Abstract — 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 will be an efficient and important interface to the grid and this paper will first briefly discuss three different alternative/renewable energy sources. Next, various configurations of the wind turbine technology are presented, as this technology seems to be most developed and cost-effective. Finally, the developments and requirements from the grid are discussed.

I. INTRODUCTION

The energy consumption is steadily increasing and the deregulation of electricity has caused that the amount of installed production capacity of classical high power stations cannot follow the demand. A method to fill out the gap is to make incentives to invest in alternative energy sources like wind turbines, photovoltaic systems, microturbines and also fuel cell systems. The wind turbine technology is one of the most promising alternative energy technology [1]-[3]. The modern development started in the 1980’s with sites of a few tens of kW to Multi-MW range wind turbines today. E.g. Denmark has a high penetration (> 20%) of wind energy in major areas of the country and in 2003 15% of the whole electrical energy consumption was covered by wind energy. A higher penetration level will even be seen in the near future. The technology used in the early developed wind turbines was based on a squirrel-cage induction generator connected directly to the grid. That almost directly transfers the wind power pulsations to the electrical grid. Furthermore, there was no fast control of the active and reactive power, which typically are the key parameters to control the frequency and the voltage of the grid. As the power range of the wind turbines increases those parameters become more and more important. The power electronics is the key-technology to change the basic characteristic of the wind turbine from being an energy source to be an active power source. Such possibilities are also used to interface other renewable energy sources [4]-[8].

This paper will first explain the basic principles of wind power conversion, fuel cells and photovoltaics. Next, the trend in power electronics is outlined. Different wind turbine configurations are reviewed, as they are the most promising alternative energy technologies today.

Finally, a general discussion about interface issues of renewable energy sources is done.

II. RENEWABLE ENERGY SOURCES

Three different renewable energy sources are briefly described. They are wind power, fuel cell and photovoltaic.

A. 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.

Wind turbine blades use airfoils to develop mechanical power. The cross-sections of wind turbine blades have the shape of airfoils as the one shown in Fig. 2.

Airflow over an airfoil produces a distribution of forces along the airfoil surface. The resultant of all these pressure and friction forces is usually resolved into two forces and a moment, lift force, drag force and pitching moment, as shown in Fig. 2.

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

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

where $\rho$ is the air density, $R$ is the turbine radius, $v$ is the wind speed and $C_p$ is the turbine power coefficient which represents the power conversion efficiency of a wind turbine. $C_p$ is a function of the tip-speed ratio ($\lambda$), as well as the blade pitch angle ($\beta$) in a pitch controlled wind turbine. $\lambda$ is defined as the ratio of the tip speed of the turbine blades to wind speed, and given by:

$$\lambda = \frac{R \cdot \Omega}{v}$$  \hspace{1cm} (2)

where $\Omega$ is the rotational speed of the wind turbine.

The Betz limit, $C_{p,\text{max}}$ (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 [1]:

- Rotation of the wake behind the rotor
- Finite number of blades and associated tip losses
- Non-zero aerodynamic drag
A typical $C_p-\lambda$ curve for a fixed pitch angle $\beta$ is shown in Fig. 3. It can be seen that there is a practical maximum power coefficient, $C_{p,\text{max}}$. Normally, a variable speed wind turbine follows the $C_{p,\text{max}}$ 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, $\lambda_{\text{opt}}$.

As the blade tip-speed typically should be lower than half the speed of sound the rotational speed will decrease as the radius of the blade increases. For MW wind turbines the rotational speed will be 10-15 rpm. A common way to convert the low-speed, high-torque power to electrical power is to use a gear-box and a normal speed generator as illustrated in Fig. 1. The gear-box is optional as multipole generator systems are alternative solutions.

The development in the wind turbine systems has been steady for the last 25 years and four to five generations of wind turbines exist. It is now a proven technology.

It is important to be able to control and limit the power at higher wind speeds, as the power in the wind is a cube of the wind speed. Wind turbines have to be cut out at a high wind speed to avoid damage. A turbine could be designed in such a way that it converts as much power as possible in all wind speeds, but then it would have to be too heavy. The high costs of such a design would not be compensated by the extra production at high winds, since such winds are rare. Therefore, turbines usually reach maximum power at a much lower wind speed, the rated wind speed (9-12 m/s).

The power limitation may be done by one of the aerodynamic mechanisms: stall control (the blade position is fixed but stall of the wind appears along the blade at higher wind speed), active stall (the blade angle is adjusted in order to create stall along the blades) or pitch control (the blades are turned out of the wind at higher wind speed).

### B. Fuel Cell power conversion

The fuel cell is a chemical device, which produces electricity directly without any intermediate stage and has recently received much attention [7]. The most significant advantages are low emission of green house gases and high power density. For example, a zero emission can be achieved with hydrogen fuel. The emission consists of only harmless gases and water. The noise emission is also low. The energy density of a typical fuel cell is 200 Wh/l, which is nearly ten times of a battery. Various fuel cells are available for industrial use or currently being investigated for use in industry, including

- Proton Exchange Membrane
- Solid Oxide
- Molten Carbonate
- Phosphoric Acid
- Aqueous Alkaline

The efficiency of the fuel cell is quite high (40%-60%). Also the waste heat generated by the fuel cell can usually be used for cogeneration such as steam, air-conditioning, hot air and heating, then the overall efficiency of such a system can be as high as 80%.
A typical curve of the cell electrical voltage against current density is shown in Fig. 4. It can be seen that there exists a region where the voltage drop is linearly related with the current density due to the Ohmic contact.

Beyond this region the change in output voltage varies rapidly. At very high current density, the voltage drops significantly because of the gas exchange efficiency. At low current level, the Ohmic loss becomes less significant, the increase in output voltage is mainly due to the activity of the chemicals. Although the voltage of a fuel cell is usually small, with a theoretical maximum being around 1.2 V, fuel cells may be connected in parallel and/or in series to obtain the required power and voltage.

The power conditioning systems, including inverters and DC/DC converters, are often required in order to supply normal customer load demand or send electricity into the grid.

C. The photovoltaic cell
Photovoltaic (PV) power supplied to the utility grid is gaining more and more visibility due to many national incentives [7]. With a continuous reduction in system cost (PV modules, DC/AC inverters, cables, fittings and man-power), the PV technology has the potential to become one of the main renewable energy sources for the future electricity supply.

The PV cell is an all-electrical device, which produces electrical power when exposed to sunlight and connected to a suitable load. Without any moving parts inside the PV module, the tear-and-wear is very low. Thus, lifetimes of more than 25 years for modules are easily reached. However, the power generation capability may be reduced to 75% ~ 80% of nominal value due to ageing. 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. An electrical model of the PV cell is depicted in Fig. 5.

Several types of proven PV technologies exist, where the crystalline (PV module light-to-electricity efficiency: $\eta = 10\% - 15\%$) and multi-crystalline ($\eta = 9\% - 12\%$) silicon cells are based on standard microelectronic manufacturing processes. Other types are: thin-film amorphous silicon ($\eta = 10\%$), thin-film copper indium diselenide ($\eta = 12\%$), and thin-film cadmium telluride ($\eta = 9\%$). Novel technologies such as the thin-layer silicon ($\eta = 8\%$) and the dye-sensitised nano-structured materials ($\eta = 9\%$) are in their early development. The reason to maintain a high level of research and development within these technologies is to decrease the cost of the PV-cells, perhaps on the expense of a somewhat lower efficiency. This is mainly due to the fact that cells based on today’s microelectronic processes are rather costly, when compared to other renewable energy sources.

The series connection of the cells benefits from a high voltage (around 25 V ~ 45 V) across the terminals, but the weakest cell determines the current seen at the terminals.
This power electronic system can be used with many loads and generators.

III. SINGLE-PHASE PV-INVERTERS

The general block diagram for single-phase grid connected photovoltaic systems is presented in Fig. 1a. It consists of PV array, PV inverter, controller and grid.

The series connection of the cells benefits from a high voltage (around 25 V ~ 45 V) across the terminals, but the weakest cell determines the current seen at the terminals. This causes reduction in the available power, which to some extent can be mitigated by the use of bypass diodes, in parallel with the cells. The parallel connection of the cells solves the 'weakest-link' problem, but the voltage seen at the terminals is rather low. Typical curves of a PV cell current-voltage and power-voltage characteristics are plotted in Fig. 6a and Fig. 6b 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.

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. 10.

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energy yield via the reduction of mismatching and partial shading losses. These superior technical characteristics lead to a reduction in the system cost, increase the energy yield and enhance the supply reliability. String inverters have evolved as a standard in PV system technology for grid connected PV plants.

An evolution of the string technology applicable for higher power levels is the multi-string inverter [1]. It allows the connection of several strings with separate MPP tracking systems (via DC/DC converter) to a common DC/AC inverter. Accordingly, a compact and cost-effective solution which combines the advantages of central and string technologies is achieved. This multi-string topology allows the integration of PV strings of different technologies and of various orientations (south, west and east). These characteristics allow time shifted solar power which optimizes the operation efficiencies of each string separately. The application area of the multi-string inverter covers PV plants of 3-10 kW.

Module integrated inverter

This system uses one inverter is used for each module (Fig 1d). This topology optimizes the adaptability of the inverter to the PV characteristics, since each module has its own MPP tracker. Although the module integrated inverter optimizes the energy yield, it has a lower efficiency than the string inverter. Module integrated inverters are characterized by more extended AC-side cabling, since each module of the PV plant has to be connected to the available AC grid (e.g. 230 V/ 50 Hz). Also, the maintenance processes are quite complicated, especially for facade-integrated PV systems. This concept can be implemented for PV plants of about 50-400 W peak.

PV inverter

The PV inverter technology has evolved quite a lot during the last years towards maturity [2]. Still there are different power configurations possible as shown in the Fig. 2.

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, as demonstrated in [3]. In the following, the different PV inverters power configurations are described in more detail.

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. 3a or on the high-frequency (HF) side in the dc-de converter as shown in the Fig. 3b. 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.

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In order to keep the magnetic components compact high switching frequencies in the range of 20 – 100 kHz are employed.

The full-bridge converter is usually utilized at power levels above 750W. The advantages of this topology are: good transformer utilization – bipolar magnetization of the core, good performance with current programmed control – reduced DC magnetization of transformer. The main disadvantages in comparison with push-pull topology are the higher active part count and the higher transformer ratio needed for boosting the dc voltage to the grid level.

The single inductor push-pull converter can provide boosting function on both the boosting inductor and transformer, reducing thus the transformer ratio. Thus higher efficiency can be achieved together with smoother input current. On the negative side it can be mentioned that higher voltage blocking switches are required and the transformer with tap point puts some construction and reliability problems.

Those shortcomings can be alleviated using the double inductor push-pull converter (DIC) where the boost inductor has been split in two. Actually this topology is equivalent with two interleaved boost converters leading to lower ripple in the input current. The transformer construction is more simple not requiring tap point. The single disadvantage of this topology remains the need for an extra inductor.

**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. 6.
PV inverters without DC-DC converter

The block diagram of this topology is shown in the Fig. 9a.

\begin{center}
\includegraphics[width=0.5\textwidth]{pv_inverter_without_ddc.png}
\end{center}

(a)

(b)

Fig. 9. PV inverter system without DC-DC converter and with isolation transformer

(a) general diagram b) practical example with full-bridge inverter and grid-side transformer [4]

In Fig. 9b are presented two topologies of PV inverters where the line frequency transformer is used. For higher power levels, self-commutated inverters using thyristors are still being used on the market [4].

PV inverters without DC-DC converter without isolation

The block diagram of this topology is shown in the Fig. 10a.

\begin{center}
\includegraphics[width=0.5\textwidth]{pv_inverter_without_ddc_isolation.png}
\end{center}

(a)

(b)

(c)

Fig. 10. Transformerless PV inverter system without DC-DC converter

(a) general diagram b) typical example with full-bridge inverter [4] c) multilevel [7]

In Fig. 10b, a typical transformerless topology is shown using PWM IGBT inverters. This topology can be used when there are available a large nr. of solar panels connected in series producing in excess of the grid voltage peak at all times.

Another interesting PV inverter topology without boost and isolation can be achieved using multilevel concept. Grid connected photovoltaic systems with a five level cascaded inverter is presented in Fig 10c [7]. The redundant inverter states of the five level cascaded inverter allow for a cyclic switching scheme which minimizes the switching frequency, equalizes stress evenly on all switches and minimizes the voltage ripple on the DC capacitors.

IV. CONTROL OF SINGLE-PHASE PV-INVERTERS

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 two types of control for the dc-dc converters: the direct duty-cycle control and the current control [8]. As shown in the Fig. 11.

\begin{center}
\includegraphics[width=0.5\textwidth]{control_strategies.png}
\end{center}

(a)

(b)

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. The current control, in the case of an isolated boost push-pull converter has some advantages against the duty-cycle control like simpler dynamics (removes one pole from the control-to output transfer function). Also as it uses a current sensor it
can provide better protection of the switch by limiting the current to acceptable levels.

Another issue is the transformer saturation. In the transformer it can be induced a dc bias current generated by small voltage imbalances due to the small differences in boost inductors and/or switches. This dc current bias increases or decreases the transistor currents. The current control will alter the switch duty cycles in a way that these imbalances tend to disappear and the transformer volt-second balance to be maintained. Finally, the current control is better suited to modularity where current sharing needs to be solved when running in parallel.

Among the drawbacks of the current control it can be mentioned that it required an extra current sensor and it has a susceptibility to noise and thus light filtering of feedback signals is required. The current control become unstable whenever the duty-cycle becomes larger than 0.5 but this drawback can be overcome by ramping the reference current signal.

Considering the above-enumerated arguments, the current control seems to be more attractive for PV inverter applications and it is widely used.

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 [9]. A typical dc-ac grid converter with LCL filter is depicted in the Fig. 12

![Fig. 13. The current loop of PV inverter. a) with PI controller; b) with PI+Resonant (PR) controller](image)

The harmonics level in the grid current is still a controversial issue for PV inverters. The IEEE 929 standard from 2000 allows a limit of 5% for the current total harmonic distortion (THD) factor with individual limits of 4% for each odd harmonic from 3rd to 9th and 2% for 11th to 15th while a recent draft of European IEC61727 suggests something similar. These levels are far more stringent than other domestic appliances such as IEC61000-3-2 as PV systems are viewed as generation sources and so are subject to higher standards than load systems.

Classical PI control with grid voltage feed-forward [10],[11] 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.

\[ G_{PI}(s) = \frac{K_p + K_i}{s} \]

In order to get a good dynamic response, a grid voltage feed-forward is used, as depicted in Fig. 13a. This leads in turn to stability problems related to the delay introduced in the system by the voltage feedback filter.

In order to alleviate these problems, a second order generalized integrator (GI) as reported in [12] can be used. The GI is a double integrator that achieves an infinite gain at a certain frequency, also called resonance frequency, and almost no attenuation exists outside this frequency. Thus, it can be used as a notch filter in order to compensate the harmonics in a very selective way. This technique has been primarily used in three-phase active filter applications as reported in [12] and also in [13] where closed-loop harmonic control is introduced. Another approach reported in [14] where a new type of stationary-frame regulators called PI+Resonant (PR) is introduced and applied to three-phase PWM inverter control. In this approach the PI dc-compensator is transformed into an equivalent ac-compensator, so that it has the same frequency response characteristics in the bandwidth of concern. The current loop of the PV inverter with PR controller is depicted in the Fig. 13b.

The PI current controller \( G_{PI}(s) \) is defined as:

\[ G_{PI}(s) = \frac{K_p}{s} + \frac{K_i}{s} \]

The P+Resonant (PR) current controller \( G_{HC}(s) \) as defined as [12],[15]:

\[ G_{HC}(s) = \frac{K_p}{s} + \frac{K_i}{s^2} + \frac{s}{s^2 + \omega^2} \]

The harmonic compensator (HC) \( G_{HC}(s) \) as defined in [10]:
\[ G_c(s) = \sum_{k=3,5,7} K_k \frac{s}{s^2 + (\omega_k h)^2} \]

is designed to compensate the selected harmonics 3\textsuperscript{rd}, 5\textsuperscript{th} and 7\textsuperscript{th} as they are the most prominent harmonics in the current spectrum. A processing delay typical equal to \( T_s \) for the PWM inverters [8] is introduced in \( G_c(s) \). The filter transfer function \( G_f(s) \) is expressed in (4) [16].

\[
G_f(s) = \frac{i(s)}{u(s)} = \frac{1}{L_s} \left( \frac{s^2 + z_{LC}^2}{s^2 + \omega_{res}^2} \right)
\]

where \( z_{LC} = \left[ L_s C_f \right]^{-1} \) and \( \omega_{res} = \frac{(L + L_s) z_{LC}^2}{L_s} \).

The current error - disturbance ratio rejection capability at null reference is defined as:

\[
\frac{\xi(s)}{u_e(s)} \bigg|_{s=0} = \frac{G_f(s)}{1 + (G_e(s) + G_c(s)) \cdot G_f(s)}
\]

where: \( \xi \) is current error and the grid voltage \( u_g \) is considered the disturbance for the system.

The Bode plots of disturbance rejection for the PI and PR controllers are shown in Fig 14. As it can be observed, the PR provides much higher attenuation for both fundamental and lower harmonics than PI. The PI rejection capability at 5\textsuperscript{th} and 7\textsuperscript{th} harmonic is comparable to that one of a simple proportional (P) controller, the integral action being in

![Fig. 14. Bode plot of disturbance rejection (current error ratio disturbance) of the PR+HC, P and PR current controllers.](image)

Thus it demonstrated the superiority of the PR controller respect to the PI in terms of harmonic current rejection. In [15] the discrete implementation on a low-cost fixed-point DSP is demonstrated. In Fig. 15 some experimental results with a 3kW PV inverter are shown demonstrating the harmonic compensation.

![Fig. 15. Experimental results at 3kW. Grid voltage and current. a) with PI controller. B) with PR; c) with PR+HC](image)

The issue of stability when several PV inverters are running in parallel on the same grid is becoming more and more important especially when LCL filters are used. In [17] it is shown that in the case of a concentration of several hundreds of solar roofs in Holland, resonance frequencies in the range of 1-2 kHz are occurring as a result of the grid interaction with the LCL filters. Thus, special attention is required when designing the current control. A method for designing both the controller and LCL filter ensuring stability is shown in [9].

**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. 16. 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**

The most commonly used MPPT algorithm is Perturb and Observe (P&O), due to its ease of implementation in its basic form [17]. Figure 16 shows the P vs. V and I curves of a PV array, which has a global maximum at the MPP. Thus, if the operating voltage of the PV array is perturbed in a given direction and \( \frac{dP}{dV} > 0 \), it is known that the perturbation moved the array's operating point toward the MPP. The P&O algorithm would then continue to perturb the PV array voltage in the same direction. If \( \frac{dP}{dV} < 0 \), then the change in operating point moved the PV array away from the MPP, and the P&O algorithm reverses the direction of the perturbation. A problem with P&O is that it oscillates around the MPP in steady state operation. It also can track in the wrong direction, away from the MPP, under rapidly increasing or decreasing irradiance levels. There are several variations of the basic P&O that have been designed to minimize these drawbacks. These include using an average of several samples of the array power and dynamically adjusting the magnitude of the perturbation of the PV operating point.

**Incremental Conductance**

The incremental conductance algorithm seeks to overcome the limitations of the P&O algorithm by using the PV array's incremental conductance to compute the sign of \( \frac{dP}{dV} \) without a perturbation [17]. It does this using an expression derived from the condition that, at the MPP, \( \frac{dP}{dV} = 0 \). Beginning with this condition, it is possible to show that, at the MPP \( \frac{dI}{dV} = -I/V \). Thus, incremental conductance can determine that the MPPT has reached the MPP and stop perturbing the operating point. If this condition is not met, the direction in which the MPPT operating point must be perturbed can be calculated using the relationship between \( \frac{dI}{dV} \) and \(-I/V\). This relationship is derived from the fact that \( \frac{dP}{dV} \) is negative when the MPPT is to the right of the MPP and positive when it is to the left of the MPP. This algorithm has advantages over perturb and observe in that it can determine when the MPPT has reached the MPP, where perturb and observe oscillates around the MPP. Also, incremental conductance can track rapidly increasing and decreasing irradiance conditions with higher accuracy than perturb and observe. One disadvantage of this algorithm is the increased complexity when compared to perturb and observe. This increases computational time, and slows down the sampling frequency of the array voltage and current.

**Parasitic Capacitance**

The parasitic capacitance method is a refinement of the incremental conductance method that takes into account the parasitic capacitances of the solar cells in the PV array [17]. Parasitic capacitance uses the switching ripple of the MPPT to perturb the array. To account for the parasitic capacitance, the average ripple in the array power and voltage, generated by the switching frequency, are measured using a series of filters and multipliers and then used to calculate the array conductance. The incremental conductance algorithm is then used to determine the direction to move the operating point of the MPPT. One disadvantage of this algorithm is that the parasitic capacitance in each module is very small, and will only come into play in large PV arrays where several module strings are connected in parallel. Also, the DC-DC converter has a sizable input capacitor used filter out small ripple in the array power. This capacitor may mask the overall effects of the parasitic capacitance of the PV array.

**Constant Voltage**

This algorithm makes use of the fact that the MPP voltage changes only slightly with varying irradiances, as depicted in Fig. 16a. The ratio of VMP/VOC depends on the solar cell parameters, but a commonly used value is 76% [17]. In this algorithm, the MPPT momentarily sets the PV array current to zero to allow a measurement of the array's open circuit voltage. The array's operating voltage is then set to 76% of this measured value. This operating point is maintained for a set amount of time, and then the cycle is repeated. A problem with this algorithm is available energy is wasted when the load is disconnected from the PV array, also the MPP is not always located at 76% of the array's open circuit voltage.

**Anti-islanding**

In addition to the typical power quality regulations concerning the harmonic distortion and EMI limits, the grid-
connected PV inverters must also meet specific power generation requirements like the islanding detection, or even certain country-specific technical recommendations for instance the grid impedance change detection (in Germany). Such extra-requirements contribute to a safer grid-operation especially when the equipment is connected in dispersed power generating networks but impose additional effort to readapt the existing equipments.

The European standard EN50330-1 (draft) [19] describes the ENS (the German abbreviation of Mains monitoring units with allocated Switching Devices) requirement, setting the utility fail-safe protective interface for the PV converters. The goal is to isolate the supply within 5 seconds after an impedance change of \( Z = 0.5 \, \text{W} \), which is associated with a grid failure. The main impedance is typically detected by means of tracking and step change evaluation at the fundamental frequency. Therefore, a method of measuring the grid impedance value and its changes should be implemented into existing PV-inverters.

One solution is to attach a separate device developed only for the measuring purpose as depicted in Fig. 17a.

![Fig. 1. Grid-impedance measurement for PV inverters. a) using external device; b) embedded on the inverter control using harmonic injection](image)

This add-on option is being commonly used in the commercial PV inverters, but the new trend is to implement this function embedded in the inverter control without extra hardware. Numerous publications exist in this field, which offer measuring solutions for the grid impedance for a wide frequency range from dc up to typically 1 kHz [20]. Unfortunately, not always can these methods easily be embedded into a non-dedicated platform, i.e. PV-inverters featuring typically a low-cost DSP. Specific limitations like real-time computation, A/D conversion accuracy and fixed-point numerical limitation, are typically occurring.

A novel approach presented in [21], [22] estimates the grid impedance on-line with the purpose of detection the step change of 0.5 \( \Omega \) as required in [19] as shown in Fig. 17b.

The solution is found by injecting a test signal trough the inverter modulation process. This signal, an interharmonic current with a frequency close to the fundamental, determines a voltage drop due to the grid impedance, which is measured by the existing PV-inverter sensors. Then, the same CPU unit that makes the control algorithm carries out the calculations and gives the grid impedance value. The principle of this method is shown in Fig. 18.

This approach provides a fast and low cost solution to meet the required standards and was successfully implemented on a TMS320F24x 16-bit fixed point DSP platform as an add-on to the existing control.

V. CONTROL OF THREE-PHASE INVERTERS

The control of a three-phase inverter connected to the grid has more in common with the control of an active rectifier/filter rather than with the control of an ac drive. In fact with the first the distributed inverter shares the characteristic to be connected to the grid on the ac side, while with second it shares the common characteristic to have less responsibilities in the management of the dc-link voltage that is usually controlled by another converter stage. Hence from the control perspective the three-phase distributed inverter as an advantage over the rectifier and a disadvantage over the motor inverter.

Its control issues will be discussed starting from its mathematical model both with L-filter and LCL-filter on the grid side.

Then simple controls as well as few advanced ones will be introduced and briefly discussed. Finally some advanced topics and some experimental results will close this Section.

Mathematical Model of the L-filter inverter

The state of the three-phase inverter is modelled by means of a switching space-vector defined with the switching functions \( p_j(t) \) \( (j = a, b, c) \)

\[
\mathbf{R}(t) = \frac{2}{3} \left[ p_a(t) + \alpha \cdot p_b(t) + \alpha^2 \cdot p_c(t) \right]
\]

then if the inverter is connected to the grid through an L-filter (Fig. 1)
\[
\begin{align*}
\nabla(t) &= \bar{v}(t) + R\bar{i}(t) + L \frac{d\bar{v}(t)}{dt} \\
\nabla(t) &= \frac{1}{2} \ddot{\bar{v}}(t)v_f(t)
\end{align*}
\]

(2)

assuming to neglect the dc voltage dynamic such as the dc voltage \(v_d(t)\) is an input for the system. Moreover \(\nabla(t)\) is the space-vector of the inverter input voltages; \(\bar{I}(t)\) is the space-vector of the inverter input currents; \(\bar{v}(t)\) is the space-vector of the input line voltages.

The mathematical model written in the state space form is

\[
\frac{d\bar{I}(t)}{dt} = \frac{1}{L} \left[ -R\bar{v}(t) - \pi(t) + \frac{1}{2} \ddot{\bar{v}}(t)v_f(t) \right]
\]

(4)

A commonly used approach in analysing three-phase systems is to adopt a \(dq\)-frame that rotates at the angular speed \(\omega\) (where \(\omega = 2\pi f \) and \(f\) is the fundamental frequency of the power grid’s voltage waveform). The space-vectors which express the inverter electrical quantities are projected on the \(d\)-axis and \(q\)-axis. As a consequence if a space-vector with constant magnitude rotates at the same speed of the frame, it has constant \(d\) - and \(q\) - components while if rotates at a different speed or it has a time-variable magnitude it has pulsating components. Thus in a \(dq\)-frame rotating at the angular speed \(\omega\) (2) becomes

\[
\begin{align*}
\frac{di_d(t)}{dt} - \omega i_q(t) &= \frac{1}{L} \left[ -R_i(t) + c_d(t) + \frac{1}{2} R_d(t) v_f(t) \right] \\
i_d(t) + \omega i_q(t) &= \frac{1}{L} \left[ -R_i(t) - c_q(t) + \frac{1}{2} R_q(t) v_f(t) \right]
\end{align*}
\]

(5)

shows how in the \(dq\)-frame the \(d\) - and \(q\) - differential equations for the current are dependent due to the cross-coupling terms \(\omega i_q(t)\) and \(\omega i_d(t)\).

Mathematical Model of the LCL-filter inverter

In the following the LCL-filter based inverter model is reported in order to highlight the increased complexity of the system. The system is shown in Fig. 2.

![Fig. 2 LCL-filter inverter connected to the grid.](image)

AC Current control

The ac current control (CC) is usually adopted because the current controlled converter exhibits, in general, better safety, better stability and faster response [1].

This solution ensures several additional advantages. The feedback loop also results in some limitations, such as that fast-response voltage modulation techniques must be employed, like PWM. Optimal techniques, which use precalculated switching patterns within the ac period, cannot be used, as they are not oriented to ensure current waveform control [1].

Generally the current control is the most inner loop of a cascade control that employ a dc-link voltage level management system and active and reactive power controller as reported in Fig. 3.

The use of an ac LCL-filter claims for a deep dynamic and stability analysis of the current control loop [2]. In order to highlight the stability problems that arise from the use of an LCL-filter it is sufficient to show the \(d\) or \(q\) system plant in Laplace domain. If the converter side current is sensed, the system plant is

\[
G(s) = \frac{i(s)}{v(s)} = \frac{1}{L_c s^2 + \omega_c^2}
\]

(7)

If the grid side current is sensed, the plant for control is

\[
G(s) = \frac{i(s)}{v(s)} = \frac{1}{L_c s^2 + \omega_c^2}
\]

(8)

where \(z_{LC}^2 = [L_c C_f]^{-1}\) and \(\omega_{cc}^2 = (L_1 + L_2) z_{LC}^2 / L_2\).

\[
\begin{align*}
\begin{bmatrix}
i_d \\
i_q \\
v_{c,d} \\
v_{c,q} \\
i_{d2} \\
i_{q2}
\end{bmatrix}
&= \frac{d}{dt}
\begin{bmatrix}
h_d \\
h_q \\
v_{c,d} \\
v_{c,q} \\
l_{d2} \\
l_{q2}
\end{bmatrix}
\begin{bmatrix}
\frac{R_1}{L_1} & \omega & -\frac{1}{L_1} & 0 & 0 & 0 \\
-\omega & \frac{R_1}{L_1} & 0 & 0 & 0 & 0 \\
\frac{1}{C_f} & 0 & 0 & \omega & -\frac{1}{C_f} & 0 \\
0 & \frac{1}{C_f} & -\omega & 0 & 0 & -\frac{1}{C_f} \\
0 & 0 & -\frac{1}{L_2} & 0 & \frac{R_2}{L_2} & \omega \\
0 & 0 & 0 & \frac{1}{L_2} & -\omega & \frac{R_2}{L_2}
\end{bmatrix}
\begin{bmatrix}
h_d \\
h_q \\
v_{c,d} \\
v_{c,q} \\
l_{d2} \\
l_{q2}
\end{bmatrix}
\end{align*}
\]

(6)
In both the cases the two poles related to the resonance of the LCL-filter challenge the current control instability, particularly the second one (sensing of the grid current) generally lead to a more stable behaviour.

Two axis-based current control

The most used control technique is the two-axis-based [1]. Then if the two-axis system is a stationary $\alpha\beta$-frame, the proportional plus resonant controller can be adopted and it is

$$D_{pr}(s)_{\alpha\beta} = \begin{bmatrix} K_p + \frac{K_s}{s^2 + \omega_0^2} & 0 \\ 0 & K_p + \frac{K_s}{s^2 + \omega_0^2} \end{bmatrix}$$  \hspace{1cm} (9)

If the frame is a rotating $dq$-frame, classical PI can be used

$$D_{pr}(s)_{dq} = \begin{bmatrix} K_p + \frac{K_s}{s} & 0 \\ 0 & K_p + \frac{K_s}{s} \end{bmatrix}$$  \hspace{1cm} (10)

If this controller is transformed into an $\alpha\beta$-frame then

$$D_{pr}(s)_{\alpha\beta} = \begin{bmatrix} K_p + \frac{K_s}{s^2 + \omega_0^2} & \frac{\omega_0 K_{i_d}}{s + \omega_0} \\ \frac{\omega_0 K_{i_q}}{s + \omega_0} & K_p + \frac{K_s}{s^2 + \omega_0^2} \end{bmatrix}$$  \hspace{1cm} (11)

(11) is equal to (9) except for non-diagonal terms. Hence the PI controller in $dq$-frame and PR controller in $\alpha\beta$-frame can achieve similar performances.

Grid voltage harmonic compensators

The grid voltage is usually affected by a background distortion that can result in a high harmonic distortion of the grid current. This problem can be solved both in a stationary $\alpha\beta$-frame both in a rotating $dq$-frame. In the first case it is sufficient to plug in other resonant controller also called harmonic compensators

$$G_h(s)_{\alpha\beta} = \sum_{h=3,5,7} k_h \frac{s}{s + (\omega_0 \cdot h)^2}$$  \hspace{1cm} (12)

where $h$ is the order of the harmonic to be compensated.

If the controller adopts a rotating $dq$-frame approach it is possible to introduce other $dq$-frame rotating at multiple speed respect to the fundamental one and adopting standard PI in each of them. In both the cases it is necessary that the harmonics to be compensated stay into the bandwidth of the current controller otherwise stability problems arise.

Current control active damping

This solution seems very attractive especially in applications above several kW, where the use of a damping resistor increases the encumbrances, the losses could claim for forced cooling and the efficiency decrement becomes a key point. In [3] a lead-lag network has been used on the filter capacitor voltage and it is possible to avoid the use of new sensors because this voltage is near to the grid which is normally sensed. Moreover, in [4] an interesting approach to perform active damping has been proposed: a virtual resistor is added. The virtual resistor is an additional control algorithm that makes the LCL-filter behaving as if there was a real resistor connected to it. However, an additional current sensor is needed if the virtual resistor is connected in series to the filter inductor or capacitor and an additional voltage sensor is needed, if it is connected in parallel. Basically all these approaches are multiloop-based [5] while an alternative solution consists in adopting a more complex controller acting as a digital filter around the resonance frequency of the LCL-filter [2].

Direct power control

In the last years the most interesting emerging technique has been the direct power control developed in analogy to the well known direct torque control used for drives. In DPC there are no internal current loops and no PWM modulator block because the converter switching states are
appropriately selected by a switching table based on the instantaneous errors between the commanded and estimated values of active and reactive power [1], [6] Fig 5. The main advantage of the DPC is in its simple algorithm instead the main disadvantage is in the need for high sampling frequency required to obtain satisfactory performances.

Reduction of the number of sensors

The basic number of needed sensors is 4 (two ac currents and two ac voltages). However this number can be reduced avoiding the use of grid voltage vector implementing a virtual sensor or using a zero crossing detector in order to have the phase reference for the current in order to have unity power factor. Moreover if a feedforward current control technique is adopted the grid current sensors can be avoided but it is essential to provide a method for overcurrent protection in industrial applications.

EMC-issues

The main EMC-issues are related to the low frequency range and thus to the correct control to the current. Thus the use of a LCL-filter on the ac side is an interesting solution: reduced values of the inductance can be used and the grid current is almost ripple free. The design of the LCL-filter has been investigated [11].

Future research topics

Some intriguing topics of research are:

- the immunity of the inverter to the presence of polluting loads connected to the same PCC
- compliance with international standards/need for new standards respect to the harmonics due to the switching;
- to reduce the number of components;
- whether use or not the Phase Locked Loop;
- whether to use grid voltage feedforward or not;
- grid current sensor position

Results

Some tests results, obtained on the set-up shown in Fig. 6, are reported in order to evaluate the impact of the non-ideal conditions on the behaviour of a PR-based controller in a αβ-frame (Fig. 7), the use of harmonic compensator in a stationary αβ-frame to mitigate these effects (Fig. 8) and finally the effect of active damping (Fig. 9).

Non-ideal conditions

The non-ideal conditions are many and they can affect very much the overall system performance. They are too long computation time, presence of acquisition filters, ac phase unbalance, location of the grid voltage sensors after a dominant reactance and passive damping if an LCL-filter is used. A proper design to take into consideration them should be provided [9].

It is well known that the grid unbalance causes even harmonics at the dc output and odd harmonics in the input current [10]. Some solutions have been studied such as the use of negative sequence in the reference current that unfortunately leads to uncontrollability of the power factor or the use of two current controllers for positive and negative sequences, which also can create stability problems.
VI. CONVERTER TOPOLOGIES FOR WIND TURBINES

In a fixed speed wind power conversion system, the power may be limited aerodynamically either by stall, active stall or by pitch control [6], [7]. 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. 11 shows different topologies for the first category of wind turbines.

All three systems are using a soft-starter (not shown in Fig. 11) in order to reduce the inrush current and thereby 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.

The next category is variable speed systems [6]-[35] 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.

![Fig. 11. Wind turbine systems without power converter but with aerodynamic power control. Pitch controlled (System I) b) Stall controlled (System II) c) Active stall controlled (System III)](image link)

Pitch controlled (System I) b) Stall controlled (System II) c) Active stall controlled (System III)
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 [9]. Fig. 13 shows four possible solutions with full-scale power converters.

The solutions shown in Fig. 13a and Fig. 13b are characterized by having a gear. A synchronous generator solution shown in Fig. 13b needs a small power converter for field excitation. Multi-pole systems with the synchronous generator without a gear are shown in Fig. 13c and Fig. 13d.

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.

The wind turbines with partially rated power electronics that are used to obtain an improved control performance. Fig. 12a 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. 12b [18]-[26]. Slip-rings are making the electrical connection to the rotor. A power converter controls the rotor currents. If the generator is running supersynchronously electrical power is delivered through both the rotor and the stator. If the generator is running subsynchronously 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 (P_{ref}) and reactive power (Q_{ref}), 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. 12b 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. 11 and Fig. 12a. 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.
VII. CONVERTER TOPOLOGIES FOR WIND TURBINES

Fig. 13 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.

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. 10.

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

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. 11a. The power converters to the grid-side and the rotor-side are voltage source inverters.

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. 11b. 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 they are able to control reactive and active power very fast and thereby the turbine can take part in the power system control.

Fig. 10. Control of wind turbine with doubly-fed induction generator system [35].
**Fig. 11. Basic control of active and reactive power in a wind turbine [17].**

a) Doubly-fed induction generator system (System V)
b) Multi-pole synchronous generator system (System VIII)

**SUMMARY**

**REFERENCES**


