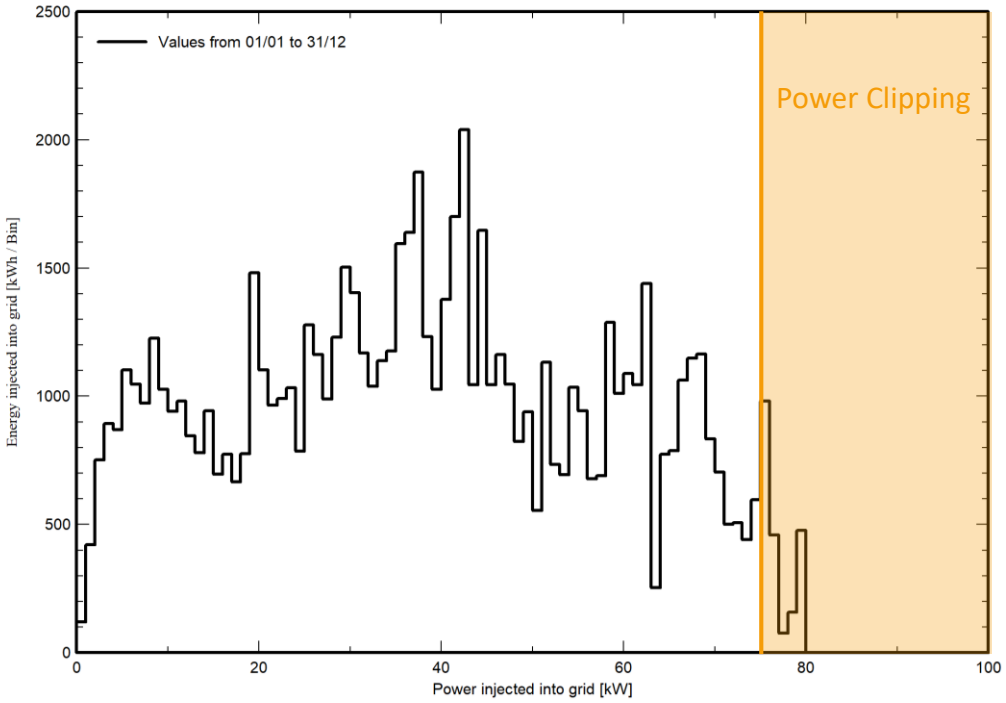
- Typically in the range of 1.05 to 1.25



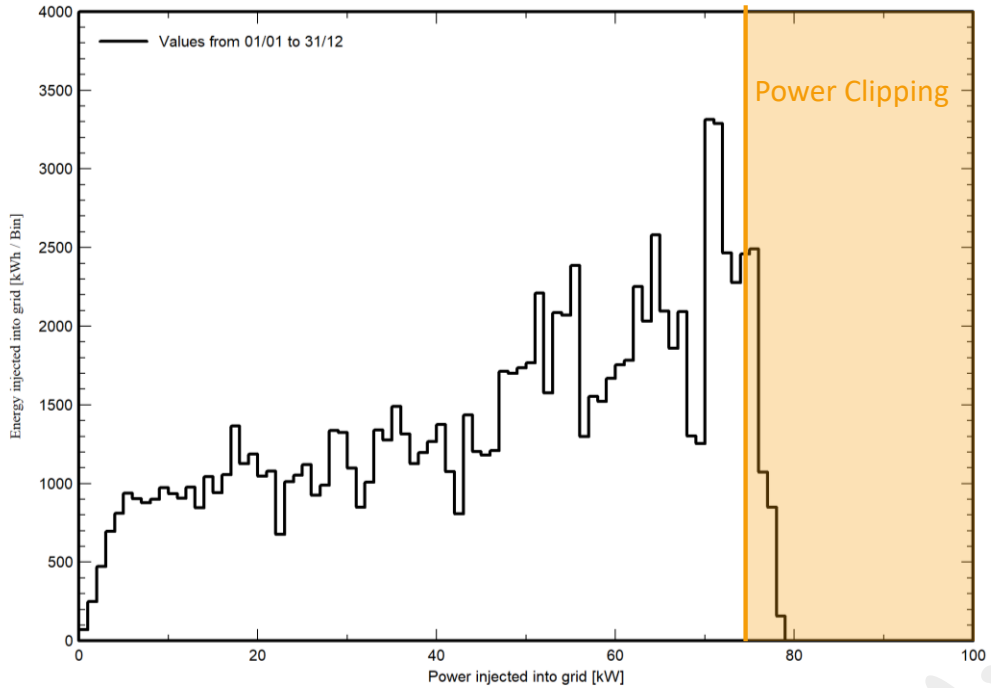
PV inverters – Power Sizing

Using DC/AC ratio to undersize inverter

- Heavily dependent of PV field type → Case study with a 95 kWp PV plant and ratio = 1.25



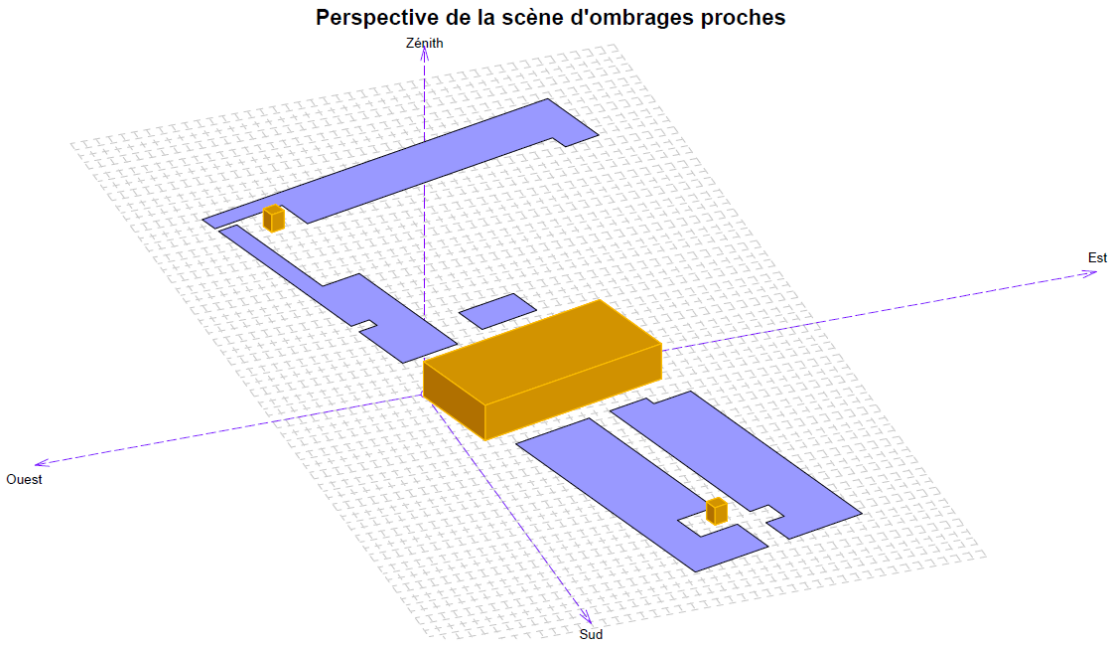
Tilt = 90°



Tilt = 15°

PV inverters – Power Sizing

Multi-MPPT configuration



Caractéristiques des champs de capteurs (3 type de champs définis)

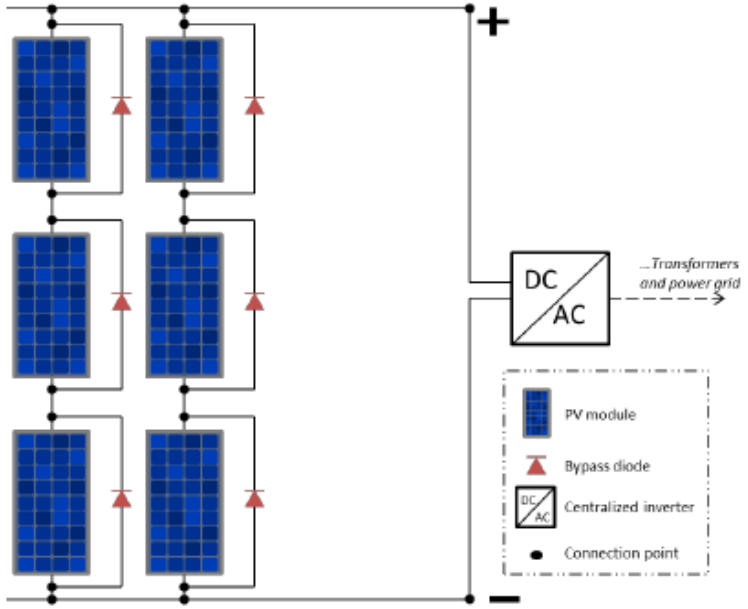
Module PV (Custom parameters definition)	Si-poly	Modèle	**P660 305**		
		Fabricant	GCL		
Sous-champ "Sous-champ #1"					
Nombre de modules PV		En série	20 modules	En parallèle	8 chaînes
Nombre total de modules PV		Nbre modules	160	Puissance unitaire	305 Wc
Puissance globale du champ		Nominale (STC)	**48.8 kWc**	Aux cond. de fonct.	44.9 kWc (50°C)
Caractéristiques de fonct. du champ (50°C)		U mpp	603 V	I mpp	74 A
Sous-champ "Sous-champ #2"					
Nombre de modules PV		En série	19 modules	En parallèle	6 chaînes
Nombre total de modules PV		Nbre modules	114	Puissance unitaire	305 Wc
Puissance globale du champ		Nominale (STC)	**34.8 kWc**	Aux cond. de fonct.	32.0 kWc (50°C)
Caractéristiques de fonct. du champ (50°C)		U mpp	573 V	I mpp	56 A
Sous-champ "Sous-champ #3"					
Nombre de modules PV		En série	18 modules	En parallèle	2 chaînes
Nombre total de modules PV		Nbre modules	36	Puissance unitaire	305 Wc
Puissance globale du champ		Nominale (STC)	**10.98 kWc**	Aux cond. de fonct.	10.10 kWc (50°C)
Caractéristiques de fonct. du champ (50°C)		U mpp	542 V	I mpp	19 A
Total	Puissance globale champs	Nominale (STC)	**95 kWc**	Total	310 modules
		Surface modules	**504 m²**		

Onduleur (Custom parameters definition)		Modèle	**SUN2000-36kTL-G400**		
		Fabricant	Huawei Technologies		
Caractéristiques	Tension de fonctionnement		200-1000 V	Puissance unitaire	36.0 kWac
Sous-champ "Sous-champ #1"		Nbre d'onduleurs	4 * MPPT 25 %	Puissance totale	36 kWac
Sous-champ "Sous-champ #2"		Nbre d'onduleurs	3 * MPPT 25 %	Puissance totale	27 kWac
Sous-champ "Sous-champ #3"		Nbre d'onduleurs	1 * MPPT 25 %	Puissance totale	9.0 kWac
Total		Nbre d'onduleurs	2	Puissance totale	72 kWac

PV inverters – Voltage / Current Sizing

Electrical design in extreme meteorological conditions

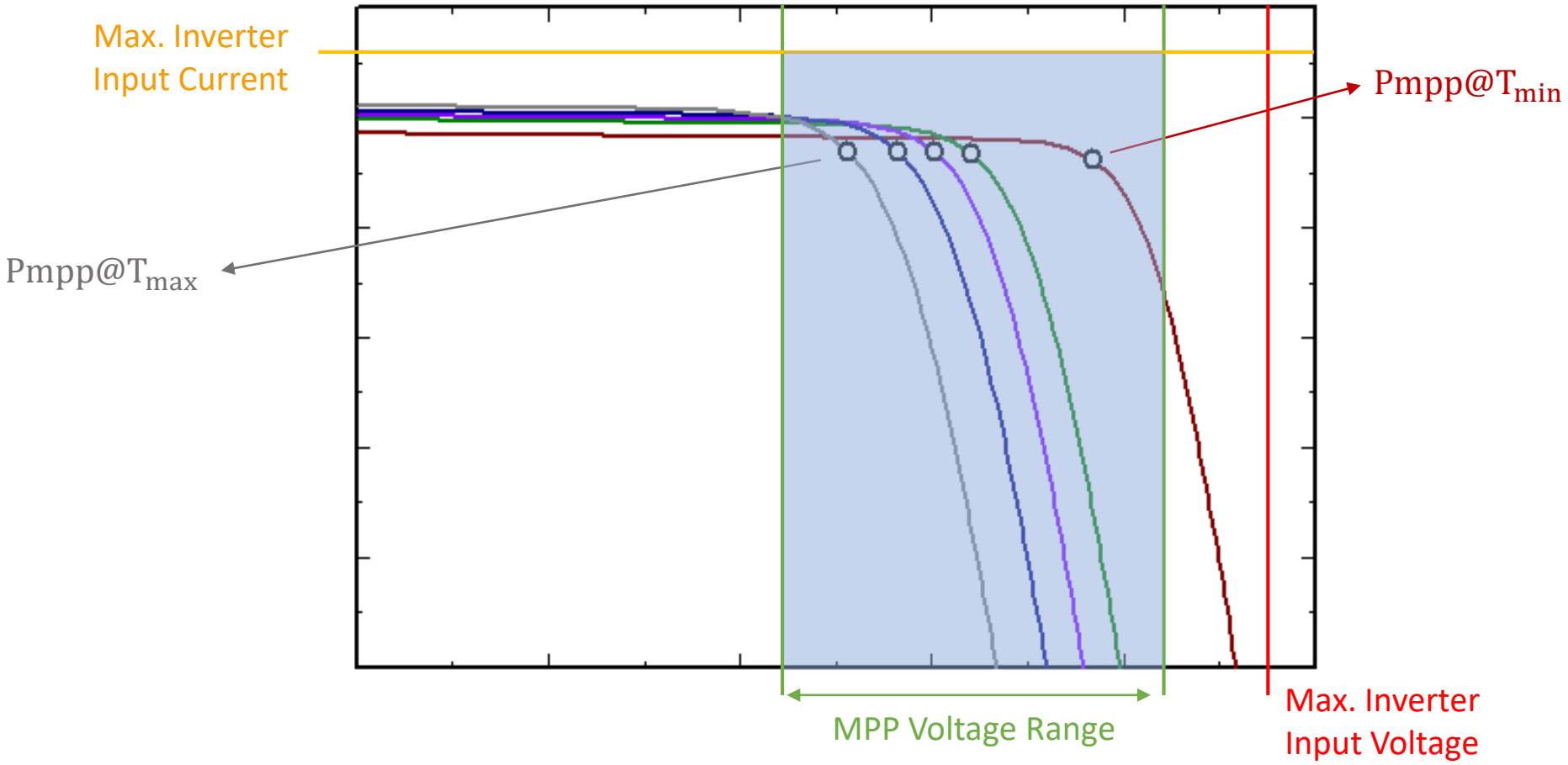
- **Max.** Voltage = PV Voltage with **Min. Temperature**
- **Min.** Voltage = PV Voltage with **Max. Temperature**
- **Max.** Current = PV Current with **Max. Global Irradiance**



➢ **Check electrical compliance with inverter electrical characteristics**

PV inverters – Voltage / Current Sizing

Electrical design in extreme meteorological conditions



PV inverters – Global Sizing

Critical inverter sizing conditions

- Peak Power STC $<$ Output AC Power $<$ Peak power STC $*$ 1.25
- Max. OC Voltage of PV array $<$ Max. Inverter Input Voltage
- Max. MPP Voltage of PV array $<$ Max. Inverter MPP Voltage Range
- Min. MPP Voltage of PV array $>$ Min. Inverter MPP Voltage Range
- Max. SC current of PV array $<$ Max. Inverter SC Input Current

PV inverters – Global Sizing

Critical inverter sizing conditions

- Peak Power STC $<$ Output AC Power $<$ Peak power STC $*$ 1.25
- $V_{OC}@T_{min} * N_{series}$ $<$ Max. Inverter Input Voltage
- $V_{MPP}@T_{min} * N_{series}$ $<$ Max. Inverter MPP Voltage Range
- $V_{MPP}@T_{max} * N_{series}$ $>$ Min. Inverter MPP Voltage Range
- $I_{SC}@T_{max}@G_{max} * N_{parallel}$ $<$ Max. Inverter SC Input Current

Objective → **Find** N_{series} **&** $N_{parallel}$

PV inverters – Case study

Critical inverter sizing conditions

Electrical Properties (STC*)

Model		LG335N1C-A5	LG330N1C-A5	LG325N1C-A5
Maximum Power (Pmax)	[W]	335	330	325
MPP Voltage (Vmpp)	[V]	34.1	33.7	33.3
MPP Current (Impp)	[A]	9.83	9.80	9.77
Open Circuit Voltage (Voc)	[V]	41.0	40.9	40.8
Short Circuit Current (Isc)	[A]	10.49	10.45	10.41
Module Efficiency	[%]	19.6	19.3	19.0
Operating Temperature	[°C]	-40 ~ +90		
Maximum System Voltage	[V]	1000 (UL / IEC)		
Maximum Series Fuse Rating	[A]	20		
Power Tolerance	[%]	0 ~ +3		

* STC (Standard Test Condition): Irradiance 1000 W/m², cell temperature 25 °C, AM 1.5
The nameplate power output is measured and determined by LG Electronics at its sole and absolute discretion.
The Typical change in module efficiency at 200 W/m² in relation to 1000 W/m² is -2.0%.

LG NeON® 2

Technical Data	Sunny Tripower 20000TL
Input (DC)	
Max. generator power	36000 Wp
DC rated power	20440 W
Max. input voltage	1000 V
MPP voltage range / rated input voltage	320 V to 800 V / 600 V
Min. input voltage / start input voltage	150 V / 188 V
Max. input current input A / input B	33 A / 33 A
Number of independent MPP inputs / strings per MPP input	2 / A:3; B:3
Output (AC)	
Rated power (at 230 V, 50 Hz)	20000 W
Max. AC apparent power	20000 VA

SMA

PV inverters – Case study

Data - Module	
Voc,max	45.0 V
Vmpp,max	37.1 V
Vmpp,min	28.9 V
Isc,max	11.6 A

Data - Inverter	
Vdc,max	1000 V
Vrange,min	320 V
Vrange,max	800 V
Idc,max (per MPP)	33 A

$$V_{OC\,MAX} * N_{series} \leq V_{input\,max}^{DC} \quad \text{i.e.} \quad N_{series} \leq \frac{1000}{45.0} = 22{,}2 \quad \text{i.e.} \quad N_{series} \leq 22$$

$$V_{mpp\,MIN} * N_{series} \geq V_{min}^{DC}\,(MPP) \quad \text{i.e.} \quad N_{series} \geq \frac{320}{28.9} = 11{,}07 \quad \text{i.e.} \quad N_{series} \geq \mathbf{12}$$

$$V_{mpp\,MAX} * N_{series} \leq V_{max}^{DC}\,(MPP) \quad \text{i.e.} \quad N_{series} \leq \frac{800}{37.1} = 21{,}6 \quad \text{i.e.} \quad N_{series} \leq \mathbf{21}$$

$$I_{SC\,MAX} * N_{parallel} \leq I_{max}^{DC} \quad \text{i.e.} \quad N_{parallel} \leq \frac{33}{11{,}6} = 2{,}9 \quad \text{i.e.} \quad \mathbf{N_{parallel} \leq 2}$$

PV grid-connected inverters – INES

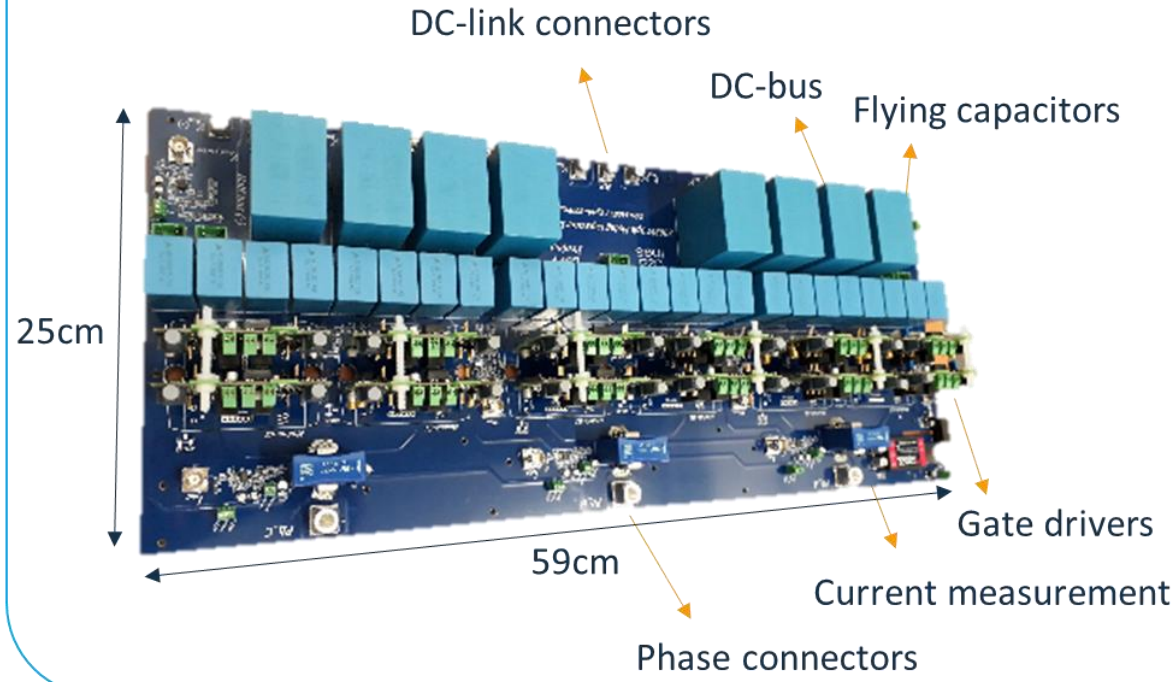
Agenda of the session

1. Inverter objectives & Operation
2. Efficiency of grid-connected inverters
3. Types of inverters & Market
4. Inverter sizing and design
5. **Inputs on GoPV project**

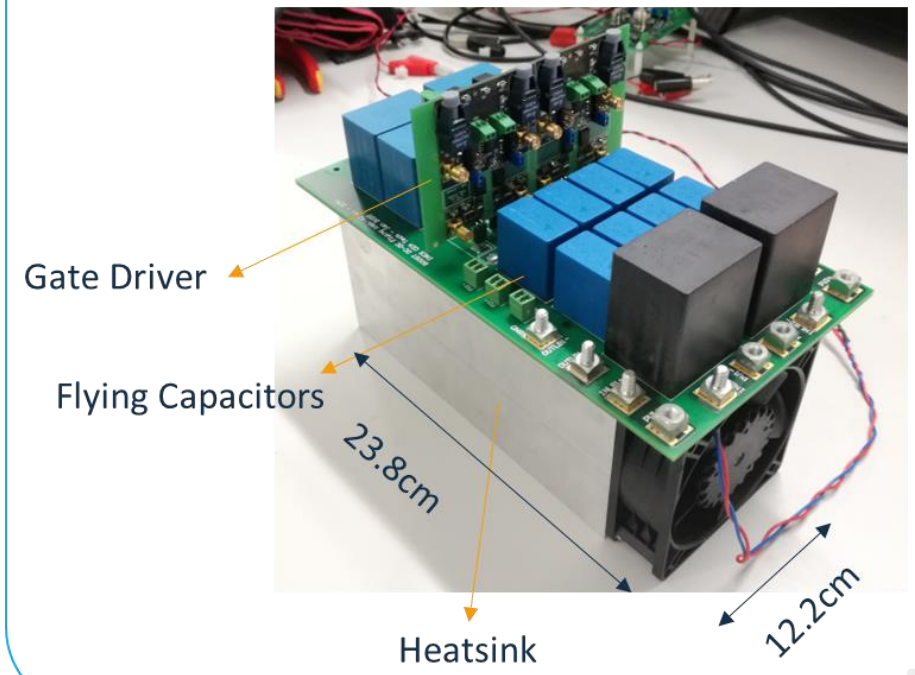
PV inverters – GoPV Project

166kVA multi-MPPT Inverter base on Flying Capacitor topology

DC/AC Power Board



DC/DC Power Board



- Up to 1500 V_{OC} PV string, inject full power on 800V 3~ grid
- Multi MPPT: 2 PV strings per MPPT, 8 MPPT in parallel (= 16 strings)

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

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Thank you for your attention!

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