TOPOLOGIES AND MAXIMUM POWER POINT TRACKING ALGORITHMS FOR PHOTOVOLTAIC SYSTEMS

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Outline of the Presentation

1. Introduction
2. Physical Specs & Characteristics PV
3. Island Mode and Grid Interactive Applications,
4. System Configurations,
5. Conversation Stage,
6. Maximum Power Point Tracking Concept,
7. DC/DC Converters,
8. DC/AC Converters,

1- Introduction

- Due to environment issues such as

  - global warming and pollution,

  - limited resources of fossil based fuels and energy crisis,

renewable energy sources such as photovoltaic (PV) array, wind turbine, fuel cell, biomass system and the geothermal systems are becoming more and more popular in industrial and also residential scale applications.

1- Introduction

Solar Energy:

- PV modules have been used since 1950s.
- They convert solar energy to DC electrical energy.
- Solar energy is inexhaustible fuel and has no cost.
- They can be installed different power levels from a few watts to Megawatts.

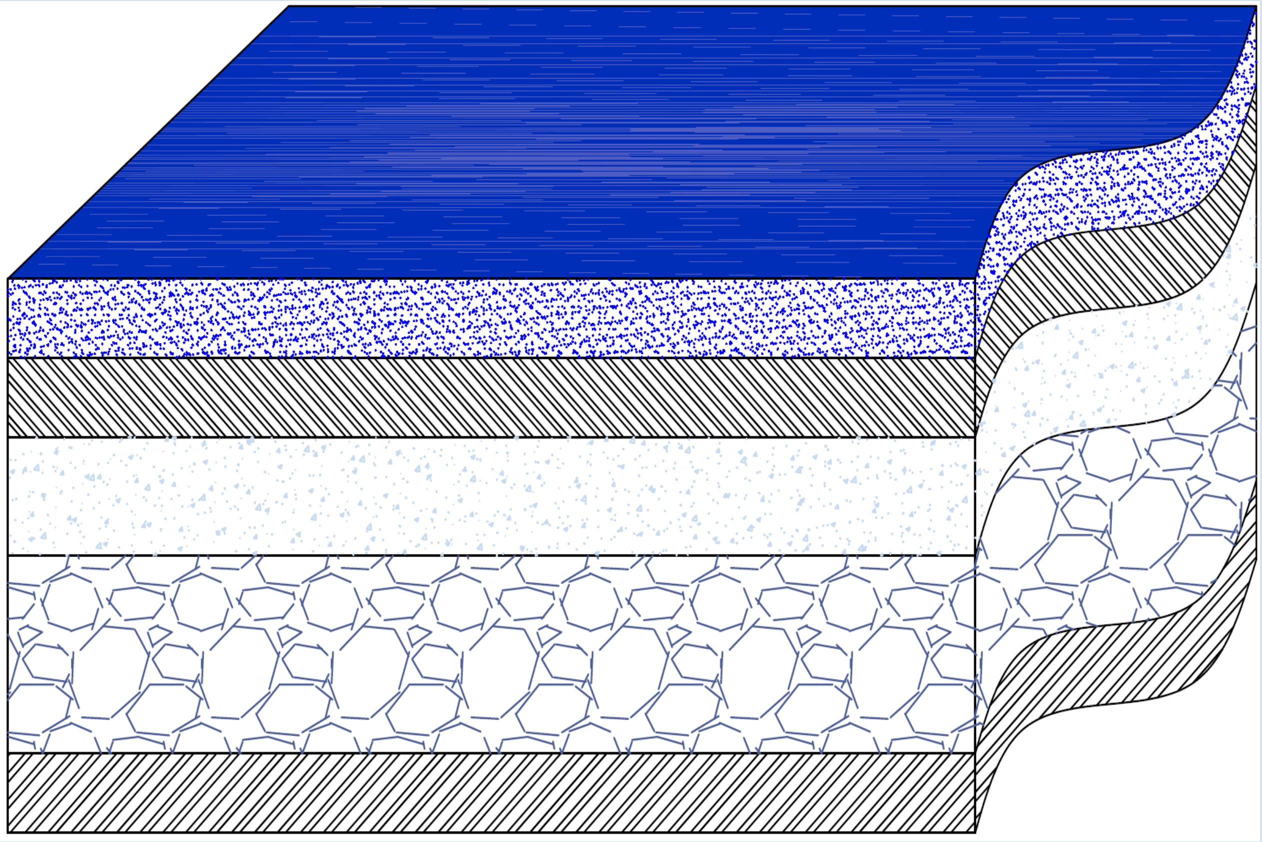
1- Introduction

- At the beginning, photovoltaic (PV) are used at remote areas where the public grid is not available.
- Agricultural irrigation, telecommunication receivers & transmitters, highway signalization and lighting systems are the instant applications of PVs.
- Residential applications of the PV increase with decreasing cost of these sources.

1- Introduction

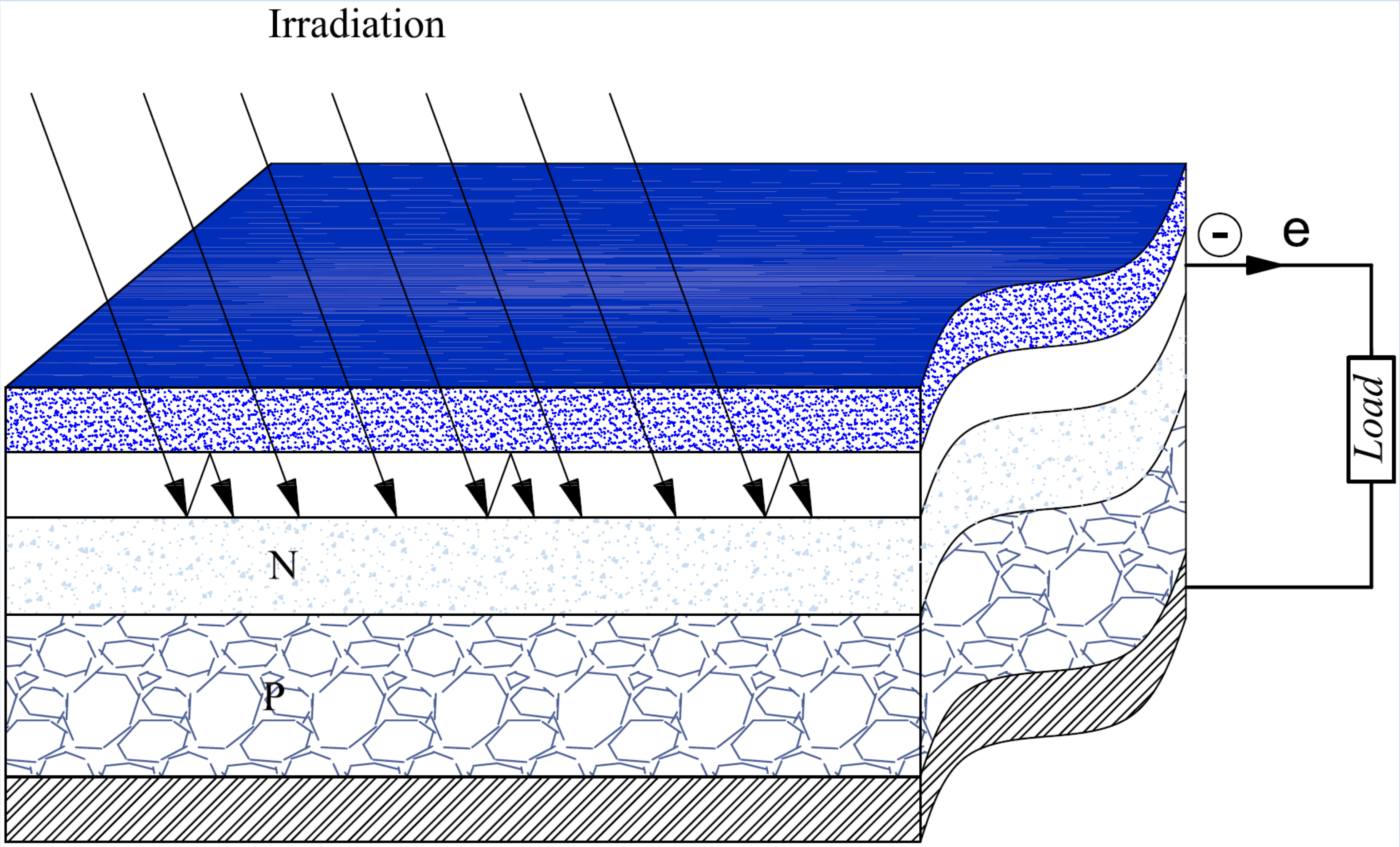
- PV generates DC electrical energy.
- Because the most of the loads operates with AC electrical energy, DC energy must be converted to AC energy with constant voltage and constant frequency (CVCF).
- Also, PV should be operated according to their efficiency characteristics.

2- Specifications & Characteristics (PV)



PV Structure

2- Specifications & Characteristics (PV)



PV Electrical Model

2- Specifications & Characteristics (PV)

Standard Test Conditions (STC) *STC = 1000 W/M² irradiance, 25°C module temperature, AM 1.5 spectrum**			
	KD315GX-LPB	KD320GX-LPB	
P_{mp}	315	320	W
V_{mp}	39.8	40.1	V
I_{mp}	7.92	7.99	A
V_{oc}	49.2	49.5	V
I_{sc}	8.50	8.60	A
$P_{tolerance}$	+5/-3	+5/-3	%

Datasheet of a commercial PV module

2- Specifications & Characteristics (PV)

Nominal Operating Cell Temperature Conditions (NOCT) *NOCT = 800 W/M² irradiance, 20°C ambient temperature, AM 1.5 spectrum**			
T_{NOCT}	45	45	°C
P_{max}	226	230	W
V_{mp}	35.8	36.1	V
I_{mp}	6.34	6.40	A
V_{oc}	45.0	45.3	V
I_{sc}	6.88	6.96	A
PTC	276.4	280.9	W

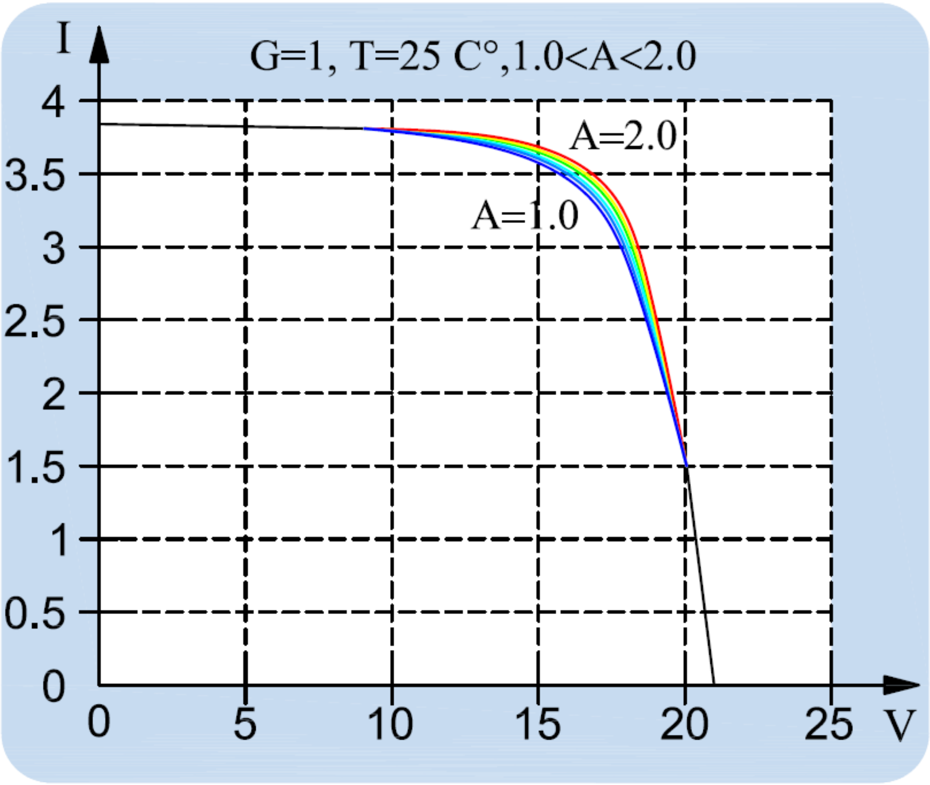
Datasheet of a commercial PV module

2- Specifications & Characteristics (PV)

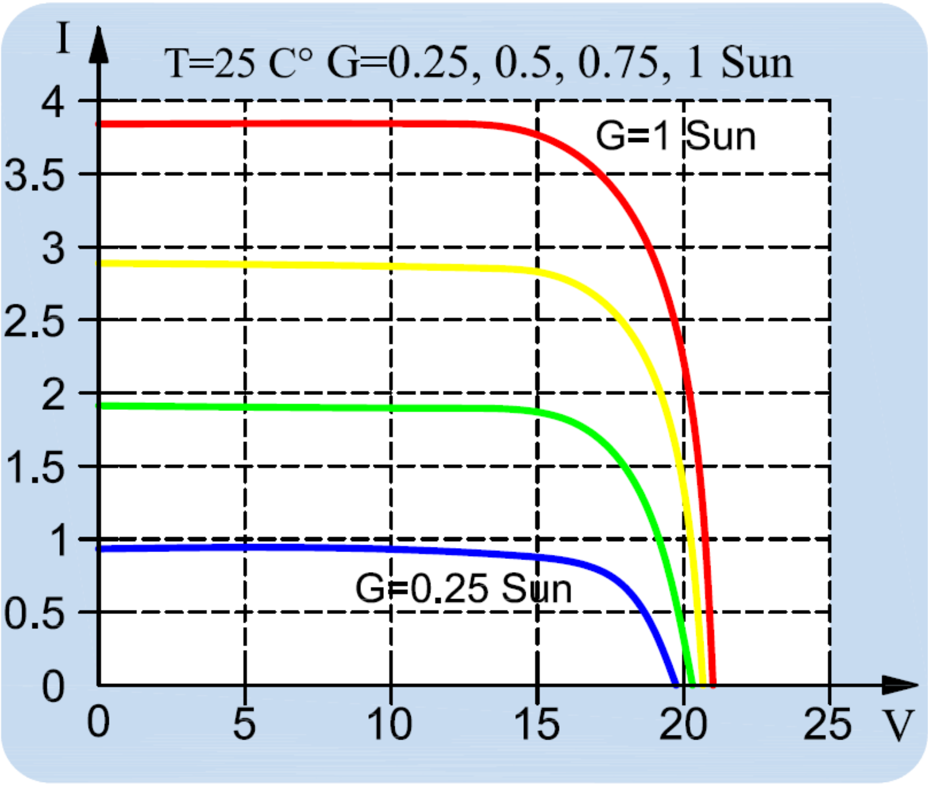
Temperature Coefficients			
P_{max}	-0.46	-0.45	%/°C
V_{mp}	-0.52	-0.51	%/°C
I_{mp}	0.0064	0.0065	%/°C
V_{oc}	-0.36	-0.36	%/°C
I_{sc}	0.061	0.060	%/°C
Operating Temp	-40 to +90	-40 to +90	%/°C

Datasheet of a commercial PV module

2- Specifications & Characteristics (PV)



(a)

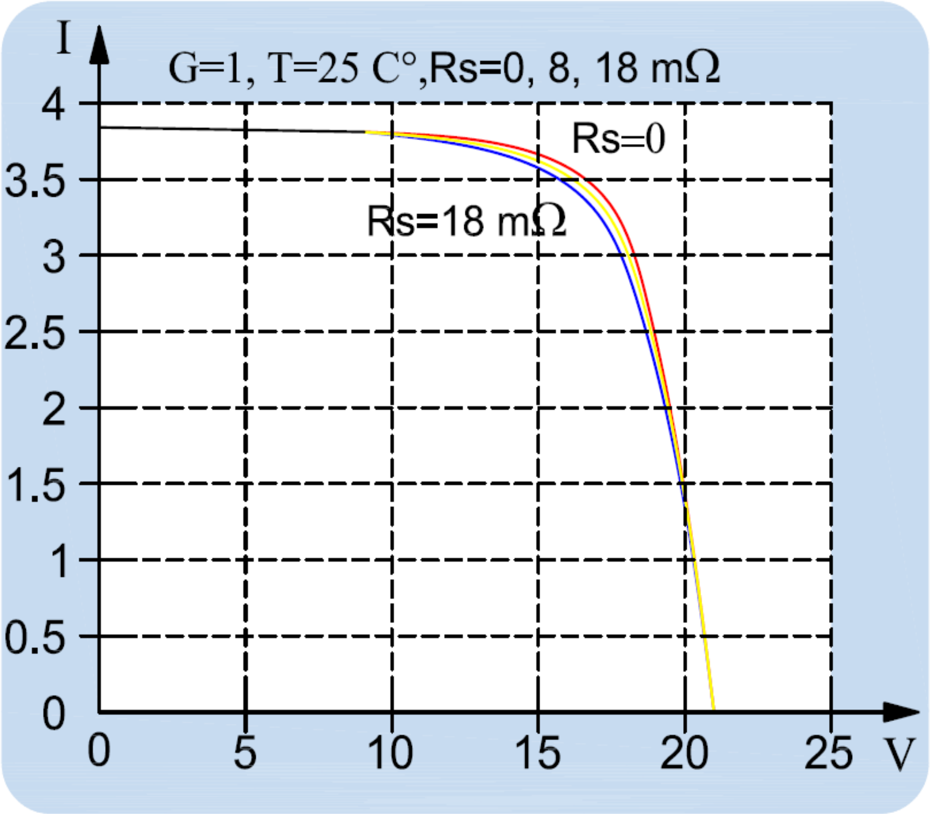


(b)

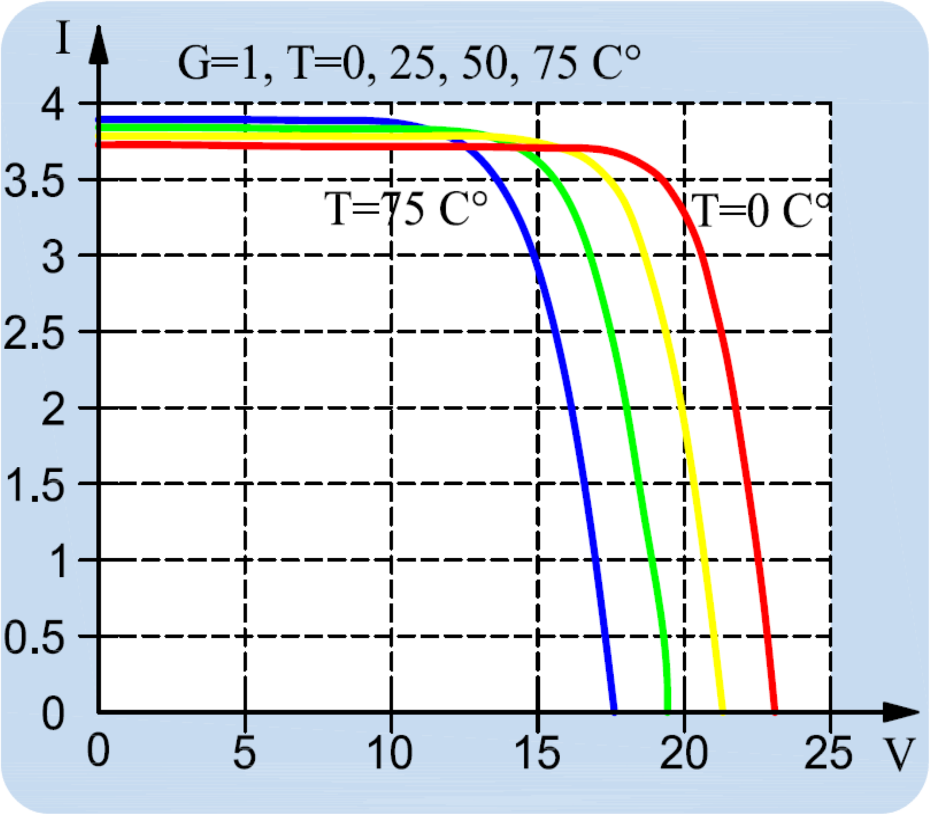
a) Variation of PV voltage and current with quality factor,

b) Variation of PV voltage and current with irradiation level,

2- Specifications & Characteristics (PV)



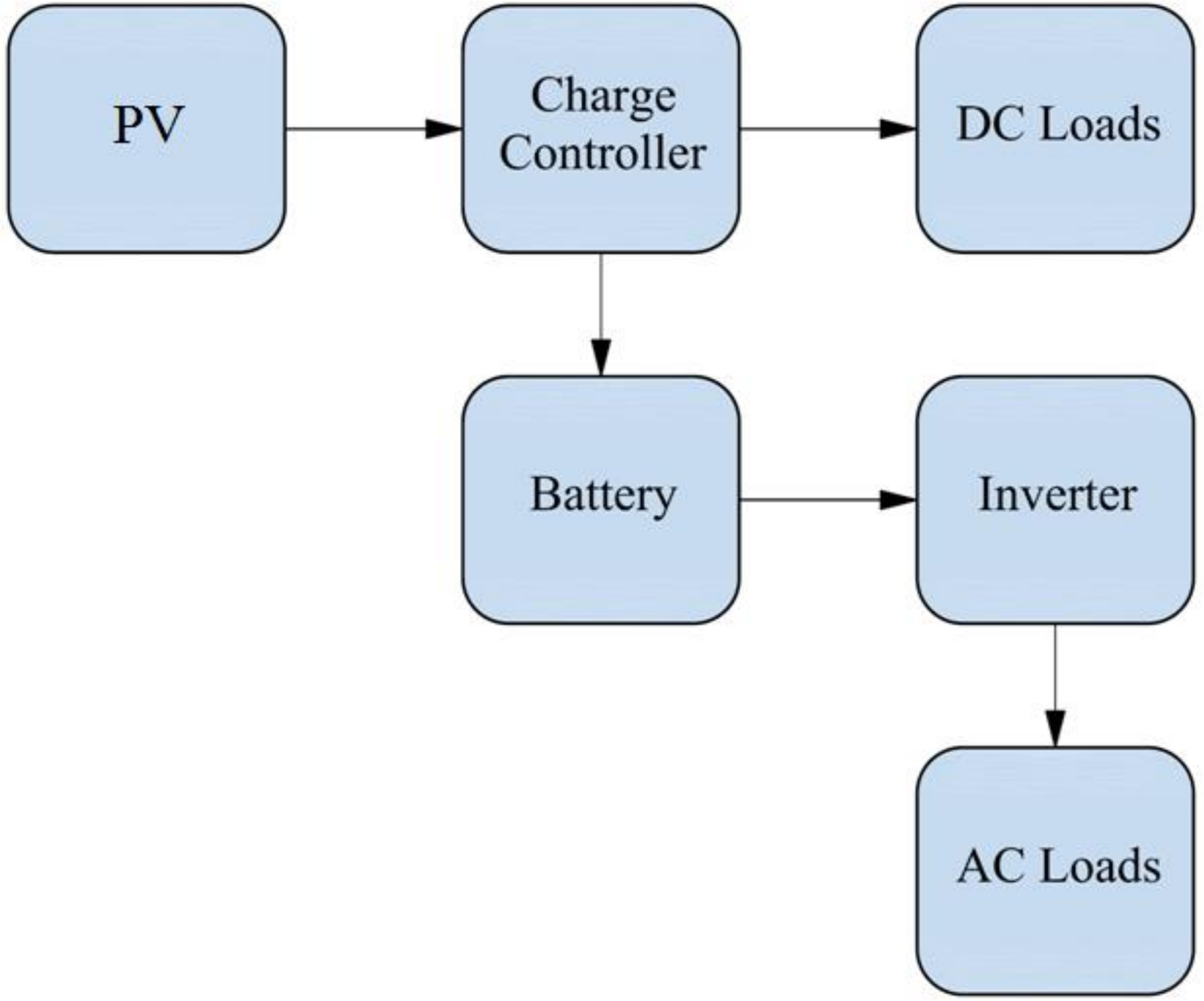
(a)



(b)

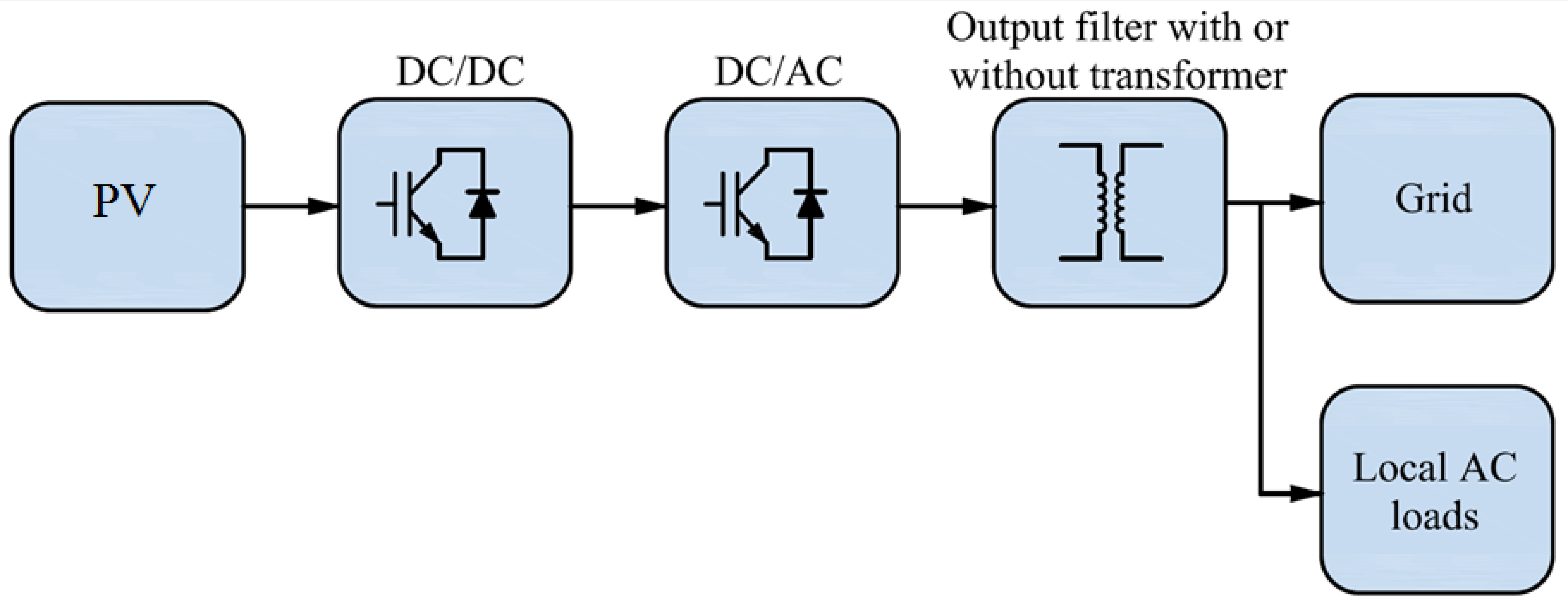
a) Variation of PV voltage and current with series resistance R_S,
b) Variation of PV voltage and current with temperature.

3-Island Mode (Local) Applications



Typical island mode renewable energy sources (RES)

3-Grid Interactive Applications



Typical grid interactive mode renewable energy sources (RES)

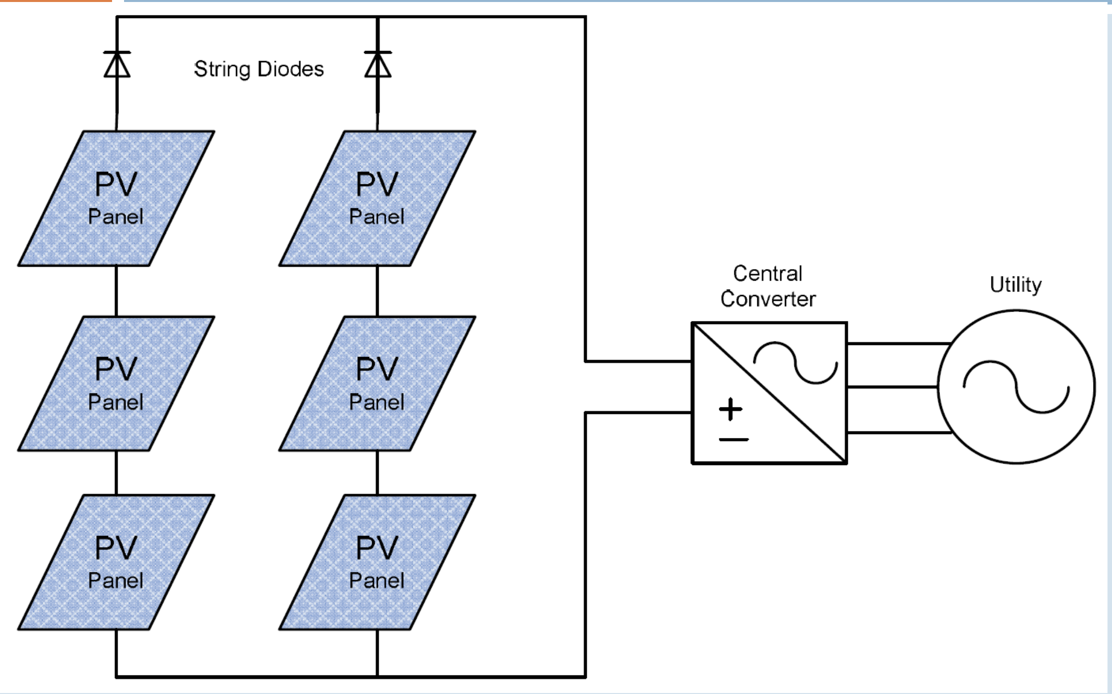
3-Grid Interactive Applications

Summary of the Most Interesting Standards Dealing With Interconnections of PV Systems to the Grid

ISSUE	IEC61727 [3]	IEEE1547 [5]	EN61000-3-2 [4]
Nominal power	10 kW	30 kW	16 A × 230 V = 3.7 kW
Harmonic currents (Order – h) Limits	(3-9) 4.0% (11-15) 2.0% (17-21) 1.5% (23-33) 0.6%	(2-10) 4.0% (11-16) 2.0% (17-22) 1.5% (23-34) 0.6% (> 35) 0.3%	(3) 2.30 A (5) 1.14 A (7) 0.77 A (9) 0.40 A (11) 0.33 A (13) 0.21 A (15-39) 2.25/h
	Even harmonics in these ranges shall be less than 25% of the odd harmonic limits listed.		Approximately 30% of the odd harmonics -see standard.
Maximum current THD	5.0%		-
Power factor at 50% of rated power	0.90	-	
DC current injection	Less than 1.0% of rated output current.	Less than 0.5% of rated output current.	< 0.22 A -corresponds to a 50 W half-wave rectifier.
Voltage range for normal operation	85% - 110% (196 V – 253 V)	88% - 110% (97 V – 121 V)	-
Frequency range for normal operation	50 ± 1 Hz	59.3 Hz to 60.5 Hz	-

International standards related to PV supplied grid interactive inverters

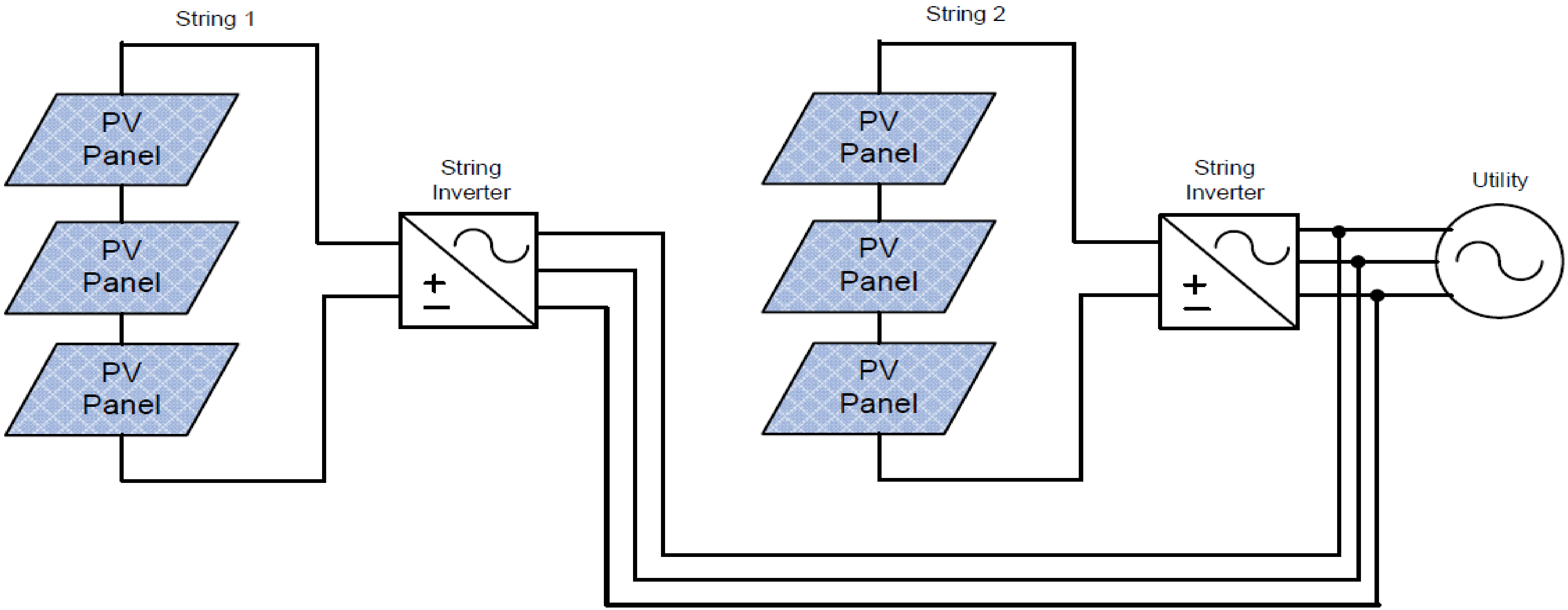
4-System Configurations (PV)



- **Centralized inverter;** The most common type of PV installation in the past. PV modules are connected in series and/or parallel and connected to a centralized DC-AC converter.

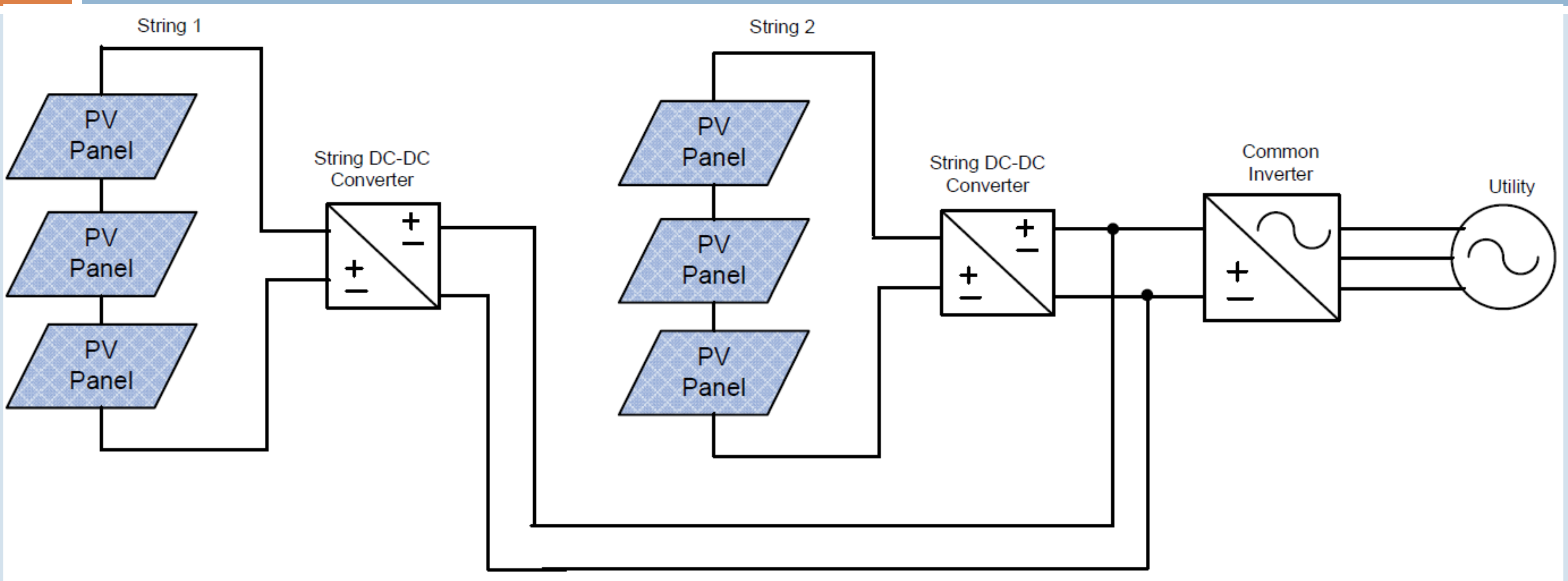
- The primary advantage of this design is the fact that if the inverter is the most costly part in the installed PV system, this system has the lowest cost design because of the presence of only one inverter. The primary disadvantage of this configuration is that the power losses can be high due to the mismatch between the PV modules and the presence of string diodes. Another disadvantage is that this configuration has a single point failure at the inverter; therefore, it has less reliability

4-System Configurations (PV)



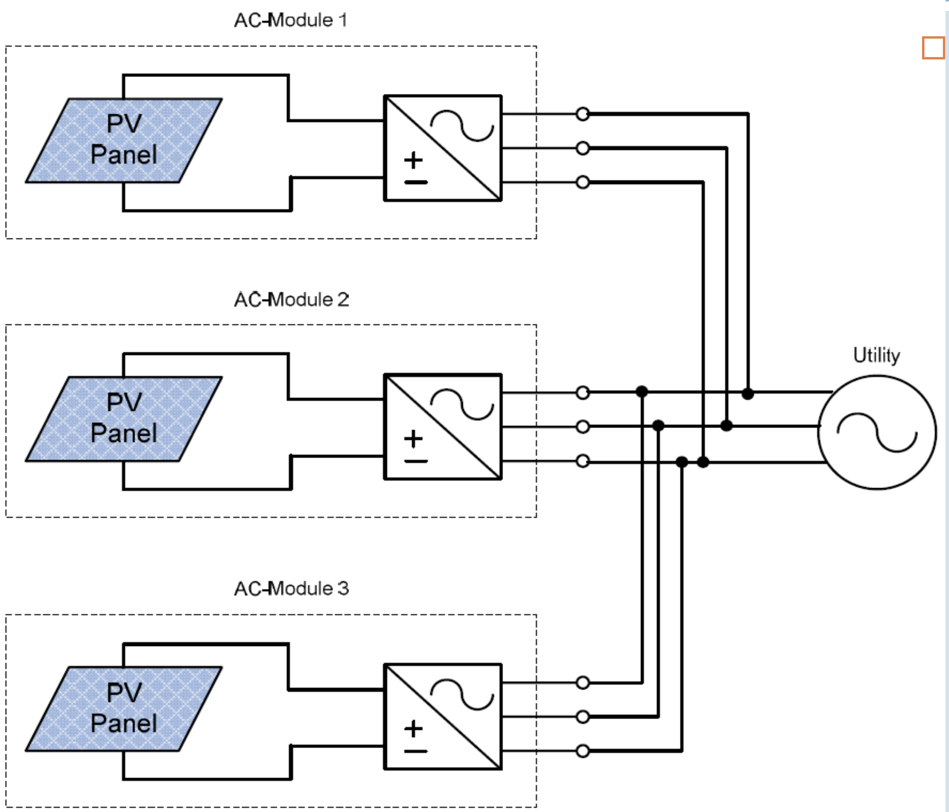
- **Strings with individual inverters;** The primary advantage of this topology is that there are no losses associated with the string diodes and a maximum power point tracker can be applied for each string. This is especially useful when multiple strings are mounted on fixed surfaces in different orientations. The disadvantage to this configuration is the increased cost due to additional inverters.

4-System Configurations (PV)



- **Multi-string configuration;** The input voltage coming from the PV strings may be high enough to avoid the need for voltage amplification. Multi-string inverters, a development of the string-inverter, have several strings that are interfaced with their own DC-DC converter for voltage boosting and are then connected to a common DC bus. A common DC-AC inverter is then used for utility interfacing.

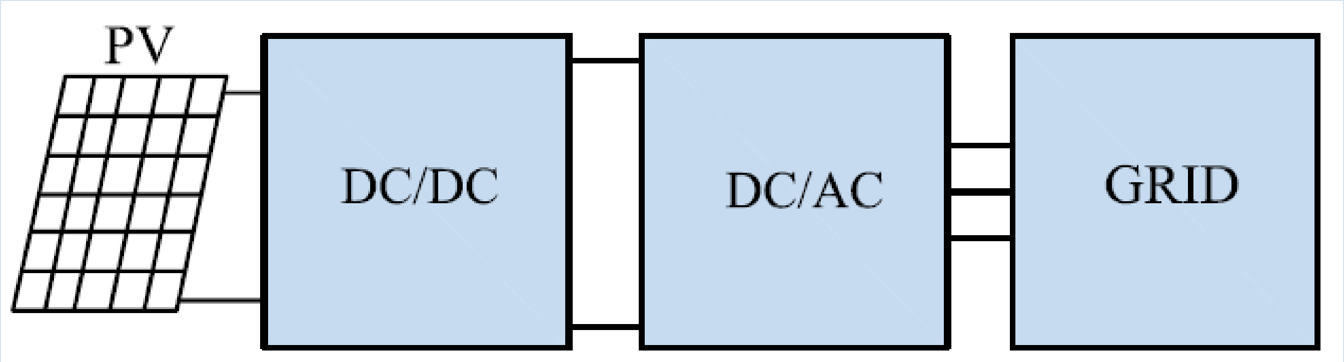
4-System Configurations (PV)



- **AC-module configuration;** Advantages of this type of system are that it is easy to add modules because each module has its own DC-AC inverter and the connection to the utility is made by connecting the inverter AC field wirings together. There is also an overall improvement in system reliability because there is no single-point failure for the system. Their power levels ususally less then 500 Watts

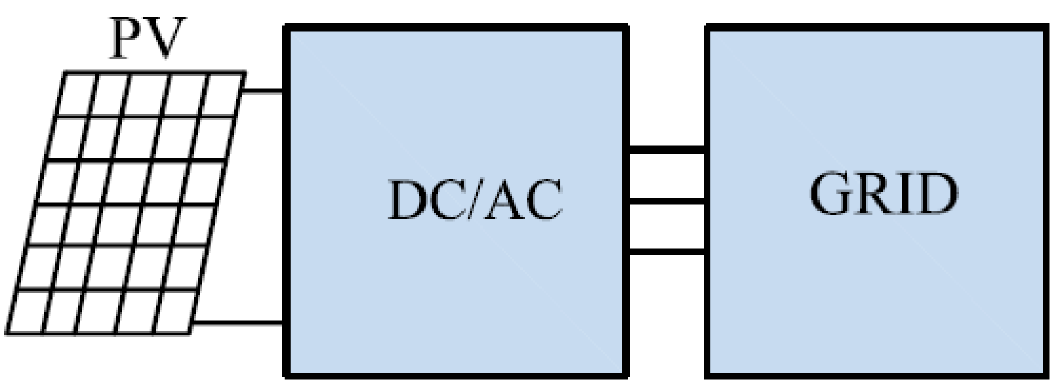
- It is a highly flexible and configurable design topology; however, prior examples of this configuration are still more costly than the conventional PV systems because of the increased number of inverters. The power loss of the system is lowered due to the reduced mismatch among the modules, but the constant losses in the inverter may be the same as for the string inverter.

5-Conversation Stage (PV)



- Double-stage converter topology is more common than single-stage converter.
- They used especially when there are big difference between the grid voltage level and PV voltage level.
- But efficiency of this topology is lower than single stage topology because there are at least two converters.
- Also multi-stage topologies are proposed.
- More then one stage system's control structures are simple.

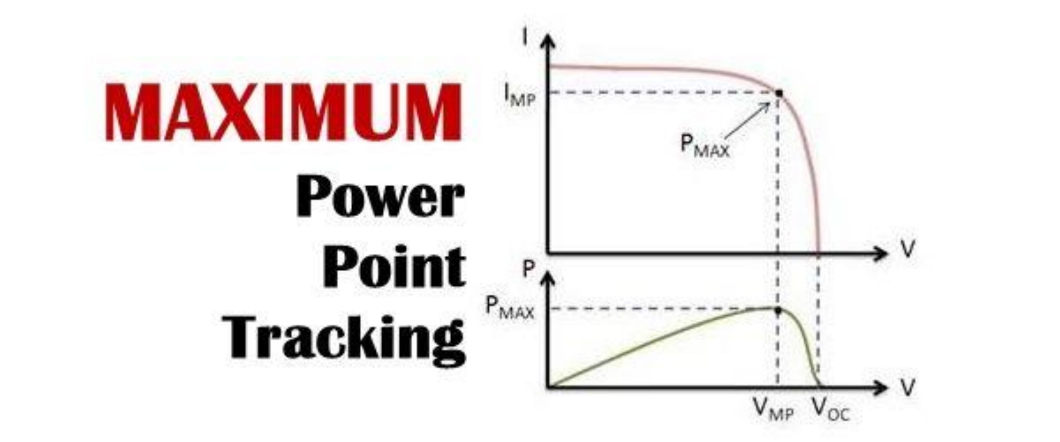
5-Conversation Stage (PV)



- Single stage topology is developing parallel with improvements in the microprocessors and power electronics.
- Their efficiencies are high but control structures are complex.

6-Maximum Power Point Tracking

- PV output power reaches its maximum value for a certain voltage and current level. And this level changes with environmental conditions such as irradiation level, pollution etc.
- Maximum power point (MPP) of the system should be tracked while these conditions are changed.



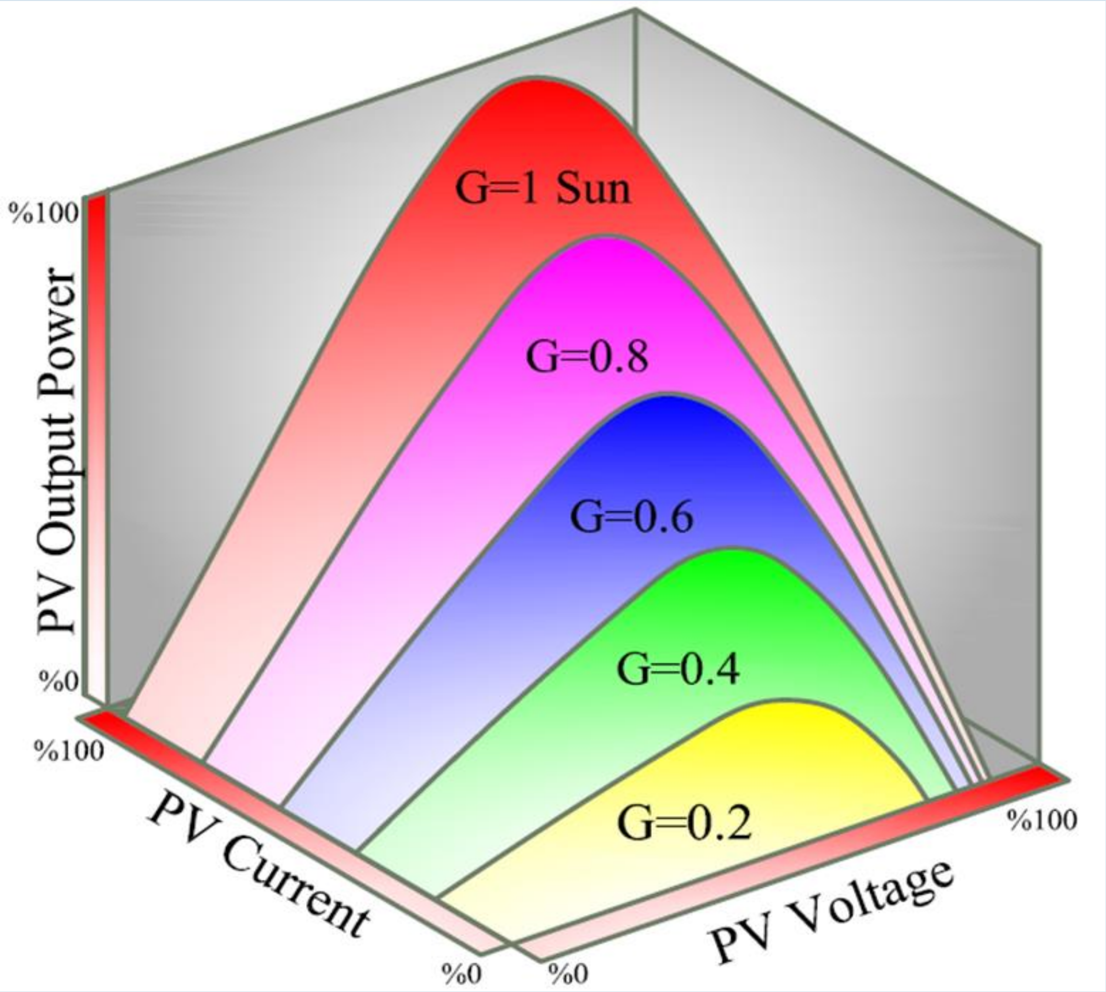
6-Maximum Power Point Tracking

- Maximum power point tracking (MPPT) should be implemented to obtain maximum energy conversion efficiency.
- MPPT can be obtained by controlling the load power via controlling output power or switching on or off the load groups.
- MPPT is an control method and implemented with the power converters.

6-Maximum Power Point Tracking (PV)

- PV MPPT control methods can be grouped in two categories as off-line and on-line methods.
- MPPT process is obtained by using PV values such as short circuit current, open circuit voltage, temperature and irradiation. These values are periodically read from the PV module, another sampling PV module or a look-up table.
- Although off-line methods are simple, low cost and useful, switching off loads to determine the MPP is a problem. Linear calculations could also cause some errors because of undesired effects such as pollution on the module surface etc.
- On-line methods obtain real MPPT independent from environmental and PV system conditions. Although response speeds of these on-line methods are variable depending on their structures and control methods, they are slower than the off-line methods.

6-Maximum Power Point Tracking (PV)

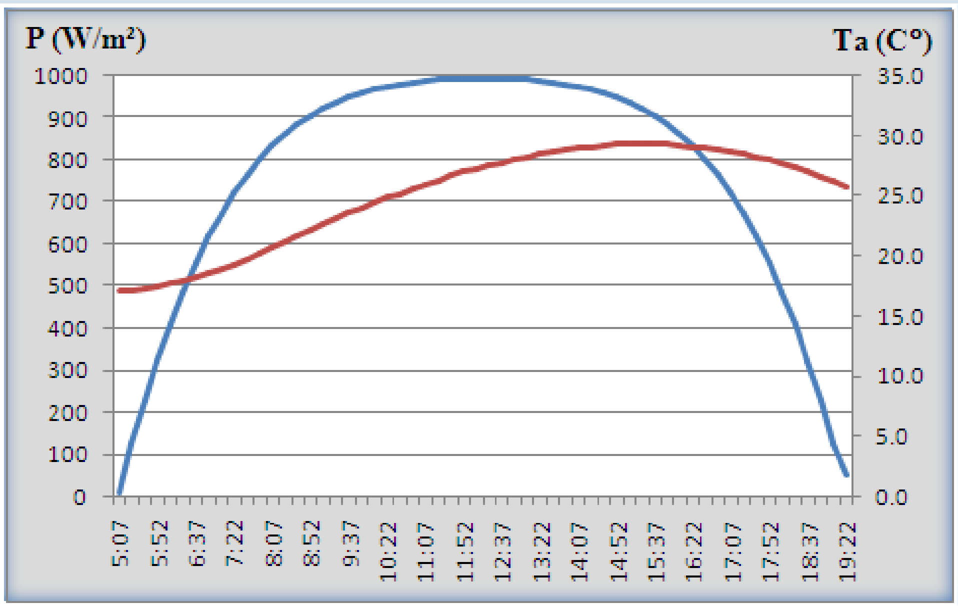


PV Maximum Power Curve

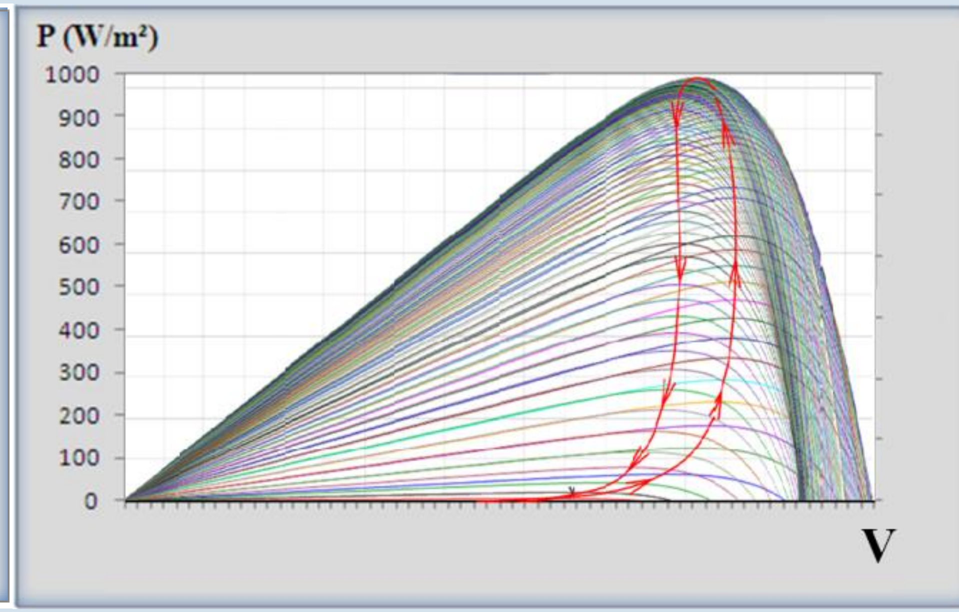
6-Maximum Power Point Tracking (PV)

- Off-line Methods
  - Constant Voltage (CV)
  - Constant Current (CC)
  - Look Up Table (LUT)
  - Curve Fitting (CF)
  - Plot Cell (PC)
- On-line Methods
  - Perturb and Observe (P&O)
  - Incremental Conductance (IC)
  - Fuzzy Logic & Neural Network (FL&NN)

6-Maximum Power Point Tracking (PV)



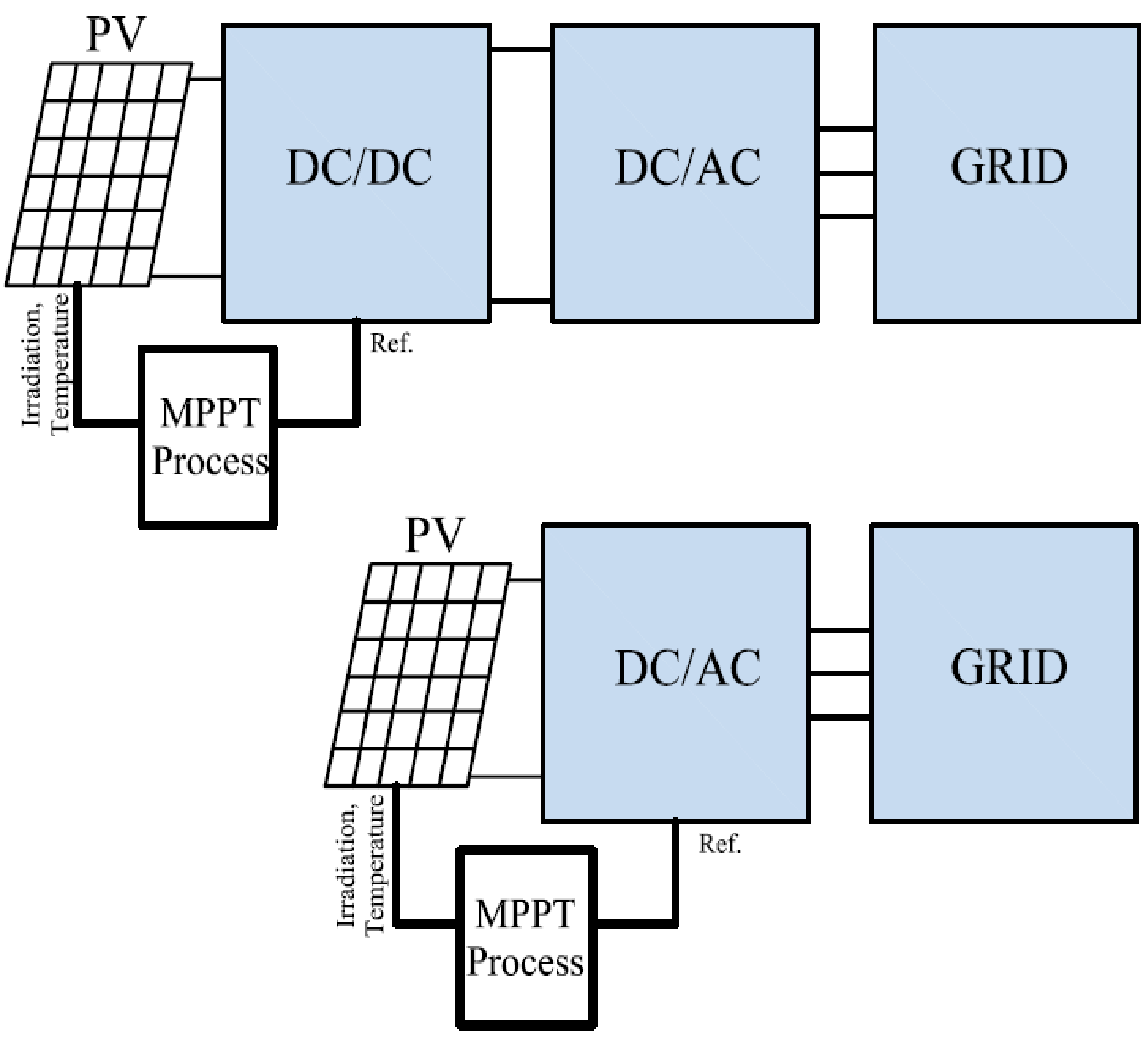
a) Daily irradiation level and temperature



b) Daily MPPT curve*

* Red line (MP traction line) shows clearly sky condition. It is affected by cloudly sky, temprature, PV pullation etc.

6-Maximum Power Point Tracking (PV)



- Off-line method
  - MPPT uses irradiation and temperature levels and mathematical equations
  - It is implemented with DC/DC converter.
- Off-line method
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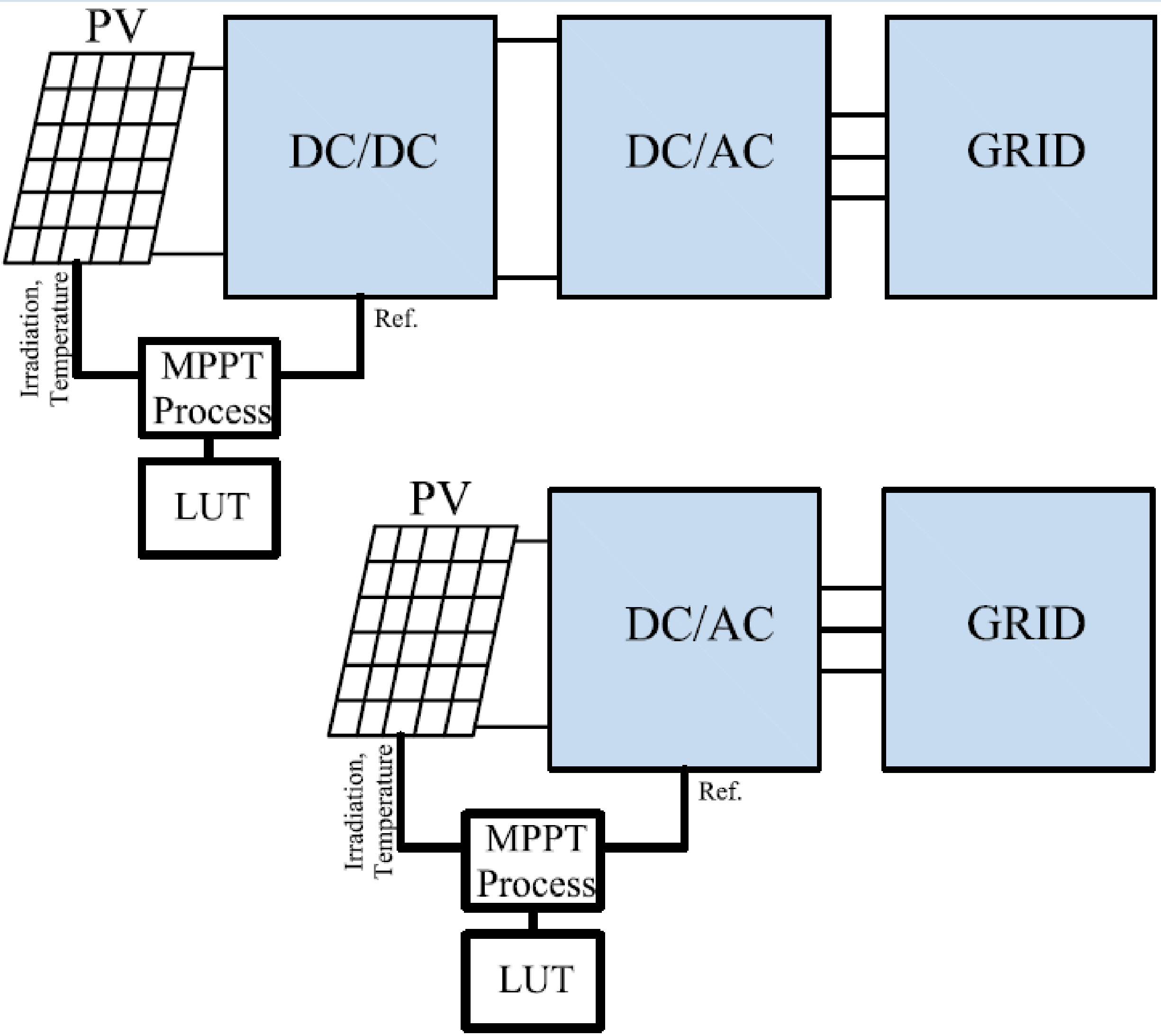
  - It is implemented with DC/AC inverter.

6-Maximum Power Point Tracking (PV)



- Off-line method
  - MPPT uses irradiation and temperature levels and look-up table (LUT).
  - It is implemented with a DC/DC converter.
- Off-line method
  - MPPT uses irradiation and temperature levels and look-up table (LUT).
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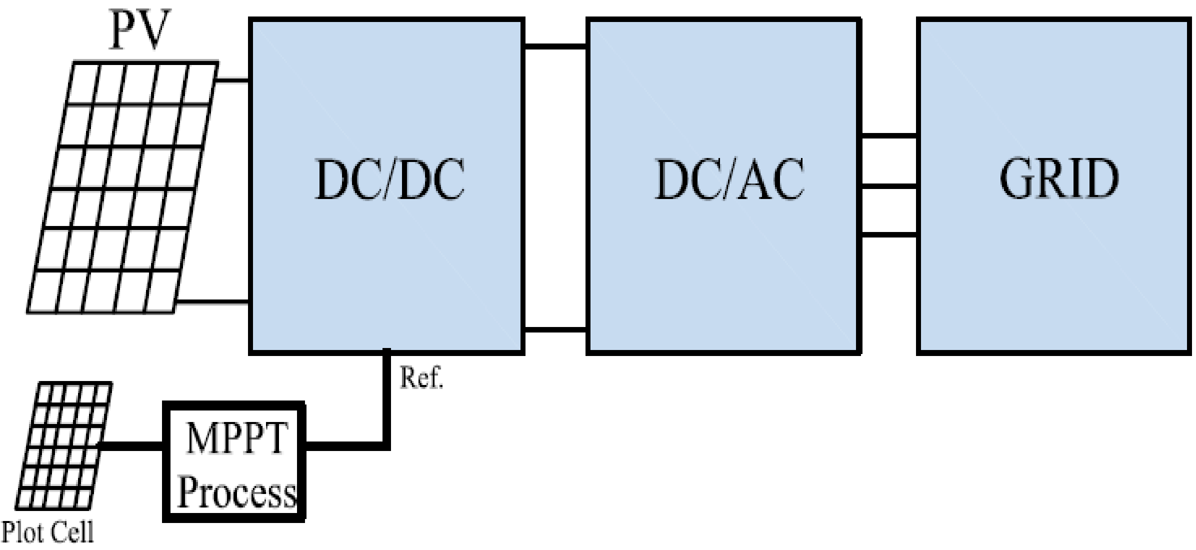
6-Maximum Power Point Tracking (PV)



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  - MPPT uses plot cell.
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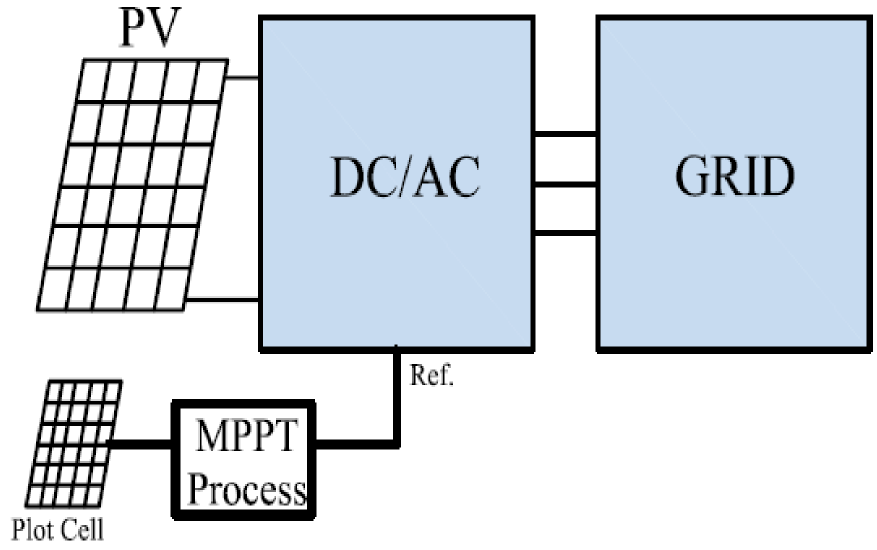

- Off-line method
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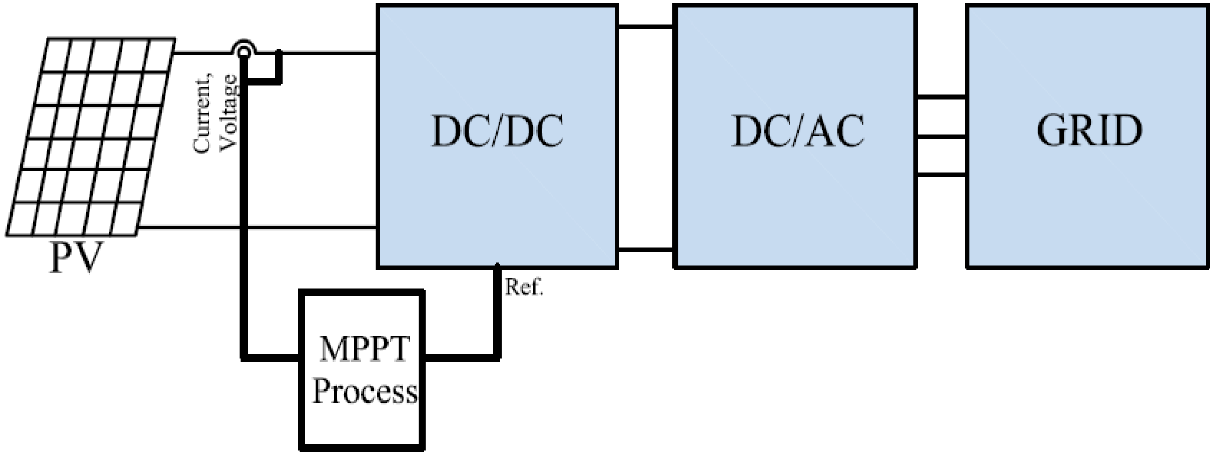
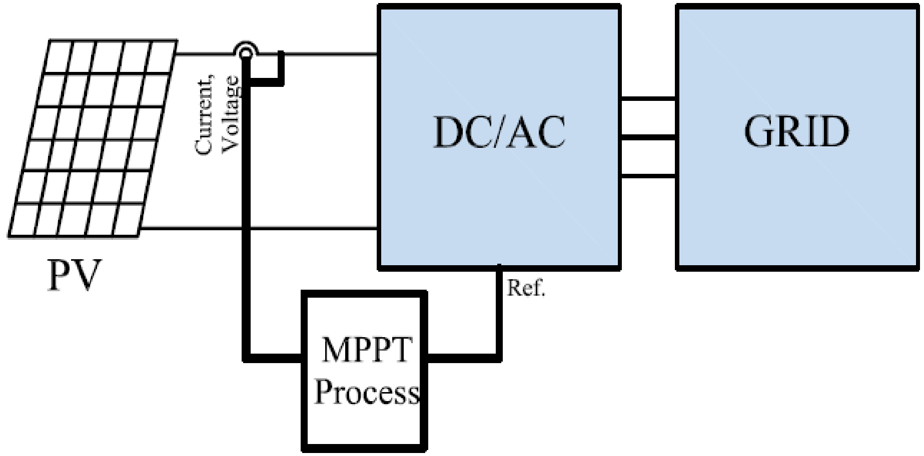
6-Maximum Power Point Tracking (PV)



- On-line method
  - MPPT uses current or/and voltage data.
  - It is implemented with DC/DC converter.



- On-line method
  - MPPT uses current or/and voltage data.
  - It is implemented with DC/AC inverter.

6-MPPT Methods: Constant Voltage (CV)-Constant Current (CC) Methods

- There is constant ratio between the open circuit voltage (Voc) and maximum power voltage (Vmp) of a PV module. This constant change with module type but in general it is between 0.73-0.8.

$$k = \frac{V_{MP}}{V_{OC}} \cong constant$$

- Similar to constant voltage method, there is a constant ratio between the short circuit current (Isc) and maximum power current (Imp) of a PV module. This constant change with module type but in general it is around 0.85.

$$I_{MP} = k.I_{SC}$$

6-MPPT Methods: Constant Voltage (CV)-Constant Current (CC) Methods

- Although these are simple methods, these constants are affected from aging, pollution of module surface and as a result, MPP could not be determined.
- In addition, Voc or Isc must be read continuosly and this requires using a plot cell or switching off the loads periodically.
- Switching off the load decrease the supply reliability and decrease the efficiency.

6-MPPT Methods: Look Up Table (LUT)

- Operation point of the system is detected from PV voltage, PV current and predetermined tables, and next control signal of power converter is determined to track the MPP.
- Data for all atmosferic conditions should be in the look-up table.
- Also a look up table is valid only one kind of panel.
- encironmental conditions affect the efficiency of this method.

6-MPPT Methods: Curve Fitting (CF)

- Model of the system is obtained via mathmatical equaliations or converging methods by using PV datasheets.
- Because the obtained model is very complex, it is difficult to implement this method with analog or digital circuits.
- Also parametres could not be found exactly for all radiation level and aging effects, so this situation decreases the effiviency.

6-MPPT Methods: Perturb and Observe (P&O)

- It is one of the most common methods. P&O method monitors the output power of PV and defines a relation between the control variable and PV output power. Next command (increase or decrease the reference) is determined by using this relation.
- Sometimes P&O method is also called as hill-climbing method. Although they are different methods, operation principle of them is same.
- P&O method can be implemented with digital circuits easily.
- Reading PV voltage and current is enough for determining MPP.
- Real MPP can be determined.

6-MPPT Methods: Perturb and Observe (P&O)

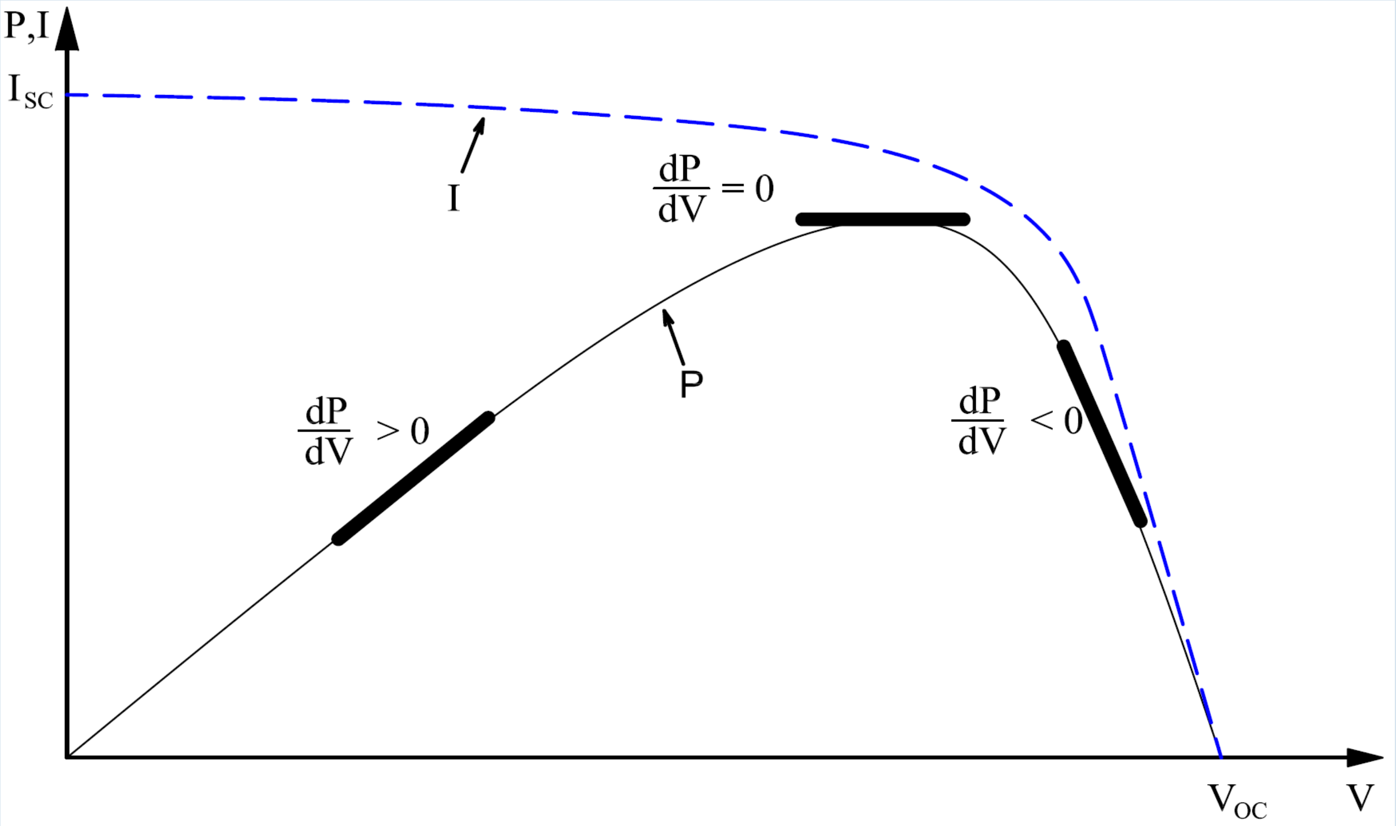
- Panel type, aging, pollution fo the PV module coauldnot affect the performance of this method.
- The main drawback of this method is oscillation around the MPP.
- Oscillation level can be decreased with desing process

Perturbation	Change in Power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

6-MPPT Methods: Incremental Conductance (IC)

- This method tracks the slope of P-V curve (dP/dV). If the slope of the curve is 0, this point is defined as MPP. dP/dV >0 means that operation point is at left side of MPP and dP/dV <0 when operation point is at right side of MPP.
- The main advantage of the IC method is capability of adapting to the rapidly changing atmospheric conditions and less oscillations than the P & O method occurring at MP.
- Alhough, initially slow response times were reported for this method, today, this negative effect has been removed with rapid development of digital technologies.

6-MPPT Methods: Incremental Conductance (IC)

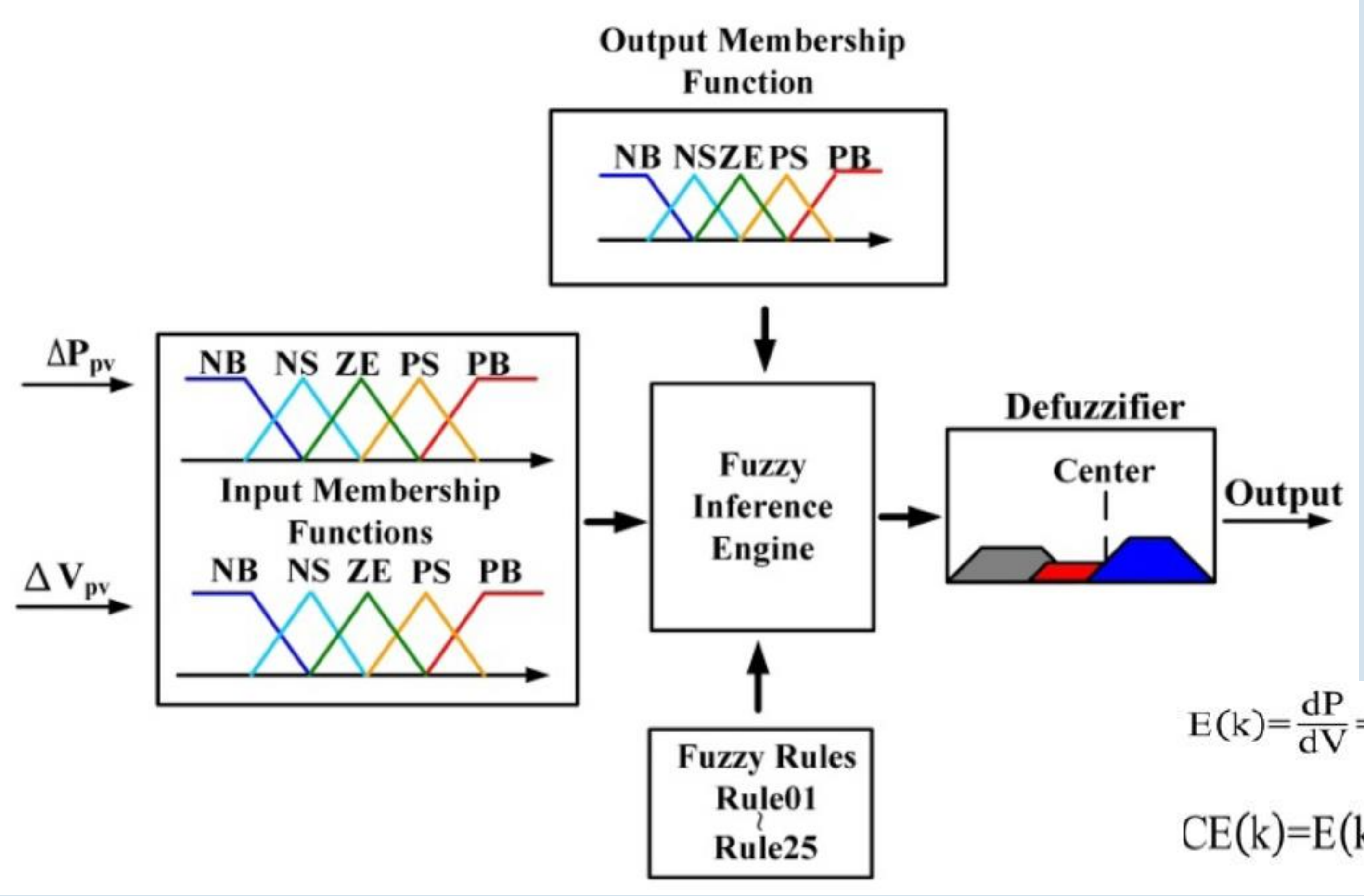


- IC method illustration

6-MPPT Methods: Fuzzy Logic & Artificial Network (FL&AN)

- These are recent methods.
- They do not require mathemetical models.
- Ther are able to adapt rapidly changing atmospheric conditions.
- However, performance of the system is related with designer capability.
- Error signal coefficient should be defined properly, otherwise it could have negative consequences.

6- FLC Based MPPT



$$E(k) = \frac{dP}{dV} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \quad (5)$$

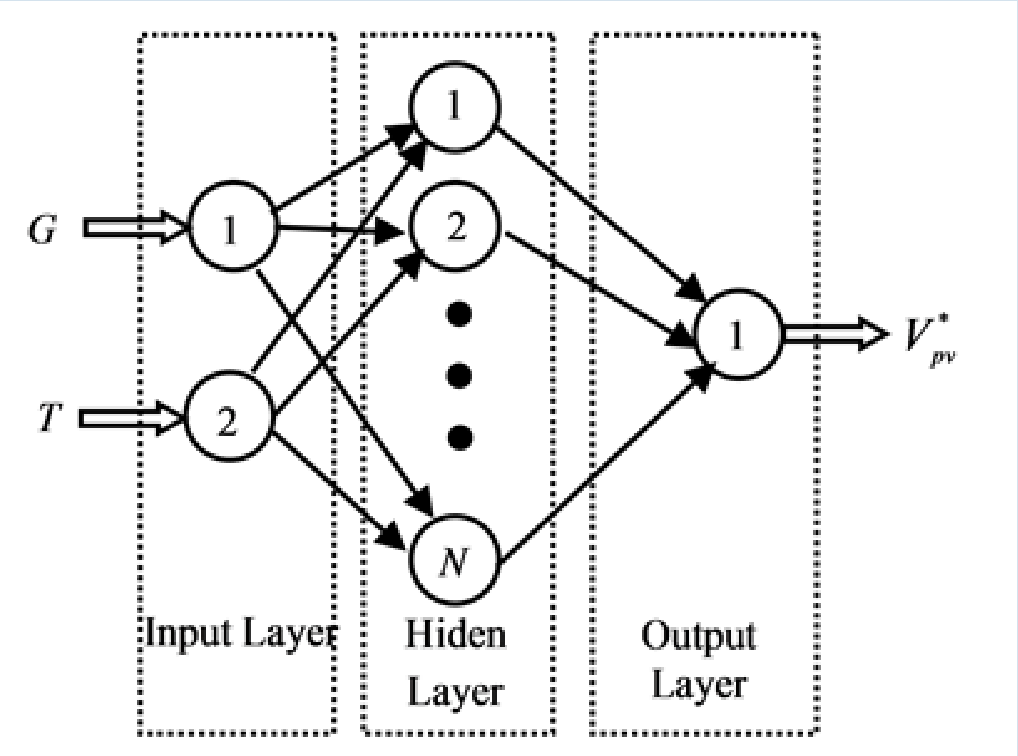
$$CE(k) = E(k) - E(k-1) \quad (6)$$

6- FLC Based MPPT

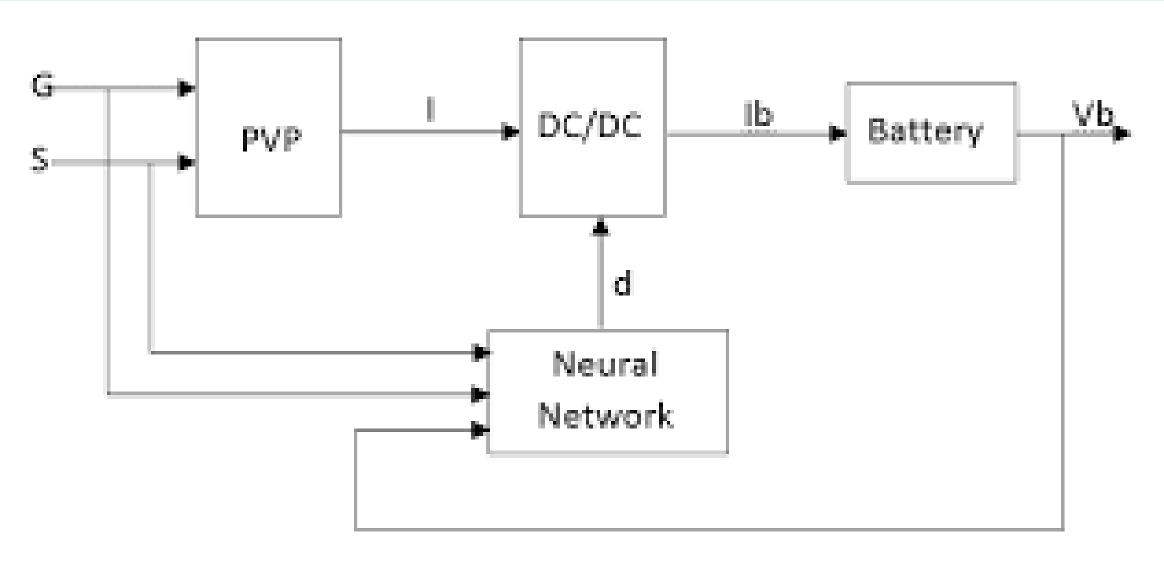
- Different FLC Designs for MPPT:

Ref.	Publication Year	Input Variables	Output Variables	Number of Rules	Inference type	Converter type	Controller Implementation
Alajmi et al. (2011)	2011	ΔP, ΔI	ΔD	16	Mamdani	Boost	Infineon TC1796
Mohd Zainuri et al. (2014)	2014	$E(k)=\Delta P/\Delta V$, $\Delta E(k)$	ΔD	25	Mamdani	Boost	DSP TMS320F28335
Radjai et al. (2014)	2014	ΔV, e_{IC}	ΔD	9	Mamdani	Cuk	dSPACE
Messai et al. (2011b)	2011	$E(k)=\Delta P/\Delta V$, $\Delta E(k)$	ΔD	25	Mamdani	Boost	FPGA V2MB1000
Algazar et al. (2012)	2012	$E(k)=\Delta P/\Delta I$, $\Delta E(k)$	ΔD	25	Mamdani	Cuk	-
Al Nabulsi and Dhaouadi (2012)	2012	$\Delta P/\Delta V$, D_{old}	ΔD	9	Mamdani	Buck	DSP TMS320F28335

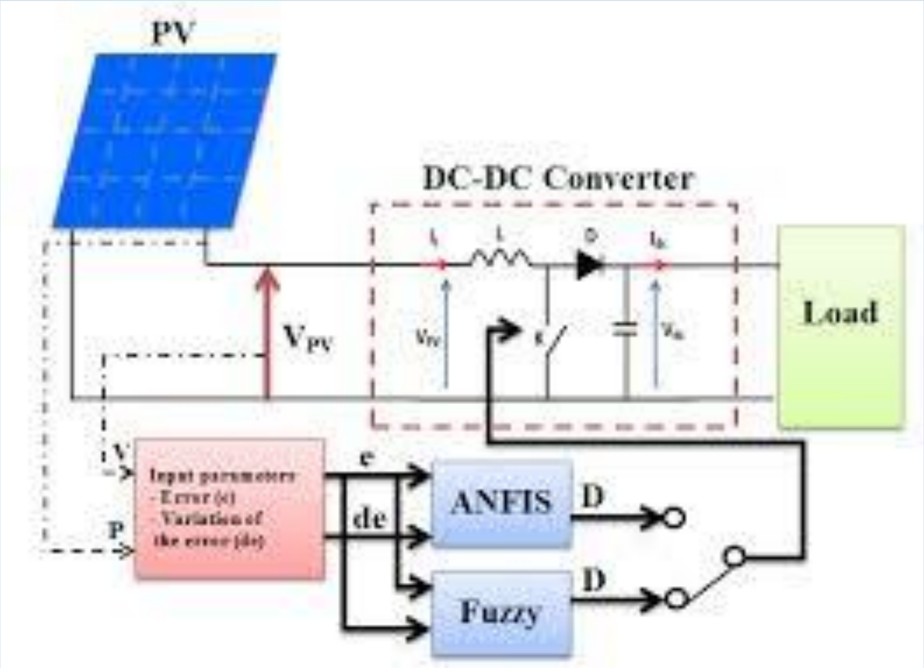
6- ANN Based MPPT

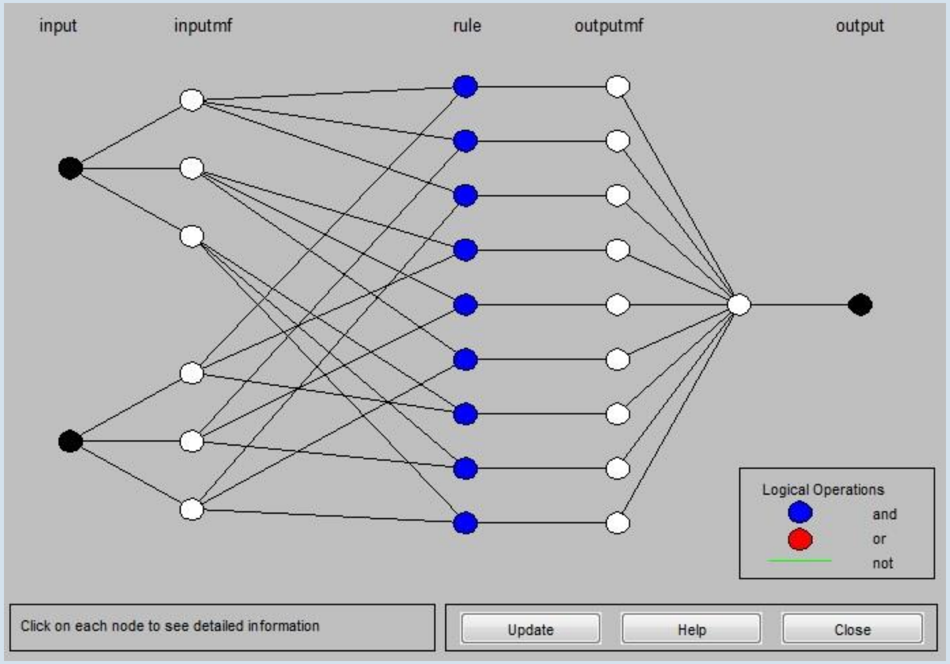


6- ANN Based MPPT



6- Neuro-Fuzzy Based MPPT

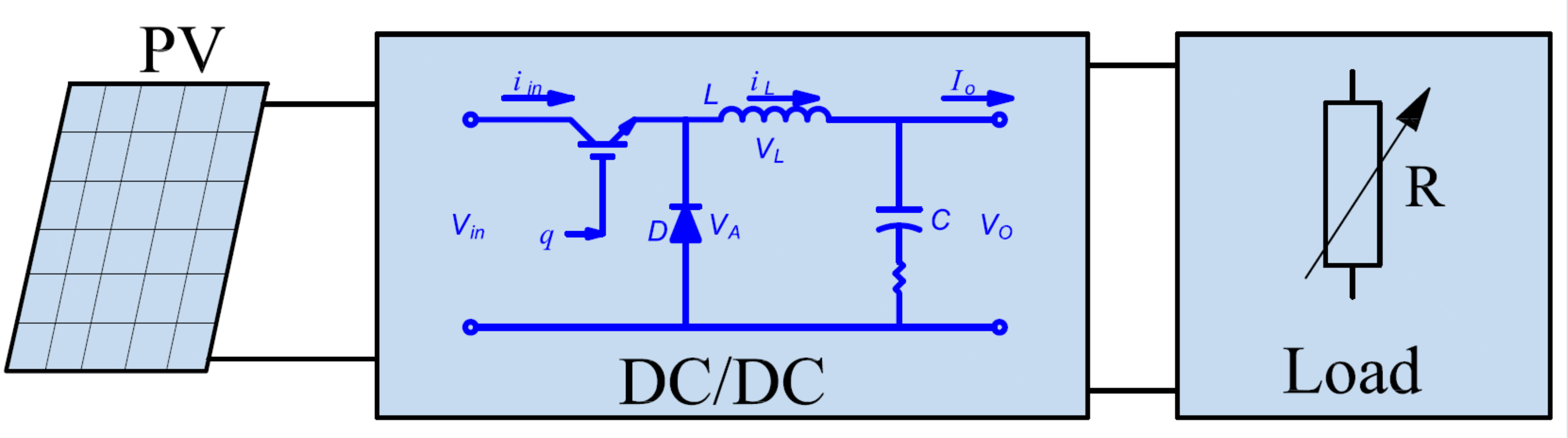




7- DC/DC Converters

- If both the supplied system and output voltage of the PV are DC, DC/DC converter is installed.
- Converter topology (buck/step-down, boost/step-up, buck-boost/step-up/down, cuk, sepic, push-pull etc.

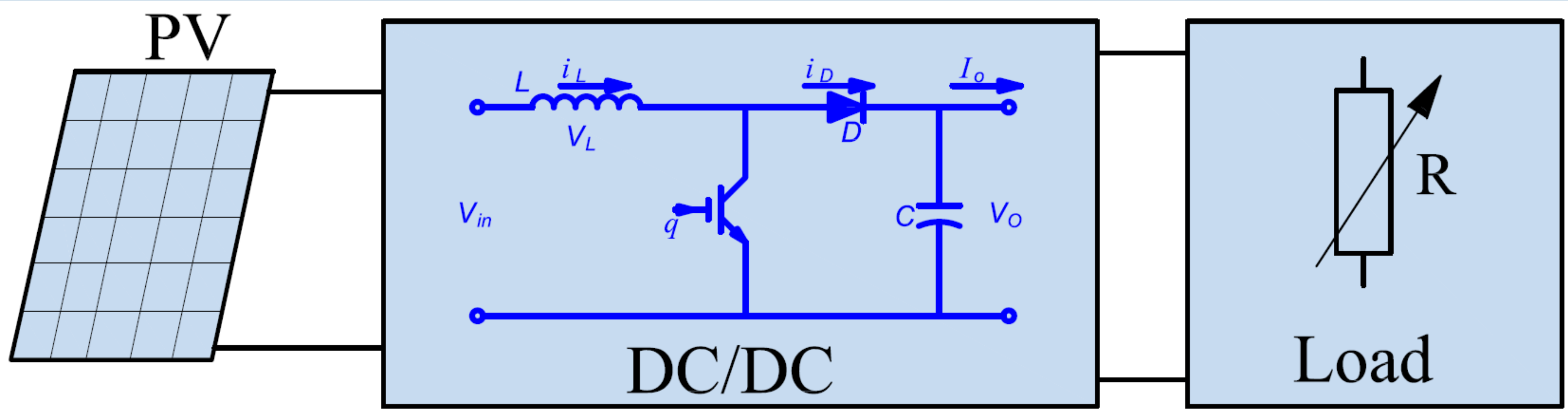
7-DC/DC Converters



Buck Converter

- They are used when the output voltage of the RES is higher than the load voltage level.
- They draws pulsating current from RES. So inbput capacitor should be increased.

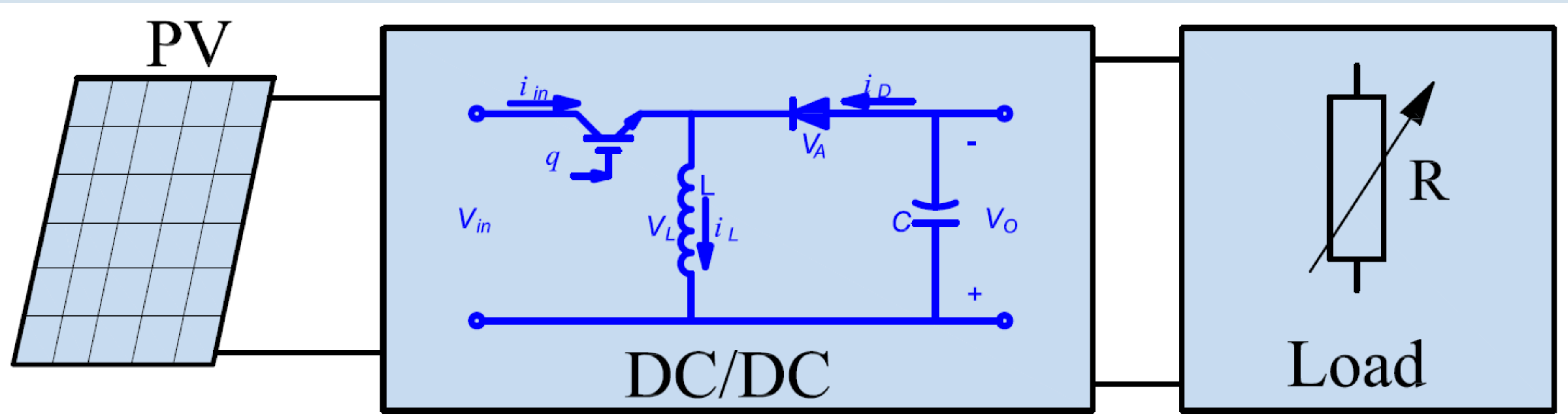
7-DC/DC Converters



Boost Converter

- This topology is used if the RES voltage is lover than the load voltage.
- Boost converter draws continious current from RES. Output voltage is equal to input voltage while converter is not running.

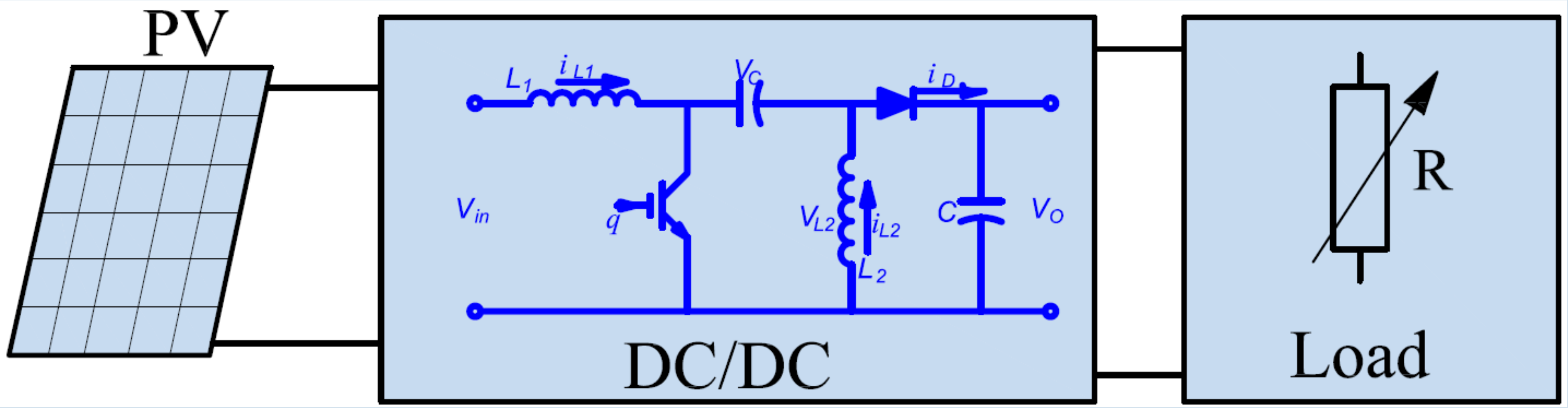
7- DC/DC Converters



Buck-Boost Converter

- This topology is used when the RES output voltage is nearly equal to the load valtage.
- This occurs because the PV voltage changes with environmental effects such as irradiation, temperature etc.

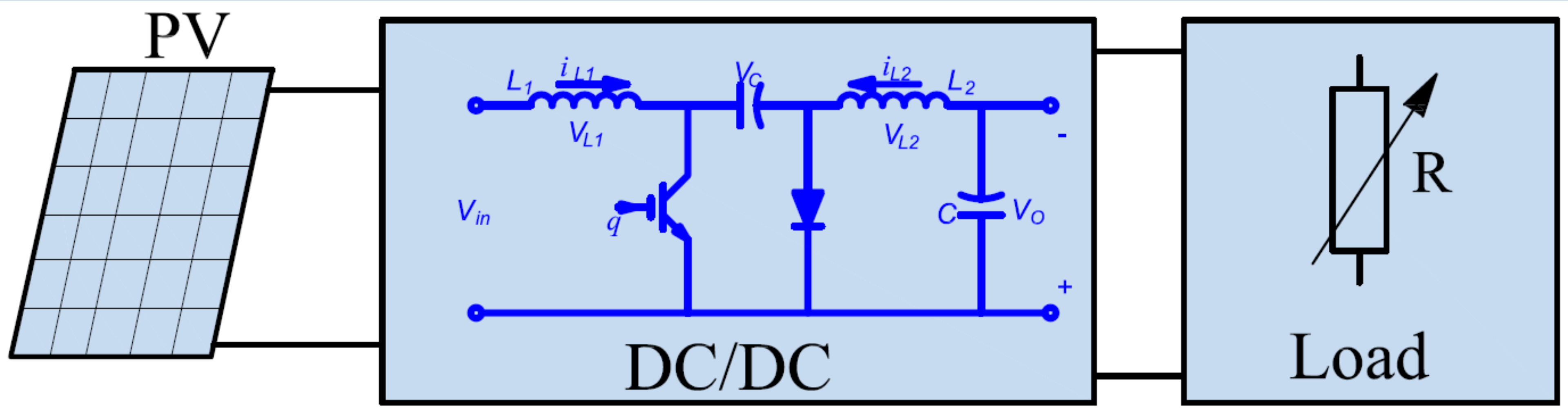
7- DC/DC Converters



SEPIC Converter

- This is an other buck-boost structure.

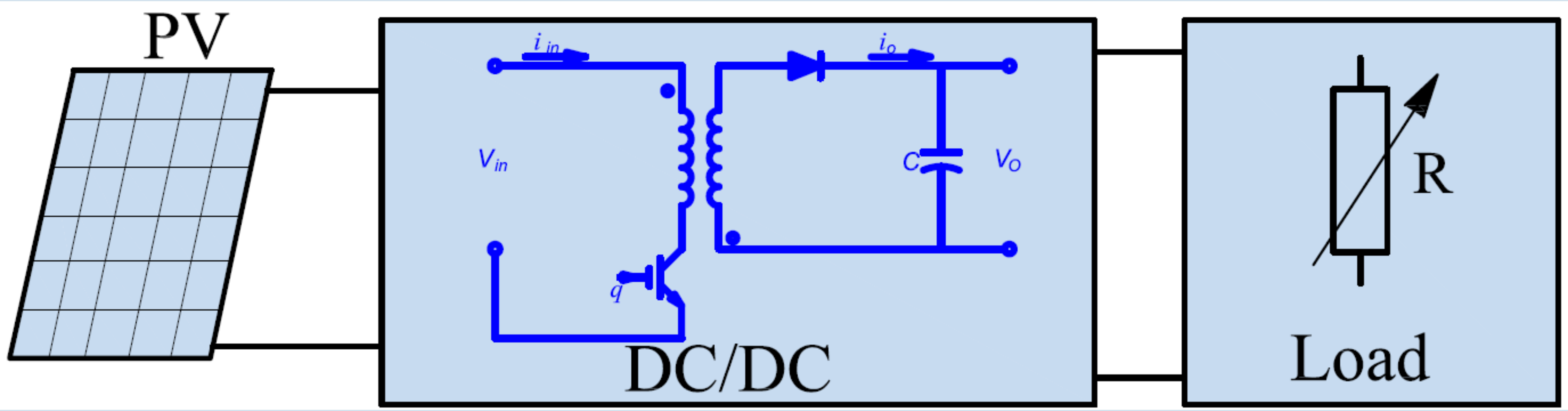
7- DC/DC Converters



CUK Converter

- This is an other buck-boost structure.

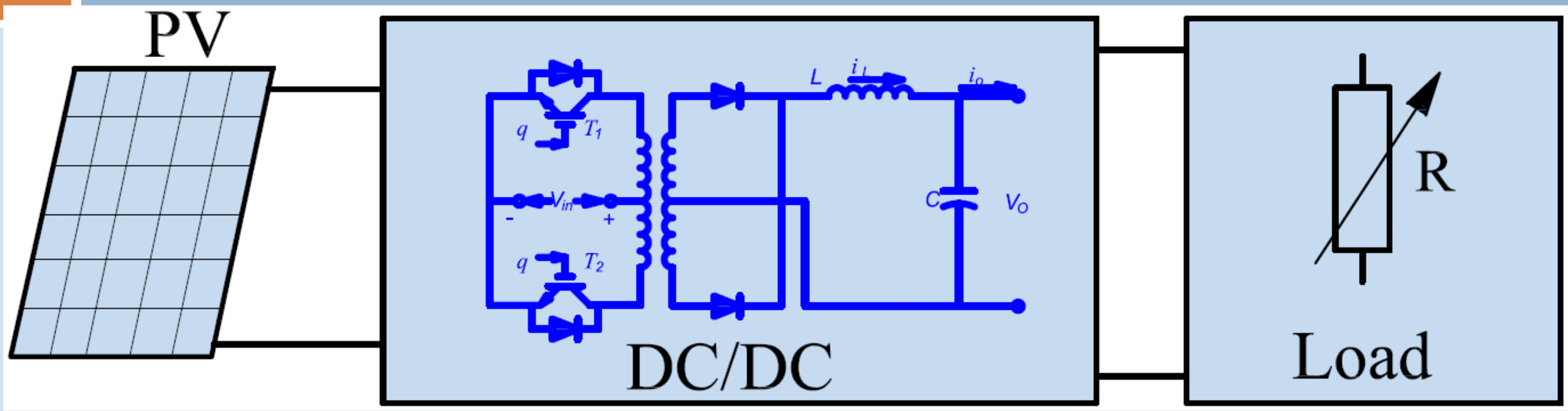
7- DC/DC Converters



Fly-back Converter

- This topology is used in low power applications where galvanic isolation is required.
- There may be big difference between the input and output voltages.
- They include a high frequency transformer.

7- DC/DC Converters



Push-Pull Converter

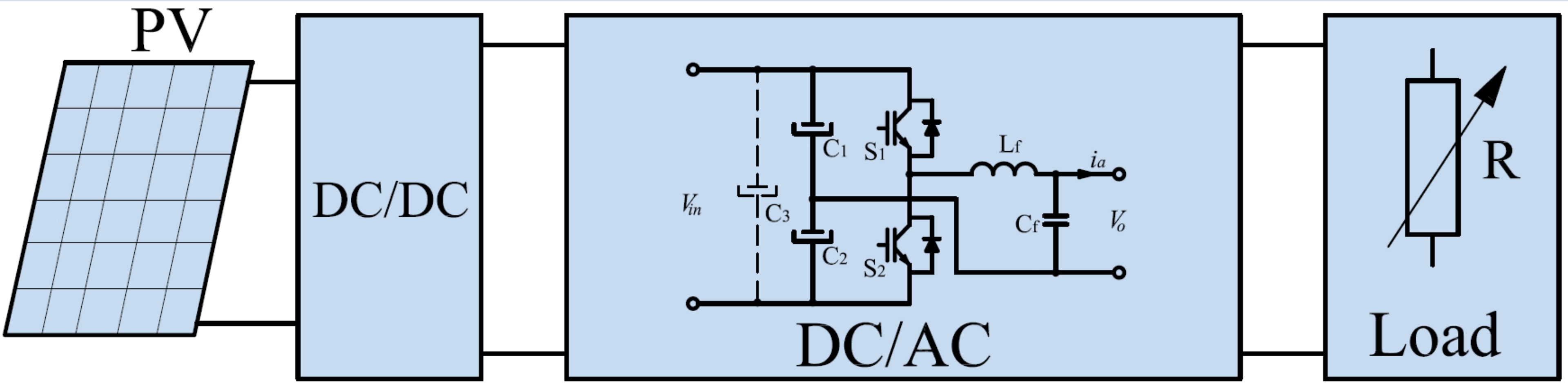
- They used in high power applications.
- They provide galvanic isolation due to high frequency transformer.

Also there are some other topologies, but they are not common methods.

8- DC/AC Converters

- They use to convert DC electrical energy generated from PV to AC with constant voltage and constant frequency.
- Single phase or three phase inverters can be designed.

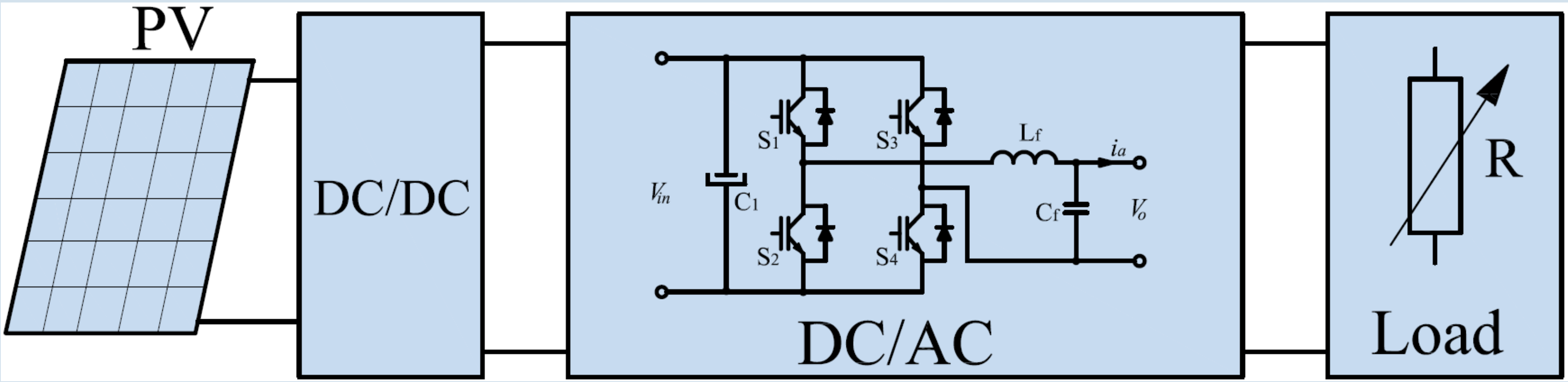
8- DC/AC Converters



Half Bridge Inverter

- Number of the switches is reduced.
- This topology requires split DC and serial connected capacitors which divide the DC bus voltage.
- DC voltage must be higher than 2xVmax

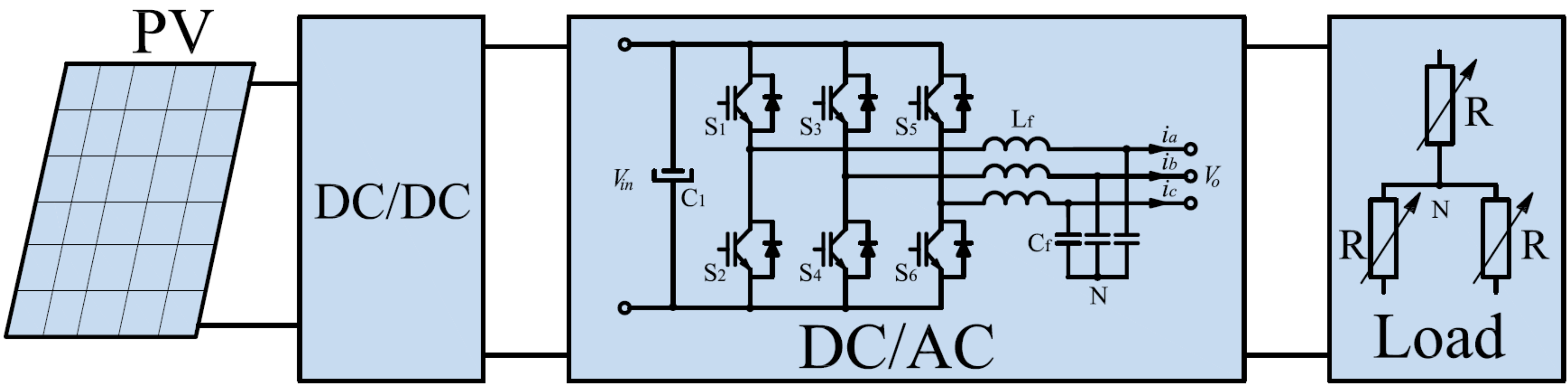
8- DC/AC Converters



Single Phase Full Bridge Inverter

- There are more power switches than half bridge topology.
- Input current level is half of the half-bridge inverter.

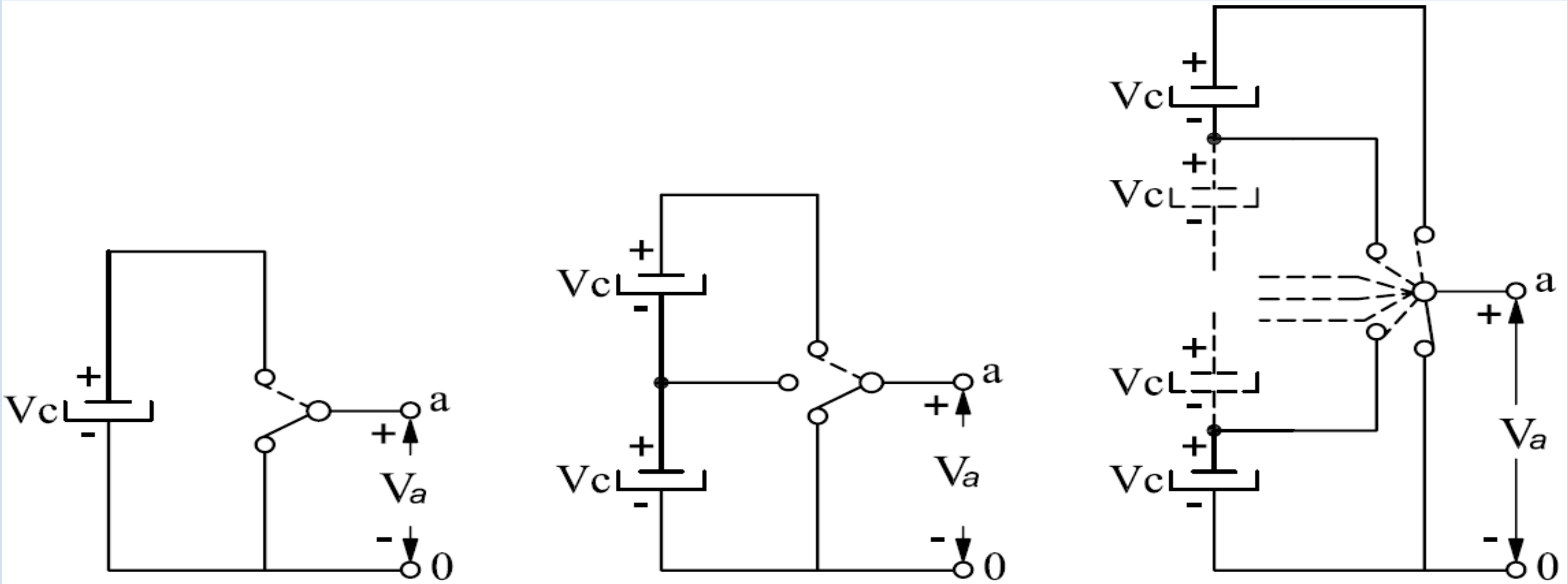
8- DC/AC Converters



Three Phase Inverter

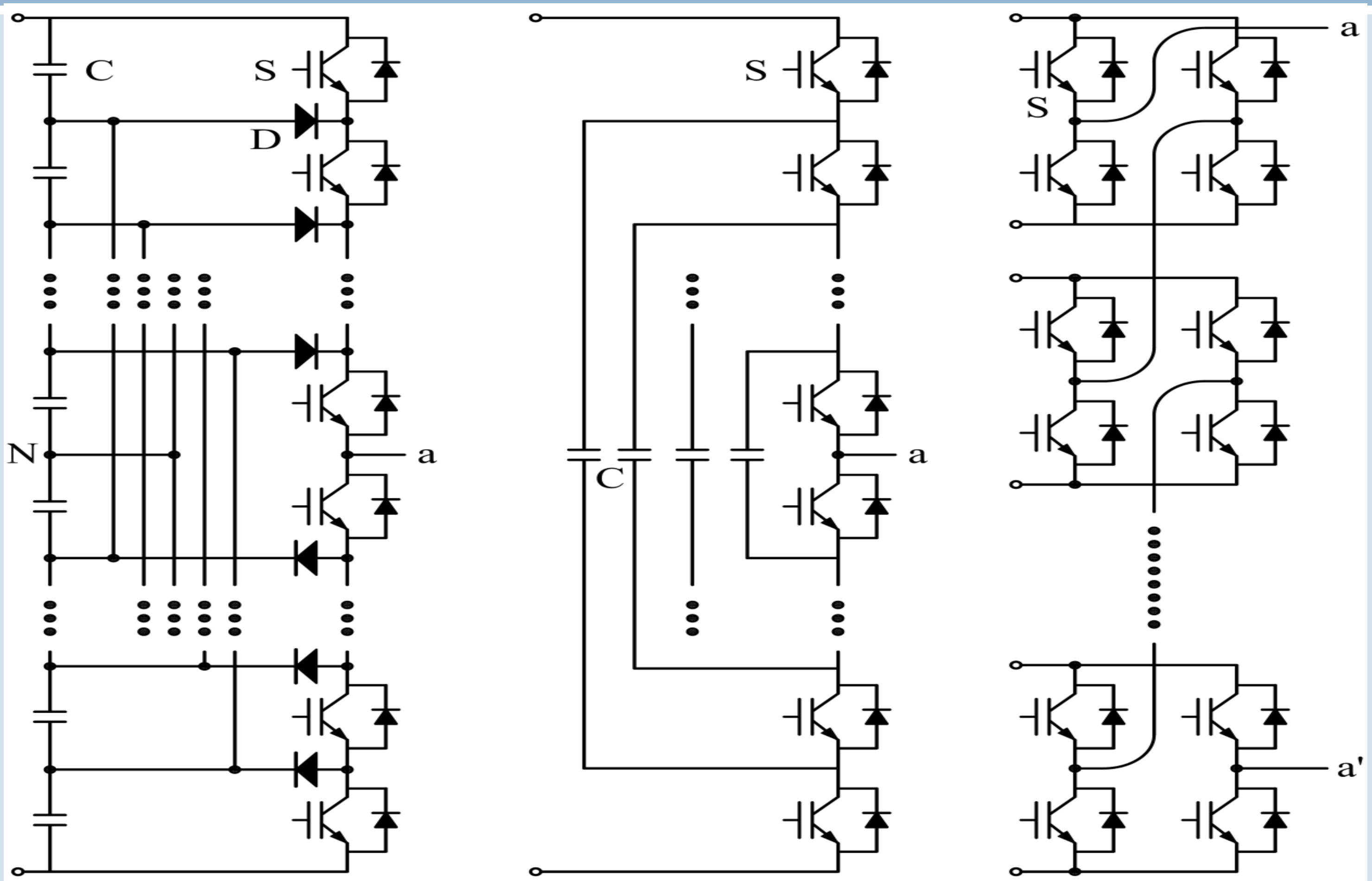
- This is the most common three-phase inverter topology.

8- DC/AC Converters (Multilevel)



- Multilevel converters became common with increasing power levels. Principle of two level converter, three-level converter and n-level converter are seen in Figure.

8- DC/AC Converters (Multilevel)

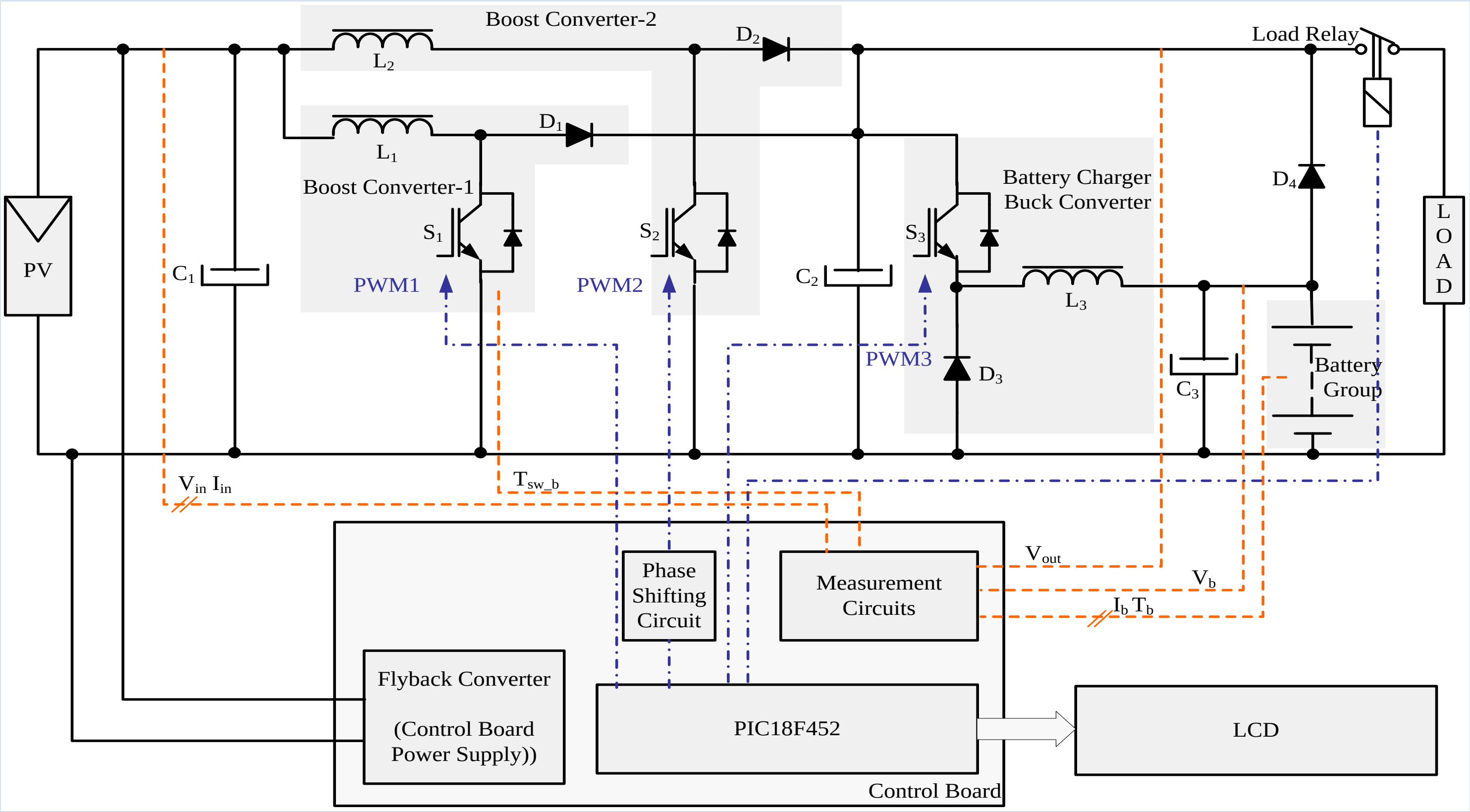


a) Neutral Point Clamped b) Flying Capacitor c) Cascaded H Bridge

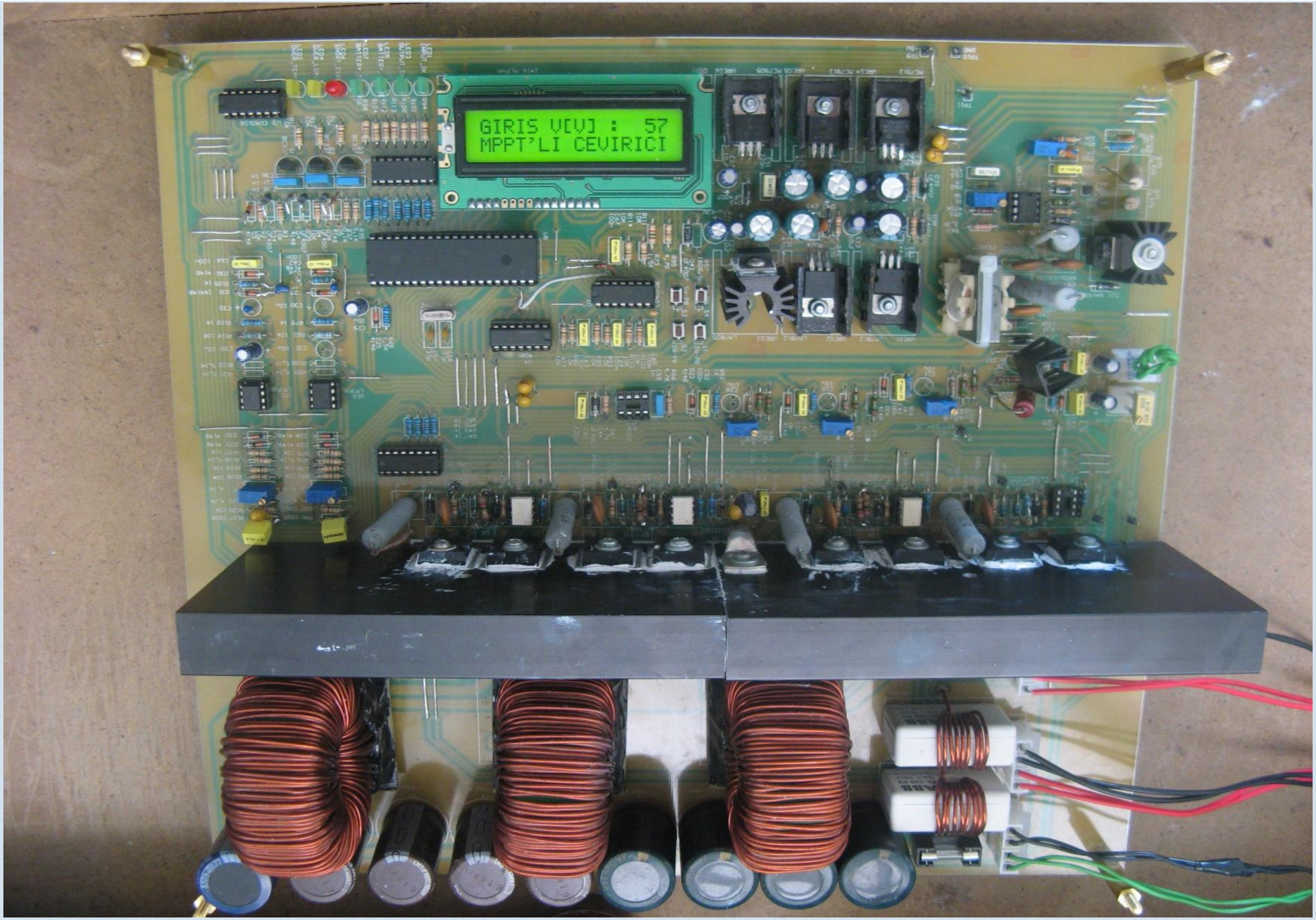
- Commonly used multilevel converter structures

Our Past Studies

- Interleaved MPPT Boost Converter with Battery Charger

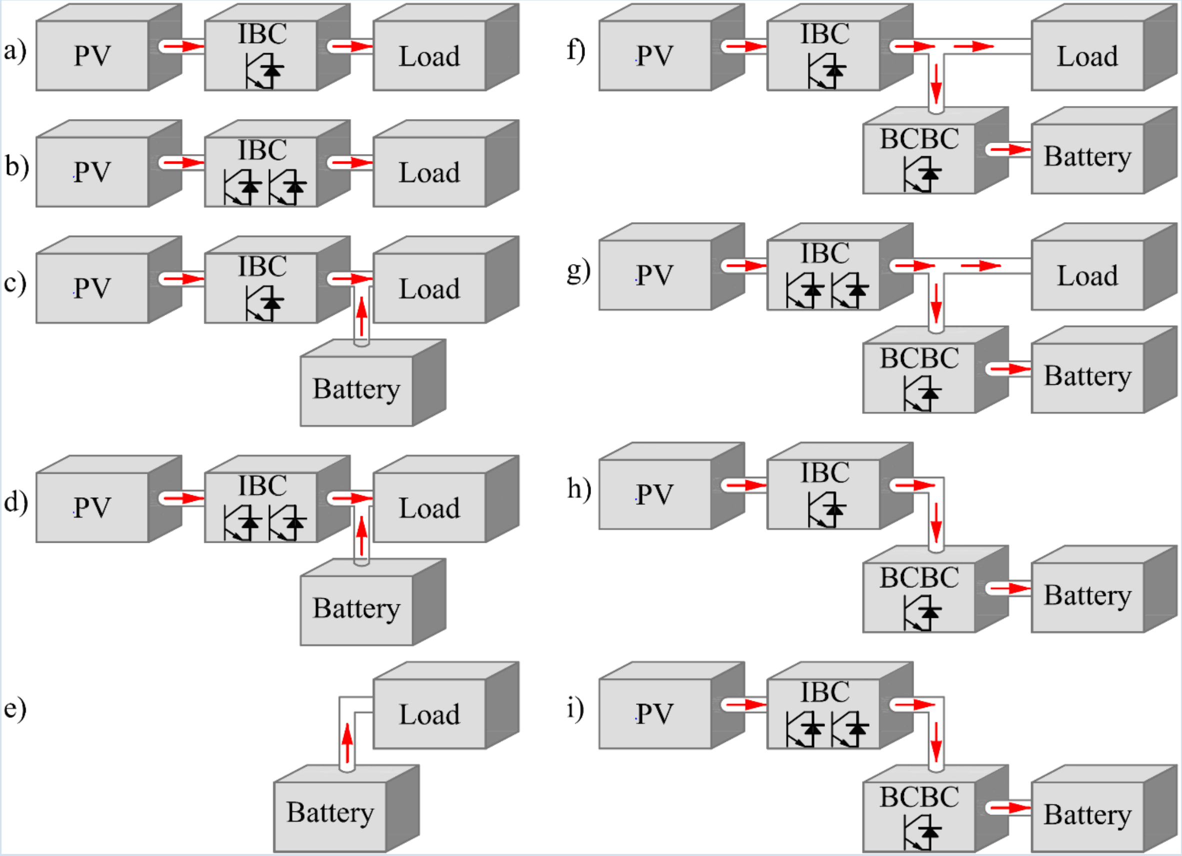


Our Past Studies (Cont.)



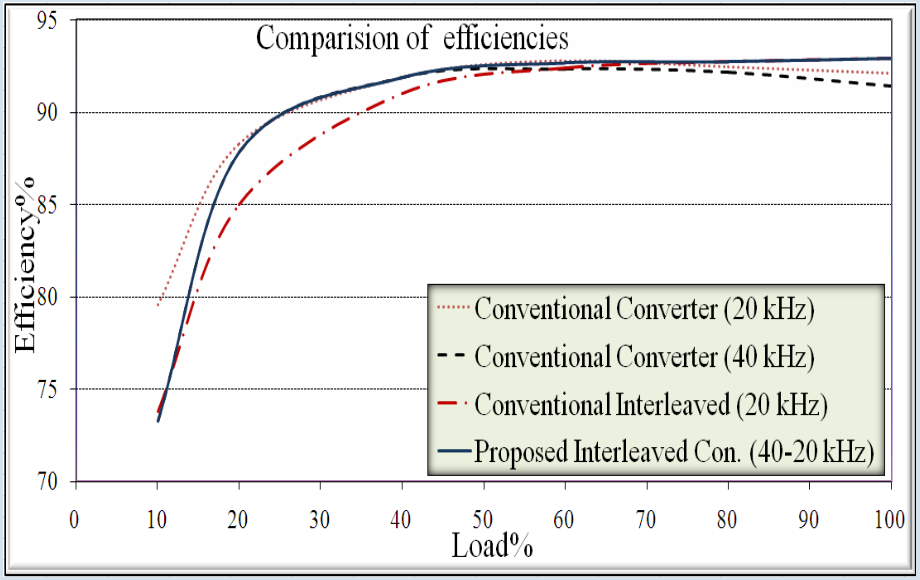
Our Past Studies (Cont.)

- Interleaved MPPT Boost Converter with Battery Charger

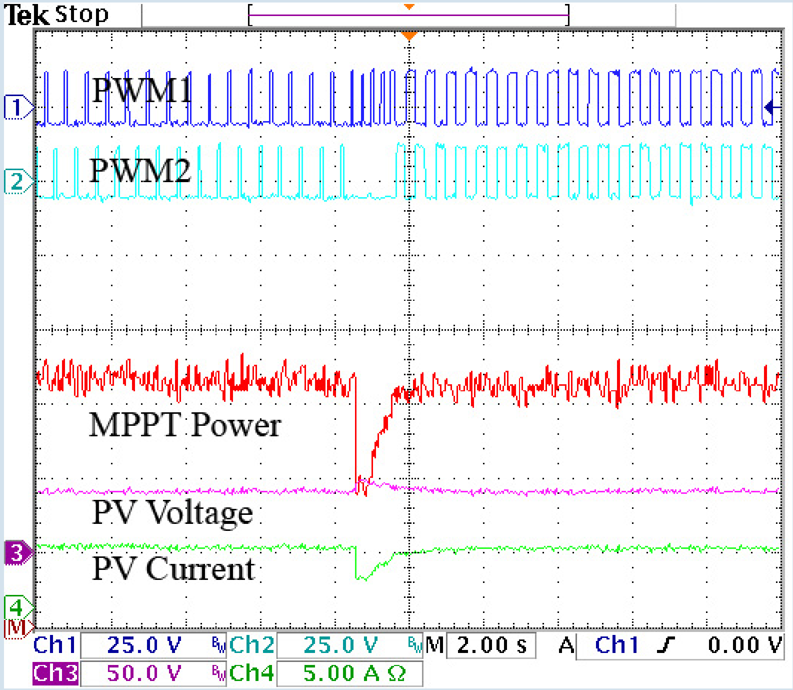


Operation modes of proposed system

Our Past Studies (Cont.)



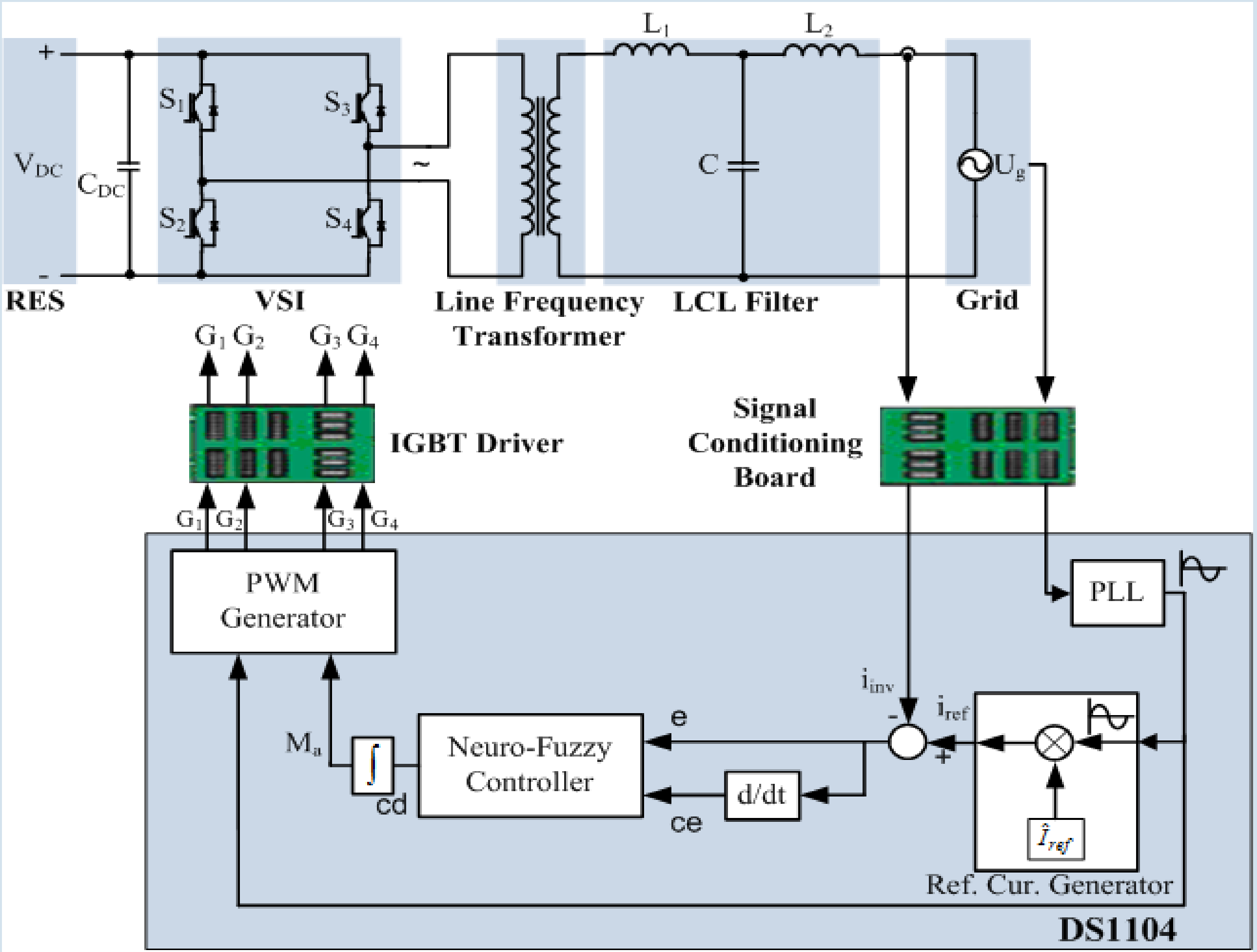
Comparison of converter topologies' efficiencies



Proposed system response to the output load changes.

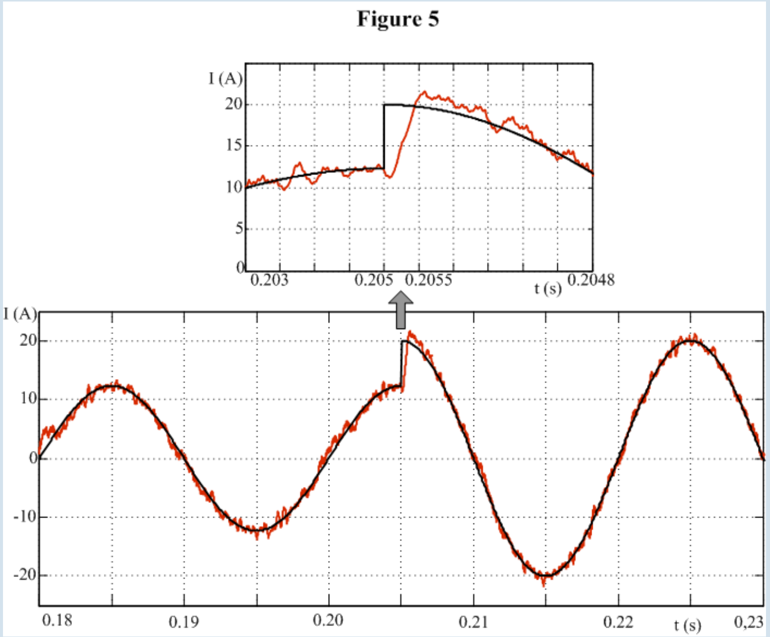
Our Past Studies (Cont.)

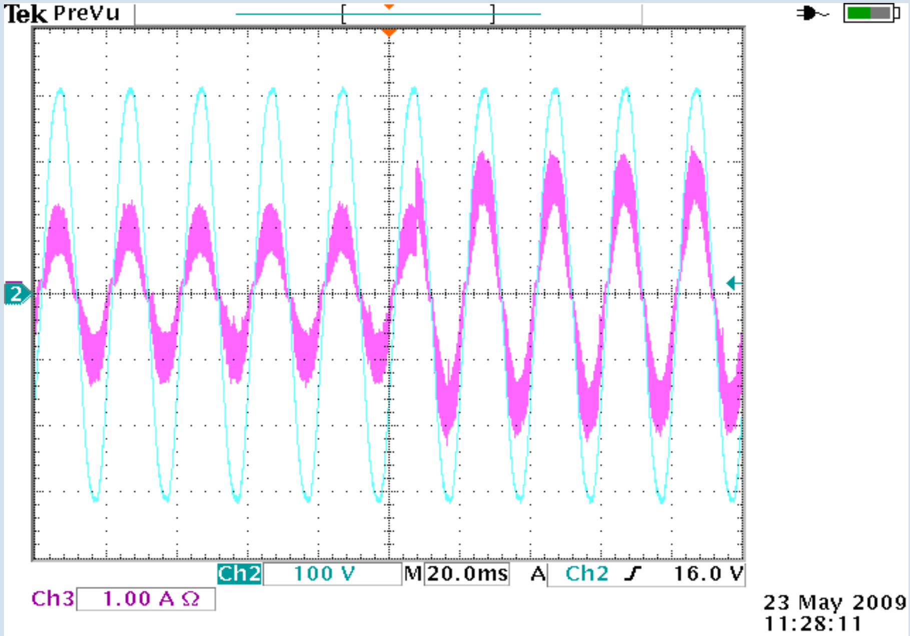
- dSpace Based Neurofuzzy Controller of Grid Interactive Inverter



Our Past Studies (Cont.)

- dSpace Based Neurofuzzy Controller of Grid Interactive Inverter

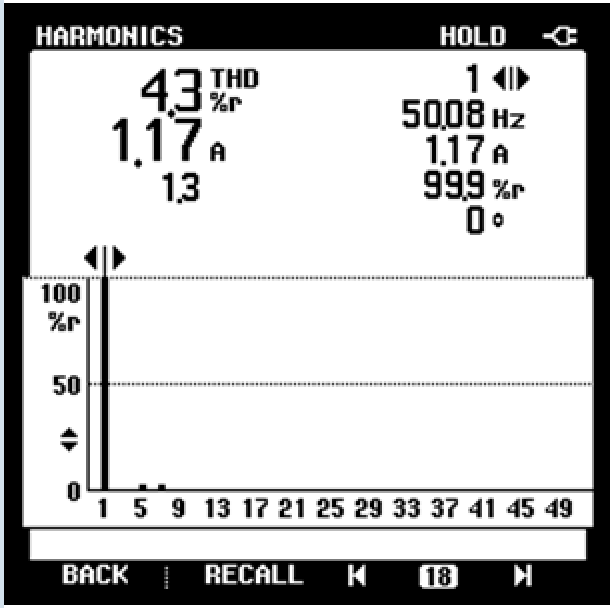




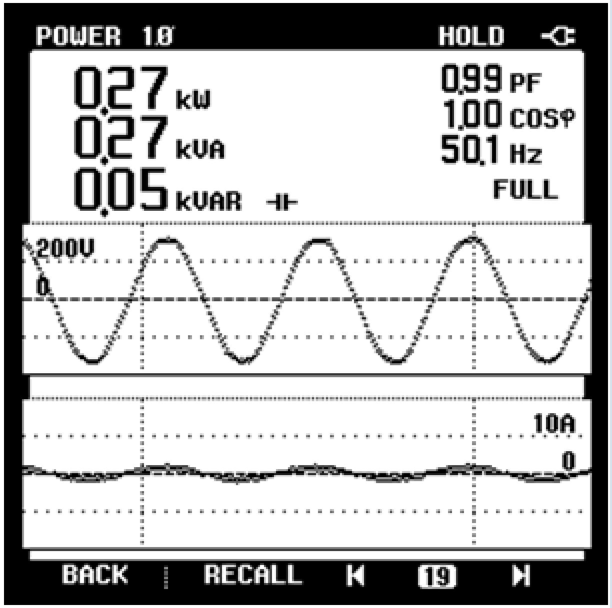
Our Past Studies (Cont.)

- dSpace Based Neurofuzzy Controller of Grid Interactive Inverter

Figure 12



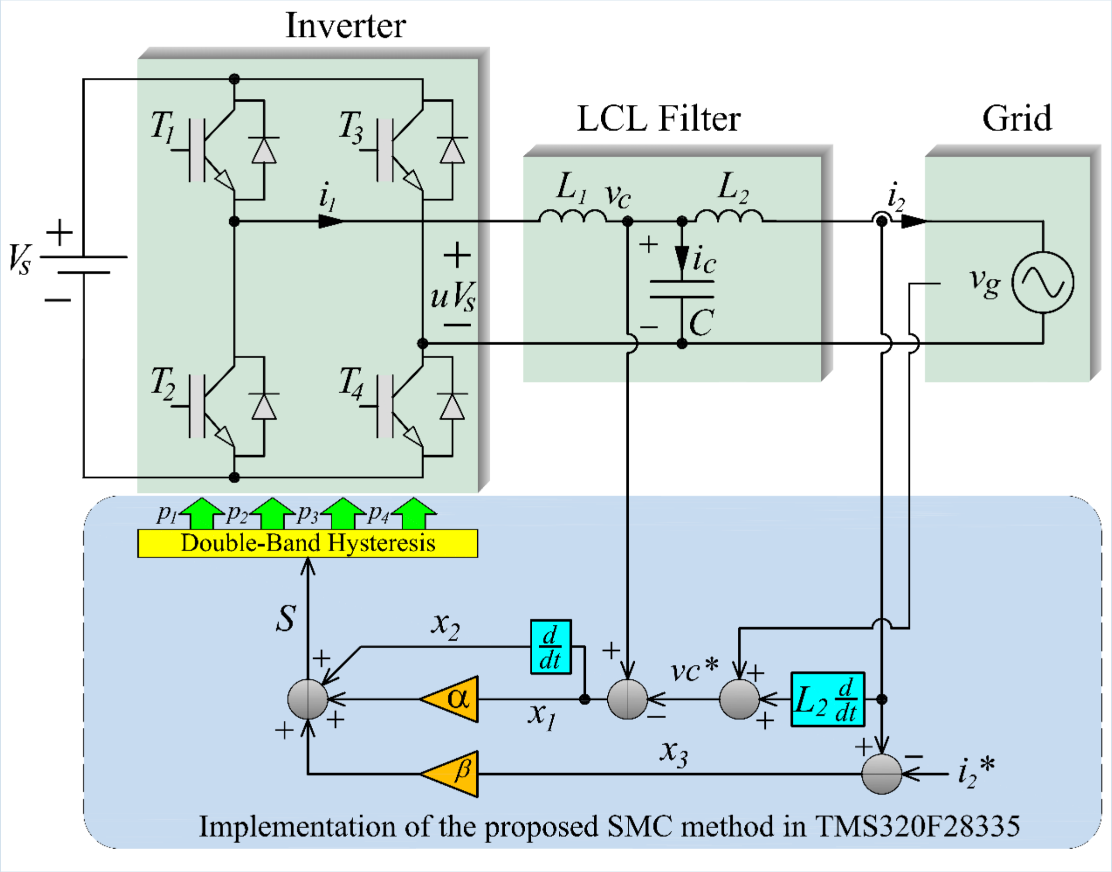
(a)



(b)

Our Past Studies (Cont.)

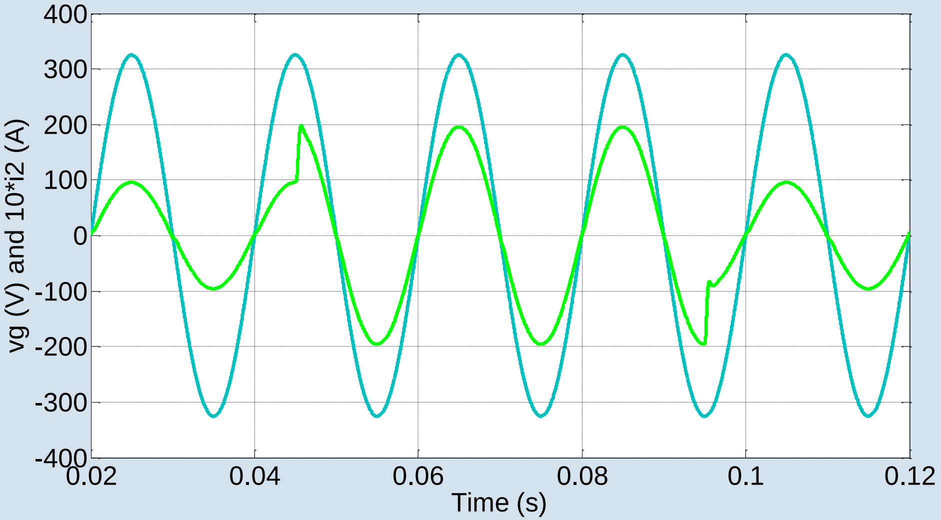
- Other Single Phase Gid Inverter Studies:

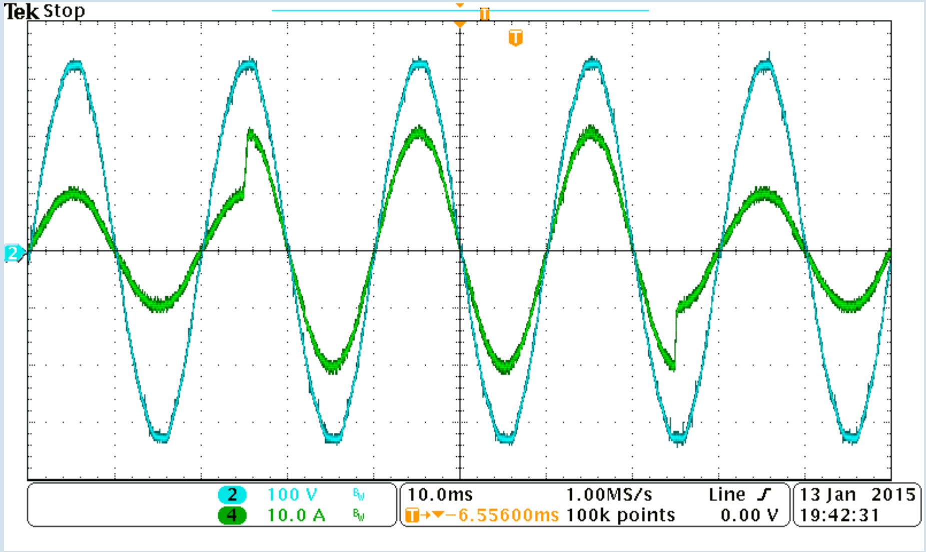


Sliding Mode Control for Single-Phase Grid-Connected LCL-Filtered VSI with Double-Band Hysteresis Scheme:

Our Past Studies (Cont.)

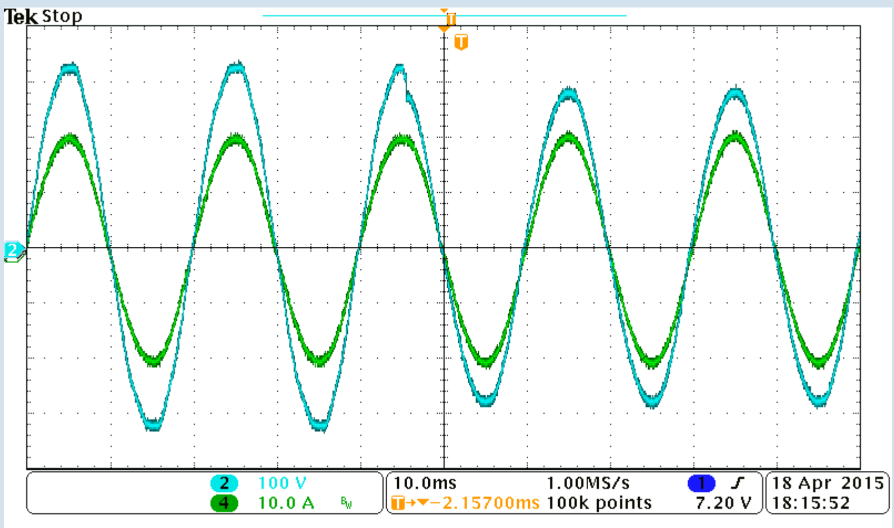
- Sliding Mode Control for Single-Phase Grid-Connected LCL-Filtered VSI with Double-Band Hysteresis Scheme:



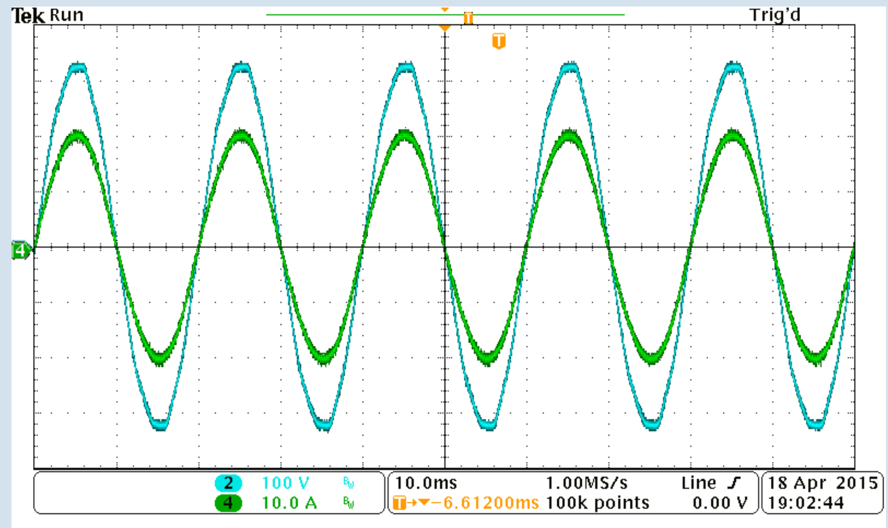


Our Past Studies (Cont.)

- Sliding Mode Control for Single-Phase Grid-Connected LCL-Filtered VSI with Double-Band Hysteresis Scheme: **Disturbance Rejection Capability**



(a)

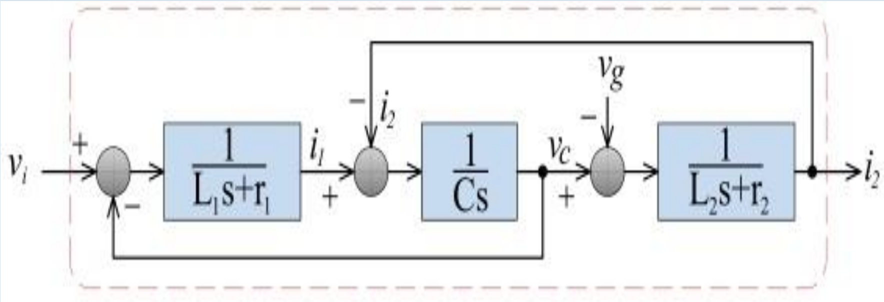


(b)

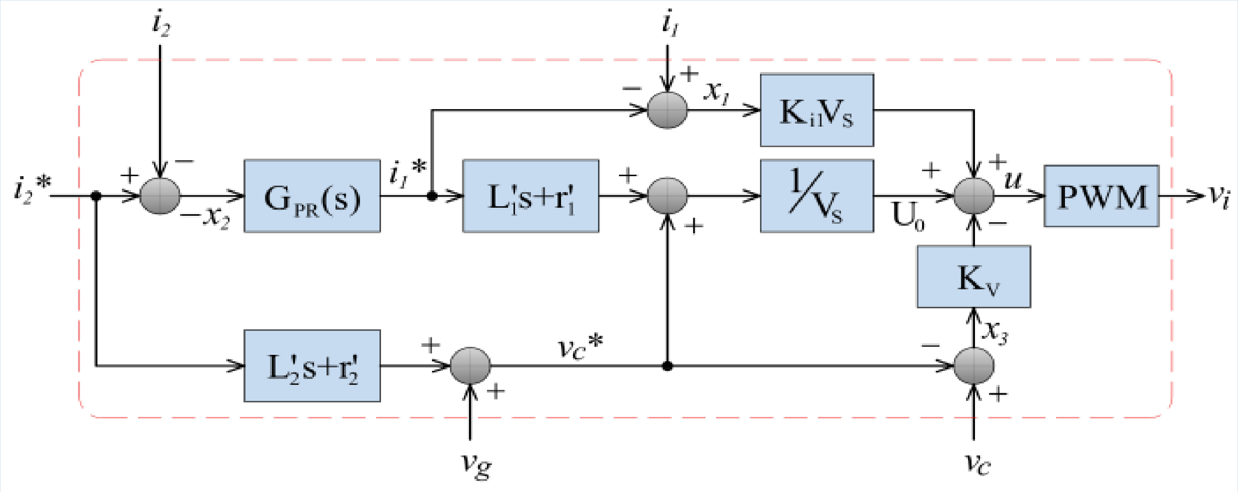
Experimental responses of and in the steady-state for: (a) a step change in from 230V (rms) to 194V (rms), (b) a 50% change in L2

Our Past Studies (Cont.)

- Other Single Phase Gid Inverter Studies:

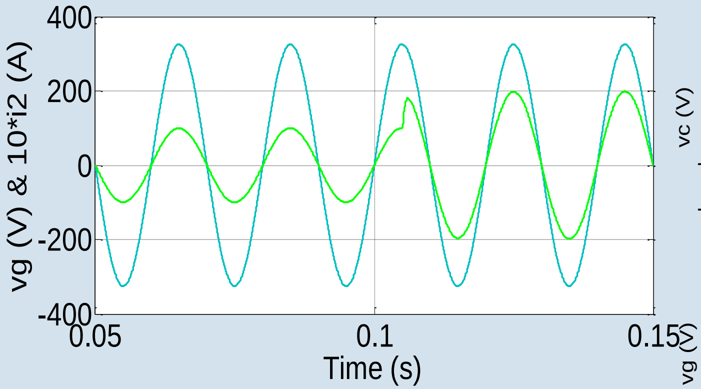


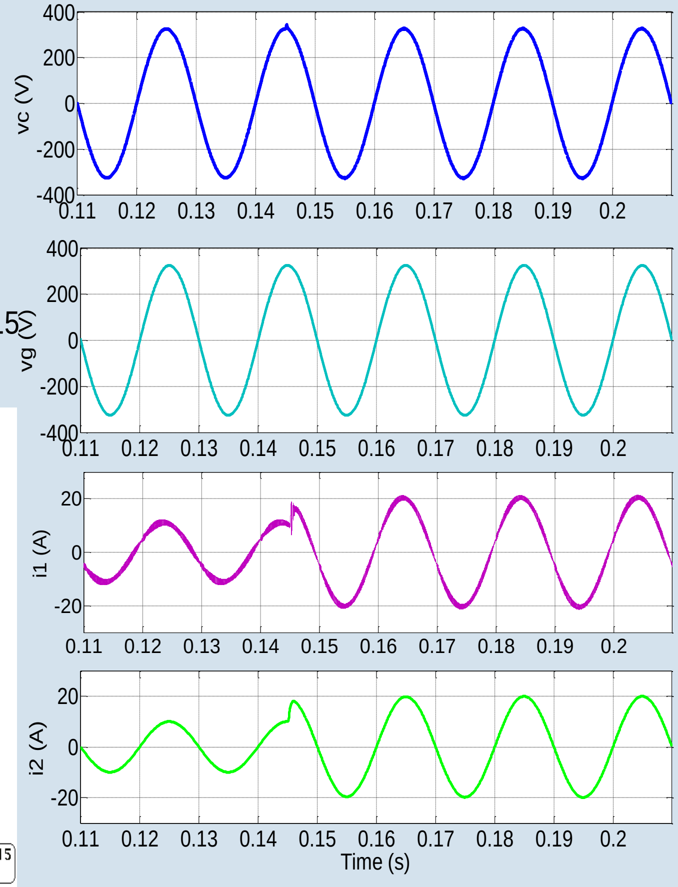
Lyapunov-Function and Proportional-Resonant Based Control Strategy for Single-Phase Grid-Connected VSI with LCL Filter:

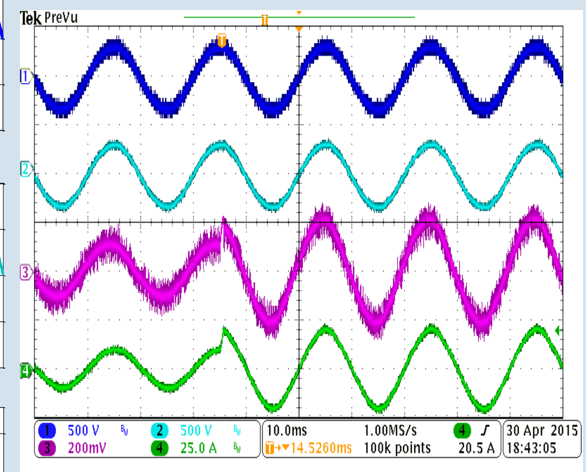


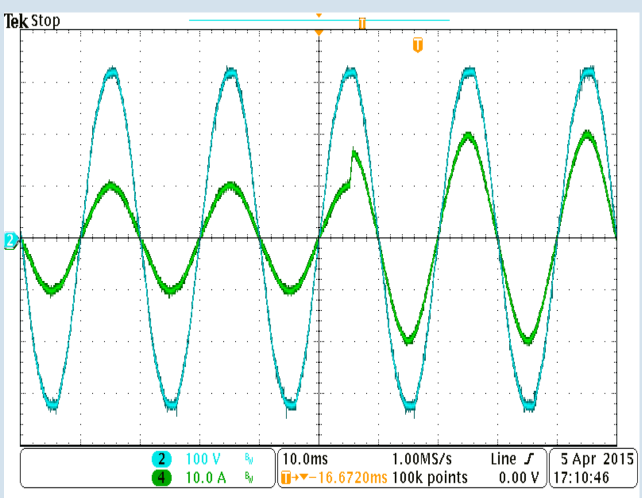
Our Past Studies (Cont.)

- Lyapunov-Function and Proportional-Resonant Based Control Strategy for Single-Phase Grid-Connected VSI with LCL Filter:



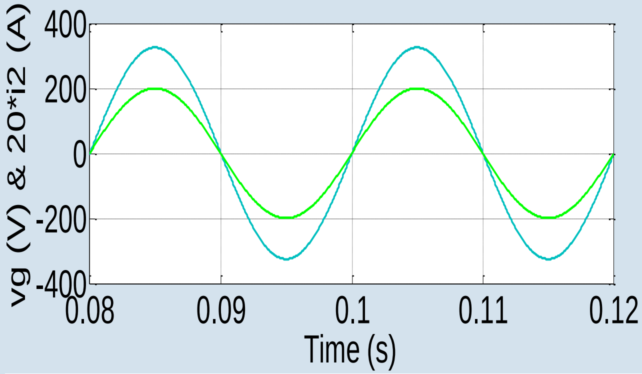


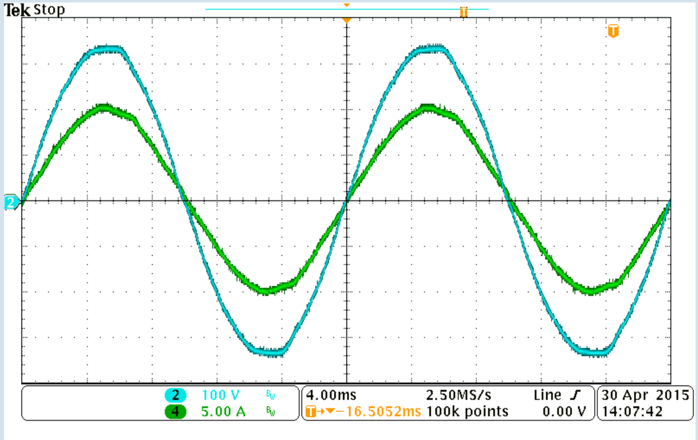




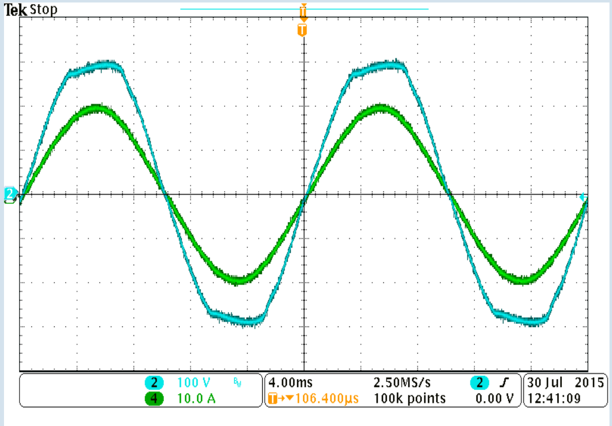
Our Past Studies (Cont.)

- Lyapunov-Function and Proportional-Resonant Based Control Strategy for Single-Phase Grid-Connected VSI with LCL Filter: **Disturbance Rejection**





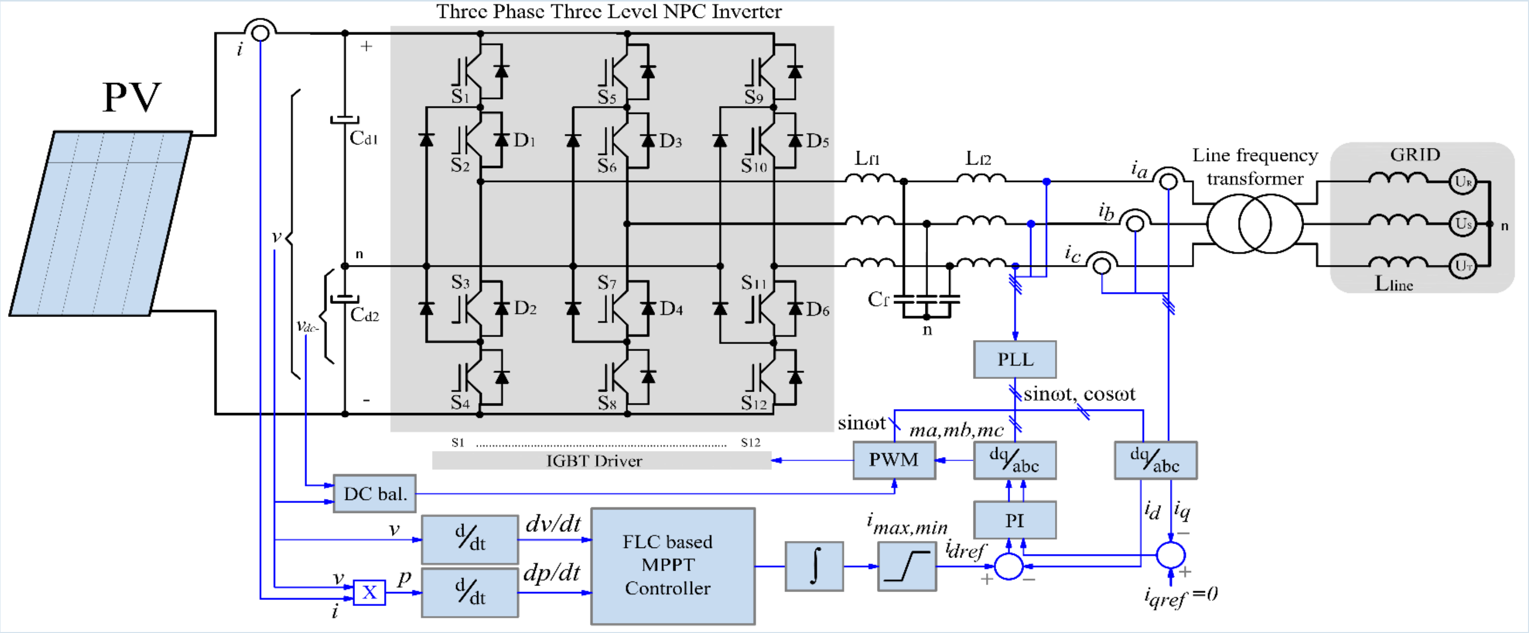
15% variation in LCL filter parameters



Distorted grid voltage (THDv=5.8%)

Our Past Studies (Cont.)

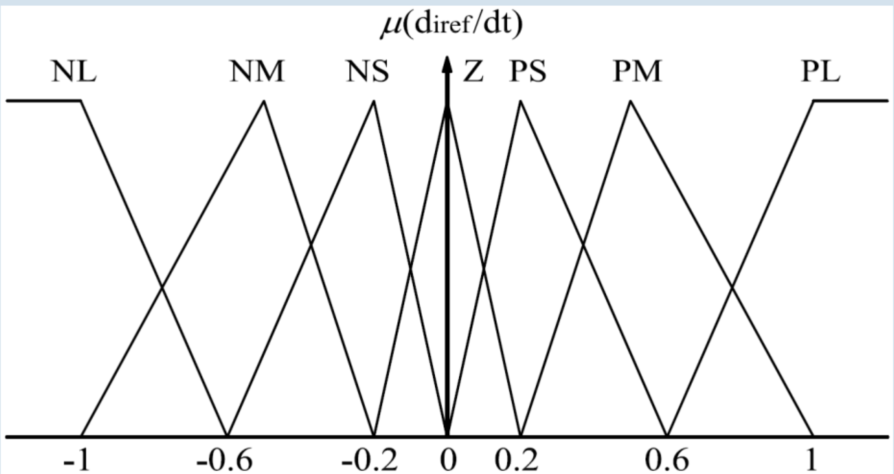
- Three-Phase Three-Level NPC Inverter

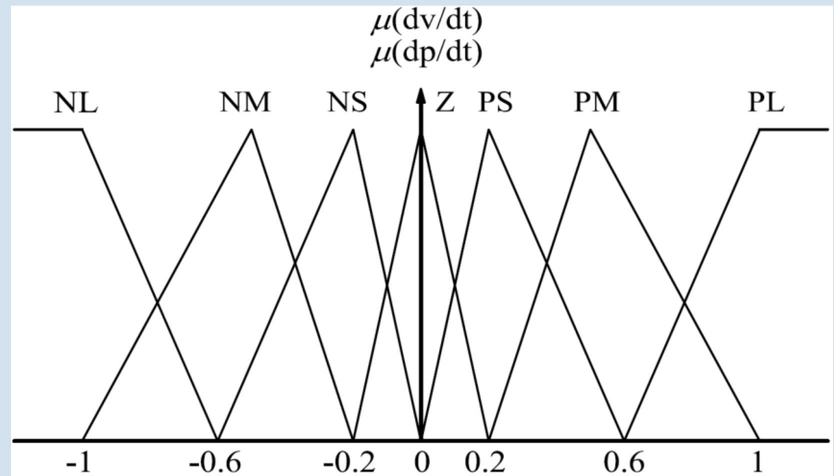


THREE-PHASE THREE-LEVEL GRID INTERACTIVE INVERTER WITH FUZZY LOGIC BASED MPPT

Our Past Studies (Cont.)

- THREE-PHASE THREE-LEVEL GRID INTERACTIVE INVERTER WITH FUZZY LOGIC BASED MPPT

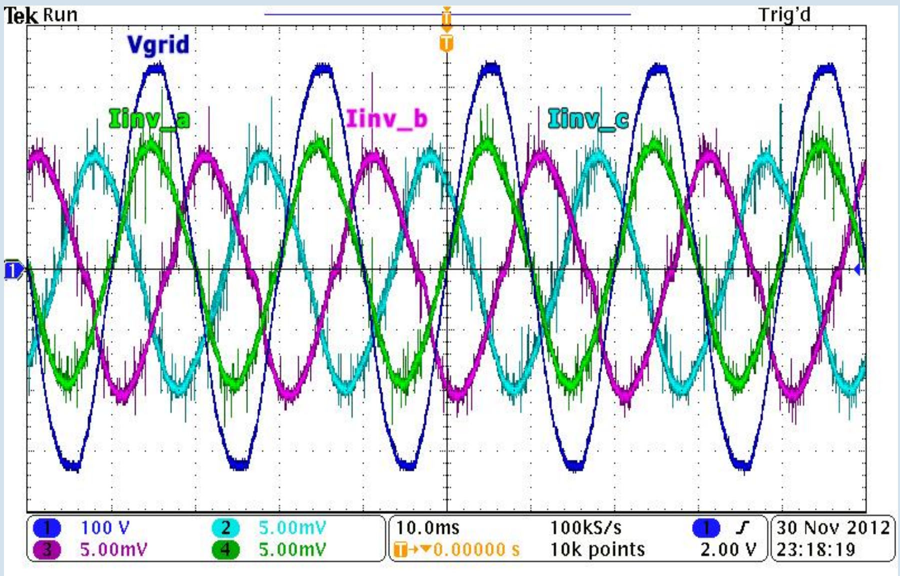


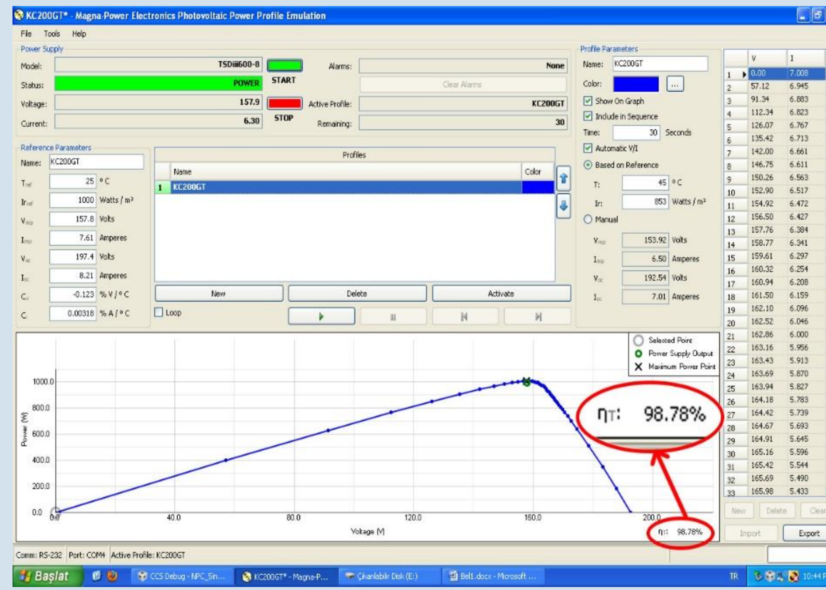


		Error (e)						
Change in error (ce)		NL	NM	NS	Z	PS	PM	PL
	NL	NL	NL	NM	Z	PM	PL	PL
	NM	NL	NM	NM	Z	PM	PM	PL
	NS	NL	NM	NS	Z	PS	PM	PL
	Z	Z	Z	Z	Z	Z	Z	Z
	PS	PS	PS	PS	Z	NS	NM	NL
	PM	PM	PM	PS	Z	NS	NM	NL
	PL	PL	PL	PM	Z	NM	NL	NL

Our Past Studies (Cont.)

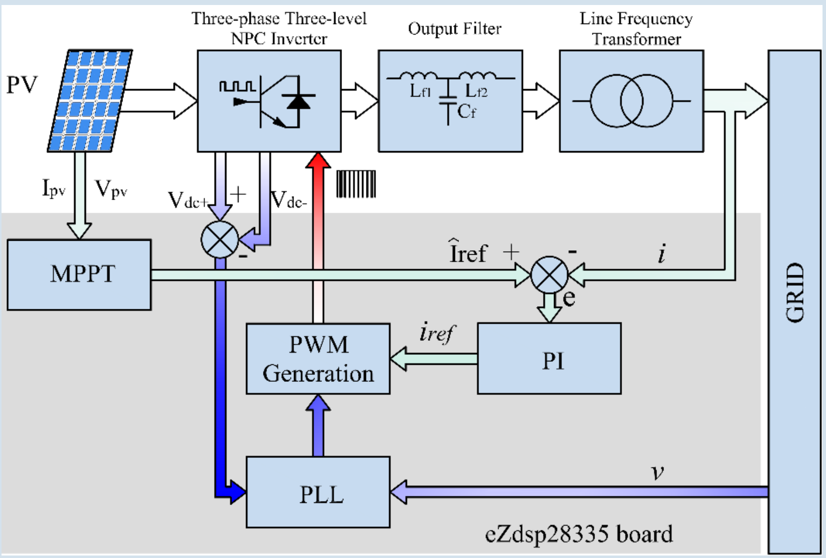
- THREE-PHASE THREE-LEVEL GRID INTERACTIVE INVERTER WITH FUZZY LOGIC BASED MPPT





Our Past Studies (Cont.)

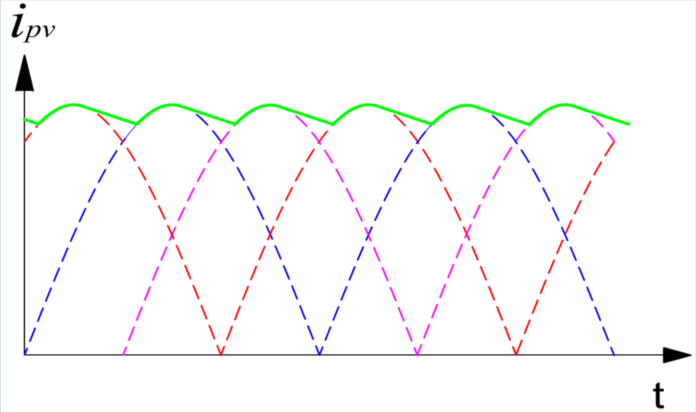
- Three-Phase Three-Level NPC Inverter



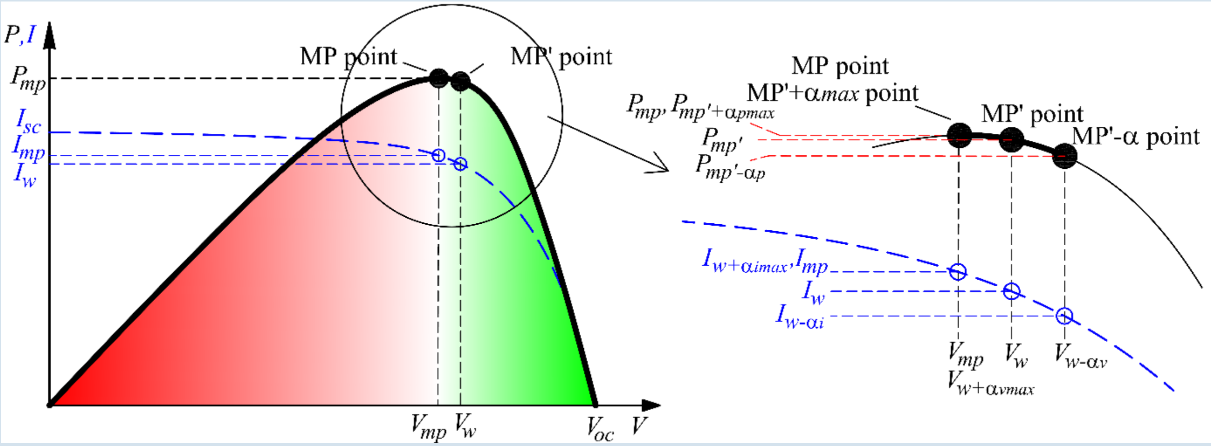
SINGLE STAGE THREE LEVEL GRID INTERACTIVE MPPT INVERTER FOR PV SYSTEMS

Our Past Studies (Cont.)

- SINGLE STAGE THREE LEVEL GRID INTERACTIVE MPPT INVERTER FOR PV SYSTEMS:



Ripple of the DC bus voltage

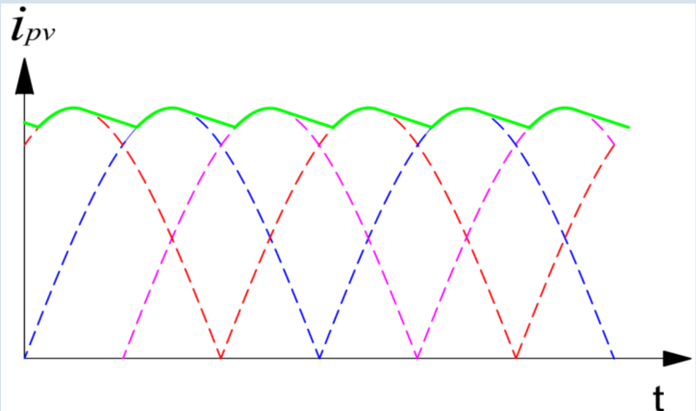


$$I_{ref\,[k]} = I_{ref\,[k-1]} \pm \alpha$$

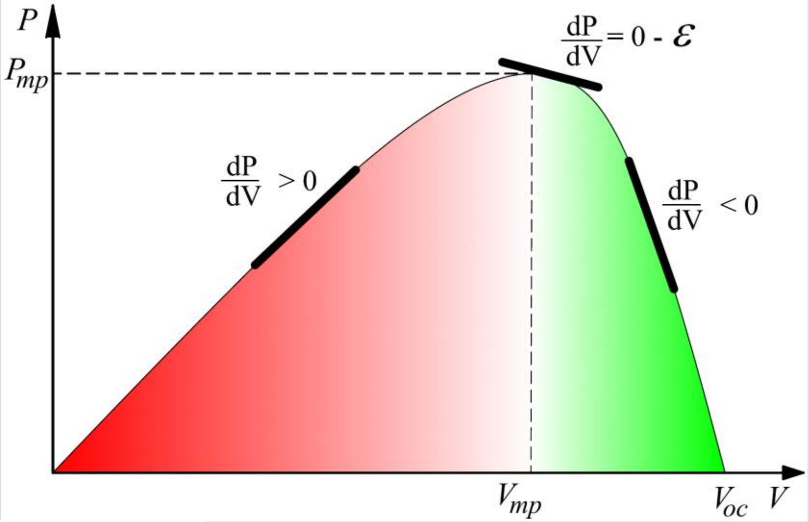
$$\alpha = \left[-\operatorname{sgn}\left(\frac{dP}{dV}\right)\right] \cdot \left(\frac{k}{1+i_{pv}}\right)$$

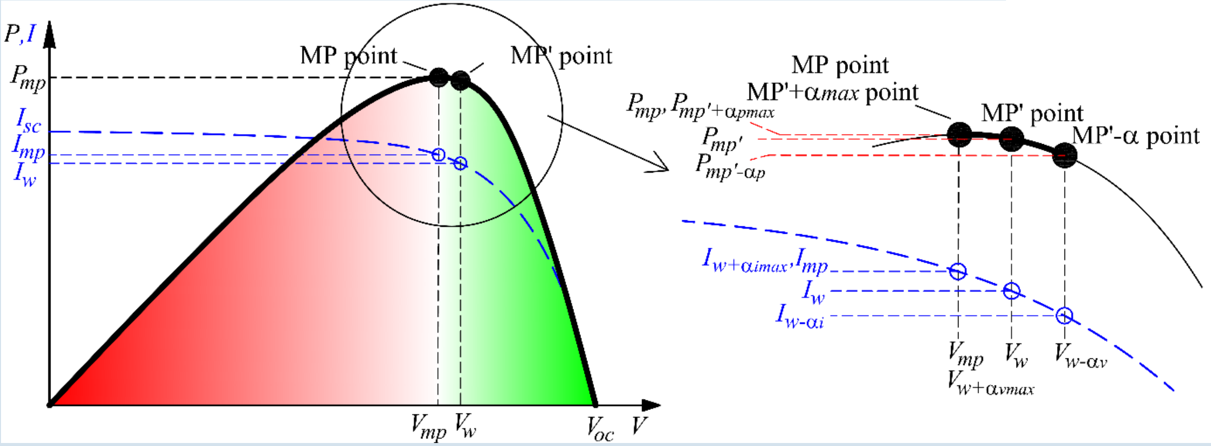
Our Past Studies (Cont.)

- SINGLE STAGE THREE LEVEL GRID INTERACTIVE MPPT INVERTER FOR PV SYSTEMS:



Ripple of the DC bus voltage



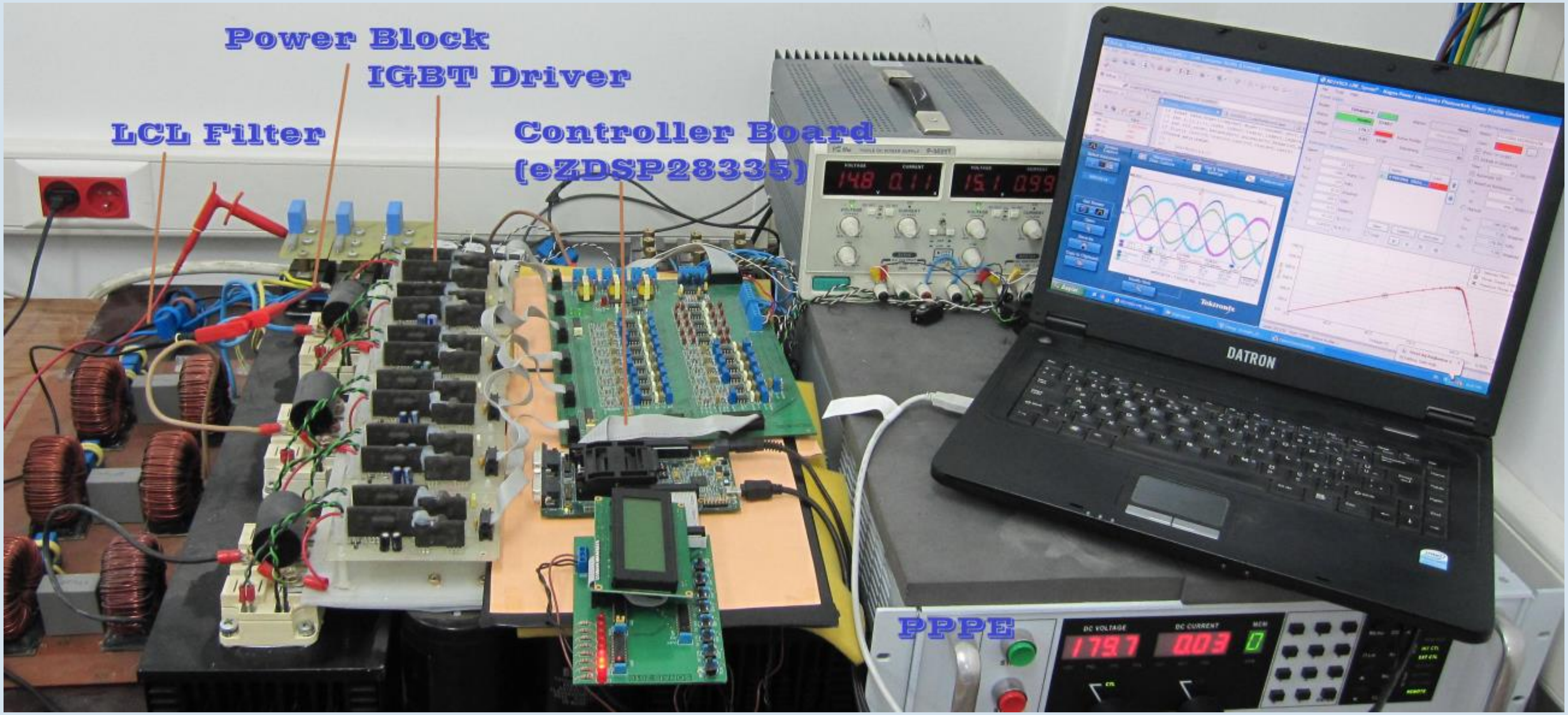


$$I_{ref\,[k]} = I_{ref\,[k-1]} \pm \alpha$$

$$\alpha = \left[-\operatorname{sgn}\left(\frac{dP}{dV} \right) \right] \cdot \left(\frac{k}{1 + i_{pv}} \right)$$

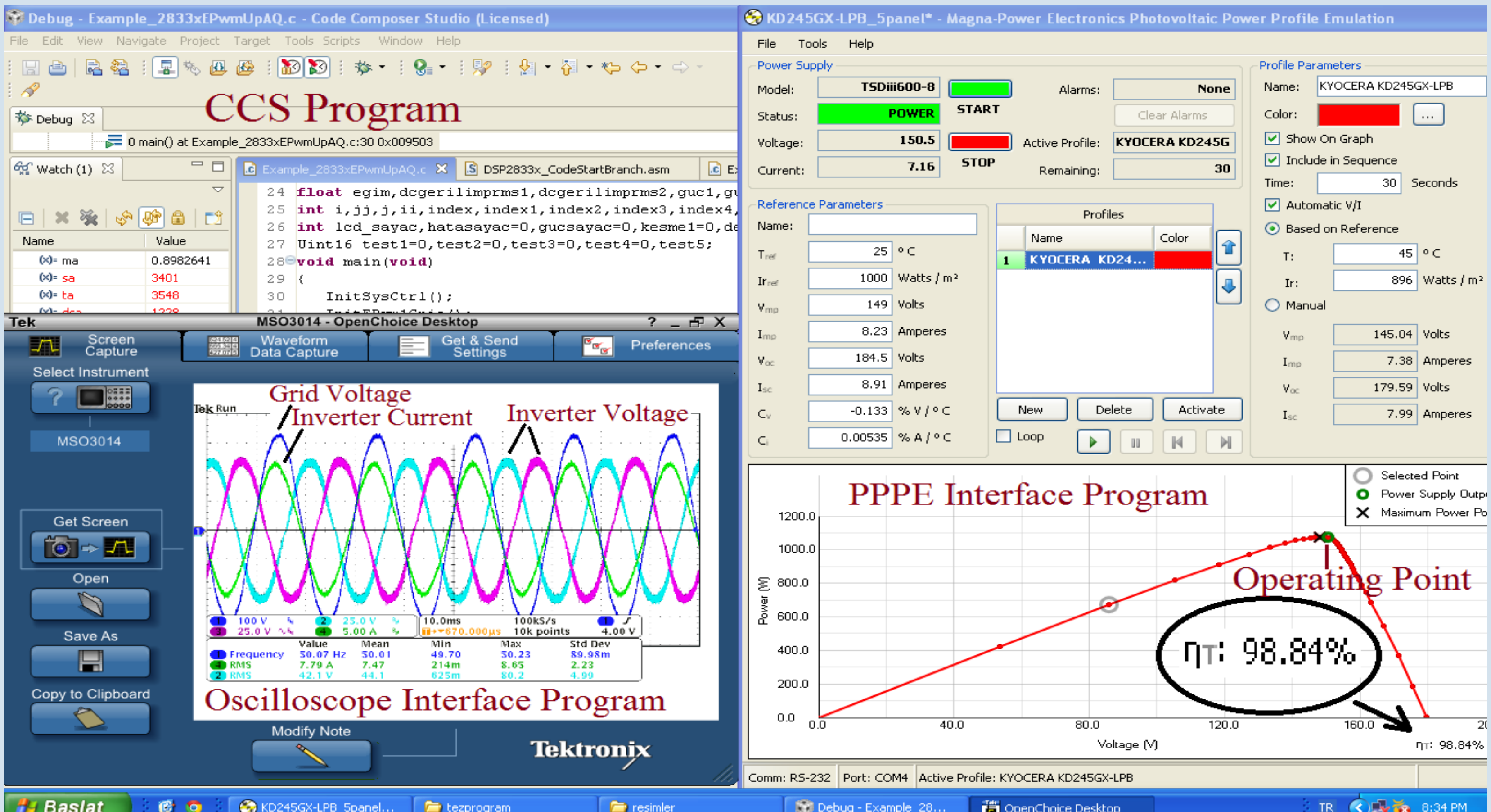
Our Past Studies (Cont.)

- SINGLE STAGE THREE LEVEL GRID INTERACTIVE MPPT INVERTER FOR PV SYSTEMS:



Our Past Studies (Cont.)

- SINGLE STAGE THREE LEVEL GRID INTERACTIVE MPPT INVERTER FOR PV SYSTEMS:



Thank You…

QUESTIONS

&

ANSWERS