HEI INGÉNIEURS POUR LE MONDE

POLITÉCNICO DE COIMBRA

O futuro construído hoje!

Course

Power Converters and Control of Renewable Energy Systems

Presented by :

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HEI-Lille

Level : Erasmus Mundus Masters Course

Area : Power Electronics Converters

Course objectives

Understanding of the various renewable energy sources, especially wind turbines and photovoltaic panels,
Principle of MPPT control
Be aware of different architectures of power converters associated with renewable energy sources with an introduction to the command.

Outcomes

At the end of this course, students should be able to:
Make a judicious choice of material (renewable source, converters, transformers, etc..) depending on the application to implement.
Modeling, simulation, control and connect all correctly.

Course organisation

Course content:

- General Introduction

- Chapiter 1 : Configurations of wind turbine systems

- Chapiter 2 :Configurations of photovoltaic systems

Practical Lab:

Modeling and simulation of a photovoltaic system under Matlab/Simulink/Simpower

General Introduction

The global electrical energy consumption is steadily rising and consequently there is a demand to increase the power generation capacity. A significant percentage of the required capacity increase can be based on renewable energy sources. Wind turbine technology, as the most cost effective renewable energy conversion system, will play an important part in our future energy supply. But other sources like microturbines, photovoltaics and fuel cell systems may also be serious contributors to the power supply. **Characteristically, power electronics wil be an efficient and important interface between sources, loads and grid. Therefore, this course will discuss two different alternative/renewable energy sources with various power electronics configurations.**

The job for the power electronics in renewable energy systems is to convert the energy from one stage into another stage to the grid (alternative voltage) with the highest possible efficiency, the lowest cost and to keep a superior performance. The basic interfacing is shown in Fig. 1.

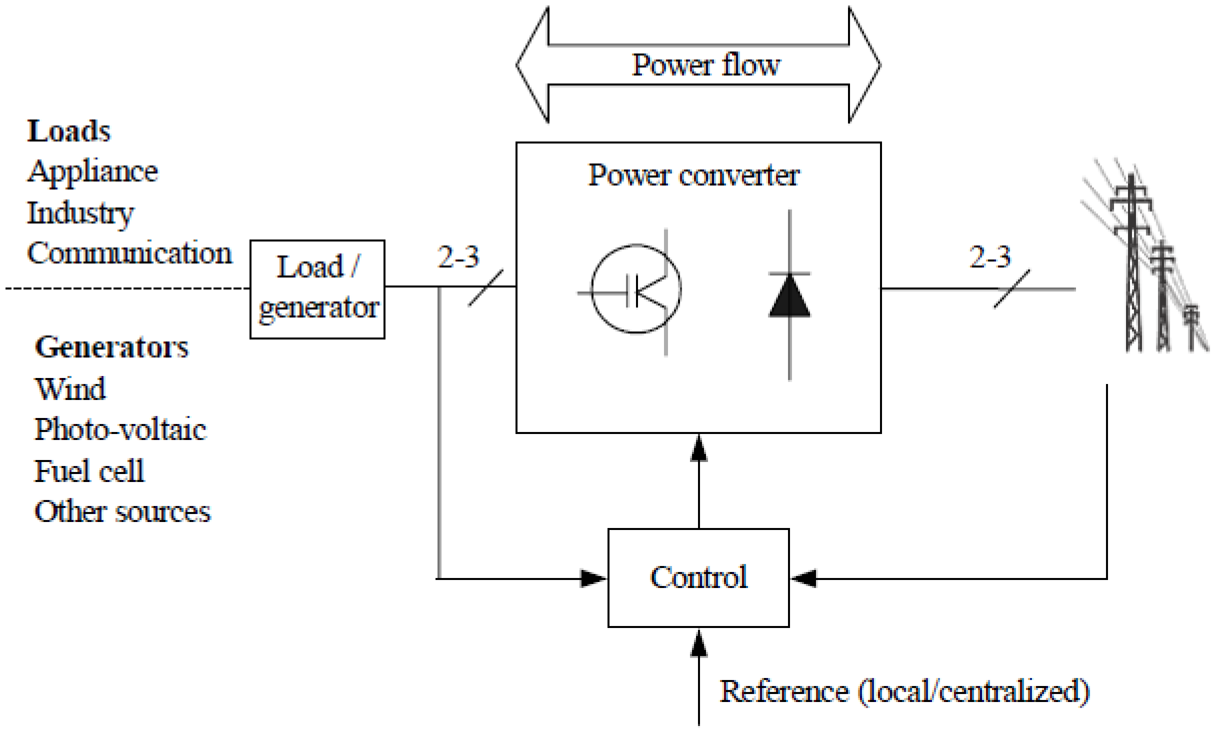
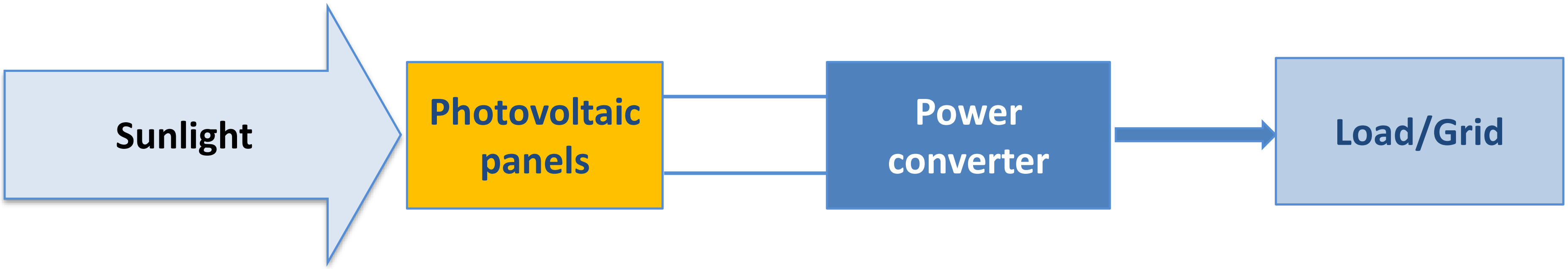
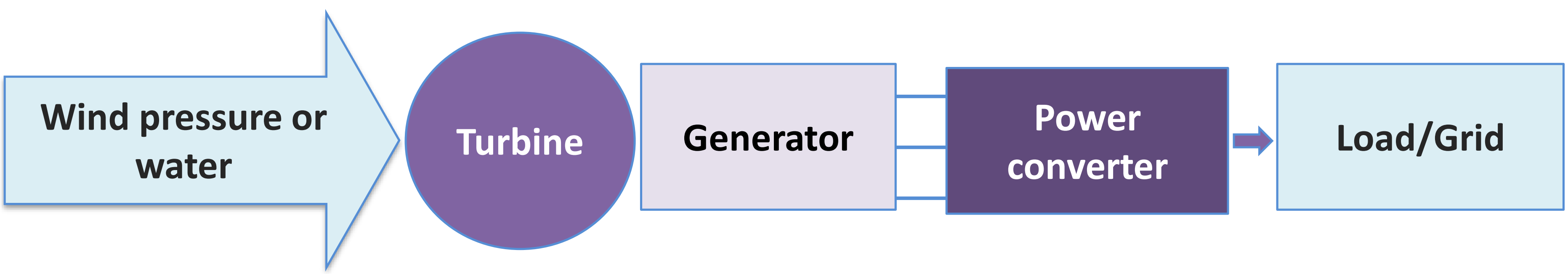


Fig. 1. Power electronic system with the grid, load/source, power converter and control.

Electricity Production Line

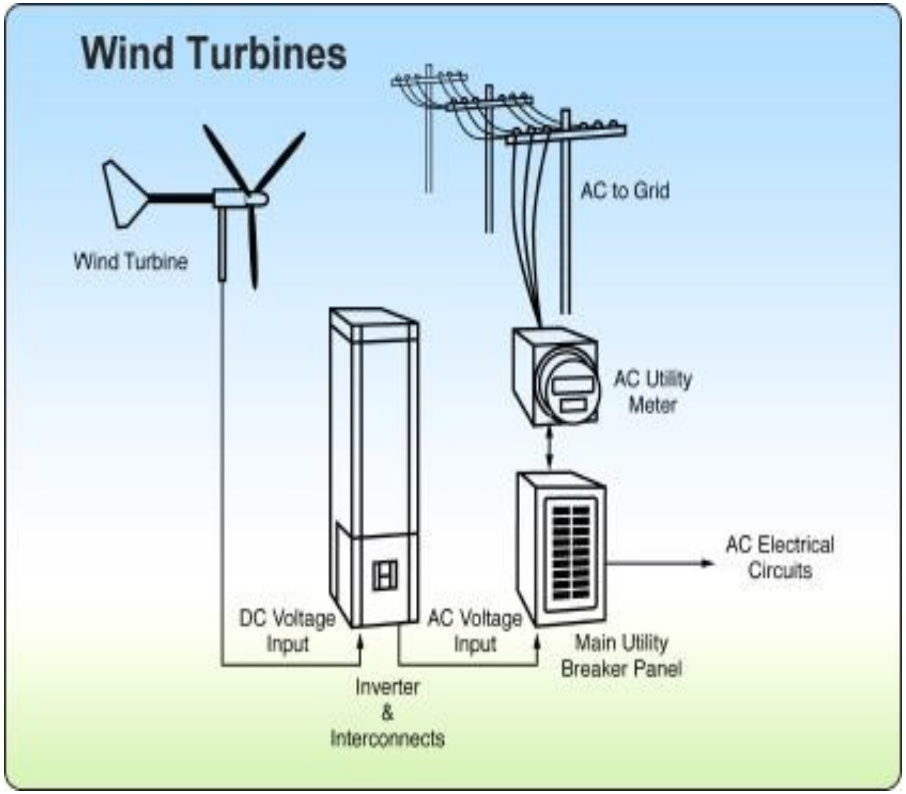


PHOTOVOLTAIC



WIND / HYDROLYC

Chapter I
Configurations of wind turbine systems



1.1. Wind power conversion

■ The function of a wind turbine is to convert the linear motion of the wind into rotational energy that can be used to drive a generator, as illustrated in Fig. 1.

■ Wind turbines capture the power from the wind by means of aerodynamically designed blades and convert it into rotating mechanical power. At present, the most popular wind turbine is the Horizontal Axis Wind Turbine (HAWTs) where the number of blades is typically three.

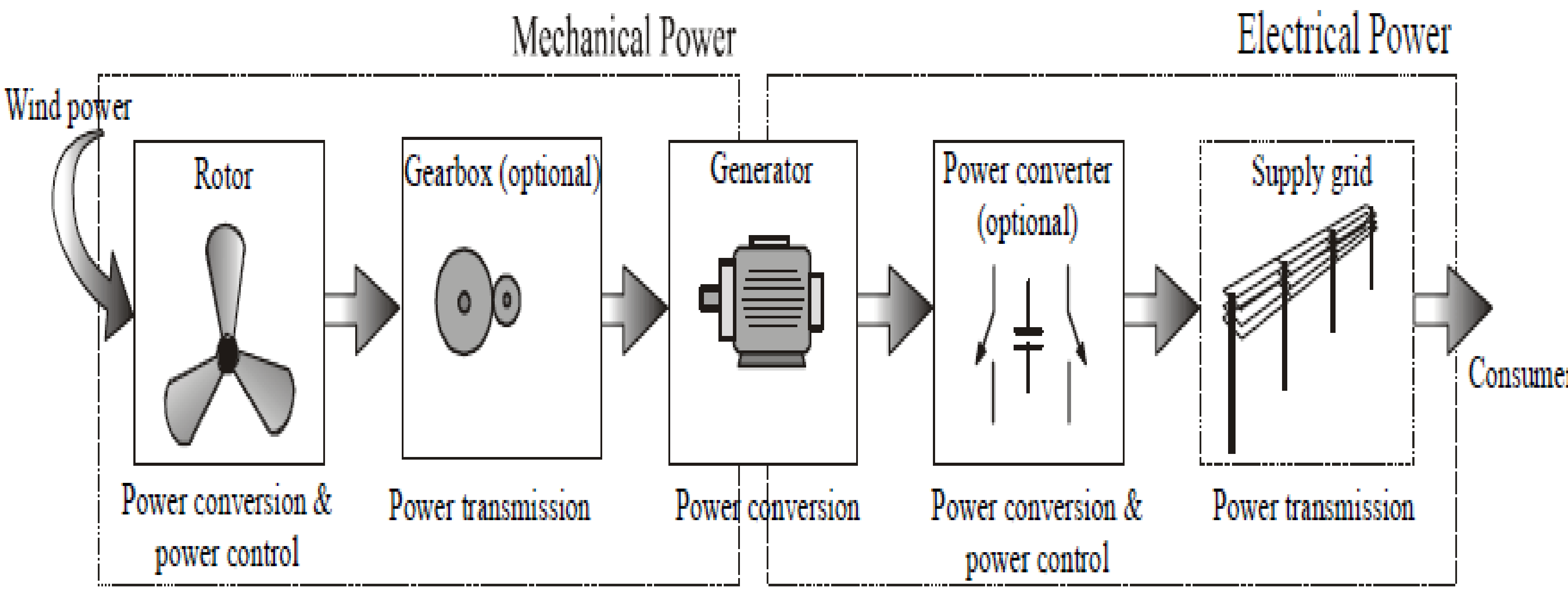


Fig. 1. Conversion from wind power to electrical power in a wind turbine

■ **The aerodynamic power, *P*, of a wind turbine is given by:**

$$P = \frac{1}{2}\rho\pi R^2 v^3 C_p$$

where ρ is the air density, *R* is the turbine radius, *v* is the wind speed and *Cp* is the turbine power coefficient which represents the power conversion efficiency of a wind turbine. *Cp* is a function of the tip-speed ratio (λ), as well as the blade pitch angle (β) in a pitch controlled wind turbine. λ is defined as the ratio of the tip speed of the turbine blades to wind speed, and given by:

$$\lambda = \frac{R \cdot \Omega}{v}$$

where Ω is the rotational speed of the wind turbine.

■ **The Betz limit, *CP*,max (theoretical) =16/27, is the maximum theoretically possible rotor power coefficient. In practice three effects lead to a decrease in the maximum achievable power coefficient :**

- **Rotation of the wake behind the rotor**
- **Finite number of blades and associated tip losses**
- **Non-zero aerodynamic drag**

* In fluid dynamics, the **drag coefficient** (commonly denoted as: c_d, c_x or c_w) is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment such as air or water.

- **A typical *Cp*-λ curve for a fixed pitch angle β is shown in Fig. 3. It can be seen that there is a practical maximum power coefficient, *Cp*,max. Normally, a variable speed wind turbine follows the *Cp*,max to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at the optimum tip-speed ratio, λopt.**

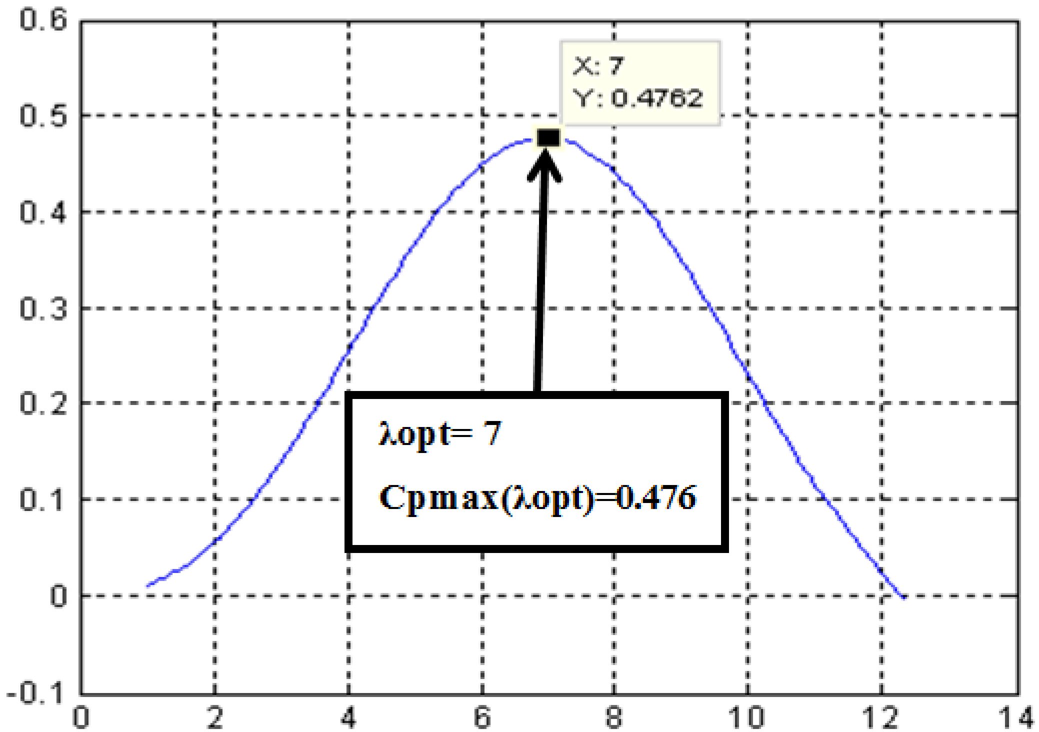


Fig. 3 : Characteristic Cp (λ) of a wind turbine for a fixed angle β

1.2. Converter topologies for wind turbines

1.3.1. Case of fixed speed wind power conversion system

In a fixed speed wind power conversion system, the power may be limited aerodynamically either by stall, active stall or by pitch control. Normally induction generators are used in fixed speed systems, which are almost independent of torque variation and operate at a fixed speed (slip variation of 1-2%). Fig. 4 shows different topologies for the first category of wind turbines.

All three systems are using a soft-starter (not shown in Fig. 4) in order to reduce the inrush current and there by limit flicker problems on the grid. They also need a reactive power compensator to reduce (almost eliminate) the reactive power demand from the turbine generators to the grid. It is usually done by continuously switching capacitor banks following the production variation (5-25 steps).

Those solutions are attractive due to cost and reliability but they are not able (within a few ms) to control the active power very fast. The generators have typically a pole-shift possibility in order to maximize the energy capture.

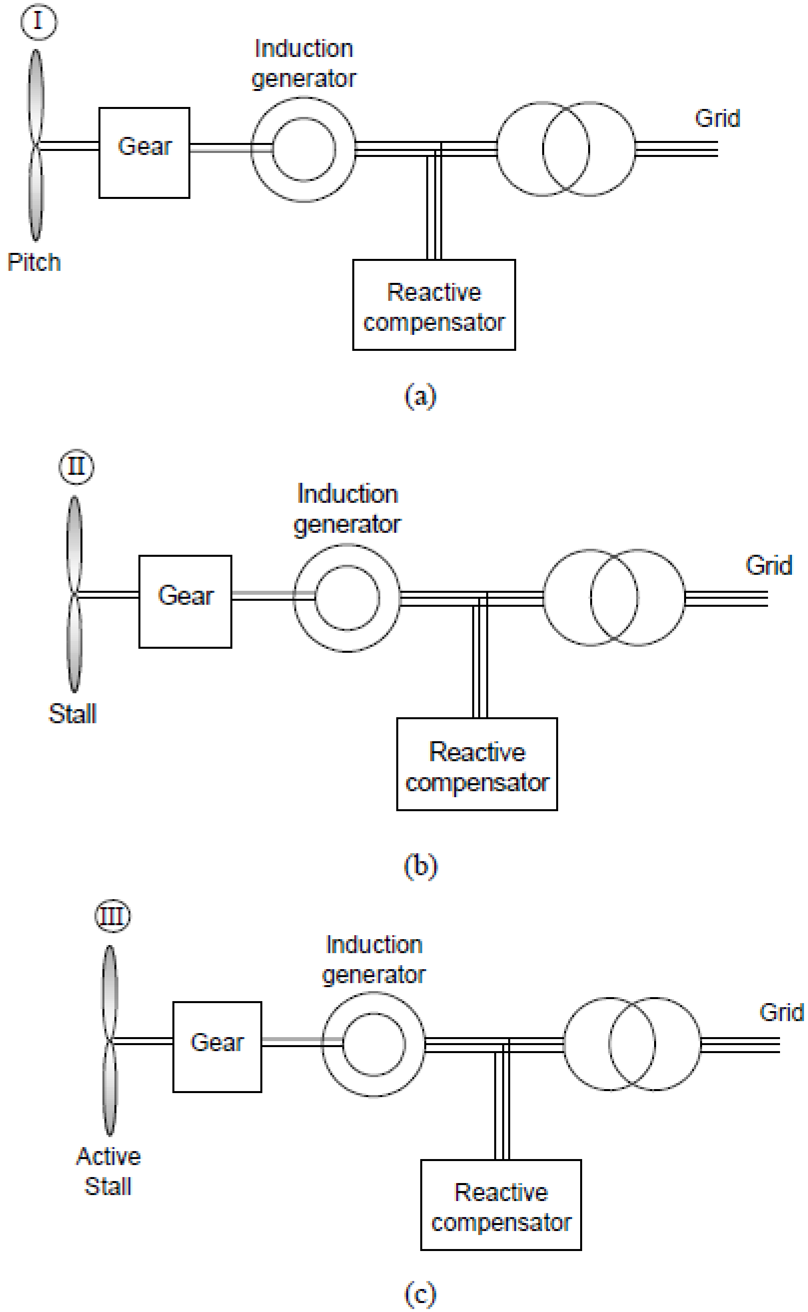


Fig. 4. Wind turbine systems without power converter but with aerodynamic power control.

a) Pitch controlled (System I)

b) Stall controlled (System II)

c) Active stall controlled (System III)

There are two basic approaches used to control a wind turbine in high wind speeds: pitch-control and stall-control. In pitch-controlled turbines, an anemometer mounted atop the nacelle constantly checks the wind speed and sends signals to a pitch actuator, adjusting the angle of the blades to capture the energy from the wind most efficiently. On a stall-regulated wind turbine, the blades are locked in place and do not adjust during operation. Instead the blades are designed and shaped to increasingly “stall” the blade’s angle of attack with the wind to both maximize power output and protect the turbine from excessive wind speeds.

- **Benefits**

✓ Simple and well known system

✓ Economic

- **Disadvantages**

❖ Energy losses due to the multiplier

❖ Significant vibrations

❖ Significant noise

❖ Faster wear

❖ Oil maintenance of the multiplier (risk of leaks)

❖ Higher fire risk

❖ The electricity produced is of lower quality

1.3.2. Case of variable speed wind power conversion system

The next category is variable speed systems where pitch control is typically used. Variable speed wind turbines may be further divided into two parts, one with partially rated power electronic converters and one with fully rated power electronic converters.

- **Variable speed wind power conversion systems with partially rated power electronic converters**

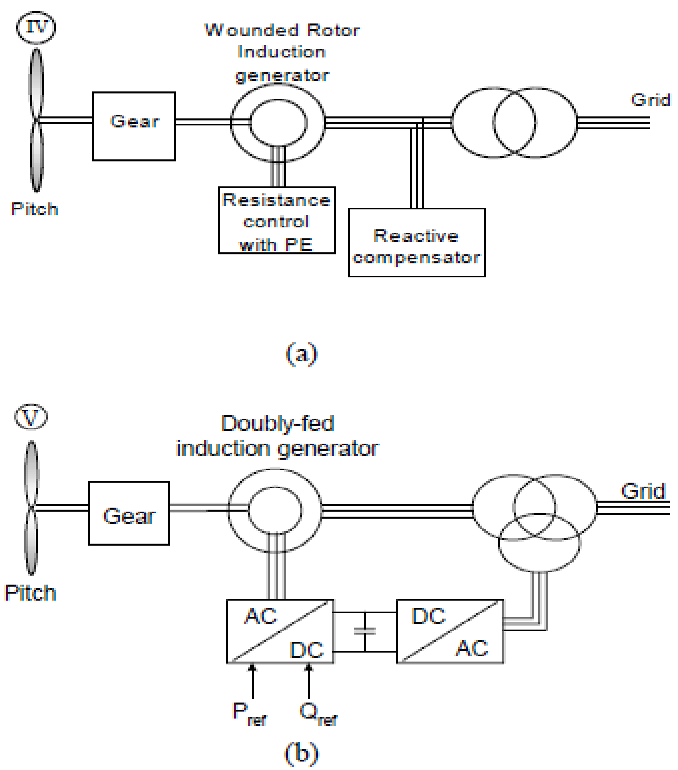
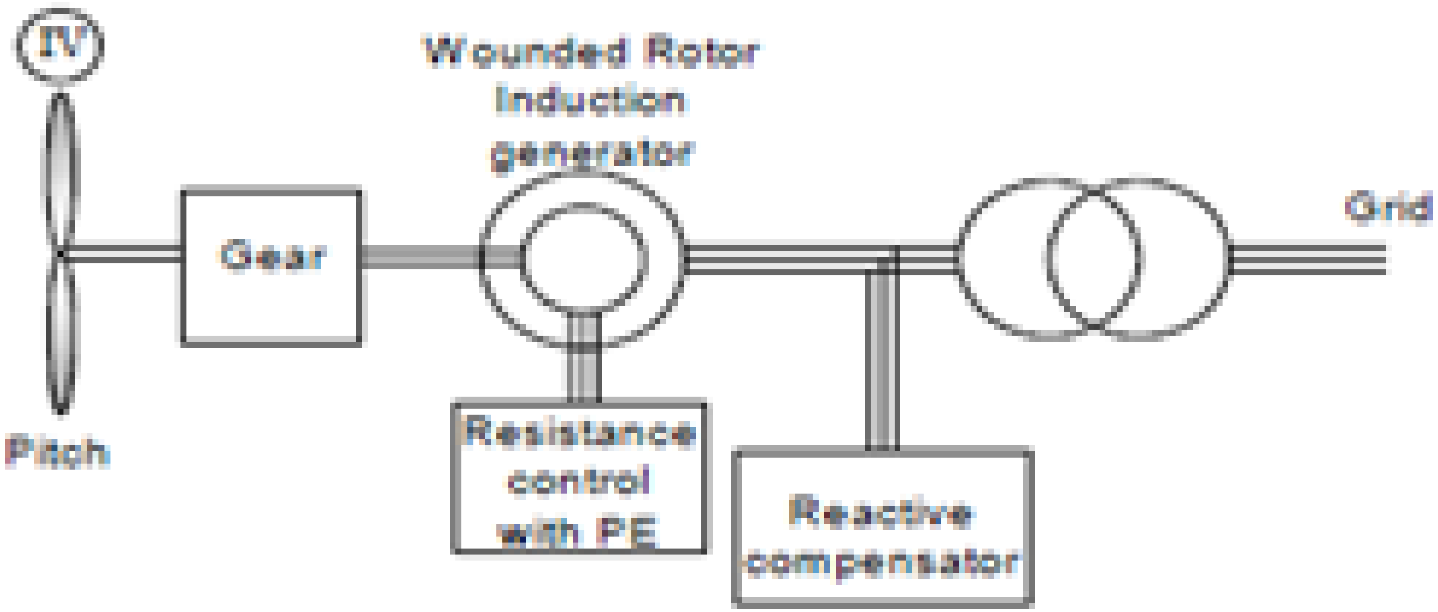


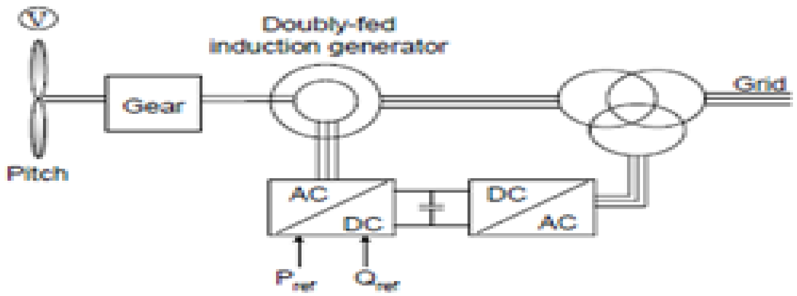
Fig. 5. Wind turbine topologies with partially rated power electronics and limited speed range,
(a) Rotor-resistance converter (System IV)
(b) Doublyfed induction generator (System V).

Fig. 5 shows wind turbines with partially rated power electronic converters that are used to obtain an improved control performance.

- Fig. 5a shows a wind turbine system where the generator is an induction generator with a wounded rotor. An extra resistance is added in the rotor, which can be controlled by power electronics. This is a dynamic slip controller and it gives typically a speed range of 2-10 %. The power converter for the rotor resistance control is for low voltage but high currents. At the same time an extra control freedom is obtained at higher wind speeds in order to keep the output power fixed. This solution still needs a soft-starter and a reactive power compensator.



A second solution of using a medium scale power converter with a wounded rotor induction generator is shown in Fig. 5b. Slip-rings are making the electrical connection to the rotor. A power converter controls the rotor currents. If the generator is running super-synchronously electrical power is delivered through both the rotor and the stator. If the generator is running sub-synchronously electrical power is only delivered into the rotor from the grid. A speed variation of ±30 % around synchronous speed can be obtained by the use of a power converter of 30 % of nominal power.



- Furthermore, it is possible to control both active (Pref) and reactive power (Qref), which gives a better grid performance, and the power electronics enable the wind turbine to act more as a dynamic power source to the grid. The solution shown in Fig. 5b needs neither a soft-starter nor a reactive power compensator. The solution is naturally a little bit more expensive compared to the classical solutions shown in Fig. 4 and Fig. 5a. However, it is possible to save money on the safety margin of gear, reactive power compensation units and it is possible to capture more energy from the wind.

Variable speed wind power conversion systems with fully rated power electronic converters

- The wind turbines with a full-scale power converter between the generator and grid give extra losses in the power conversion but it may be gained by the added technical performance. Fig. 6 shows four possible solutions with full-scale power converters.

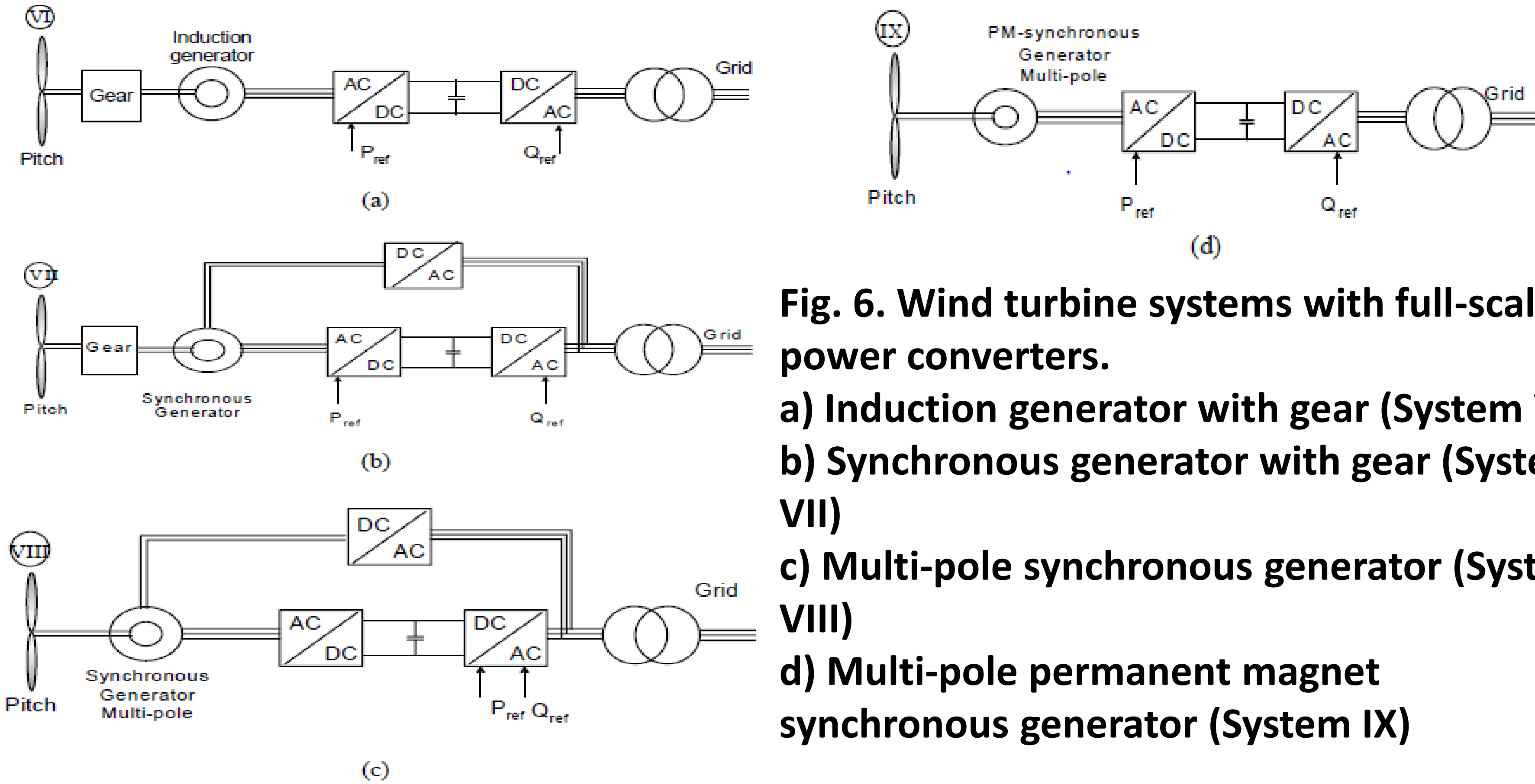


Fig. 6. Wind turbine systems with full-scale power converters.
a) Induction generator with gear (System VI)
b) Synchronous generator with gear (System VII)
c) Multi-pole synchronous generator (System VIII)
d) Multi-pole permanent magnet synchronous generator (System IX)

The solutions shown in Fig. 6a and Fig. 6b are characterized by having a gear. A synchronous generator solution shown in Fig. 6b needs a small power converter for field excitation. Multi-pole systems with the synchronous generator without a gear are shown in Fig. 6c and Fig. 6d.

The last solution uses permanent magnets, which are still becoming cheaper and thereby more attractive.

All four solutions have the same controllable characteristics since the generator is decoupled from the grid by a dc-link. The power converter to the grid enables the system very fast to control active and reactive power. However, the negative side is a more complex system with a more sensitive electronic part.

By introducing power electronics many of the wind turbine systems get a performance like a power plant. In respect to control performance they are faster but of course the produced real power depends on the available wind. The reactive power can in some solutions be delivered without having any wind.

Fig. 6 also indicates other important issues for wind turbines in order to act as a real power source for the grid. They are able to be active when a fault appears at the grid and so as to build the grid voltage up again quickly; the systems have the possibility to lower the power production even though more power is available in the wind and thereby acting as a rolling capacity. Finally, some are able to operate in island operation in the case of a grid collapse.

1.4. Converters control for wind turbines

Controlling a wind turbine involves both fast and slow control. Overall the power has to be controlled by means of the aerodynamic system and has to react based on a setpoint given by dispatched center or locally with the goal to maximize the production based on the available wind power.

The power control system should also be able to limit the power. An example of an overall control scheme of a wind turbine with a doubly-fed generator system is shown in Fig.7.

Below maximum power production the wind turbine will typically vary the speed proportional with the wind speed and keep the pitch angle θ fixed. At very low wind the speed of the turbine will be fixed at the maximum allowable slip in order not to have overvoltage.

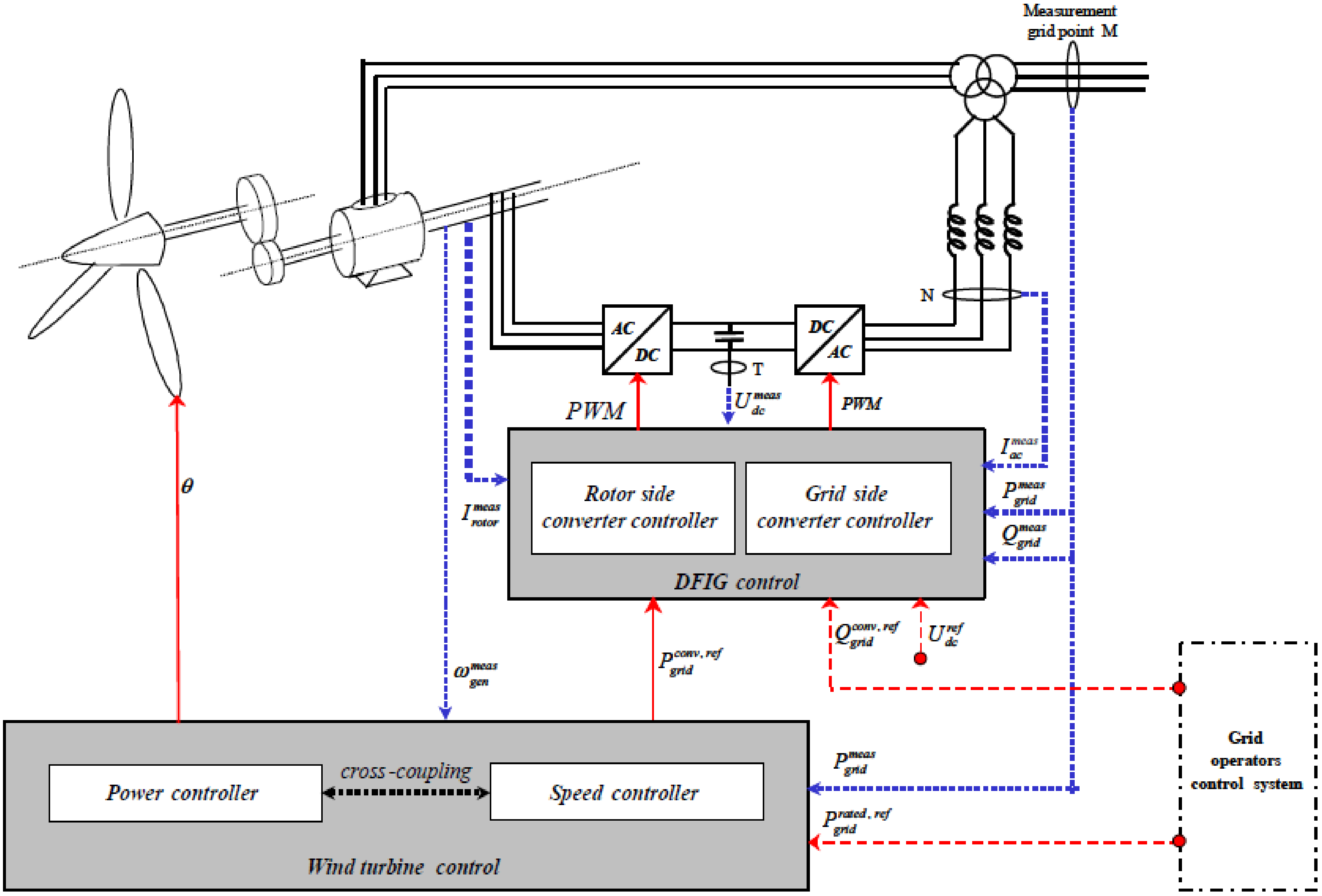


Fig. 7. Control of wind turbine with doubly-fed induction generator system .

A pitch angle controller will limit the power when the turbine reaches nominal power. The generated electrical power is done by controlling the doubly-fed generator through the rotor-side converter. The control of the grid-side converter is simply just keeping the dc-link voltage fixed. Internal current loops in both converters are used which typically are linear PI-controllers, as it is illustrated in Fig.8a. The power converters to the grid-side and the rotor-side are voltage source inverters.

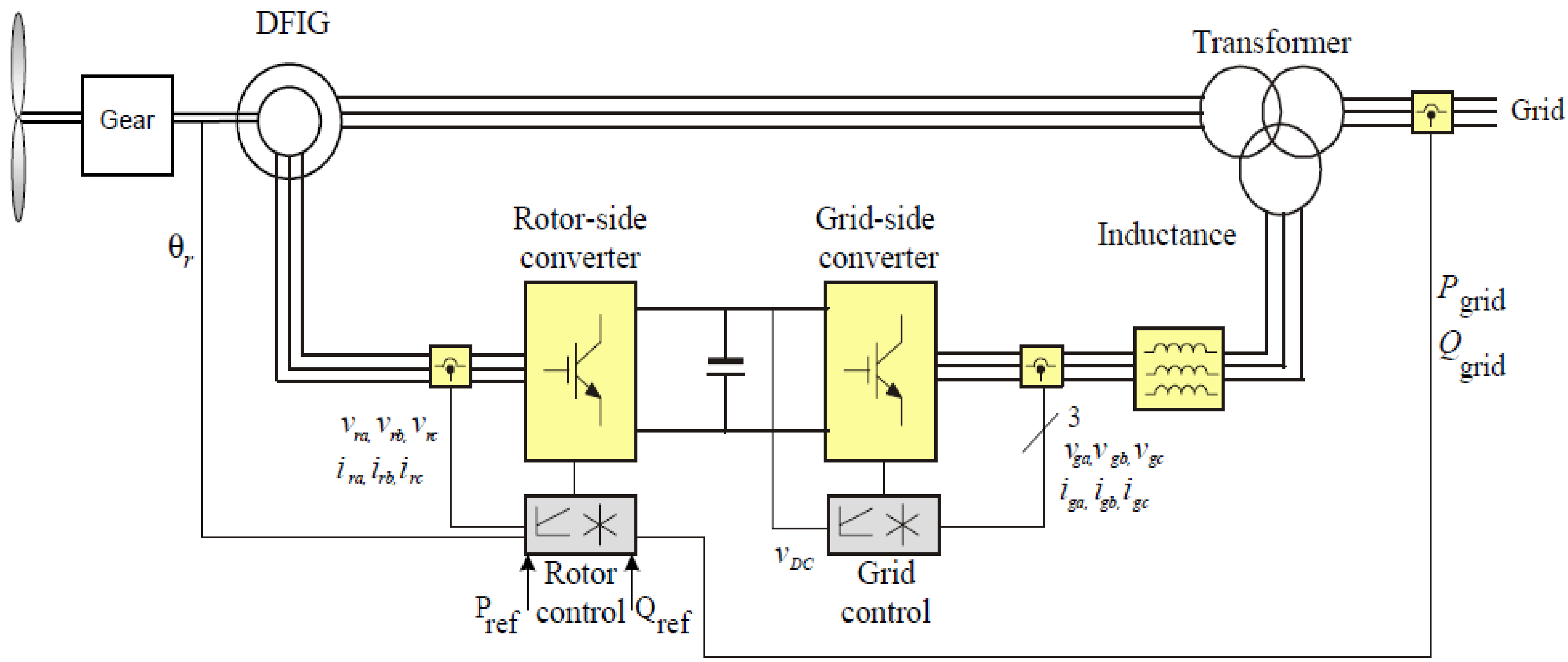


Fig. 8. Basic control of active and reactive power in a wind turbine
a) Doubly-fed induction generator system (System V)

Another solution for the electrical power control is to use the multi-pole synchronous generator. A passive rectifier and a boost converter are used in order to boost the voltage at low speed. The system is industrially used today. It is possible to control the active power from the generator. The topology is shown in Fig. 8b. A grid inverter is interfacing the dc-link to the grid. Here it is also possible to control the reactive power to the grid. Common for both systems are able to control reactive and active power very fast and thereby the turbine can take part in the power system control.

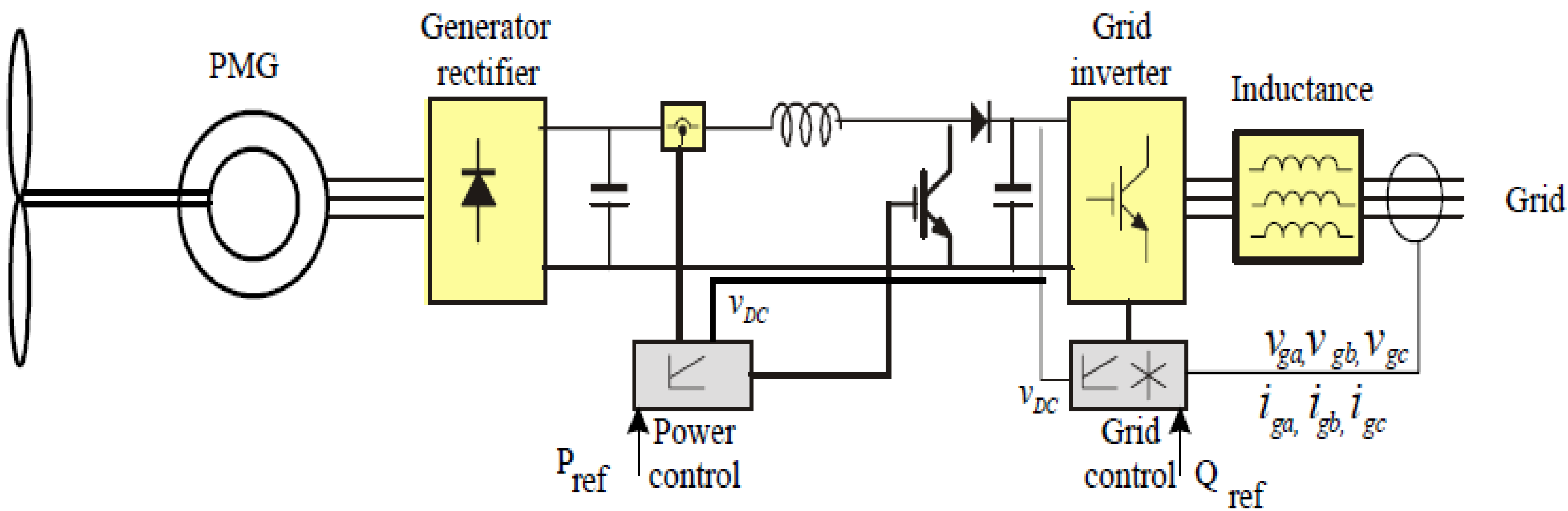


Fig. 8. Basic control of active and reactive power in a wind turbine
b) Multi-pole synchronous generator system (System VIII)

1.5. Exercise

Application Example : Design of a 5 MW Variable-Speed Wind-Power Plant to Operate at an Altitude of 1,600 m

Design a wind-power plant feeding the rated power $P_{out} = 5$ MW at unity power factor into the three-phase distribution system at a line-to-line voltage of $V_{L-L\ system} = 12.47$ kV. The wind-power plant consists of

- One (Y-grounded/Δ) three-phase, step-up transformer, N_{inv} parallel-connected three-phase PWM inverters with an input voltage of $V_{DC} = 600\ V + 600\ V = 1{,}200$ V, where each inverter delivers an output AC current $I_{phase\_inverter}$ at unity power factor $\cos\Phi = 1$ to the low-voltage winding of the transformer (e.g., the angle Φ between the line-to-neutral voltage of the inverter $V_{L-n\_inverter}$ and the phase current of the inverter $I_{phase\_inverter}$ is zero). Note that the midpoint of the DC inverter voltage is grounded or represents a virtual ground
- N_{rect} ($=N_{inv}$) three-phase rectifiers, each one equipped with one self-commutated switch and six diodes operating at a duty cycle of $\delta = 50\%$. Note that each rectifier feeds one inverter
- One synchronous generator
- One mechanical gear and
- One wind turbine

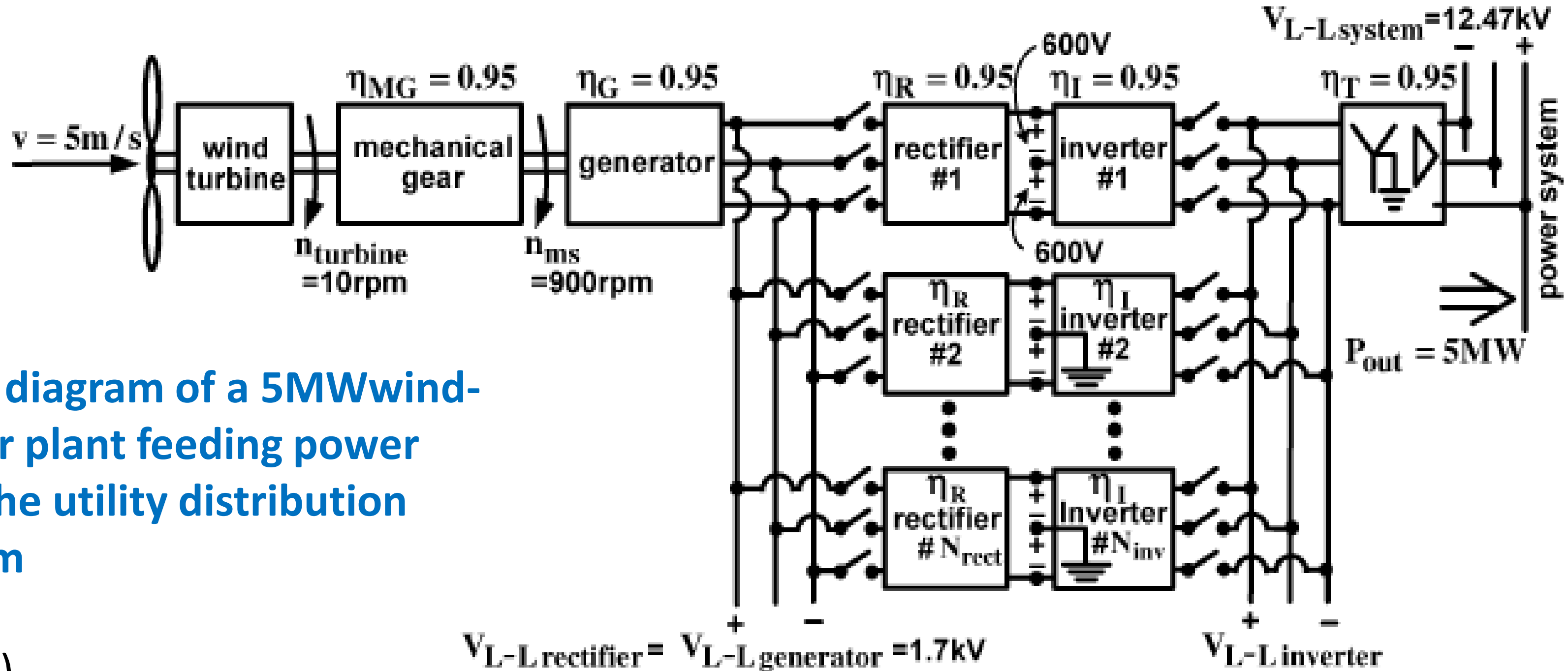
At rated operation, the efficiencies of (one) gear box, (one) generator, (one) rectifier, (one) inverter, and (one) transformer are $\eta = 0,95$, each. Note there are Nrect parallel rectifiers and Ninv parallel inverters, and each rectifier feeds one inverter. At an operation of less than rated load the efficiencies will be smaller. The parallel configuration of inverters and rectifiers permits an efficiency increase, because at light and medium loads only a few inverters and rectifiers must be operated and some can be disconnected. Rated operation is when all rectifiers and inverters are connected.

1) **Draw a block diagram of the above-mentioned components.**
2) **For rated operation determine the output power of each component, e.g., transformer, inverters, rectifiers, generator, gear box, and wind turbine.**

3) Determine for a modulation index of $m = 0.8$ the inverter output line-to-neutral voltage $V_{L-n\_inverter}$ such that the inverter can deliver at unity power factor an approximately sinusoidal current to the transformer. N_{inv} commercially available three-phase PWM inverters are connected in parallel and one inverter has the output power rating $P_{inverter} = 500$ kW. What is the number of inverters required? Determine $I_{phase\_inverter}$ of one inverter, the resulting output current of all N_{inv} inverters, that is, $\Sigma I_{phase\_inverter}$, and the transformer ratio $a = (N_s/N_p)$ of the (Y-grounded/Δ) step-up transformer, where N_p is the # of turns of the grounded Y per phase and N_s is the # of turns of the Δ per phase. For your calculations you may assume (one) ideal transformer and an ideal power system, where all resistances and leakage inductances are neglected. However, the resistances of the transformer are taken into account in the efficiency calculation of the transformer. Why do we use a Y-grounded/ Δ transformer configuration?

Correction

1)



Block diagram of a 5MWwind-power plant feeding power into the utility distribution system

2)

The output powers of the power plant components are:

$$P_{out}^{transformer} = 5\,\mathrm{MW}, \qquad P_{out}^{N\_inverters} = \frac{P_{out}^{transformer}}{0.95} = 5.26\,\mathrm{MW},$$

$$P_{out}^{N\_rectifiers} = \frac{P_{out}^{N\_inverters}}{0.95} = 5.54\,\mathrm{MW}, \qquad P_{out}^{generator} = \frac{P_{out}^{N\_rectifiers}}{0.95} = 5.83\,\mathrm{MW},$$

$$P_{out}^{gear} = \frac{P_{out}^{generator}}{0.95} = 6.14\,\mathrm{MW}, \qquad P_{out}^{wind\_turbine} = \frac{P_{out}^{gear}}{0.95} = 6.46\,\mathrm{MW}.$$

3)

The output phase (line-to-neutral) voltage of the inverter is as a function of the input DC voltage

$$V_{\mathrm{L-N\_inverter}} = m \frac{\frac{V_{DC}}{2}}{\sqrt{2}} = 0.8 \frac{1200/2}{\sqrt{2}} = 340\,\mathrm{V}$$

The number of inverters required is

$$N_{\mathrm{inverter}} = \frac{P_{\mathrm{out}}^{\mathrm{N\_inverters}}}{P_{\mathrm{inverter}}} = \frac{5,260\,\mathrm{kW}}{500\,\mathrm{kW}} \approx 11 \text{ inverters.}$$

The phase current of one inverter is

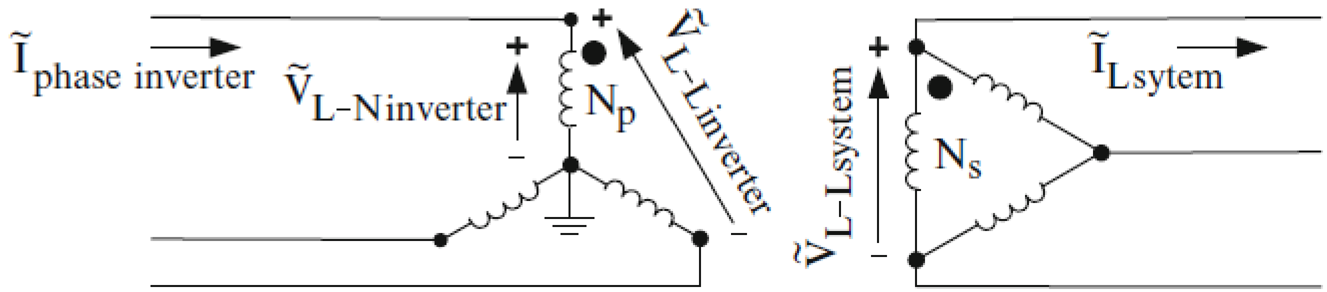
$$I_{\mathrm{phase\_inverter}} = \frac{P_{\mathrm{inverter}}/3}{V_{\mathrm{L-N\_inverter}}} = \frac{500\,\mathrm{kW}/3}{340\,\mathrm{V}} = 490\,\mathrm{A},$$

and the resulting output current of the 11 inverters is $\Sigma I_{\mathrm{phase\_inverter}} = 11 \cdot I_{\mathrm{phase\_inverter}} = 5.392\,\mathrm{kA}$ or the total inverter phase current can be obtained from

$$\frac{P_{\mathrm{out}}^{\mathrm{N\_inverters}}/3}{V_{\mathrm{L-N\_inverter}}} = \frac{5,260\,\mathrm{kW}/3}{340\,\mathrm{V}} = 5.16\,\mathrm{kA}.$$

The transformer ratio is :

$$a = \frac{N_s}{N_p} = \frac{V_{L-L\,system}}{V_{L-N\_inverter}} = \frac{12.47k}{340} = 37.$$

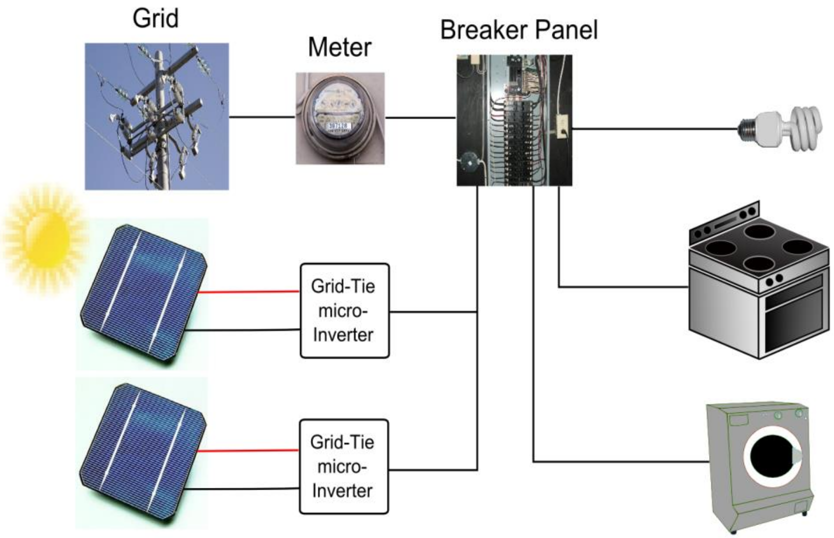


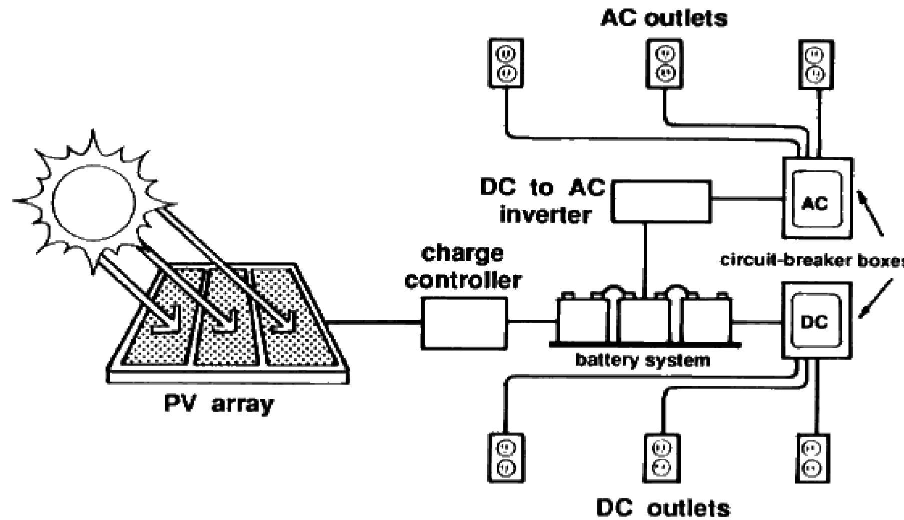
Y-grounded/Δ transformer

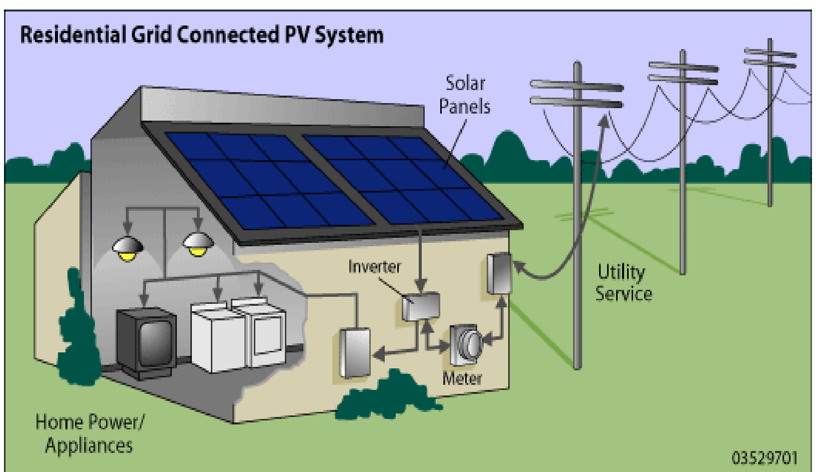
The Y-grounded /Δ transformer is used to avoid zero-sequence components entering the power system.

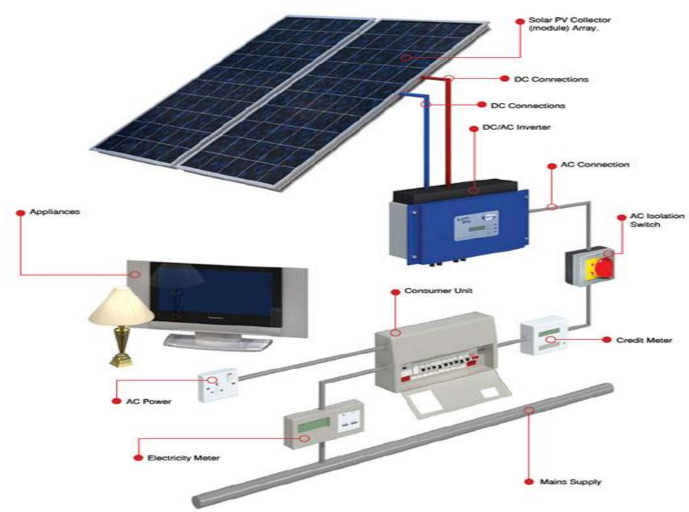
* In a three-phase system, one set of phasors has the same phase sequence as the system under study (positive sequence; say ABC), the second set has the reverse phase sequence (negative sequence; ACB), and in the third set the phasors A, B and C are in phase with each other (zero sequence). Essentially, this method converts three unbalanced phases into three independent sources, which makes asymmetric fault analysis more tractable.
By expanding a one-line diagram to show the positive sequence, negative sequence and zero sequence impedances of generators, transformers and other devices includingoverhead lines and cables, analysis of such unbalanced conditions as a single line to ground short-circuit fault is greatly simplified. The technique can also be extended to higher order phase systems. http://en.wikipedia.org/wiki/Symmetrical_components

Chapter II
Configurations of photovoltaic systems









2.1. Introduction

Photovoltaic (PV) power supplied to the utility grid is gaining more and more visibility due to many national incentives. With a continuous reduction in system cost (PV modules, DC/AC inverters, cables, fittings and manpower), the PV technology has the potential to become one of the main renewable energy sources for the future electricity supply.

2.2. PV cell

The PV cell is an all-electrical device, which produces electrical power when exposed to sunlight and connected to a suitable load.

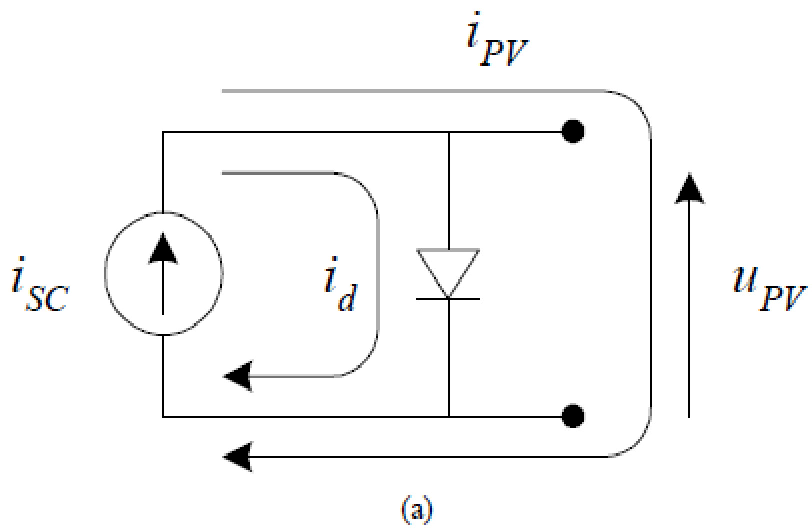


Fig. 1. Basic model and characteristics of a Photovoltaic (PV) cell.
(a) Basic Electrical model with current and voltages defined.

A typical PV module is made up around 36 or 72 cells connected in series, encapsulated in a structure made of e.g. aluminum and tedlar.

Several types of proven PV technologies exist, where the crystalline (PV module light-to-electricity efficiency: η =10% - 15%) and multi-crystalline (η = 9% - 12%) silicon cells are based on standard microelectronic manufacturing processes. Other types are: thin-film amorphous silicon (η =10%), thin-film copper indium diselenide (η = 12%), and thin-film cadmium telluride (η = 9%). Novel technologies such as the thin-layer silicon ,(η = 8%) and the dye-sensitised nano-structured materials (η = 9%) are in their early development.

Typical curves of a PV cell current-voltage and power-voltage characteristics are plotted in Fig. 2a and Fig. 2b respectively, with insolation and cell temperature as parameters. The graph reveals that the captured power is determined by the loading conditions (terminal voltage and current). This leads to a few basic requirements for the power electronics used to interface the PV module(s) to the utility grid.

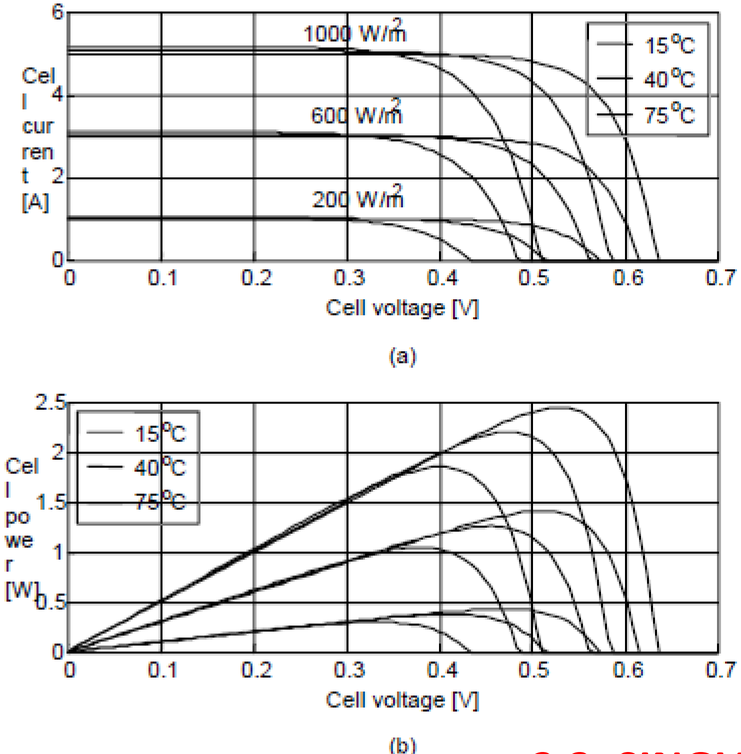


Fig. 2. Characteristics of a PV cell. Model based on the British Petroleum BP5170 crystalline silicon PV module. Power at standard test condition (1000 W/m2 irradiation, and a cell temperature of 25 °C): 170 W @ 36.0 V. Legend: solid at 15 oC, dotted at 40 oC, and dashdot at 75 oC.

2.3. SINGLE-PHASE PV-INVERTERS

The general block diagram for single-phase grid connected photovoltaic systems is presented in Fig. 3a. It consists of PV array, PV inverter, controller and grid.

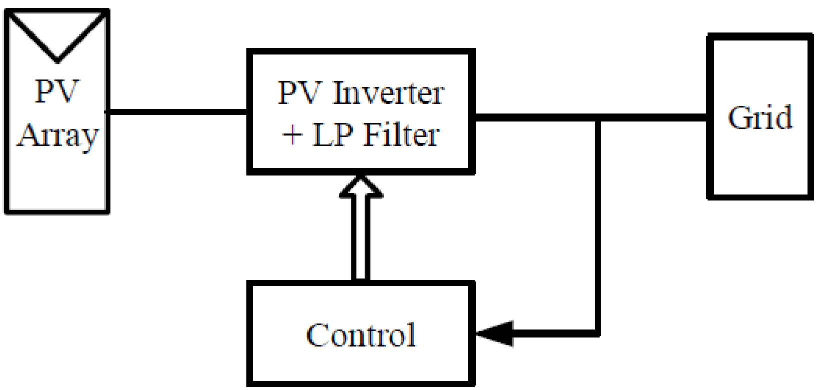


Fig 3. General schema for single-phase grid connected photovoltaicsystems. a) Block diagram

The PV array can be a single panel, a string of PV panels or a multitude of parallel strings of PV panels. Centralized or decentralized PV systems can be used as depicted in the Fig. 3,b,c,d .

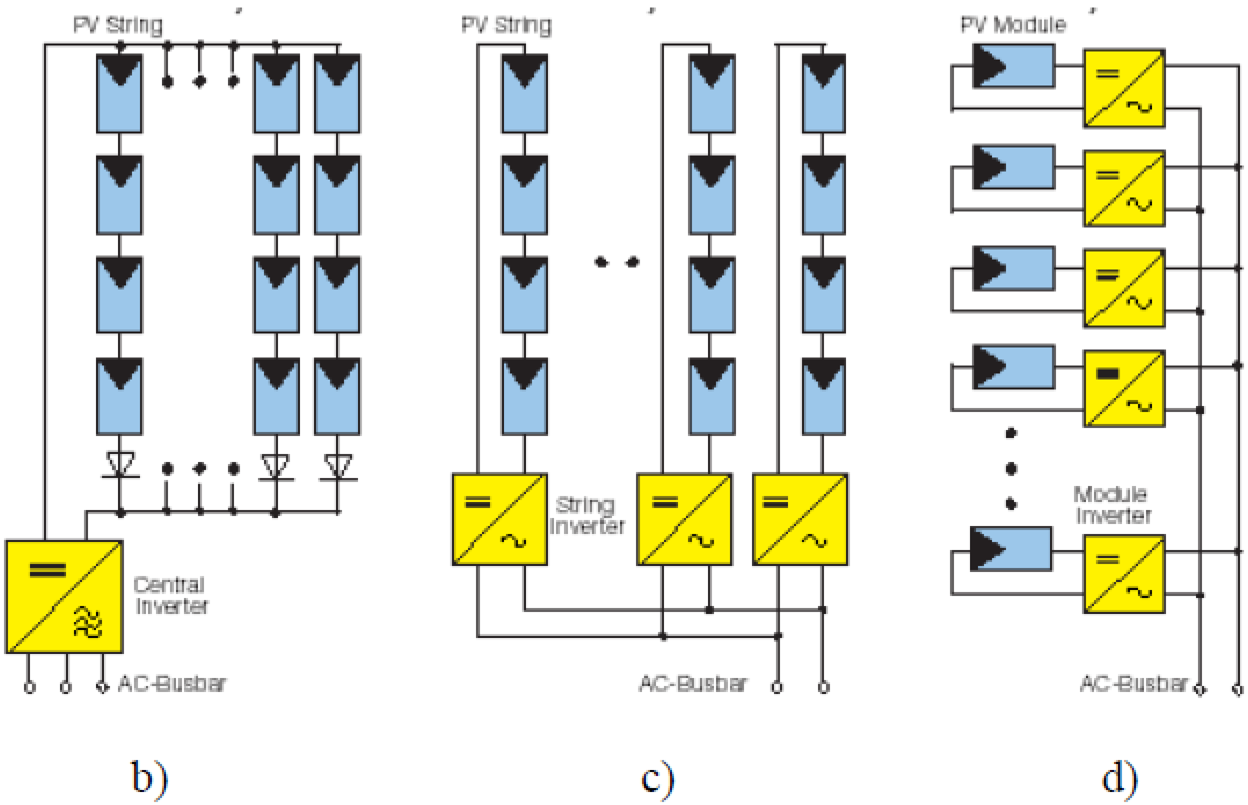


Fig 3. General schema for single-phase grid connected photovoltaic systems. b) Central inverter; c) String inverter; d)Module integrated inverter

2.3.1. PV inverter

There are different power configurations possible as shown in the Fig. 4.

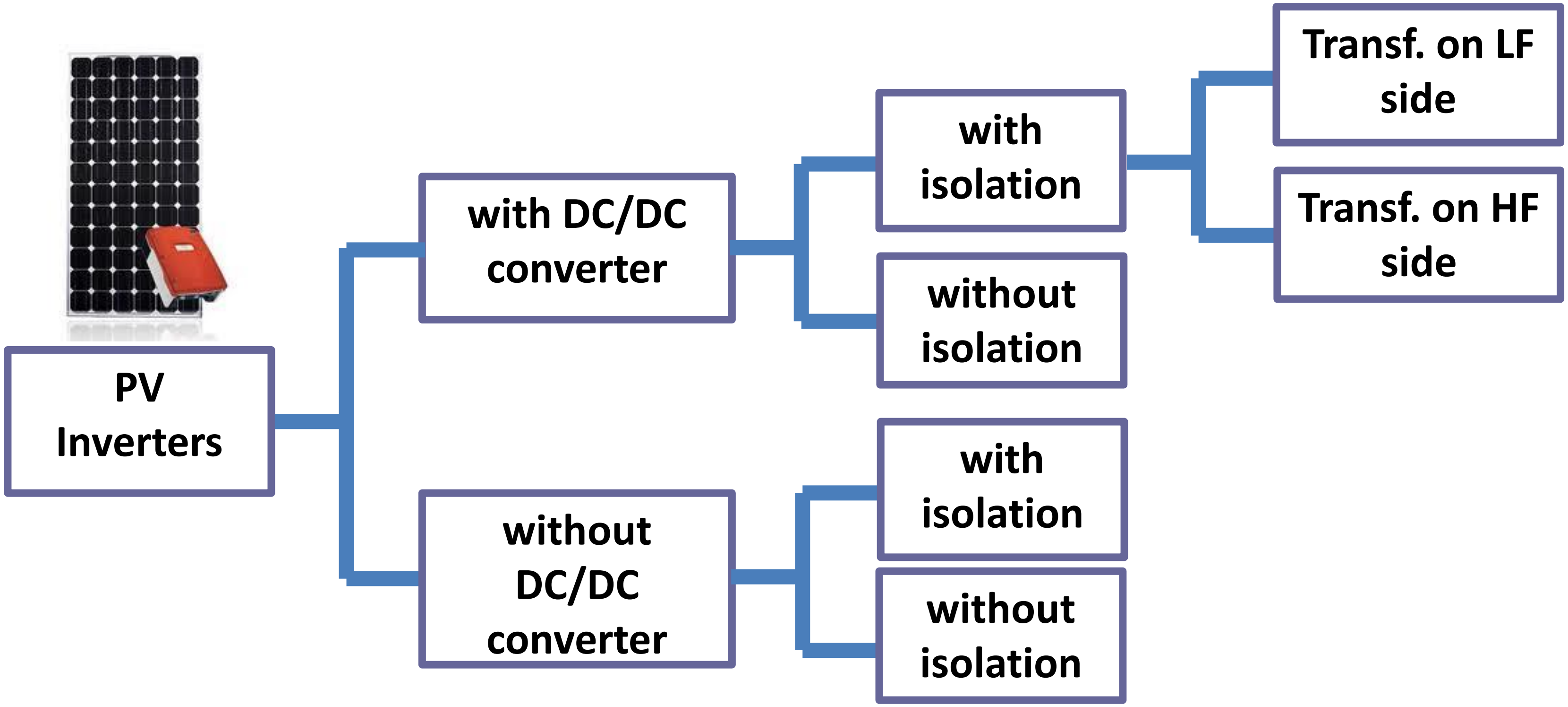


Fig. 4: Power configuration for PV inverters

The question of having or not a dc-dc converter is first of all related to the PV string configuration. Having more panels in series and lower grid voltage, like in US and Japan, it is possible to avoid the boost function. Thus a single stage PV inverter can be used leading to higher efficiency.

The issue of isolation is mainly related to safety standards and is for the moment only required in US. The drawback of having so many panels in series is that MPPT is harder to achieve especially during partial shading.

PV inverters with DC-DC converter with isolation

The isolation is typically acquired using a transformer that can be placed on either the grid frequency side (LF) as shown in the Fig. 5a or on the high-frequency (HF) side in the dc-dc converter as shown in the Fig. 5b. The HF transformer leads to more compact solutions but high care should be taken in the transformer design in order to keep the losses low.

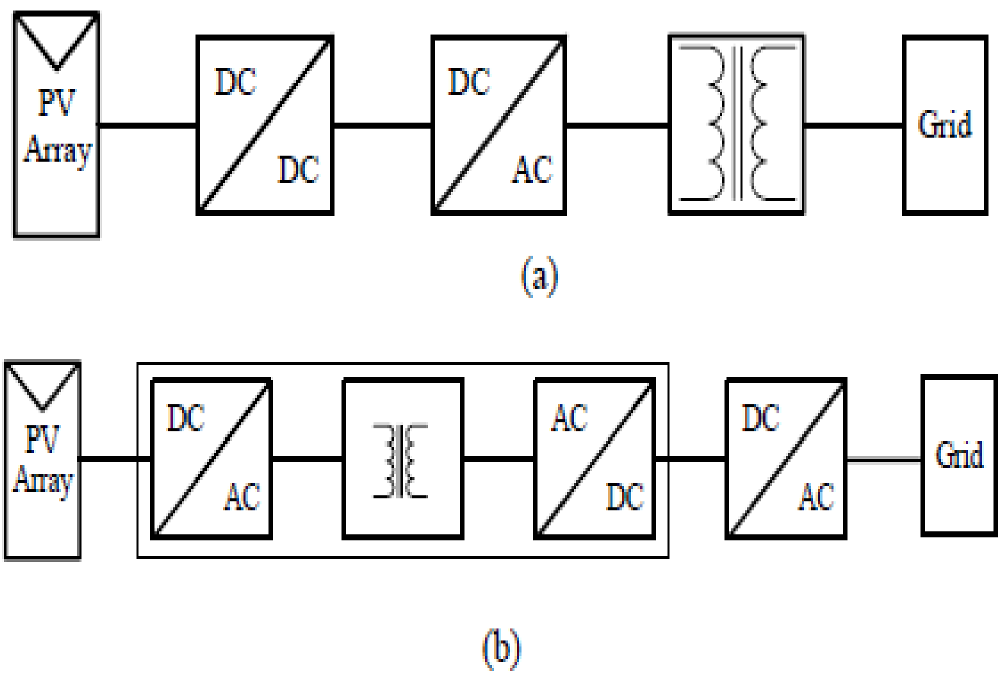


Fig. 5. PV inverter system with DC-DC converter and isolation transformer a) on the LF side b) on the HF side

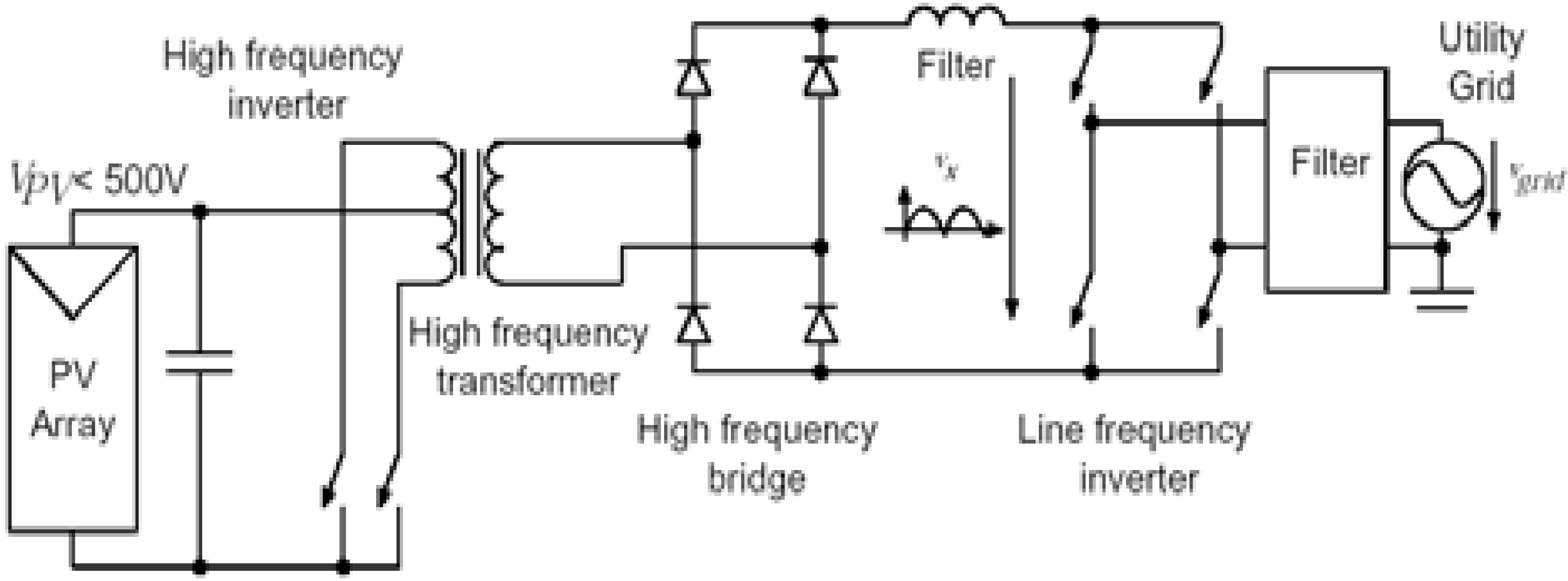


Fig. 6. PV inverter with HF transformer in the dc-dc converter

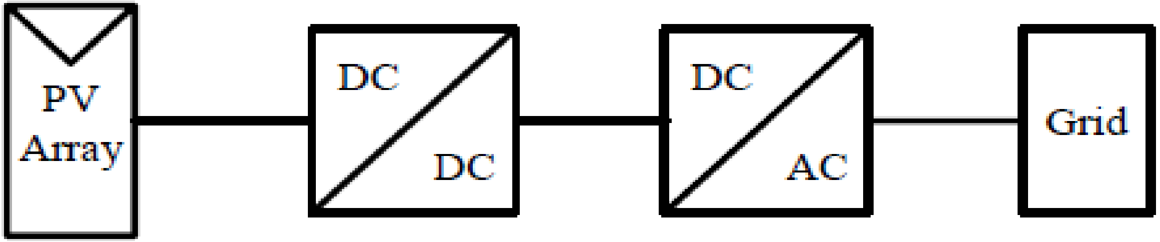
In the Fig.6 is presented a PV inverter with HF transformer using an isolated push-pull boost converter.

Also, the dc-ac inverter in this solution is a low cost inverter switched at the line frequency. The new solutions on the market are using PWM dc-ac inverters with IGBT switched typically at 10-20 kHz leading to better power quality performances.

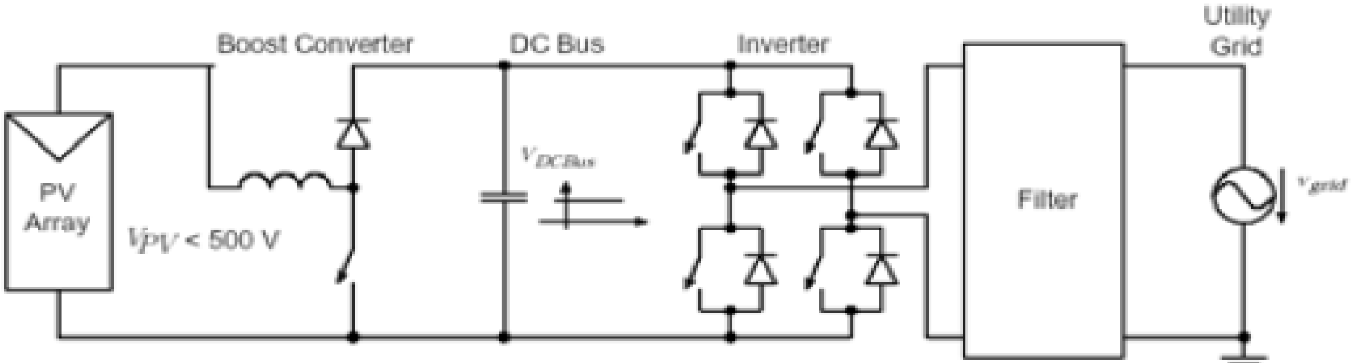
Other solutions for high frequency dc-dc converters with isolations includes: full-bridge isolated converter, single inductor push-pull converter (SIC) and double-inductor converter (DIC).

PV inverters with DC-DC converter without isolation

In some countries as the grid-isolation is not mandatory, more simplified PV inverter design can be used, as shown in Fig. 7.



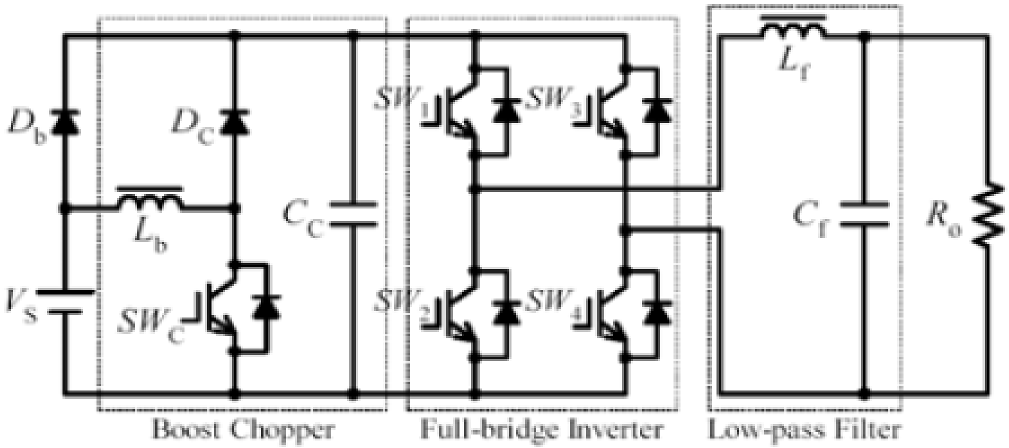
(a)



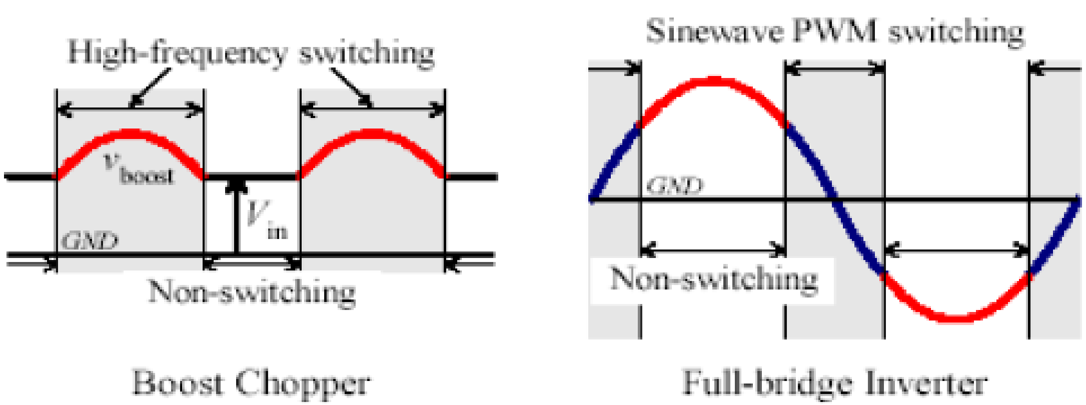
(b)

Fig 7. PV inverter system with DC-DC converter without isolation transformer
a) General diagram
b) Practical example with boost converter and full-bridge inverter

Another novel transformerless topology featuring a high efficiency time-sharing dual mode single-phase partially controlled sinewave PWM inverter composed of quasi time-sharing sinewave boost chopper with a new functional bypass diode *Db* in the boost chopper side and complementary sinewave PWM full-bridge inverter (Fig. 8)



a)



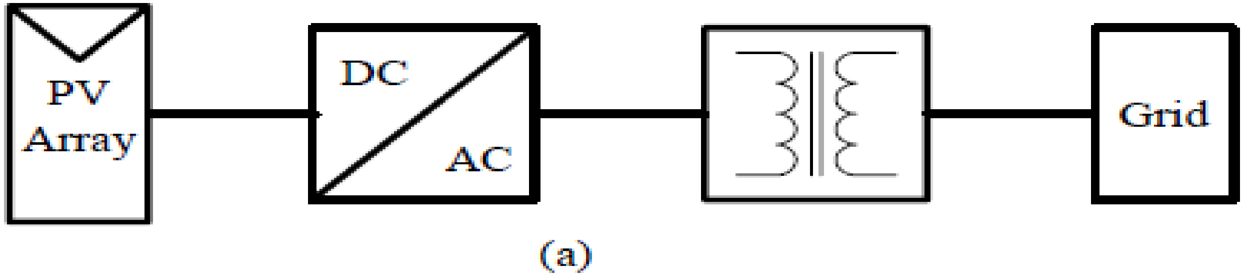
b)

Fig.8. Time-sharing dual-mode sinewave modulated single-phase inverter with boost chopper

a) Circuit system configuration.

b) Operating principle

PV inverters without DC-DC converter



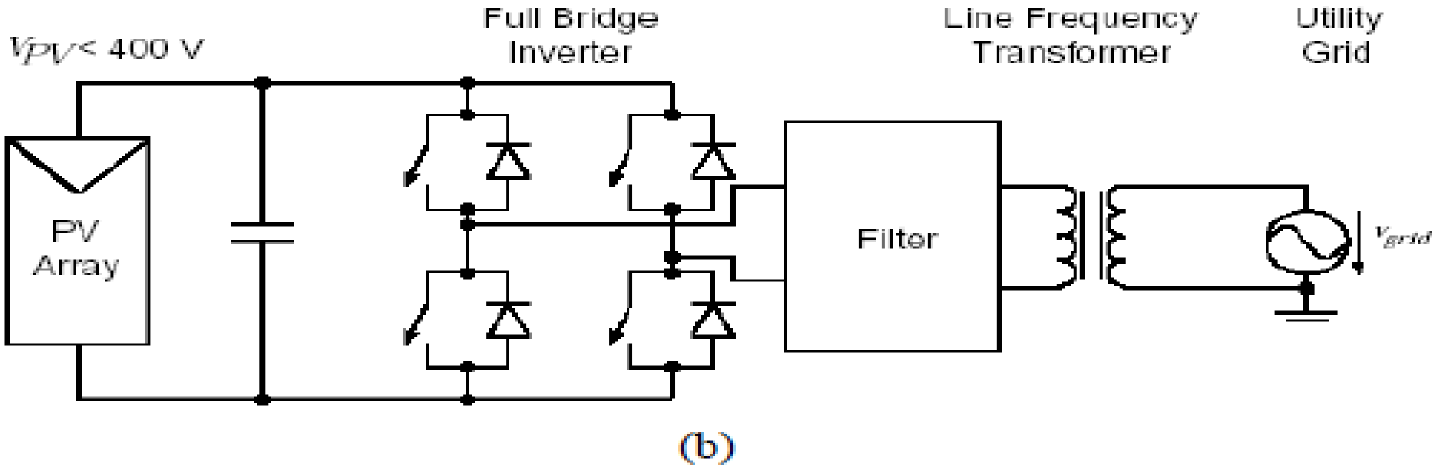


Fig. 9. PV inverter system without DC-DC converter and with isolation transformer a) general diagram b) practical example with full-bridge inverter and gridside transformer

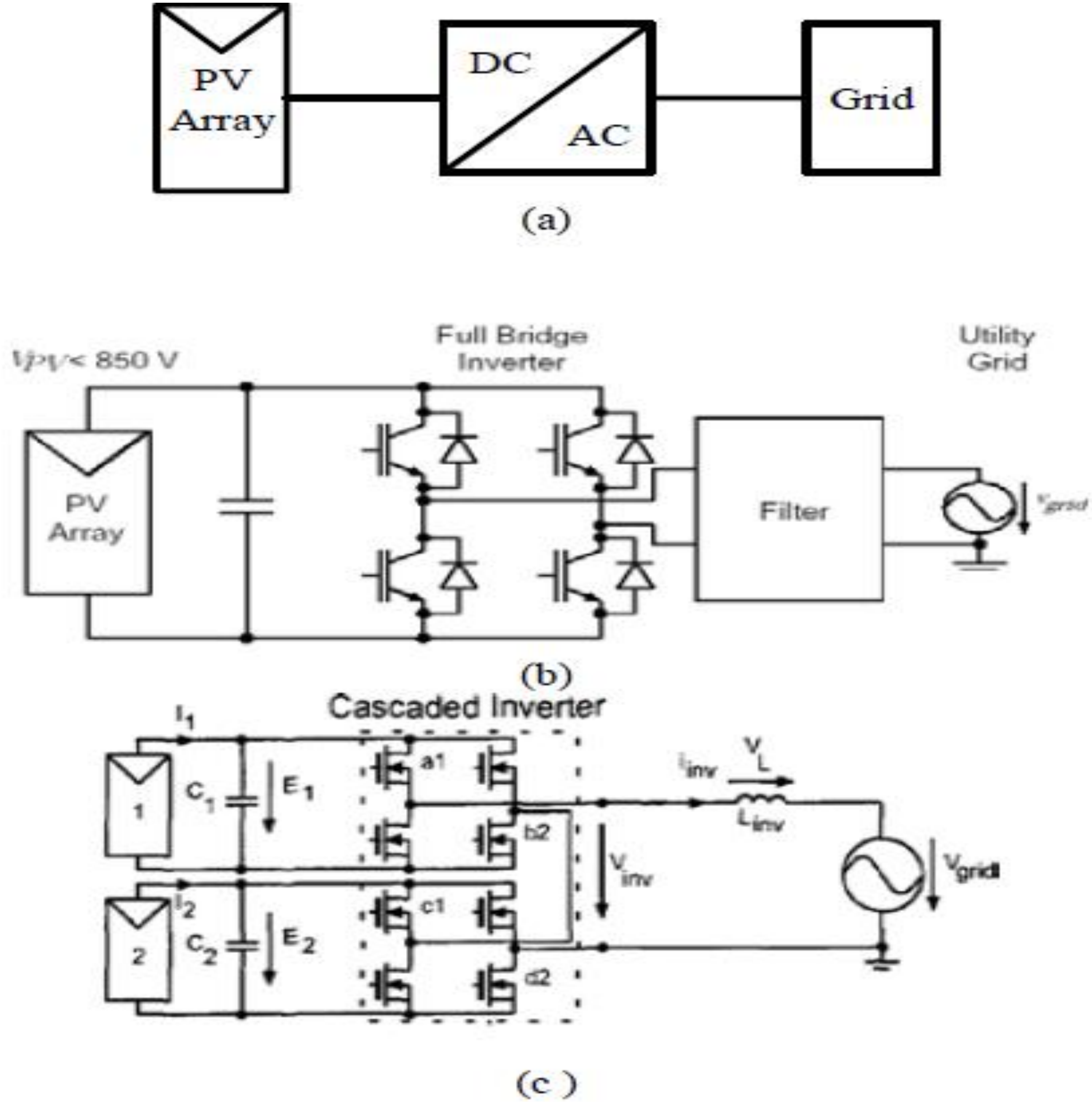


Fig. 10. Transformerless PV inverter system without DC-DC converter a) general diagram b) typical example with full-bridge inverter c) multilevel

2.4. CONTROL OF SINGLE-PHASE PV-INVERTERS

2.4.1- Control DC-DC boost converter

In order to control the output dc-voltage to the desired value, a control system is needed which can automatically adjust the duty cycle, regardless of the load current or input changes. There are two types of control for the dc-dc converters: the *direct duty-cycle* control and the *current control*. As shown in the Fig. 11.

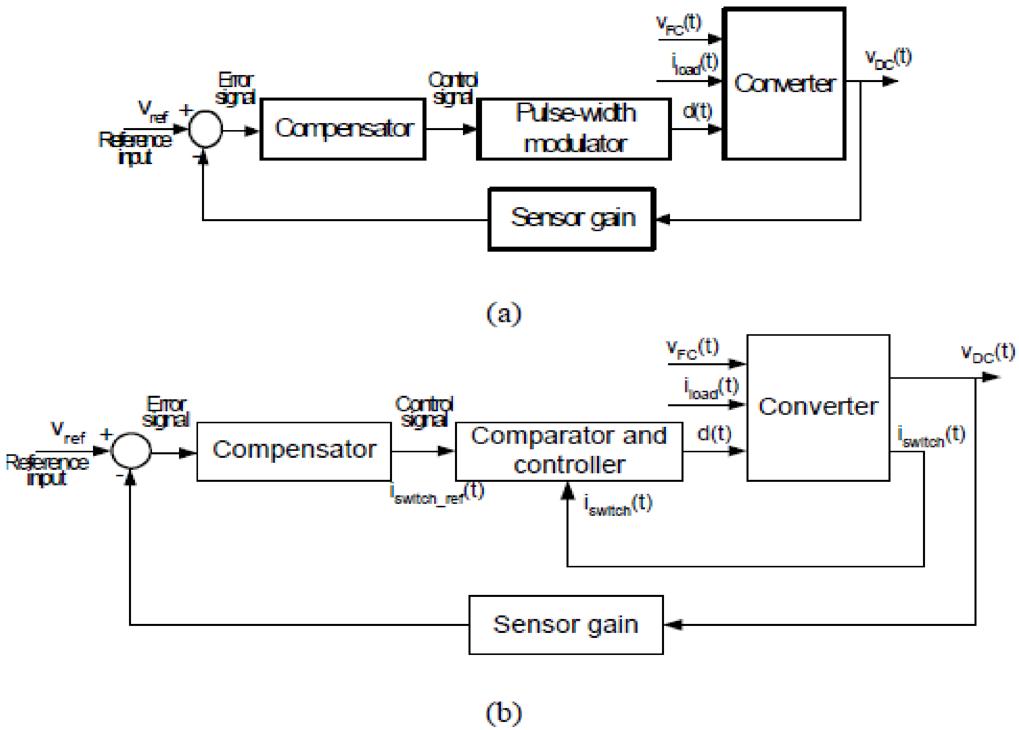


Fig. 11. Control strategies for switched dc-dc converters a) direct duty-cycle control b) current control

Duty-Cycle control

The output voltage is measured and then compared to the reference. The error signal is used as input in the compensator, which will compute from it the duty-cycle reference for the pulse-width modulator.

Current Control

The converter output is controlled by choice of the transistor peak current. The control signal is a current and a simple control network switches on and off the transistor such its peak current follows the control input.

2.4.2 . Control of DC-AC grid converter

For the grid-connected PV inverters in the range of 1-5 kW, the most common control structure for the dc-ac grid converter is using a current-controlled H-bridge PWM inverter having a low-pass output filter. Typically L filters are used but the new trend is to use LCL filters that being a higher order filter (3rd) leads to more compact design. The drawback is that due to its own resonance frequency it can produce stability problems and special control design is required. A typical dc-ac grid converter with LCL filter is depicted in the Fig. 12

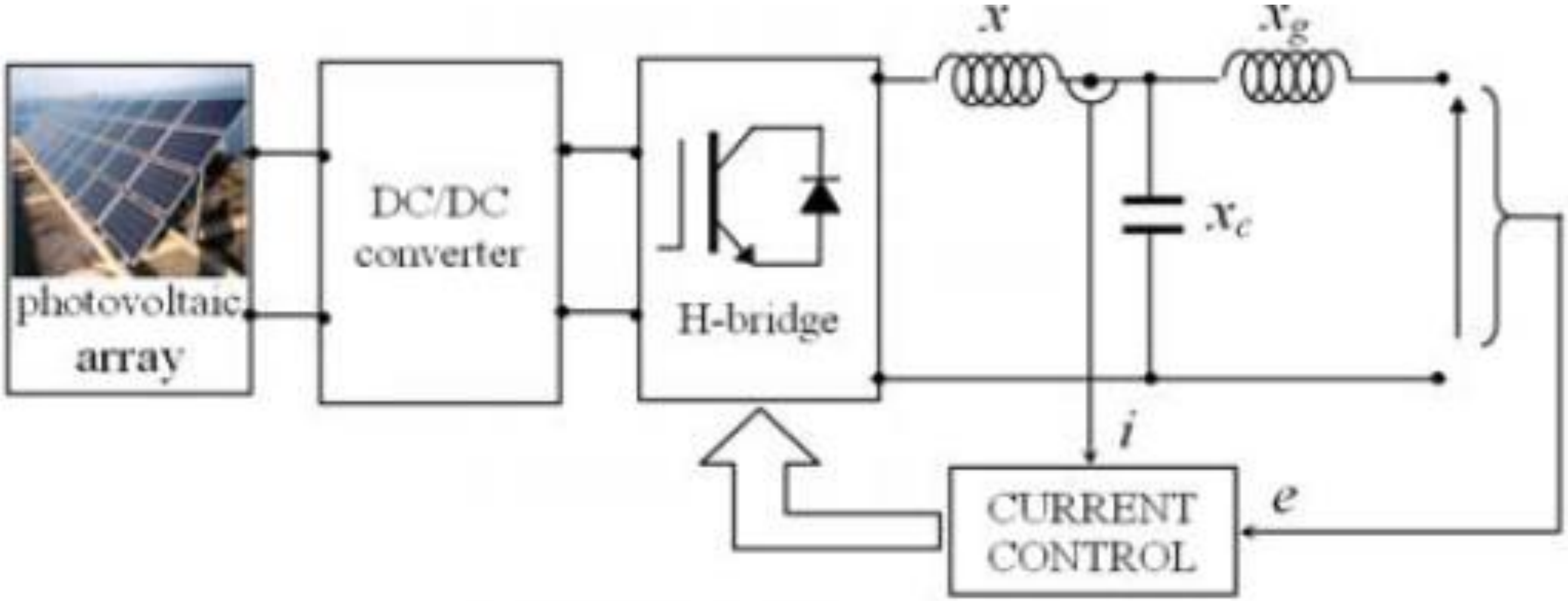


Fig.12. The H-bridge PV inverter connected to the grid through an LCL filter

Classical PI control with grid voltage feed-forward as depicted in Fig. 13a is commonly used for current-controlled PV inverters, but this solution exhibits two well known drawbacks: inability of the PI controller to track a sinusoidal reference without steady-state error and poor disturbance rejection capability. This is due to the poor performance of the integral action.

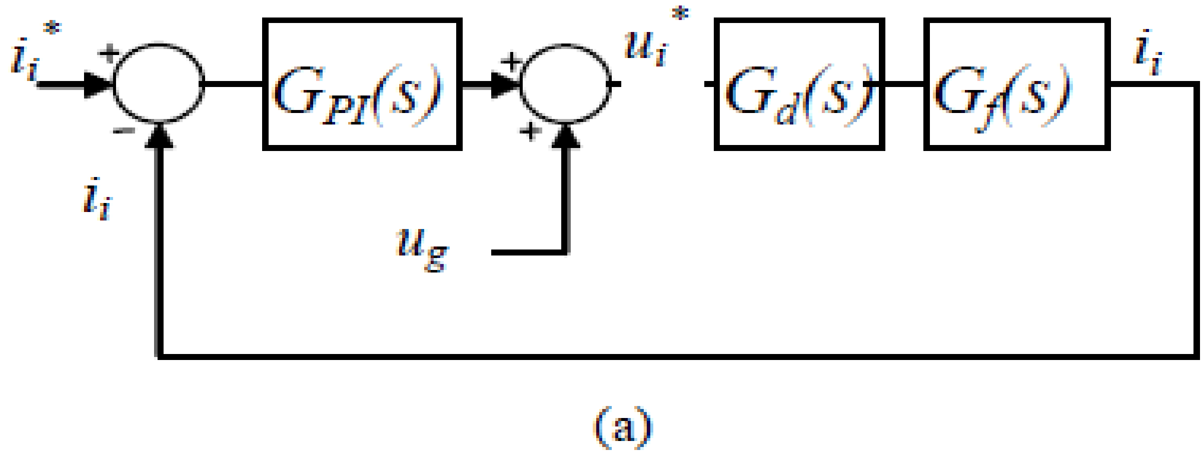


Fig. 13.The current loop of PV inverter. a) with PI controller;

The PI current controller *GPI(s)* is defined as:

$$G_{PI}(s) = K_P + \frac{K_I}{s}$$

The P+Resonant (PR) current controller Gc(s) is defined as :

$$G_c(s) = K_P + K_I \frac{s}{s^2 + \omega_o^2}$$

The harmonic compensator (HC) *Gh(s)* :

$$G_h(s) = \sum_{h=3,5,7} K_{Ih} \frac{s}{s^2 + (\omega_o h)^2}$$

is designed to compensate the selected harmonics 3rd, 5th and 7th as they are the most prominent harmonics in the current spectrum .

2.4.3 . MPPT

In order to capture the maximum power, a maximum power point tracker (MPPT) is required. The maximum power point of solar panels is a function of solar irradiance and temperature as depicted in Fig.14. This function can be implemented either in the dc-dc converter or in the dc-ac converter. Several algorithms can be used in order to implement the MPPT as followings :

- ***Perturb and Observe***
- ***Incremental Conductance***
- ***Parasitic Capacitance***
- ***Constant Voltage***
- ***Anti-islanding***
- ***etc.***

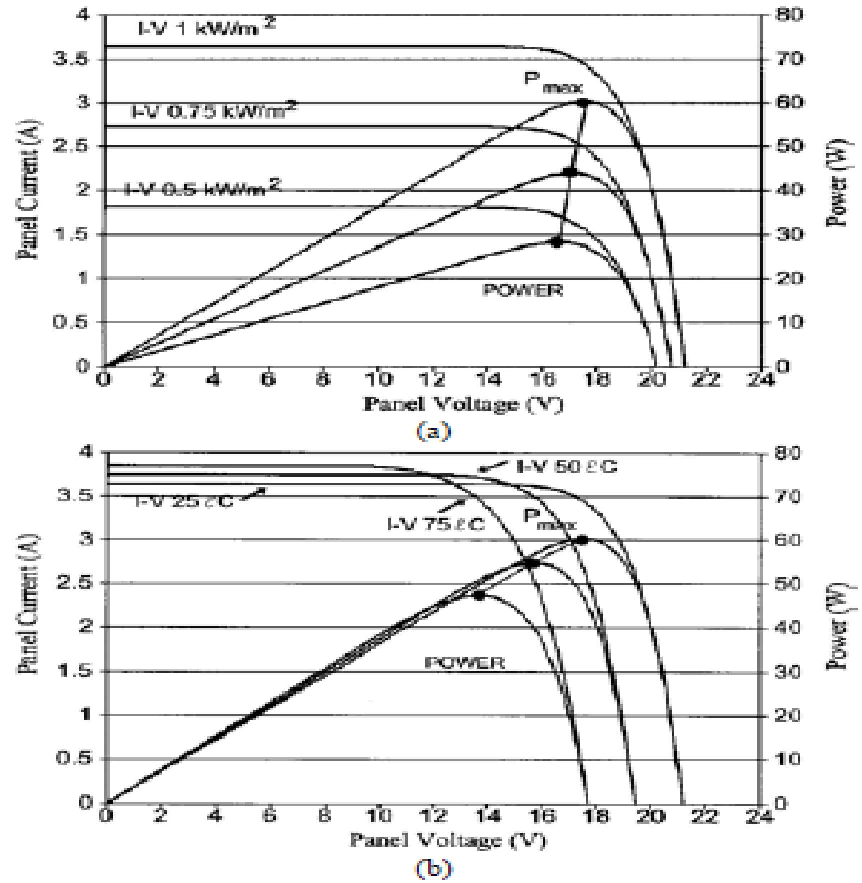


Fig. 14: PV characteristics.
a) Irradiance dependence
b) temperature dependence

Example of a Maximum Power Point Tracking (MPPT) algorithm

In our case, an improved P&O algorithm is chosen with adaptive increment step. Fundamental principle of this method is increment step variation to converge faster towards optimal point (MPP) while reducing oscillations around. Indeed, in order to quickly converge, increment step C is reduced or adapted from a region to another: C = 0.01 in "S" region and 0.001 in "r" region (Figure 15). MPPT algorithm is detailed Figure 16.

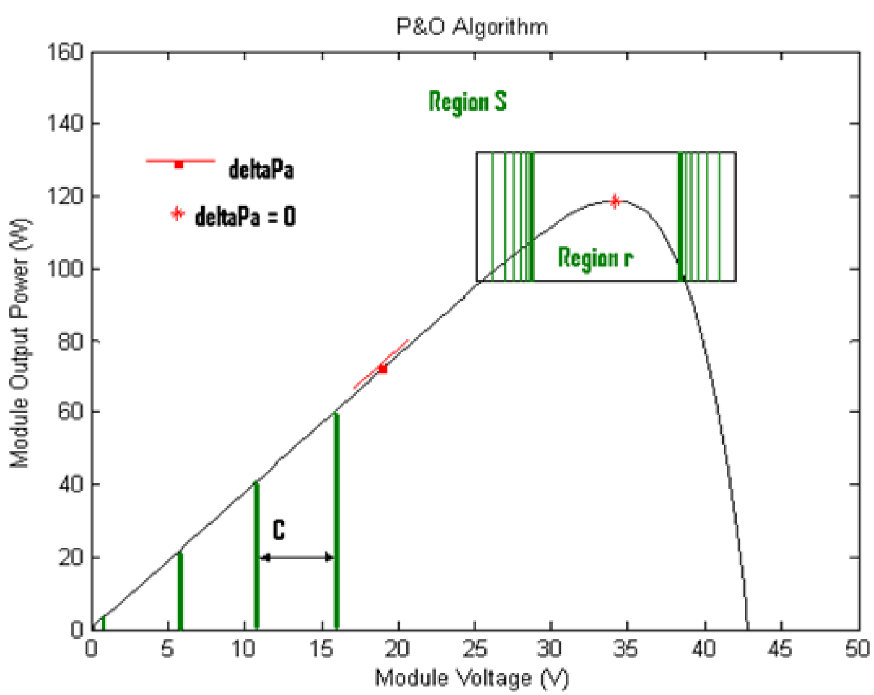


Fig. 15 : Principle of the P&O algorithm with an adaptive step increment

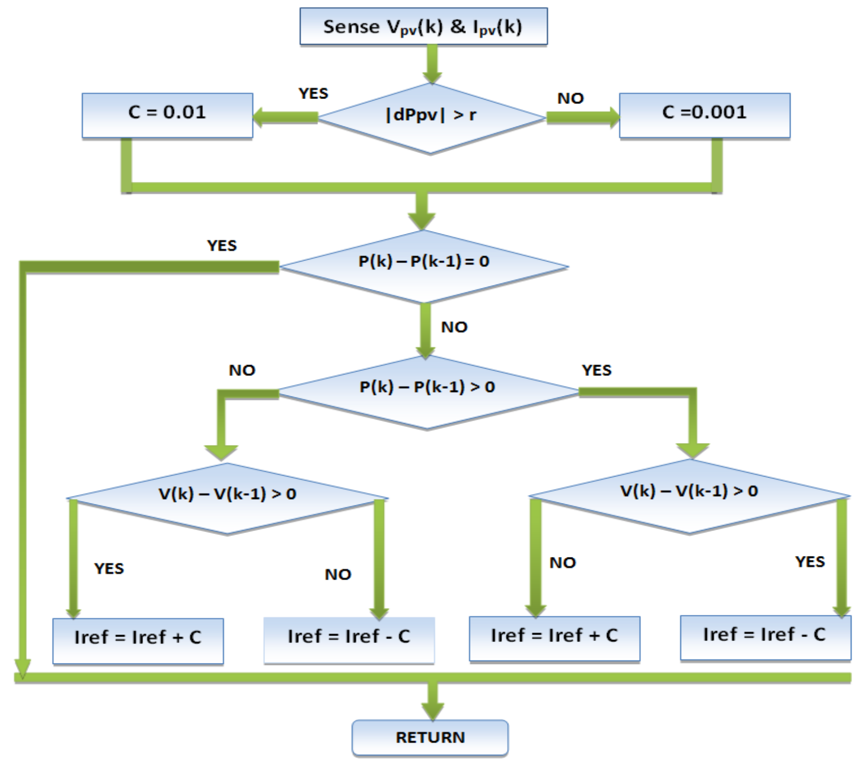


Fig. 16 : flowchart of the improved P&O MPPT algorithm

2.5. Exercise

Application Example : 5 MW Central Photovoltaic (PV)

A central PV power plant consists of solar panels, peak-power or maximum power tracker (MPT) , step-down/step-up DC-to-DC converter, (three-phase) inverter, Y-Δ three-phase transformer, and power system absorbing the output power of the transformer $P_{out\ transformer} = 5$ MW. Note: 5 MW can provide power to 1,800 residences.

Performance of 5 MW PV plant:

(a) Draw a block diagram of the above-mentioned components.

(b) If the power efficiencies of the maximum power tracker, step-down/step-up DC-to –DC converter, inverter, and transformer are $\eta = 90\%$ each, what is the required maximum power output of the solar array ($P_{solar\ array\ max}$) for a transformer output power of $P_{out\ transformer} = 5$ MW?

(c) Provided the efficiency of the solar cells is $\eta_c = 15\%$, what is the insolation power ($P_{Qs\ max}$) required?

(d) The solar array consists of 43,000 solar panels each having an area of $(0.8 \times 1.60)\,m^2$. What is the total area of all solar panels ($area_{total\ array}$), and what is the maximum insolation required (Q_s measured in kW/m^2) at the location of this photovoltaic plant?

(e) What is the payback period (in years) if 1 kW installed output power capacity of the 5 MW PV plant costs \$4,000 provided the average price of 1 kWh during the future 15 years is \$0.20? Note: The fuel costs are zero and the operational costs are negligible; you may assume 6 h operation of the plant per day at 80% of power capacity (0.8×5 MW $= 4$ MW).

Some useful data pertaining to a 5 MW PV plant:

Construction timeframe: 1 year

Payback period: 10–20 years, depending upon rebates

Warranty: 25 years limited warranty

Exposure to hail, snow and wind loading: no damage whatsoever

efficiency (photovoltaic): 10–15% reduction of efficiency through aging: 0.5–0.75% per year

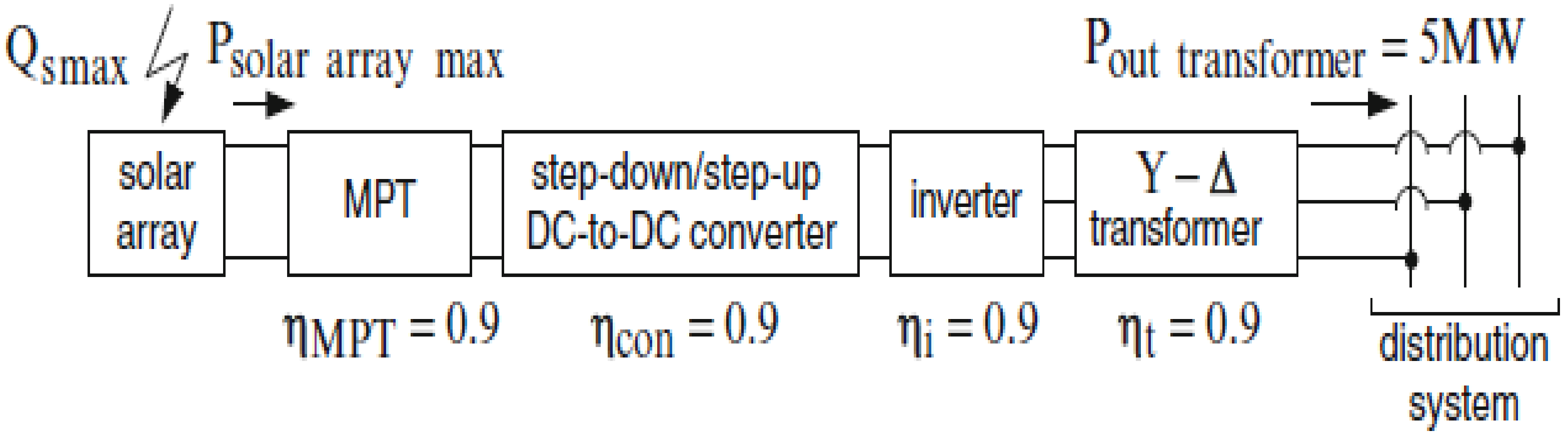
power factor: unity-power factor, there is no power-factor control

Number of AC/DC inverters required: 10–20

Peak-power tracking: on-line search for maximum power

Bypass diodes: 18 solar cells are bypassed by one diode, that is, for 72 solar cells in series four bypass diodes are used

Correction



Block diagram of 5 MW PV plant

(b) Maximum output power of solar array

$$P_{\text{solar array max}} = \frac{P_{\text{out transformer}}}{\eta_t \cdot \eta_i \cdot \eta_{\text{con}} \cdot \eta_{\text{MPT}}} = \frac{5\text{ MW}}{(0.9)^4} = 7.62\text{ MW}.$$

(c) The required insolation power at a solar cell efficiency of $\eta_{\text{cell}} = 0.15$: $P_{\text{Qsmax}} = \frac{P_{\text{solar array max}}}{\eta_{\text{cell}}} = \frac{7.62\text{ MW}}{0.15} = 50.81\text{ MW}.$

(d) Required solar array area

$$\text{area}_{\text{total array}} = 43,000 \cdot 0.8 \cdot 1.6 = 55.04 \cdot 10^3\text{ m}^2$$

resulting in the maximum insolation level

$$Q_{\text{smax}} = \frac{P_{\text{Qsmax}}}{\text{area}_{\text{total array}}} = \frac{50.81 \cdot 10^3\text{ kW}}{55.04 \cdot 10^3\text{ m}^2} = 0.92\text{ kW/m}^2.$$

(e) Payback period of the PV plant in years
Construction cost: $\text{cost}_{1\text{kW}} = \$4\text{k}$ per 1 kW installed power capacity leads to $\text{cost}_{5\text{MW}} = \$20\text{ M}$.

The earnings are based on $\text{price}_{1\text{kWh}} = \$0.20$. At 80% power capacity = 4 MW the earnings per y years are $\text{earning} = 4\text{k}\cdot 0.20 \cdot 365 \cdot 6 \cdot y = \$1.752\text{M}\cdot y$ or the payback period is $y = 20/1.752 = 11.42$ years neglecting any tax, rebates or interest payments.

References

Frede Blaabjerg, Remus Teodorescu, Zhe Chen, Marco Liserre,
Power Converters and Control of Renewable Energy Systems, Research paper,
http://www.andretahim.com/Projeto/Literatura/power%20converters%20and%20control%20of%20renewable%20energy%20systems%20paper.pdf

Ewald F. Fuchs l Mohammad A.S. Masoum, **Power Conversion of Renewable Energy Systems,**
Book,
ISBN 978-1-4419-7978-0 e-ISBN 978-1-4419-7979-7
DOI 10.1007/978-1-4419-7979-7
Springer New York Dordrecht Heidelberg London

Dhaker Abbes, André Martinez, Gérard Champenois, Benoit Robyns,
Real time simulation and supervision for a renewable hybrid power system, Research paper**,**
Under review Elsevier: Simulation Modelling Practice and Theory Journal.

Dhaker Abbes, Gérard Champenois, André Martinez, Benoit Robyns,
Modeling and simulation of a photovoltaic system: An advanced synthetic study,
Research paper, 3d International Conference on Systems and Control (ICSC13),
29 to October 31, 2013, in Algiers, Algeria.