Power Electronics as Efficient Interface in Dispersed Power Generation Systems

Frede Blaabjerg, *Fellow, IEEE*, Zhe Chen, *Senior Member, IEEE*, and Soeren Baekhoej Kjaer, *Member, IEEE*

***Abstract*—The global electrical energy consumption is rising and there is a steady increase of the demand on the power capacity, efficient production, distribution and utilization of energy. The traditional power systems are changing globally, a large number of dispersed generation (DG) units, including both renewable and nonrenewable energy sources such as wind turbines, photovoltaic (PV) generators, fuel cells, small hydro, wave generators, and gas/steam powered combined heat and power stations, are being integrated into power systems at distribution level. Power electronic, the technology of efficiently processing electric power, plays an essential part in the integration of the dispersed generation units for good efficiency and high performance of the power systems. This paper reviews the applications of power electronics in the integration of DG units, in particularly, wind power, fuel cells and PV generators.**

***Index Terms*—Distributed power generation, fuel cells, photovoltaic (PV), power electronics, renewable energy, wind energy.**

I. INTRODUCTION

IN TRADITIONAL power systems, large power generation plants located at adequate geographical places produce most of the power, which is then transferred toward large consumption centers over long distance transmission lines. The system control centers monitor and control the system continuously to ensure the quality of the power, namely the frequency and the voltage. However, the power system is changing, a large number of dispersed generation (DG) units, including both renewable and nonrenewable sources such as wind turbines, wave generators, photovoltaic (PV) generators, small hydro, fuel cells and gas/steam powered combined heat and power (CHP) stations, are being developed [1]–[3]. A wide spread use of renewable energy sources in distribution networks and a high penetration level will be seen in the near future. E.g., Denmark has a high penetration (>20%) of wind energy in major areas of the country and today 14% of the whole electrical energy consumption is covered by wind energy. The main advantages of using renewable sources are the elimination of harmful emissions and the inexhaustible resources of the primary energy. However, the main disadvantage, apart from the higher costs, e.g., photovoltaic, is the uncontrollability. The availability of renewable energy sources has strong daily and seasonal patterns. But the power demand by the consumers could have a very different characteristic. Therefore, it would be difficult to operate a power system installed with only renewable generation units due to the characteristic differences and the high uncertainty of the availability of the renewable sources. The way of fully exploiting the renewable energy is the grid connection, normally at distribution level.

In conventional generation stations, the generators operate at a fixed speed and thereby with a fixed grid-frequency, however, the dispersed generation presents a quite different and challenging picture. For example, the voltage generated by variable speed wind power generators, PV generators and fuel cells cannot be directly connected to the grid. The power electronic technology plays a vital role to match the characteristics of the dispersed generation units and the requirements of the grid connections, including frequency, voltage, control of active and reactive power, harmonic minimization etc.

Power electronic, being the technology of efficiently converting electric power, plays an important role in the field of modern electrical engineering [4], [5], it is an essential part for the integration of dispersed generation unit to achieve high efficiency and performance in power systems. This paper will show how the present development of modern power electronic technology has enabled a successful integration. In the paper, the characteristics of some dispersed generation units and the general structures of the systems interfacing the power generation units will be presented, in particularly, wind power, fuel cells, and PV generators.

II. POWER ELECTRONIC FOR WIND POWER GENERATION SYSTEMS

A. Characteristics of Wind Power Conversion

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

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

where ρ 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 (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

$$\lambda = \frac{R\cdot\Omega}{v} \qquad (2)$$

where Ω is the rotational speed of the wind turbine. A typical $C_P - \lambda$ curve for a fixed pitch angle β is shown in Fig. 1. It can be seen that there is a maximum power coefficient, $C_{P,\max}$.

Manuscript received June 9, 2003; revised June 1, 2004. Recommended by Associate Editor R. Zhang.

The authors are with the Institute of Energy Technology, Department of Electrical Energy Conversion, Aalborg University, Aalborg East DK-9220, Denmark (e-mail: fbl@iet.aau.dk).

Digital Object Identifier 10.1109/TPEL.2004.833453

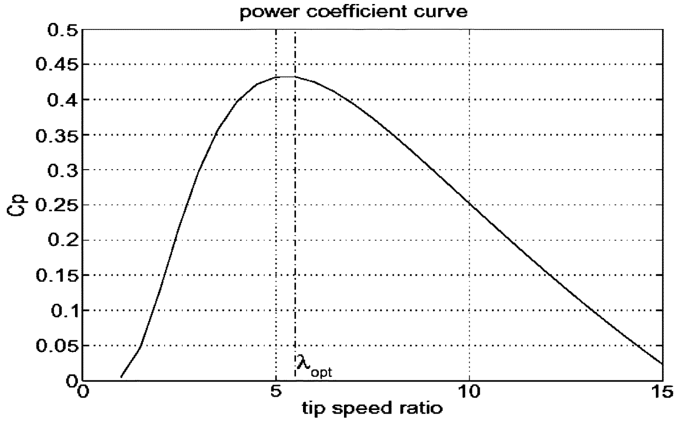


Fig. 1. Typical $\mathrm{Cp} - \lambda$ curve for a wind turbine.

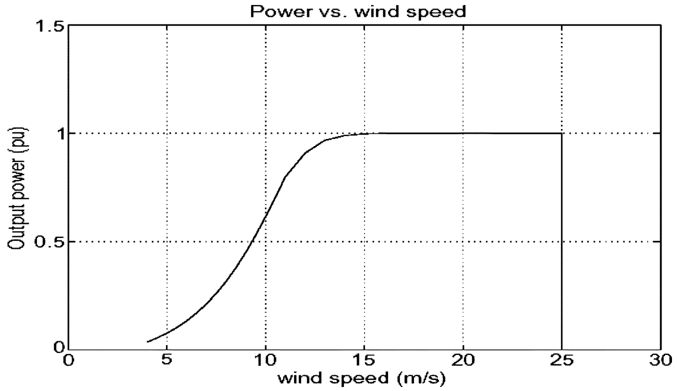


Fig. 2. Power-wind speed characteristics for a wind turbine.

Normally, a variable speed wind turbine follows the $C_{P,\max}$ to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at λ_{opt}. Then it operates at the rated power with power regulation during the periods of high wind by the active control of the blade pitch angle or the passive regulation based on aerodynamic stall. A typical power- wind speed curve with a cut-off wind speed of 25 m/s is shown in Fig. 2, however, the cut-off wind speed may vary depending on the type of wind turbines.

B. Variable Speed Wind Turbines

The development in wind turbine systems has been steady for the last 25 years and four to five generations of wind turbines exist [1]. The wind turbine technology can basically be divided into three categories: the systems without power electronics, the systems with partially rated power electronics and the systems with full-scale power electronic interfacing wind turbines.

The wind turbine systems in Fig. 3 using induction generators, which independent of torque variation, keep an almost fixed speed (variation of 1–2%). The power is limited aerodynamically either by stall, active stall or by pitch control. A soft-starter is normally used in order to reduce the inrush current during start-up. Also a reactive power compensator is needed to reduce (almost eliminate) the reactive power demand from the turbine generators. It is usually done by activating continuously the capacitor banks following load variation (5–25 steps). Those solutions are attractive due to low cost and high reliability.

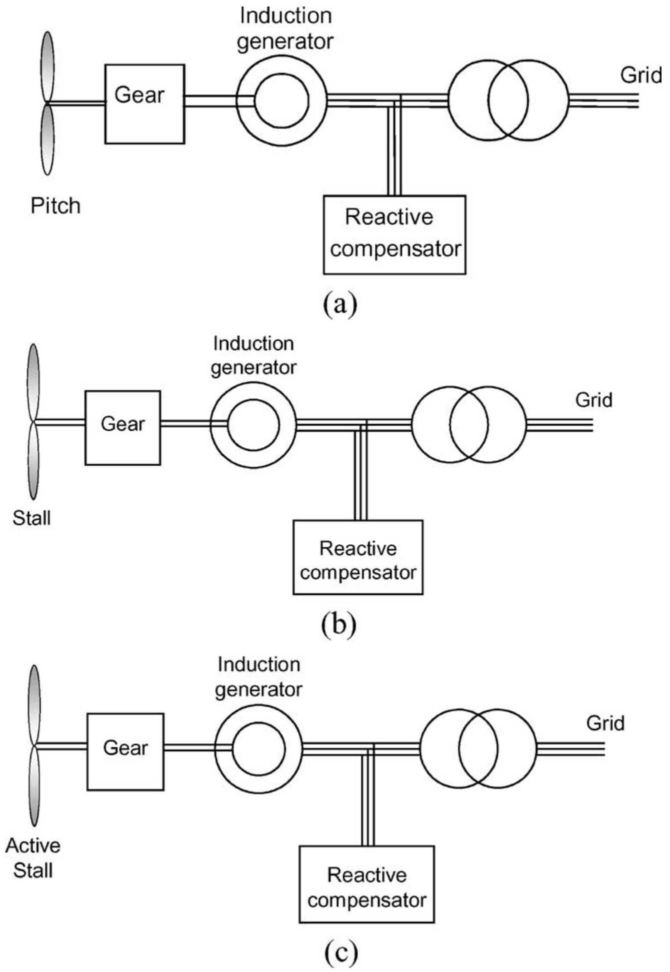


Fig. 3. Wind turbine systems without power converter but with aerodynamic power control: (a) pitch controlled, (b) stall controlled, and (c) active stall controlled.

The next category is wind turbines with partially rated power converters and much more improved control performance can be obtained. Fig. 4 shows two such solutions. Fig. 4(a) shows a wind turbine system where the generator is an induction generator with a wounded rotor. An extra resistance controlled by power electronics is added in the rotor, which gives a speed range of 2 to 4%. 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 also needs a softstarter and a reactive power compensator.

Another solution of using a medium scale power converter with a wounded rotor induction generator is shown in Fig. 4(b). A power converter connected to the rotor through slip rings controls the rotor currents. If the generator is running super-synchronously, the electrical power is delivered through both the rotor and the stator. If the generator is running sub-synchronously the electrical power is only delivered into the rotor from the grid. A speed variation of 60% around synchronous speed may be obtained by the use of a power converter of 30% of nominal power. Furthermore, the required rating of the power converter can be higher, depending on the designed fault handing capability as well as the ability of controlling reactive power,

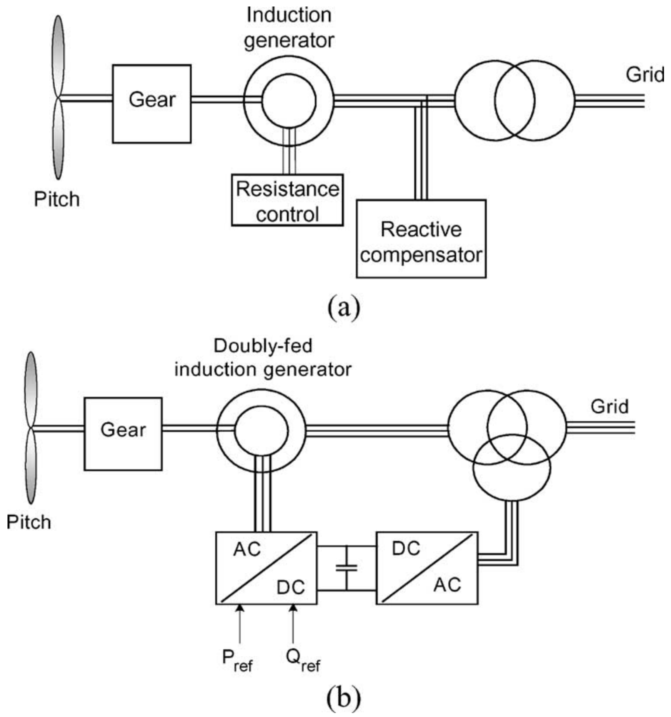


Fig. 4. Wind turbine topologies with partially rated power electronics: (a) rotor-resistance converter and (b) doubly fed induction generator.

which give a better grid performance. The solution is naturally a little bit more expensive compared to the classical solutions, however it is possible to save on the safety margin of gear, having reactive power compensation/production and more energy captured from the wind.

The third category is wind turbines with a full-scale power converter between the generator and grid, which gives extra losses in the power conversion but it will gain the added technical performance. Fig. 5 shows four possible solutions with full-scale power converters.

The solutions shown in Fig. 5(a) and (b) are characterized by having a gear. A synchronous generator solution shown in Fig. 5(b) needs a small power converter for field excitation. Multipole generator systems with the synchronous generator without a gear are shown in Fig. 5(c) and (d). Permanent magnets are used for the system shown in Fig. 5(d), which are still becoming cheaper. Various power electronic interfaces may be used with permanent magnet wind power generators [6]–[8]. Simulation tools are developed to investigate the design and operation of the wind turbines [9]. All four solutions have the same controllable characteristics since the generator is decoupled from the grid by a voltage-sourced dc-link. The power converter to the grid enables a fast control of active and reactive power. However, the negative side is a more complex system with a more sensitive power electronic part. Comparing the different wind turbine systems in respect to performance shows a contradiction between the cost and the performance. By introducing power electronics many of the wind turbine systems behave like a power plant [10]. In respect to control performance they are faster, but the produced real power depends on the available wind. On the other hand they may always be able to deliver reactive power, which can be used for power system control.

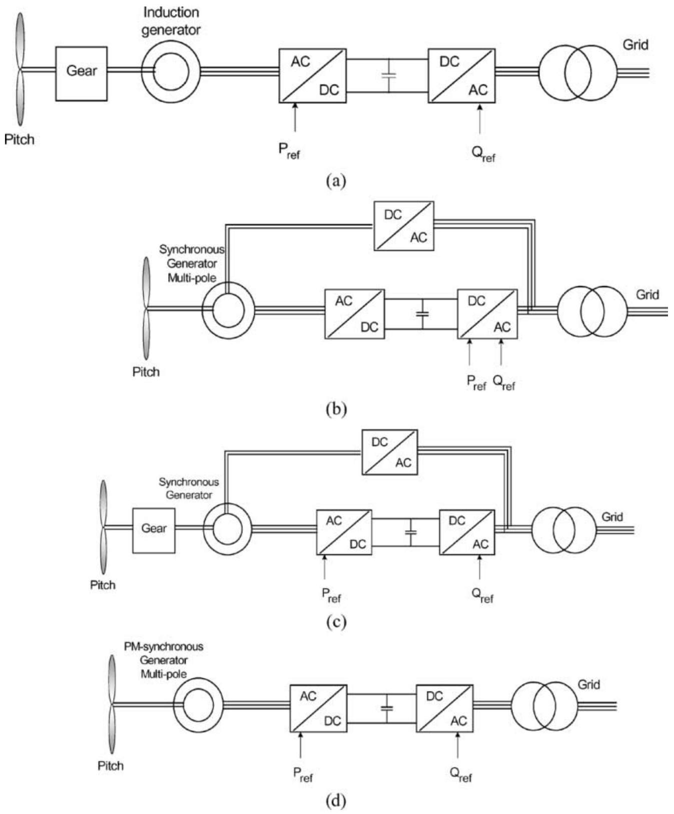


Fig. 5. Wind turbine systems with full-scale power converters with active and reactive power control: (a) induction generator with gear, (b) synchronous generator with gear, (c) multipole synchronous generator, and (d) multipole permanent magnet synchronous generator.

C. Power Electronics for Offshore Wind Farms

Wind energy systems are developing toward higher capacity and offshore locations. For example, ambitious energy planning in Denmark has scheduled a level of 50% wind energy penetration in the year 2030—mainly covered by large offshore wind farms. These wind farms present a significant power contribution on the grid, and therefore, play a very important role on the power quality and the control of power systems. Consequently high technical demands are expected to be met by these renewable generation units, such as to perform frequency and voltage control, regulation of active and reactive power, quick responses under power system transient and dynamic situations. The power electronic technology is again an important part in both system configurations and the control of the offshore wind farms in order to fulfill the future demands [11].

The wind farms may be connected into different types of configurations with various control and compensation arrangements. For example, ac local network with centralized compensation or with a dc transmission system, and dc local network, decentralized control with a dc transmission system. In Rejsby Hede, Denmark, a test installation with ac local network and centralized compensation, an 8-MVAr GTO based advanced static VAr compensation unit (ASVC), as sketched in Fig. 6(a), is a 24 MW wind farm with 40 stall regulated wind turbines. The power electronic based ASVC controls the reactive power of the wind farm and therefore the system voltage. It is noted that for the wind turbines directly connected to the ac grid without

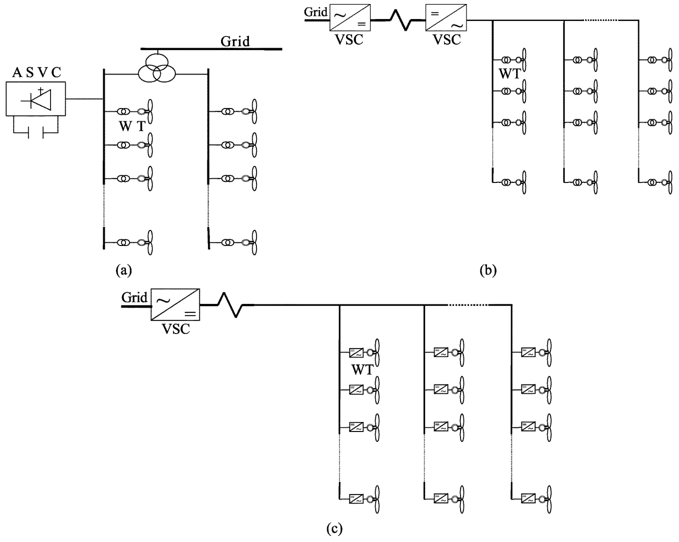


Fig. 6. Wind farm arrangements: (a) a wind farm (40 turbines) with an ASVC unit, (b) a wind farm with a VSC based HVDC transmission and common ac-grid, and (c) a wind farm with an internal dc network and individual power control.

power electronic interface, the real power cannot easily be controlled without a pitch control mechanism or dumping devices. However, if the rotor is connected to the grid via power electronic converters as shown in Fig. 4(b), the offshore wind farm equipped with doubly fed induction generators can perform both real and reactive power control while operate the wind turbines in variable speed to maximize the energy capture and to reduce the mechanical stress and noise. The power electronic converters are normally only rated as a small part of the system capacity, say 20–30%. Since the controllability is related to the rating of the power electronic converters, other compensation methods/devices may still be required dependent on system demands. For long distance transmission of power from offshore wind farm, HVDC may be a viable option. In a HVDC transmission, the low or medium ac voltage at the wind farm is converted into a high dc voltage on the transmission side and the dc power is transferred to the on-shore system where the dc voltage is converted back into ac voltage as shown in Fig. 6(b). For certain power level, a voltage source converter (VSC) based HVDC transmission system may be used instead of the conventional thyristor based HVDC technology. A configuration of using dc local network, decentralized control with a dc transmission is shown in Fig. 6(c), where each wind turbine has its own power electronic converter, so that it is possible to operate each wind turbine at an individual optimal speed. Each system configuration has its own feature and suitability; the most suitable system configuration for a particular wind farm has to be determined by taking the details of the concerned wind farm into consideration.

III. POWER ELECTRONICS IN FUEL CELL SYSTEMS

A. *Fuel Cells*

The fuel cell is a chemical device, which produces electricity directly without any intermediate stage and has recently received much attention. The most significant advantages are low emission of green house gases and high power density.

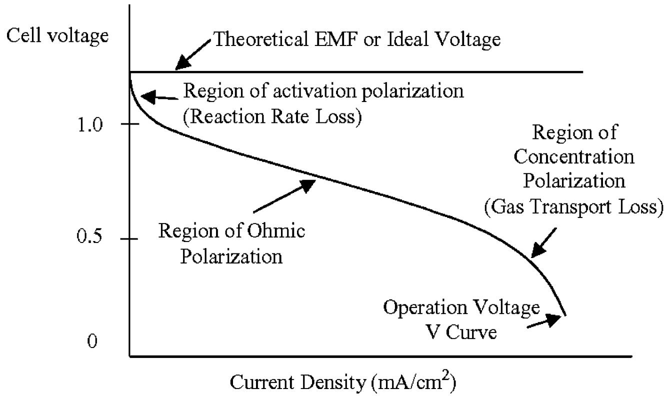


Fig. 7. V–I characteristics of a cell [12].

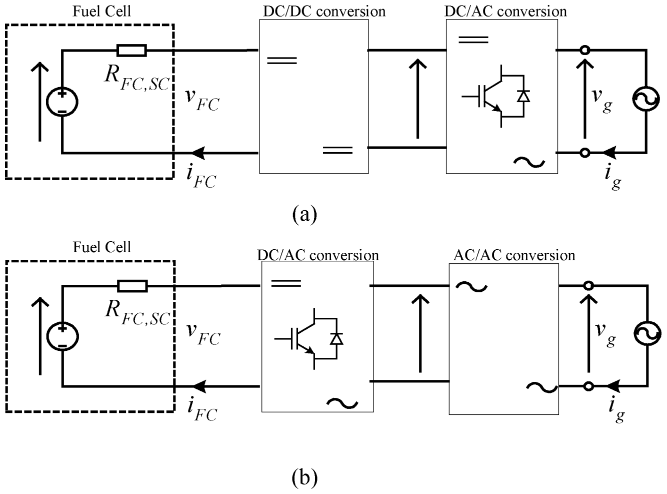


Fig. 8. Schematics of fuel cell power electronic conditioning systems. (a) dc/dc, dc link, and dc/ac conversion and (b) dc/ac, ac link, and ac/ac conversion.

For example, a zero emission can be achieved with hydrogen fuel. The emission consists of only harmless gases and water. The noise emission is 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:

1) proton exchange membrane;
2) solid oxide;
3) molten carbonate;
4) phosphoric acid;
5) 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 could be as high as 80%.

A typical curve of the cell electrical voltage against current density is shown in Fig. 7 [12]. It can be seen that there exists a linear 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

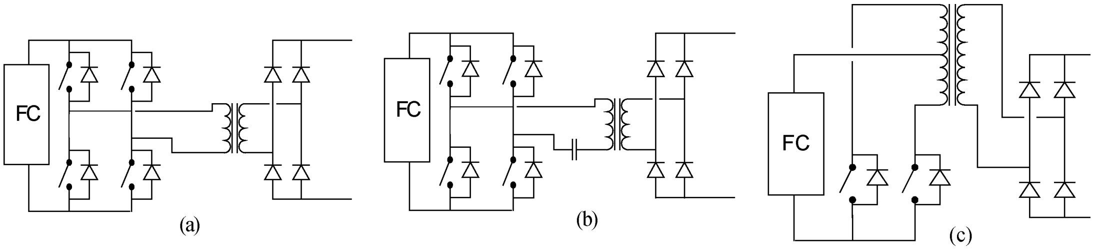


Fig. 9. Isolated dc/dc converters: (a) H-bridge dc/dc converter, (b) series resonant H-bridge dc/dc converter, and (c) push–pull dc/dc converter.

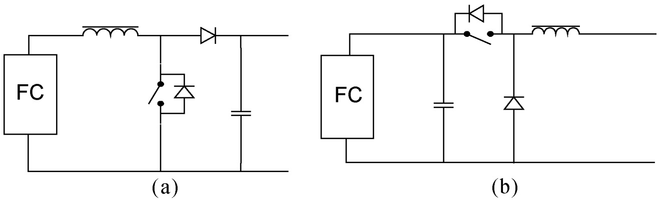


Fig. 10. Nonisolated dc/dc converters: (a) a boost dc/dc converter and (b) a buck dc/dc converter.

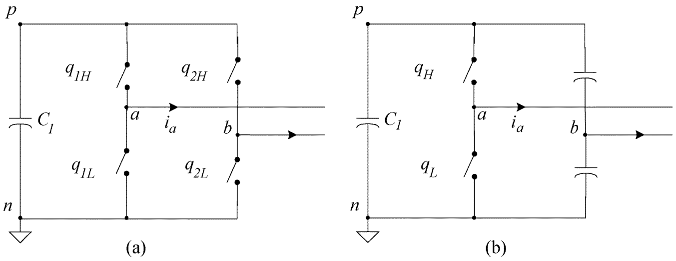


Fig. 11. Single-phase dc/ac inverters: (a) full bridge inverter and (b) half bridge inverter.

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. Some possible power electronic conditioning circuits for fuel cells are described in the following section.

B. Power Electronic Conditioning System for Fuel Cells

The power conditioning circuit of a fuel cell system often consists of a dc/dc converter and a dc/ac inverter as shown in Fig. 8(a), another possible configuration of the system includes a dc/ac converter which converts the voltage into a high-frequency ac voltage, then a cycloconverter is used to change the high-frequency voltage into a power-frequency ac voltage as shown in Fig. 8(b) [13]. Various configurations of the commonly used system, the system with a dc/dc converter plus an inverter, will be discussed.

If the isolation or a high ratio of the voltage conversion is required, a transformer is usually integrated into the system. It is preferred to place the transformer in the high-frequency section of the circuit rather than at the ac output-frequency, since a low-frequency transformer is bulky and expensive.

In a dc/dc + dc/ac converter system, the dc/dc converter is used for isolation and voltage step-up and the inverter is needed for ac output. In general both dc/dc converters and dc/ac inverters have many topologies for selection, including the hard-switching and soft-switching circuits.

1) DC/DC Converters in Fuel Cell Conditioning Systems: A dc/dc converter is usually put between the fuel cell and the inverter to perform two functions. One is the dc isolation for the inverter because a low-frequency transformer is placed at the output of the inverter is very bulky, and the second is to produce sufficient voltage for the inverter input, so that the required magnitude of the ac voltage can be produced. For example, only 200-V fuel cell stack cannot produce 380-V line voltage, then a step up dc converter is needed.

The classical dc/dc converter such as H-bridge type forward converter shown in Fig. 9(a) is well-developed and proven technology. However, in order to reduce the switching loss, a soft-switching type of the converter, the H-bridge series resonant converter shown in Fig. 9(b) may be used. The main advantage of the converter is its inherited short-circuit protection and there is no saturation problem of the transformer whereas the hard-switching forward converter requires very accurate bi-polar waveform or current mode control otherwise the transformer may experience saturation and cause extra losses. Fig. 9(c) shows a push pull type of a dc/dc converter, which requires the high dc voltage and current. The diode rectifier bridges shown in Fig. 9 can be replaced with half bridge diode rectifiers as well.

If the isolation is not required and the voltage conversion ratio is not high, then nonisolated dc/dc converters as shown in Fig. 10 may be used.

2) DC/AC Converters in Fuel Cell Conditioning Systems: The dc/ac conversion circuit may be chosen from a selection of various circuit topologies, Fig. 11 shows two single-phase inverters. Fig. 11(a) is an H-bridge inverter while Fig. 11(b) shows that the dc-link capacitor is composed by two capacitors in series, where the midpoint is used in the inverter stage. This makes it possible to save two switches at the cost of a twice as high dc-link voltage compared with the full-bridge in order to produce the same level of the ac voltage.

Various three-phase inverters may be used for three-phase applications [14].

a) Hard-switching three-phase voltage source inverter (VSI): the design is well proven and the converter is widely used in industrial applications, but it suffers from switching loss.

b) Resonant-phase leg inverter (RPLI): it is an improvement to the hard-switching inverter with zero-voltage switching. A modified variable-frequency modulation can further improve the soft-switching range.

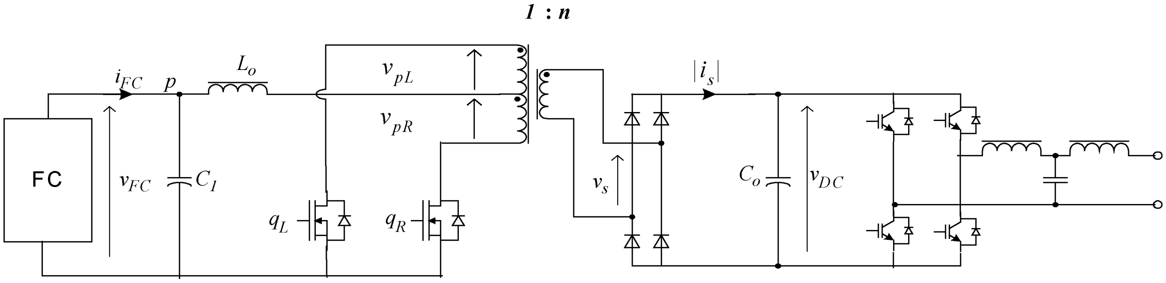


Fig. 12. Interface of a fuel cell consisting of a push–pull dc/dc converter with high-frequency transformer and a single-phase dc/ac inverters [13].

c) Auxiliary resonant commutated pole inverter (ARCPI): it uses auxiliary transistors to assist the zero-voltage switching of the main devices. The operation of zero voltage switching is wider, but more components are needed.

d) Active clamp resonant dc link inverter (ACRDI): it is an improvement to the classical resonant dc link inverter where the dc link voltage is as twice high as the original dc link voltage. After using additional clamping devices, the dc link voltage can be controlled to 1.3 times of the input voltage. However, only the delta modulation method can be used.

A conditioning system with a dc/dc converter and a dc/ac inverter can be constructed by a combination of the converters discussed above. An example of a fuel cell system with power electronic interfacing into a single-phase ac system is shown in Fig. 12, where a current fed push pull dc/dc converter with an isolation transformer and a single-phase bridge inverter are used [13].

There are also many recently developed and/or proposed circuit configurations [15]–[23] for fuel cell applications, including Z-source converter that combines functionality of dc/dc boost and VSI [23].

IV. POWER ELECTRONICS IN PHOTOVOLTAIC (PV) SYSTEMS

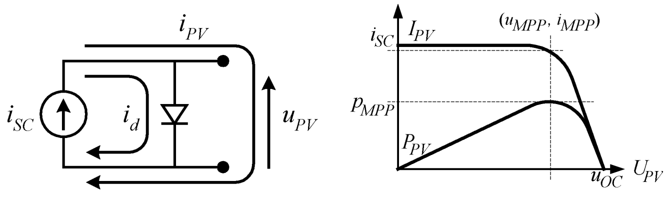
A. *PV Cell*

PV power supplied to the utility grid is gaining more and more visibility, while the world's energy demand is steadily increasing. With reduction in the 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.

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 $\sim$ 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. A simplified electrical model of the PV cell is depicted in Fig. 13.

Several types of proven PV technologies exist, where the crystalline (PV module light-to-electricity efficiency: $\eta = 10\% - 15\%$) and multicrystalline ($\eta = 9\% - 12\%$) silicon cells are based on standard microelectronic manufacturing processes [24]. 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-sensitized nano-structured materials ($\eta = 9\%$) are in their early development [24], [25]. 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.



(a) (b)

Fig. 13. Model and characteristics of a PV cell. (a) Electrical model with current and voltages defined. (b) Electrical characteristic of the PV cell, exposed to a given amount of sunlight at a given temperature.

The series connection of the cells benefits from a high voltage (around 25 $\sim$ 45 V) across the terminals, but the weakest cell determines the current seen at the terminals [26]. 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. 14(a) and (b), respectively, with insolation and cell temperature as parameters. The equations describing the currents and voltages of a PV cell can be found in [27]. 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.

B. *Power Electronic Interfaces*

The power electronic interface for PV systems has two main tasks: one is to convert the generated dc voltage into a suitable ac current for the utility; the other is to control the terminal conditions of the PV module(s) so as to track the Maximum Power Point (MPP) for maximizing the energy capture. This must be done at the highest possible efficiency, over a wide range, due to

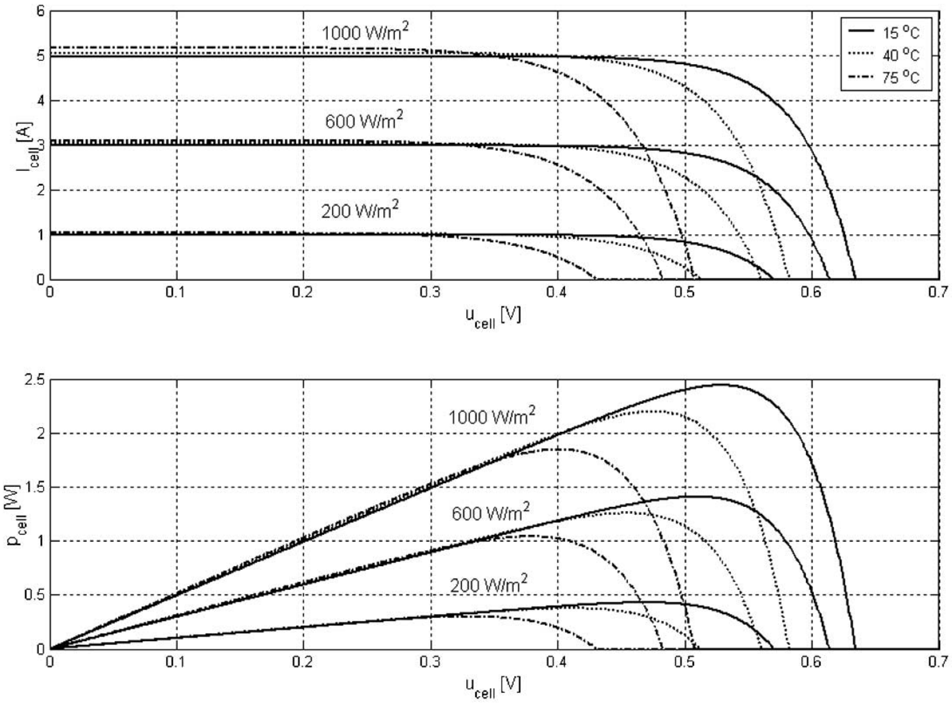
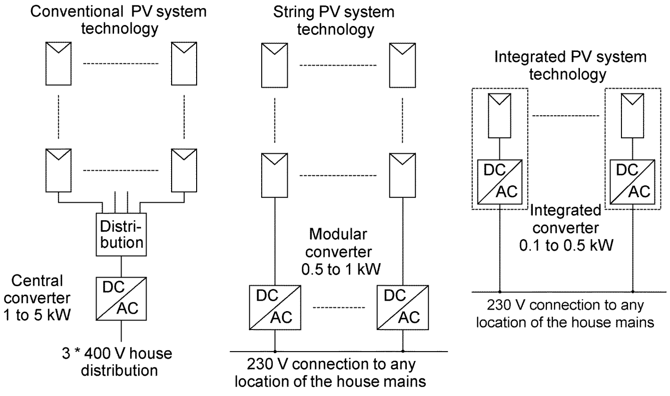


Fig. 14. Characteristics of a PV cell. Model based on the British Petroleum BP5170 crystalline silicon PV module. Power at standard test condition (1000 W/m^2 irradiation, and a cell temperature of 25 °C): 170 W @ 36.0 V. Legend: solid at 15 °C, dotted at 40 °C, and dashdot at 75 °C: (a) voltage-current and (b) voltage-power.

the morning-noon-evening and winter-summer variations [28]. The MPP is tracked by means of a MPP Tracker (MPPT) device, based on one of the following schemes: perturb-and-observe, incremental-conductance, parasitic capacitance or constant voltage [29]. Besides this, the power injected into a single-phase utility follows a sinusoidal raised to the second power (the power injected into a three-phase utility is constant). If this alternating power is not decoupled by means of an energy buffer, the module(s) cannot be operated at the MPP [28]. Finally, the current injected into the utility must obey the regulations, such as the EN61000-3-2 and the IEEE519, which states the maximum allowable amount of injected current harmonics. Excellent utility current control is reported with a P + Resonant controller in [30], and with a standard PI controller in [13]. Besides these regulations, inverters intended for the utility must also include a device for determine the state of islanding operation, which is not allowed due to personnel safety [32].

1) The Past: Centralized Inverters: The centralized inverter system is illustrated in Fig. 15(a), where ten's of PV modules are connected in series and/or parallel, and connected to the inverter. This may require an individual design for each installation, thus a nonflexible design is achieved. The inverters for this power range are mostly connected to a three-phase utility, thus no decoupling is necessary. The power losses are normally higher in this configuration, than for the two other systems presented, mainly due to mismatch between the modules and the necessity of string diodes. However, the voltage generated by the series connected modules may be high enough to avoid voltage amplification, e.g., transformers or boost converters. Moreover, the benefits of mass-production cannot be reached, and for that reason the inverters may be rather expensive.



(a) (b) (c)

Fig. 15. Configuration of PV systems: (a) centralized scheme, (b) string technology, and (c) modular concept.

2) Present: String Inverters: The string inverter system shown in Fig. 15(b), is a reduced version of the centralized inverter with a single string of modules connected to the inverter [33]. The input voltage may be high enough to avoid the voltage amplification. This requires roughly 15 modules in series (like the British Petroleum BP5170 in Fig. 14) for European systems. PV-modules are still rather expensive as discussed above. Therefore, voltage amplification must be a part of the string inverter in order to allow for fewer modules to be connected to the inverter. Besides this, the total open-circuit voltage for 15 modules may reach as high as 700 V, which calls for 900-V MOSFETs/IGBTs in order to allow a 75% voltage derating of the devices. The voltage amplification can be realized with a boost dc/dc converter, or with a transformer embedded in a high-frequency dc/dc converter. There are no losses associated with the string diodes and a separate MPPT can be applied for each string. This is believed to increase the overall efficiency, when compared to the centralized inverter.

3) Future: Multistring Inverters, AC Modules, and Single Cell Converter Systems: The multistring inverter is a further development of the string-inverter, where several strings are interfaced with their own dc/dc converter to a common dc/ac inverter [31], [33], [34]. Thus, the operator may start his/her own PV power plant with a few modules. Further enlargements are easily done because a new dc/dc converter, with belonging PV modules, can be plugged into the existing platform, with all electrical connections in a single connector on the back plane. A flexible design with high efficiency is hereby achieved.

The ac-module shown in Fig. 15(c) is a reduction of the string inverter, where each PV module has its integrated power electronic interface to the utility [28], [32], [36]. The power loss of the system is lowered due to the reduced mismatch among the modules, but the constant losses in the inverter may be the same as for the string inverter. Also the ac-module concept supports optimal operation of each module, which leads to an overall optimal performance. Moreover, it has the possibility to be used as a plug-in device by individuals without specialized knowledge.

Finally, the single cell converter system is the case where one large PV cell is connected to a dc/ac converter [37], [38]. This is beneficial for the thin-film types of PV cells, including the photo electro-chemical cells [25], which can be made arbitrary large by an inexpensive "roll on-roll off" process. The main difficulty in realizing such a converter is that the input power may reach 100 W per square meter cell, at 1 V across the terminals.

C. Power Electronic Conditioning Systems

The topologies presented in the following sections are either transformer-less, or they utilize high-frequency transformers embedded in a dc/dc converter. This avoids the bulky low-frequency transformers, which are regarded as a poor component, mainly due to their relatively large size and low efficiency. Hence, single stage inverters for a single module are not treated here. Besides this, inverters for all-centralized systems, like the one presented in Fig. 15(a), are also omitted, while they are more or less obsolete. The number of stages in the presented topologies refers to the number of converters/inverters in cascade.

1) Two Stage Topologies for a Single Module: The two-stage conversion systems may have many varieties. The most common two-stage topologies consist of a dc/ac grid-connected voltage source PWM inverter with some kind of dc/dc PV-connected converters, which are similar to those discussed in the conditioning systems for fuel cells except that the MPPT needs to be performed here. Some typical topologies are depicted in Figs. 9–11.

A novel flyback-type inverter is presented in [39], and further developed in [40], cf. Fig. 16. The inverter is made up around a buck-boost converter, a flyback converter, which shares a common inductor (transformer), and a cyclo-converter in the output stage. Assuming no currents within the circuit, except for the grid current in the output filter, and all transistors turned off, the modes of operation are as follows.

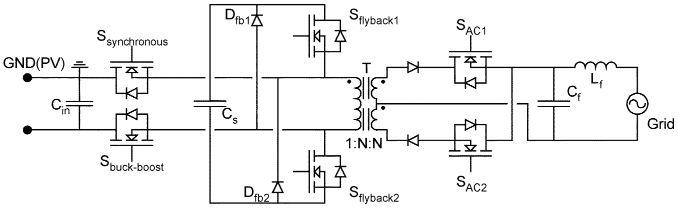


Fig. 16. Modified topology of the inverter in [39] and [40].

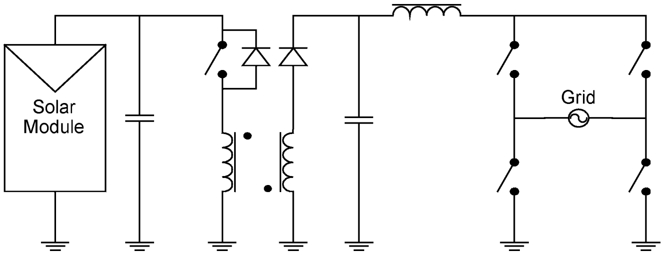


Fig. 17. Fly-back current-fed (FBCF) inverter [41]. A fly-back converter plus current source thyristor inverter.

a) The buck-boost and the synchronous rectifier transistors are turned on at time zero, causing the input current to rise linearly through the magnetizing inductor in the transformer.
b) The transistors are turned off when the first reference is reached, thus the current commutates through the body diodes of the flyback transistors, and energy is transferred into the intermediate capacitor. One of the transistors in the cyclo-converter is commanded on, simultaneous with turning off the buck-boost and synchronous rectifier transistors.
c) The flyback transistors must be commanded on, before the magnetizing current again reaches zero. Thus, the magnetizing current starts to decrease toward the second reference, which is negative, discharging the intermediate capacitor. Hence, the intermediate capacitor acts as an energy buffer.
d) The flyback transistors are turned off when the second reference is reached. Thus, the power stored in the magnetizing inductance is transferred into the secondary side and into the utility, through the output filter.
e) Finally, the secondary current reaches zero and a new cycle can start.

The benefits within this topology is the low count of components, which amounts to six transistors, four diodes and only two magnetic components, whereas most other topologies require at least three magnetic components, and an absolute minimum of eight semiconductors.

The fly-back current-fed (FBCF) inverter [41] shown in Fig. 17 can be controlled to provide a rectified sine-wave output current into the inverter and to keep the module voltage following the MPP. Thus the grid inverter may be implemented with thyristors. The current into the fly-back is discontinuous and hence the buffer capacitor must be suited for both low and high-frequency ripple.

Fig. 18 shows a series resonant dc/dc converter plus a full bridge grid-connected inverter that is modified by adding two additional diodes [42]. The dc/dc converter may be operated at

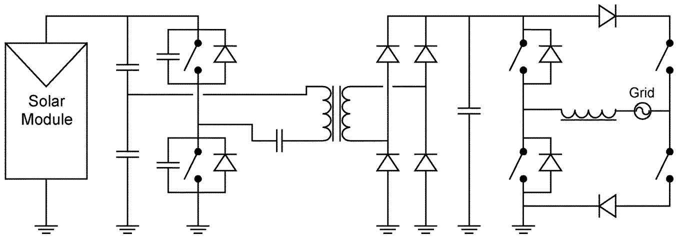


Fig. 18. Inverter proposed in [42]. A series resonant dc/dc converter plus a grid connected-inverter.

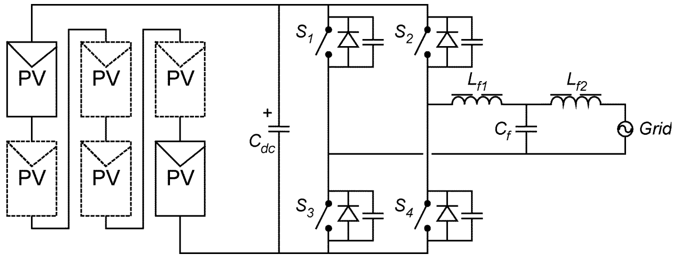


Fig. 19. Single stage inverter for multiple modules [43].

100 kHz and has a fixed voltage transfer ratio as a "dc-transformer." The resonant tank creates the zero-voltage switching opportunities. The switching losses from the converter can be significantly reduced. The MPPT is realized by the grid inverter, which uses both high and low switching frequencies. The left leg of the inverter in Fig. 18 is controlled by a hysteresis-band controller and operates at switching frequencies between 20–80 kHz. The right leg of the inverter is controlled according to the polarity of the grid voltage with a grid switching-frequency.

2) Single Stage Topologies for Multiple Modules: The single stage inverter for multiple modules is depicted in Fig. 19 [43]. The inverter is made up around a standard voltage source PWM inverter, connected to the utility through an LCL filter. The input voltage, generated by the PV modules, should at all times be higher than the peak voltage of the utility. The efficiency is in the vicinity of 97%, which is high. On the other hand, all the modules are connected to the same MPPT device. This includes severe power losses during partial shadowing. Finally, a large capacitor is required for power decoupling between the PV modules and the utility [44]. The problem is that the inverter lifetime is mainly determined by this electrolytic capacitor.

Multilevel inverter topologies are especially suitable for PV applications since different dc voltage levels can easily be provided with the modular structure of PV arrays [45], [46]. The multilevel inverter can synthesize an almost sinusoidal output voltage with low harmonic distortion, at low switching-frequency.

A half bridge diode clamped three-level inverter (HBDC) is shown in Fig. 20. The three-level inverter can be expanded into five, seven or even more levels, by adding more modules and switches. This allows for further reduction of the harmonic distortion. Drawbacks of this topology are the high number of required semiconductors and imbalanced loading of the different PV strings. Therefore, maximum power transfer from each individual string can be difficult to reach.

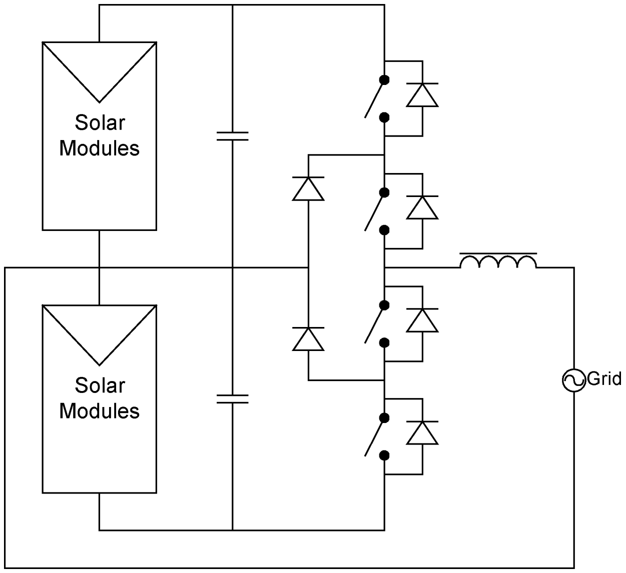


Fig. 20. Grid connected system with half bridge diode clamped three-level inverter (HBDC) [45], [46].

3) Two Stage Topologies for Multiple Modules: In two-stage configurations, the connection of the modules and the inverter may be classified into two categories: one is that all modules are connected in series as shown in Fig. 21(a), which is similar to the two stage solution for single modules. Therefore, many dual stage inverters for the fuel cells and single PV modules can be used, though the major difference is the voltage level at the input and hence the variations of the voltage boost stage. In this case, a grid-tie inverter plus a simple dc/dc converter, such as boost, buck or buck-boost can be used for the dc/dc conversion stage, if isolation is not required. The second category includes a dc/dc converter for each string and a common grid-connected inverter, shown in Fig. 21(b). The strings can operate at their individual MPP therefore a better overall efficiency is expected.

The generation control circuit (GCC) is shown in Fig. 22 [26], [47], which consists of two buck-boost converters with a common inductor. The left leg of the inverter can control the voltage across each string individually. The upper switch together with the freewheeling diode in the lower switch and the input inductor plus the capacitors across the strings forms one buck-boost, and the same is true for the opposite arrangement. The right leg of the inverter is controlling the current through the output inductor, and hence the current injected into the utility grid. The amplitude of the grid current is determined by means of a MPPT. Thus, the MPPT controls the voltages across each string in order to achieve the maximum power. The GCC seems to be a good solution for a multimodule system since it increases the overall efficiency without adding extra components, it may also be expanded to multiple modules, by adding more chopper stages.

Finally, two multistring inverters are shown in Fig. 23 [34] and Fig. 24 [35]. The inverter in Fig. 23 consists of up to three boost-converters, one for each PV string, and a common half bridge PWM inverter. The circuit can also be realized with a galvanic isolated current- or voltage-fed push–pull [13] or full-bridge converter [35], like the one in Fig. 24, and a full-bridge inverter toward the utility. The voltage across each string can be controlled individually, thus leading to a high utilization of each string.

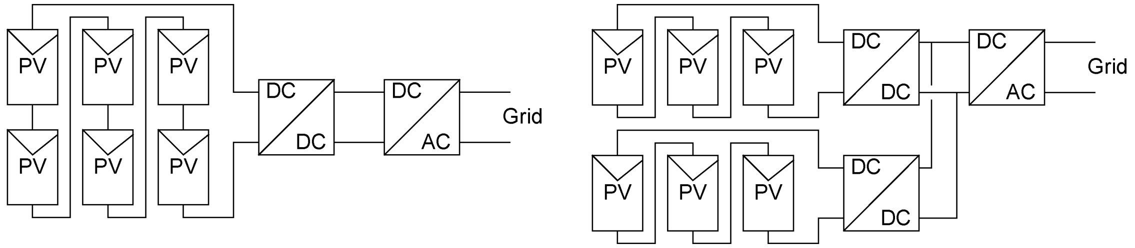


Fig. 21. Configurations of dual stage inverters for multiple PV modules. (a) Modules with a common dual stage inverter. (b) Strings with their own dc/dc converter and a common grid-connected inverter.

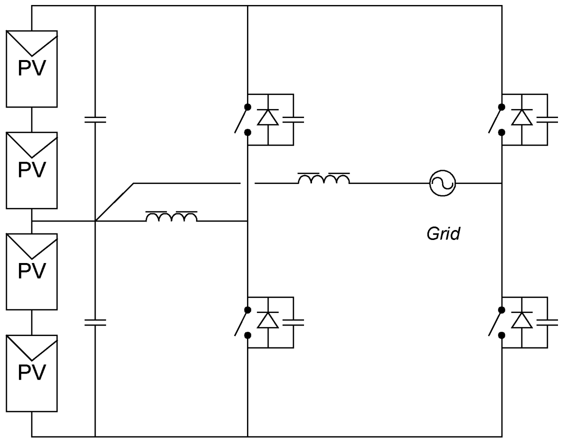


Fig. 22. Utility interactive photovoltaic inverter with generation control circuit (GCC) [26], [47].

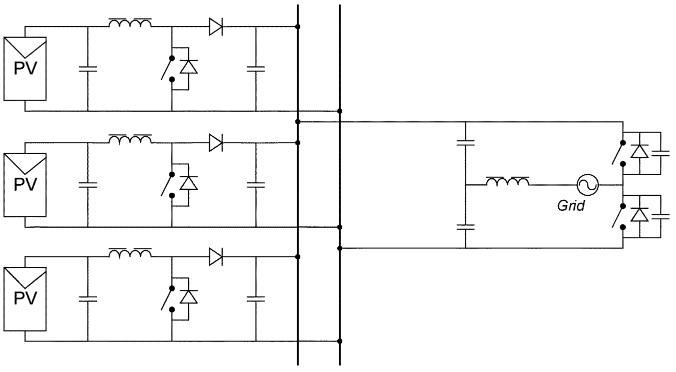


Fig. 23. Topology of the power electronics of the multistring inverter in [34]. Maximum power per string equals 2200 W at 150 ~ 750 V.

V. CONCLUSION

More and more dispersed generation units are being integrated into power systems. The difference in the characteristics between the dispersed generation units and the load/system demand requires a conditioning system. Power electronic converters play a vital role in the integration. In this paper, the developments of modern power electronics have been discussed. The applications of power electronics in various dispersed generation units, in particular wind turbine generation systems and offshore wind farms, fuel cells and PV generators have been reviewed and it is clear that power electronics is the enabling technology for dispersed power generation.

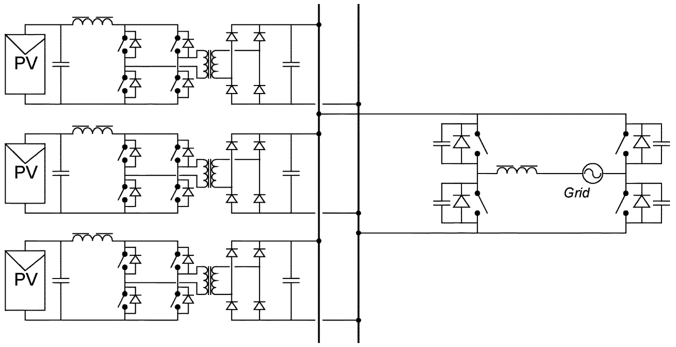


Fig. 24. Topology of the power electronics of the three-string inverter in [35]. Maximum power per string equals 1500 W at 200 ~ 500 V.

REFERENCES

[1] S. Heier, *Grid Integration of Wind Energy Conversion Systems*. New York: Wiley, 1998.

[2] E. Bossanyi, *Wind Energy Handbook*. New York: Wiley, 2000.

[3] T. Markvart, *Solar Electricity*, 2nd ed. New York: Wiley, 2000.

[4] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics-Converters, Applications and Design*, 3rd ed. New York: Wiley, 2003.

[5] P. Thocgersen and F. Blaabjerg, "Adjustable speed drives in the next decade. Future steps in industry and academia," *J. Electric Power Compon. Syst.*, vol. 32, no. 1, pp. 13–32, 2004.

[6] Z. Chen and E. Spooner, "Voltage source inverters for high-power, variable-voltage dc power sources," *Proc. Inst. Elect. Eng.*, vol. 148, no. 5, pp. 439–447, Sept. 2001.

[7] F. Blaabjerg and Z. Chen, "Power electronics as an enabling technology for renewable energy integration," *J. Power Electron.*, vol. 3, no. 2, pp. 81–89, Apr. 2003.

[8] Z. Chen and E. Spooner, "Grid power quality with variable-speed wind turbines," *IEEE Trans. Energy Conv.*, vol. 16, pp. 148–154, June 2001.

[9] F. Iov, Z. Chen, F. Blaabjerg, A. Hansen, and P. Sorensen, "A new simulation platform to model, optimize and design wind turbine," in *Proc. IECON'02 Conf.*, vol. 1, 2002, pp. 561–566.

[10] *Proc. Eur. Wind Energy Conf.*, P. Helm and Z. Arthouros, Eds., Copenhagen, Denmark, July 2001.

[11] F. Blaabjerg, Z. Chen, and P. H. Madsen, "Wind power technology status, development and trends," in *Proc. Workshop on Wind Power and Impacts on Power Systems*, Oslo, Norway, June 2002.

[12] E. Santi, D. Franzoni, A. Monti, D. Patterson, F. Ponci, and N. Barry, "A fuel cell based domestic uninterruptible power supply," in *Proc. APEC'02 Conf.*, vol. 1, 2002, pp. 605–613.

[13] G. K. Andersen, C. Klumpner, S. B. Kjær, and F. Blaabjerg, "A new green power inverter for fuel cells," in *Proc. PESC'02 Conf.*, vol. 2, 2002, pp. 727–733.

[14] K. W. E. Cheng, D. Sutanto, Y. L. Ho, and K. K. Law, "Exploring the power conditioning system for fuel cell," in *Proc. PESC'01 Conf.*, vol. 4, 2001, pp. 2197–2202.

[15] M. G. Simoes, J. Severson, P. K. Sen, and J. A. Palmer, "Resonant AC link system converter for fuel cell grid interface," in *Proc. IECON'01 Conf.*, vol. 3, 2001, pp. 1953–1958.

[16] J. Mazumdar, I. Batarseh, N. Kutkut, and O. Demirci, "High-frequency low cost dc–ac inverter design with fuel cell source for home applications," in *Proc. IAS'02 Conf.*, vol. 2, 2002, pp. 789–794.

[17] G. Spiazzi, S. Buso, G. M. Martins, and J. A. Pomilio, "Single-phase line-frequency commutated voltage source inverter suitable for fuel cell interfacing," in *Proc. PESC'02 Conf.*, vol. 2, 2002, pp. 734–739.

[18] A. M. Tuckey and J. N. Krase, “A low-cost inverter for domestic fuel cell applications,” in *Proc. PESC’02 Conf.*, vol. 1, 2002, pp. 339–346.

[19] C. Liu, T. Nergaard, L. Leslie, J. Ferrell, X. Huang, T. Shearer, J. Reichl, J. Lai, and J. Bates, “Power balance control and voltage conditioning for fuel cell converter with multiple sources,” in *Proc. PESC’02 Conf.*, vol. 4, 2002, pp. 2001–2006.

[20] A. Di Napoli, F. Crescimbini, S. Rodo, and L. Solero, “Multiple input dc–dc power converter for fuel-cell powered hybrid vehicles,” in *Proc. PESC’02 Conf.*, vol. 4, 2002, pp. 1685–1690.

[21] P. T. Krein and R. Balog, “Low cost inverter suitable for medium-power fuel cell sources,” in *Proc. PESC’02 Conf.*, vol. 1, 2002, pp. 321–326.

[22] G.-J. Su, F. Z. Peng, and D. J. Adams, “Experimental evaluation of a soft-switching dc/dc converter for fuel cell vehicle applications,” in *Proc. Power Electronics in Transportation*, 2002, pp. 39–44.

[23] F. Z. Peng, “Z-source inverter,” in *Proc. IAS’02 Conf.*, vol. 2, 2002, pp. 775–781.

[24] J. P. Benner and L. Kazmerski, “Photovoltaics gaining greater visibility,” *IEEE Spectrum*, vol. 29, pp. 34–42, Sept. 1999.

[25] E. Bezzel, H. Lauritzen, and S. Wedel, “The photo electro chemical solar cell,” PEC Solar Cell Project, Danish Technological Institute, Taastrup, Denmark, [Online] Available: www.solarcell.dk, 2004.

[26] T. Shimizu, M. Hirakata, T. Kamezawa, and H. Watanabe, “Generation control circuit for photovoltaic modules,” *IEEE Trans. Power Electron.*, vol. 16, pp. 293–300, May 2001.

[27] F. Valenciaga, P. F. Puleston, and P. E. Battaiotto, “Power control of a photovoltaic array in a hybrid electric generation system using sliding mode techniques,” *IEEE Trans. Control Theory Applicat.*, vol. 148, pp. 448–455, Nov. 2001.

[28] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, “Power inverter topologies for photovoltaic modules—A review,” in *Proc. IAS’02 Conf.*, vol. 2, 2002, pp. 782–788.

[29] D. P. Hohm and M. E. Ropp, “Comparative study of maximum power point tracking algorithms using an experimental, programmable, maximum power point tracking test bed,” in *Proc. 28th IEEE Photovoltaic Specialists Conf.*, 2000, pp. 1699–1702.

[30] E. Twining and D. G. Holmes, “Grid current regulation of a three-phase voltage source inverter with an LCL input filter,” *IEEE Trans. Power Electron.*, vol. 18, pp. 888–895, May 2003.

[31] M. Calais, J. Myrzik, T. Spooner, and V. G. Agelidis, “Inverters for single-phase grid connected photovoltaic systems—An overview,” in *Proc. PESC’00 Conf.*, vol. 4, pp. 1995–2000.

[32] B. Verhoeven, Ed., “Utility aspects of grid connected photovoltaic power systems,” Tech. Rep. IEA PVPS T5-01:1998, [Online] Available: http://www.iea-pvps.org, 1998.

[33] M. Meinhardt and G. Cramer, “Past, present and future of grid connected photovoltaic- and hybrid-power-systems,” in *Proc. IEEE Power Engineering Society Summer Meeting*, vol. 2, 2000, pp. 1283–1288.

[34] M. Meinhardt and D. Wimmer, “Multistring-converter. The next step in evolution of string-converter technology,” in *Proc. EPE’01 Conf.*, 2001.

[35] C. Dorofte, “Comparative analysis of four dc/dc converters for photovoltaic grid interconnection & design of a dc/dc converter for photovoltaic grid interconnection,” Tech. Rep., Aalborg Univ., Aalborg, Denmark, 2001.

[36] H. Oldenkamp and I. J. de Jong, “AC modules: past, present, and future,” in *Proc. Workshop Installing the Solar Solution*, 1998.

[37] M. Wuest, P. Toggweiler, and J. Riatsch, “Single cell converter system (SCCS),” in *Proc. 1st World Conf. Photovoltaic Energy Conversion*, vol. 1, 1994, pp. 813–815.

[38] H. Wilk, D. Ruoss, and P. Toggweiler, Eds., “Innovative electrical concepts,” Tech. Rep. IEA PVPS 7-07:2002, [Online] Available: http://www.iea-pvps.org, 2001.

[39] T. Shimizu, K. Wada, and N. Nakamura, “A flyback-type single-phase utility interactive inverter with low-frequency ripple current reduction on the dc input for an ac photovoltaic module system,” in *Proc. PESC’02 Conf.*, vol. 3, 2002, pp. 1483–1488.

[40] S. B. Kjaer and F. Blaabjerg, “Design optimization of a single-phase inverter for photovoltaic applications,” in *Proc. PESC’03 Conf.*, vol. 3, 2003, pp. 1183–1190.

[41] S. Saha and V. P. Sundarsingh, “Novel grid-connected photovoltaic inverter,” *Proc. Inst. Elect. Eng.*, vol. 143, no. 2, pp. 219–224, Mar. 1996.

[42] A. Lohner, T. Meyer, and A. Nagel, “A new panel-integratable inverter concept for grid-connected photovoltaic systems,” in *Proc. ISIE’96 Conf.*, vol. 2, 1996, pp. 827–831.

[43] B. Lindgren, “Topology for decentralised solar energy inverters with a low voltage ac-bus,” in *Proc. EPE’99 Conf.*, 1999.

[44] S. B. Kjaer and F. Blaabjerg, “A novel single-stage inverter for the AC-module with reduced low-frequency ripple penetration,” in *Proc. EPE’03 Conf.*, 2003.

[45] M. Calais, V. G. Agelidis, L. J. Borle, and M. S. Dymond, “A transformerless five level cascaded inverter based single-phase photovoltaic system,” in *Proc. PESC’00 Conf.*, vol. 1, 2000, pp. 224–229.

[46] M. Calais and V. G. Agelidis, “Multilevel converters for single-phase grid connected photovoltaic systems—aAn overview,” in *Proc. ISIE’98 Conf.*, vol. 1, 1998, pp. 224–229.

[47] T. Shimizu, O. Hashimoto, and G. Kimura, “A novel high-performance utility-interactive photovoltaic inverter system,” *IEEE Trans. Power Electron.*, vol. 18, pp. 704–711, Mar. 2003.

Frede Blaabjerg (S’86–M’88–SM’97–F’03) received the M.Sc.EE. and Ph.D. degrees from Aalborg University, Aalborg, Denmark, in 1987 and 1995, respectively.

He was with ABB-Scandia, Randers, Denmark, from 1987 to 1988. He became an Assistant Professor at Aalborg University in 1992, an Associate Professor in 1996, and a Full Professor in power electronics and drives in 1998. He is the author or coauthor of more than 300 publications in his research fields including *Control in Power Electronics* (New York: Academic, 2002). He is an Associate Editor for the *Journal of Power Electronics* and the Danish journal *Elteknik*. His research areas are in power electronics, static power converters, ac drives, switched reluctance drives, modeling, characterization of power semiconductor devices and simulation, wind turbines, and green power inverters.

Dr. Blaabjerg received the 1995 Angelos Award for his contribution in modulation technique and control of electric drives, the Annual Teacher Prize at Aalborg University in 1995, the Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society in 1998, four IEEE Prize paper awards during the last six years, the C. Y. O’Connor Fellowship from Perth, Australia in 2002, the Statoil-Prize in 2003 for his contributions in power electronics, and the Grundfos-prize in 2004 for his contributions in power electronics and drives. He is an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS and the IEEE TRANSACTIONS ON POWER ELECTRONICS. He has held a number of chairman positions in research policy and research funding bodies in Denmark.

Zhe Chen (M’95–SM’98) received the B.Eng. and M.Sc. degrees from the Northeast China Institute of Electric Power Engineering, Jilin City, China, and the Ph.D. degree from The University of Durham, Durham, U.K.

He was a Lecturer and then a Senior Lecturer with De Montfort University, Leicester, U.K. Currently, he is a Research Professor with Aalborg University, Aalborg, Denmark. His main research areas are renewable energy, power electronics, power systems, and protection.

Dr. Chen is an Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS, a member of the Institution of Electrical Engineers (IEE), London, U.K., and is a Chartered Engineer in the U.K.

Soeren Baekhoej Kjaer (S’98–A’00–M’04) was born in Thisted, Denmark, on May 2, 1975. He received the M.Sc.E.E. degree from the Institute of Energy Technology, Aalborg University, Aalborg, Denmark, in 2000, where he is currently pursuing the Ph.D. degree.

He is a Laboratory Engineer with the Power Electronic Systems Section, Aalborg University. He also teaches photovoltaic systems for terrestrial and ex-terrestrial applications (Power System for the AAU student satellite: AAU CUBESAT and AAUSAT-II). He has authored ten papers, coauthored five papers, and has two pending patents. His main research interest covers switching inverters, in particular control and optimized design for fuel cell and photovoltaic applications.

Mr. Kjær is a member of The Society of Danish Engineers (IDA).