Chapter 7
Power Electronic Converters in AC Microgrid

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Abstract As the major worldwide infrastructure distribution systems are in AC, the chapter intends to review the main power converter types for Energy Sources integration. The requirements imposed by the existing standards are envisaged. An effective solution for injection of electrical power from Renewable Energy Sources (DC and AC power sources) into the grid is presented. Additionally, the efficiency improvement by means of the modulation techniques is implemented and shown in this chapter. Due to the higher power energy in three-phase power systems (PSs), despite of the AC single-phase PSs, the large energy storage systems are not necessary.

Keywords Microgrid · Power converter · Topologies · Wind power · Photovoltaic · Standards

7.1 Introduction

Some convergent factors (power demand, environmental pollution, limited fossil fuel formation, consumers growing) led the world to think seriously about other alternative sources of energy. The main advantages introduced by RES are related both to sustainability developing, and to friendly environment assurance. This chapter underline the worldwide tendency to a clean environment, green energy assurance,

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predicting for the long term the evolution of the primary energy. As identified high penetration tendency, RES are the main candidates to providing clean energy. In this chapter the authors have in view the following:—to state the formulation problem of using the alternative energy sources through power converters;—to review the main standards to integrate power converters into distributed systems;—specific requirements of static power converters used in AC microgrids;—classification of power converters (DC-DC and DC-AC);—to put in evidence the modern power structures for both the future wind, and photovoltaic power systems;—to present the experimental results of the implemented modulation strategies on the AC Power Converters used in microgrids. The chapter provides the technical aspects of network to meet the utilities connection rules, including harmonics improvements, power factor control, the assurance of the required performances and stability. This chapter begins with an overview of the current state of power converters topologies into the microgrids. The requirements defined by the actual microgrid power converters standards are mentioned in this chapter. The specific case study, based on the hybrid system integration (wind and fuel cells primary energy sources) is provided. Through the adequate modulation strategies, the overall efficiency of the PS has been increased. The chapter ends with the Reference Section.

7.2 Overview

The challenges of development of power converters technology are [1]:

- The increased electricity demand obtained by controlled energy conversion from primary sources (Fig. 7.1);
- Off-shore power distribution for long distance;
- The requirements of the systems components (materials, and devices) to handle normally high power in extreme conditions.

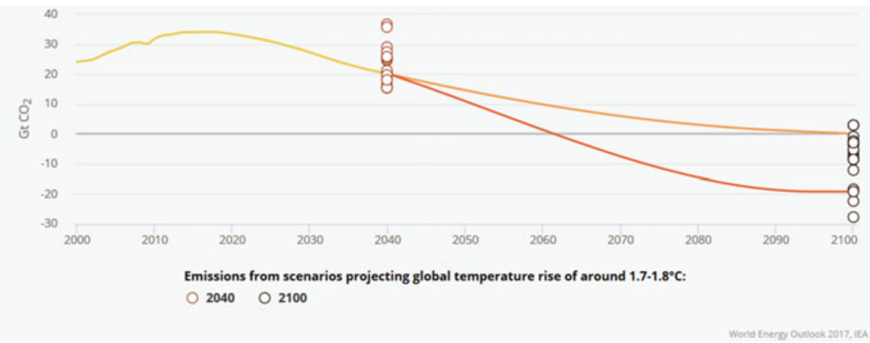


Fig. 7.1 The sustainable development scenario [3]

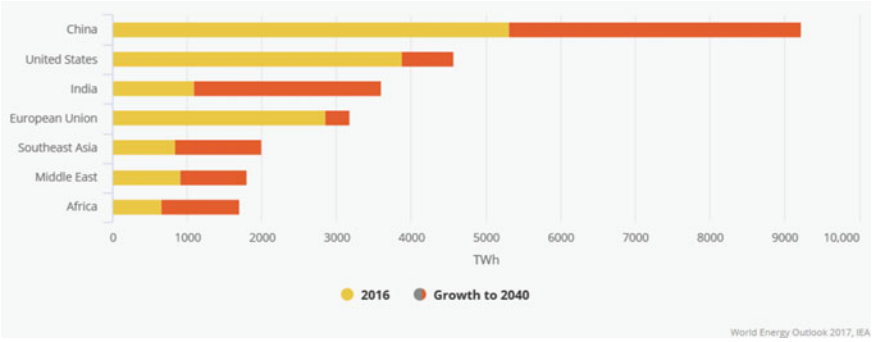


Fig. 7.2 The electricity demand by specific region [3]

To face-up to the above-mentioned challenges, the future power converters should includes

- Increased high-performance cost-ratio for power converters;
- Capability of self-healing power converters and materials; dynamic reconfigurations of the distributed power converters [2];
- The fast development of the material properties (insulators, conductors, magnetics, so on).

Due to the progress of new technology in order to increase the comfort and fast development of the industry, smart cities, fast spreading of the Internet of Things concept, penetration of the autonomous vehicles, the electricity demand is an ascendant way; it depends on the specific region (Fig. 7.2). Global average annual net capacity additions of primary energy sources are shown in Fig. 7.3. From the Fig. 7.3 can be concluded that the development of the electrifying sector would rise yearly. In the near future (up to 2030) the electrifying sector will be developed mainly by introducing Renewable Energy Sources and by increasing the shares of gas energy primary source (Figs. 7.4 and 7.5) [4]. Therefore, the technology development of the power converters in RES area is a priority.

Currently the power systems are based on fossil fuels (coal, gas, oil) energy conversion systems. The fossil fuels are exhausted and no environment friendly. The energy security is more vulnerable in bulk power systems as it is nowadays in many worldwide countries. Therefore, the global energy strategy is oriented through diminishing the energy obtained based on fossil fuels. International Energy Agency (IEA) makes a realistic scenario regarding the fossil fuel decreasing trend (Fig. 7.3) [5]. The no pollutant energy resources [6] combined with the renewable energy conversion power systems will replace gradually the conventional electricity generation (Fig. 7.5).

The Renewable Energy Sources (wind, biomass, solar, hydro)—RES—are inexhaustible, no costs, and without greenhouse gas emissions being considered as green energy. Therefore, the conventional energy systems based on the synchronous generators will be completed with new generation of power conversion systems. The

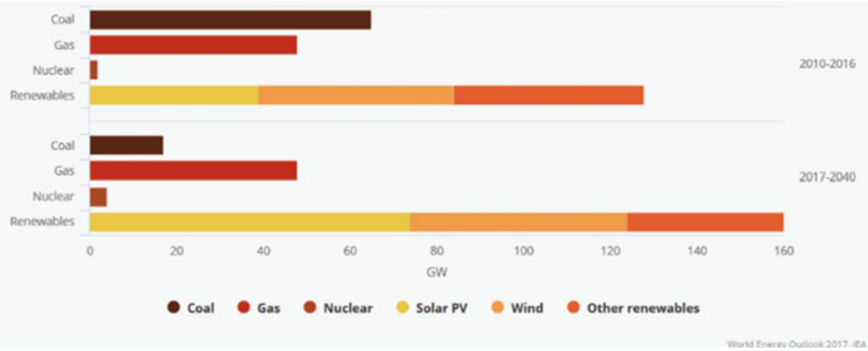


Fig. 7.3 Global average annual net capacity additions by type [3]

Fig. 7.4 World commercial energy use [4]

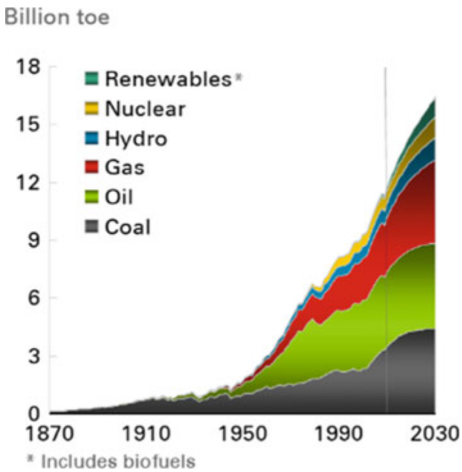
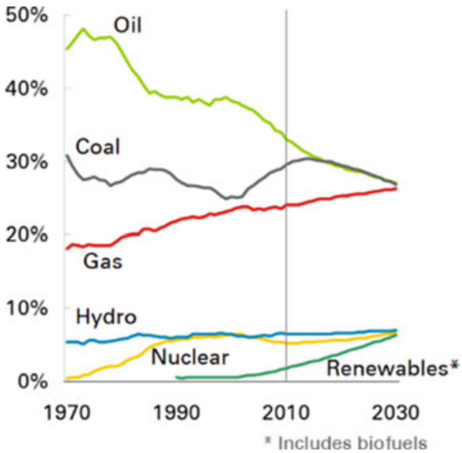


Fig. 7.5 Shares of world primary energy by type [4]



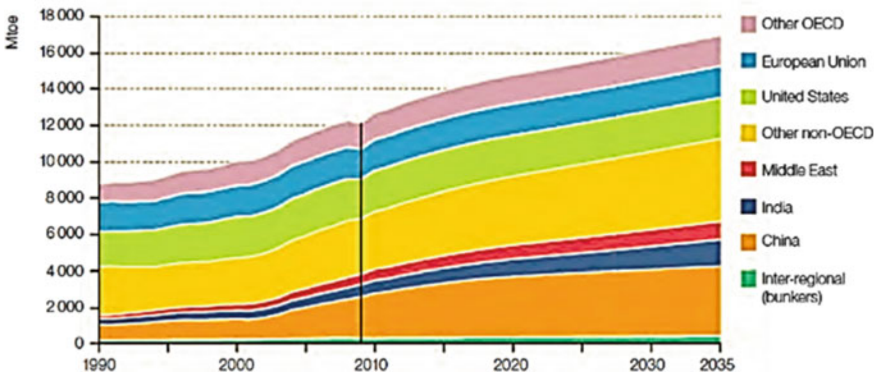


Fig. 7.6 The demand of the electricity by region in IEA policies scenario [5]

electrical parameters of the utility network the modern energy conversion systems can be controlled based on the static power converters.

The main factors (stability, flexibility and expandability) of developing the utility network through the *distributed energy* (*DE*) systems are taken into consideration. The DE power systems include the RES, microturbine, fuel cells, and internal combustion engines.

The future worldwide demand of primary energy is envisaged by IEA making a Policy Energy Scenario provided in the Fig. 7.6 (*OECD*) [5].

From the energy security point of view the DER power systems are more appropriate than the utility network.

7.3 Problem Formulation

The alternative energy by definition includes any other source energy different from fossil fuel combustion (e.g. wave and tidal power, solar and wind power, biomass or biogas, hydrogen power, gas micro turbines and small hydropower farms).

On the one hand, the large *distributed generation* (*DG*) PS includes RES units (photovoltaic panels, generators for wind turbines, wave, hydro and tidal, generators), and on the other hand the generators based on fuel cells or *combined heat and power stations*—*CHP*—using the steam or natural gas as primary fuel [7, 8].

There are many low consumption isolated sites (rural communities), and extending power grids to meet the end-users necessary energy which requires high-costly investments to assure the upgrades in transmission and distribution PSs. Therefore, the locally alternative energy sources are more attractive and economic solutions, which require renewable energy technologies. From the other point of view the use of RES clean the environment and helps to regenerate it.

During the last years, the small power resources up to 1 MVA (wind turbines, fuel-cells, microCHP plants, and microturbines) connected to the utility network has been increased.

The main tasks of the power converters operating in the grid-connected mode are related to direct and quadrature current control, DC-link voltage control, and the frequency control which has to be synchronized with the utility grid. Additional power quality features are required. In the grid connected operation mode the power converters can deliver the adequate grid frequency through the phase-locked loop.

In islanded power operation, the power converters have to take the additionally tasks: to deliver the appropriate voltage level with the same frequency as PS has.

In the Fig. 7.7 the generic microgrid architecture is shown (C-converter, EV-electric vehicle, T-power transformer). Into the autonomous microgrid the sensitivity to the load variations is high [8]. The continuity, stability, and the resiliency can be

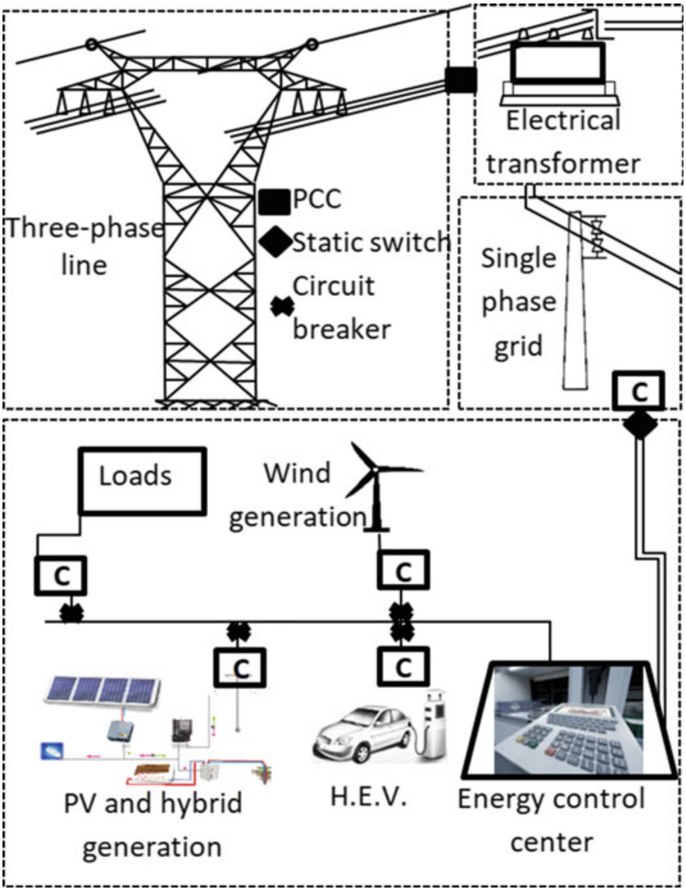


Fig. 7.7 The power structure of the microgrid

assured by cooperative control among all power converter interfaces, taken into account the optimization of the energy prices, reliability, efficiency, primary fuel costs.

7.4 Standards for Power Converters as Interfaces Into the Distributed Energy Resources

The specific standards for distributed energy resources (DER) are still under the development. However, the standards can be grouped as:

1. The *IEEE 1547–2018 Interconnection Standard*, in which the requirements of the equipment for power system connection (this includes default activation for anti-islanding, fault response, and automatic reconnection) are specified. The standard for Photovoltaic (PV) systems, *IEC61727*, named as *Characteristics of the utility interface*—2004. This standard specific the rules related to parameters of the power quality feature: power factor, harmonics, voltage range, frequency range, flicker, waveform distortion, and the allowable DC injection component. *IEC 62116* Edition 1, 2005: this standard specify the measures for photovoltaic inverter which interacts with the utility (the tests for the IEC 61727 standard) for the testing procedure of islanding prevention (approved in 2007);—the standard *VDE0126-1-1* (*2006*) for specifying the requirements of an automatic disconnection device placed between the public low-voltage grid and the generator;—the Italian standard, *CEI 0–21* regarding the Safety issues- applied on Italy market, respectively E-On, for German utility.

Voltage Quality—*EN50160* standard is dedicated to three phase inverters, and specifies the voltage unbalance. The unbalance allowable limit voltage is 3%; the maximum amplitude variations of the voltage: $+/-10\%$; the maximum frequency variations is $+/-1\%$; the deep <60% specification for the voltage dips with duration <1 s; the 8% maximum voltage THD harmonic levels.

2. The *IEEE 2030.5* (SEP2), IEEE 1815 (DNP3), SunSpec Modbus *Interoperability Standards*, which defines the DER communications
3. The *IEEE 1547.1 Certification Test Standard*, compatibilized with UL 1741, *IEC 62109* (Safety of Static Inverters), defines the procedure for equipment validation for the interconnection or interoperability standards. Inverter Testing *IEEE* 1547.1, Efficiency Testing *CEC-300*; testing procedure of Islanding Prevention and Methods for Utility-Interactive Photovoltaic Inverters have been addressed in the *IEC 62116* standard.

Regarding the available standards, for the wind power plant systems there are important requirements regarding the:

(1) Voltage and frequency admissible domain for uninterruptible operation;

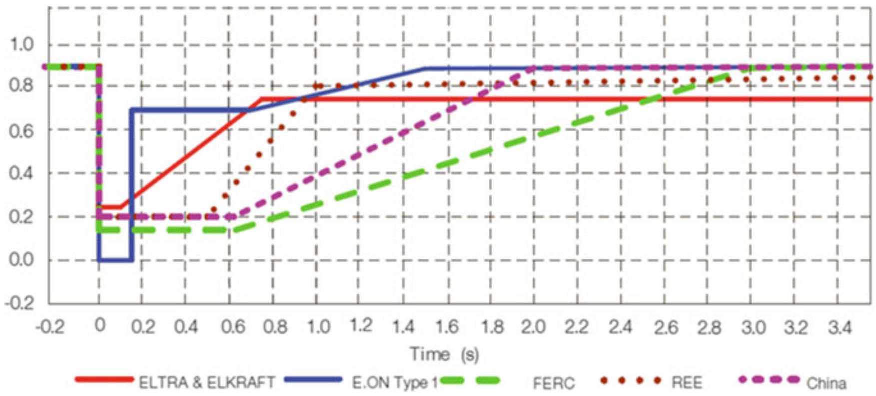


Fig. 7.8 The different requirements for important grid companies (E.ON Netz—Germany) or countries [9]

(2) the control of the active and reactive power for power quality and voltage regulation;
(3) Low-voltage ride-through requirement (LVRT): Fig. 7.8 shows the different requirements for important grid companies (E.ON Netz—Germany) or countries [9]. In order to maintain the voltage stabilization during fault period (voltage recovery) the reactive power requirement is necessary.

7.5 Specific Requirements of Power Converters in AC Microgrids

In order to ensure the frequency and voltage stabilization in disturbed conditions, the operators should inject the appropriate active or reactive into the grid.

In order to configure and design the appropriate power converters topology into the microgrid, the basic control requirements in the conventional power systems should be revised:

- Frequency control (should reacts on a seconds-to-minutes time scale). The *automatic generation control* (*AGC*) regulates the generators;
- Power control: a quick response time (within 10 min of disturbed utility grid the adequate power should be available from the generators) and a slower response time (used generators in case of failure of other generators).
- Voltage support: the reactive power should be injected by the synchronous generators. In this manner, the voltage raises.
- Black-start capacity: this feature is necessary to assure the power system restarting when a cascading black-out occurs.

Another important feature of one robust power system is to follow the loads demand. In the traditionally power system this function is assured through the “fast energy market”. When a peak power occurs (in the morning or evening) into the microgrids, the required surplus of energy could be obtained through the utility grid or by introducing a battery system.

Taking into account the intervention of the operators, the solar and wind power generation could be integrated into the grid. For low penetration of RES, the problems appear into the local grid and more on the primarily device (i.e. the subsynchronous resonance due to the wind turbine or the harmonics due to the power converters). Therefore, by assuring an appropriate topology with the associated power converter control the problems are locally solved.

For high penetrations of RES the power balance at grid level is necessary. The Energy Management System (EMS) block should be inserted in the overall topology of the utility network.

The generated power could operate adequately if the decision time is taken into consideration (Fig. 7.9) [10].

Figure 7.9 shows the places into the power systems where the action is done [10]. As component, the EMS includes the SCADA system and the support functions in order to assure normal operation of the utility network.

The EMS system takes part of the smart power grid. On the one hand, in order to take the data from the RES and of the real prices from the power market and on the

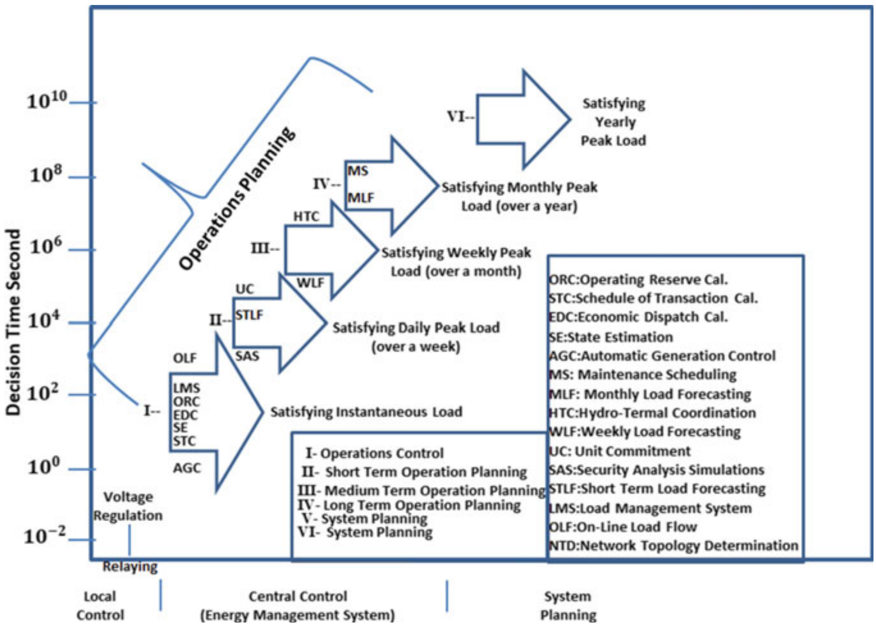


Fig. 7.9 Energy Management System and its functions versus decision time

other hand, to manage the stability operation the communication channel should be inserted into the smart grid power architecture.

The power converters technologies are developed function on the renewable energy generation technology.

In the energy production area different types of green power sources should agree with the grid requirements. The dc power sources, like fuel cells or photovoltaic arrays should deliver the maximum power at fixed voltage level. The ac green power sources delivers variable frequency different from the grid one (wind turbines or micro gas-turbines). The induction generators connected to wind turbines can be directly connected to the grid, but in most cases, the green power sources require the power converters as interfaces with the power grid. The AC power sources, in most cases, require two stages of power conversion: from AC to DC and from DC to AC grid. The controlled power semiconductor devices, as IGBTs, MCTs, GTOs or more recently devices based on *Silicon carbide* (*SiC*), and *Galium ARsenide* (*GAAS*) technologies can manipulate large power at high switching frequency [11]. Therefore, the use of power converters instead of the conventional synchronous machine conducts to increased control opportunities. During power outages a grid connected inverter-based solution can be used (*uninterruptible power supply*- *UPS*). Moreover, in order to improve the power quality, the UPS can be used also in normal operation conditions [12]. In this manner, the UPS can add the other functions than as main generator function like mitigating swell/voltage sag or the waveform distortion. The most cases include the use of the three-phase power inverters. Due to the component availability, reliability and cost only low power inverter applications have been developed.

Power quality problem implies control of the two variables (the line current and the voltage) such that the power factor can be controlled. Due to the standard restriction [12]: at the point of common coupling the power, inverter does not control the voltage (PCC). Therefore, in [13] the authors underline that the power quality problem is solved by acting on the current. The presence of the zero sequence or the DC components in the generated voltage in distributed system should be avoided. This task is performed through a grid connected isolating transformer.

The control architectures of the power distribution systems imply the phase-locked loop, DC link voltage, current and power control loops.

The utility network is slow to evolve; different technical issues (voltage and frequency regulations, protection, low voltage ride through, so on) are the challenges for the new generation of the power inverters.

7.6 Classification of Power Converters for RES

A global power conversion block diagram for RES penetration is presented in Fig. 7.10. Generally, the Power Conversion System for RES integration supposes three power conversion stages: AC to DC, DC to DC, and DC to AC [14, 15]. Figure 7.10 presents a classical energy converter incorporating power factor correc-

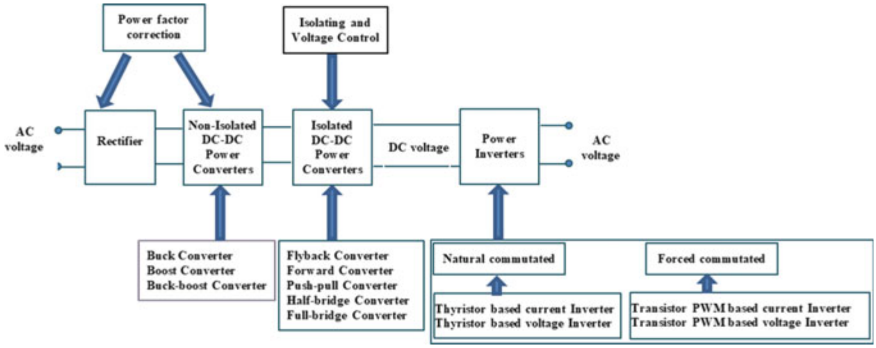
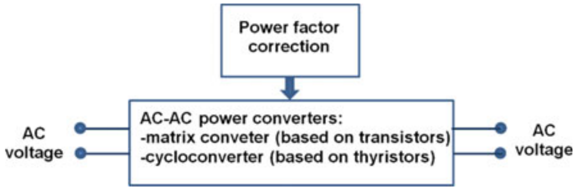


Fig. 7.10 Classification of AC-AC power converters, with changes of voltage type, integrated into a power factor correction regulated scheme

Fig. 7.11 Classification of power converters based on direct AC-AC power conversion



tion feature. It presents the types of converters that can be fitted to such a system, which involves changing the type of power two times (AC to DC, and DC to AC). Because of nonlinear loads and switching the static power converters, the power electronic devices can interact with other sensitive electronic equipment, disturbing the smooth functioning of the latter.

For this reason, both at the conversion AC into DC, and vice versa, circuit able to improve the power factor (Fig. 7.10) are provided. In Fig. 7.11, classification of the power converters based on direct AC-AC power conversion (without changes of voltage type) integrated into a power factor correction regulated scheme is represented.

In the Fig. 7.12, the corresponding power converters for AC-DC power conversion stage are depicted.

In Fig. 7.13, the topology of the voltage grid or source power converter (VSC) is shown. The power flow circulates from AC side to DC side. From topology point of view, taken into consideration the four quadrants operation, the VSC is similar with Voltage Source Inverter (VSI). In this case, the power flows from the DC to AC side. This basic principle is used to develop the specific control into a microgrid.

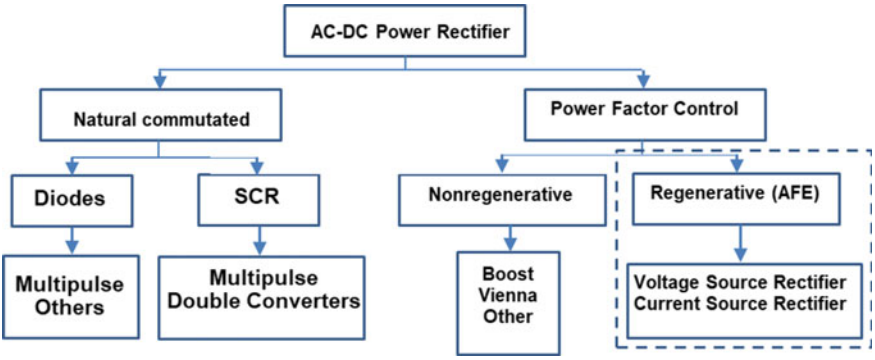
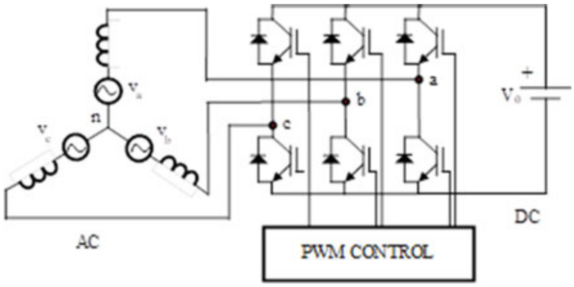


Fig. 7.12 Rectifiers classification

Fig. 7.13 Voltage source converter



7.6.1 *Topologies of the Power Inverters (DC-AC Power Conversion)*

The inverters can be classified in VSI (voltage source inverter) and CSI (current source inverter). The VSI produces switched voltage in order to supply the electrical machine, and the CSI delivers a switched current waveform. In the case of a VSI, the voltage in the DC link is maintained at a constant value by using a capacitor. Instead of the DC link voltage, the current delivered by the VSI depends on the load and the electrical machine speed.

The power switching devices in the VSI and CSI can be controlled by using different modulation strategies: square or quasi-square modulation; pulse amplitude modulation or pulse width modulation, PWM. The most implemented modulation technique into a commercial power inverter is sinusoidal modulation. The improving modulation techniques increase the DC link voltage utilization: third harmonic insertion, space vector modulation strategy, harmonic elimination.

According to the voltage type (number of power stages converted), there are two categories of power inverters:

1. Direct Conversion;
2. Indirect Conversion.

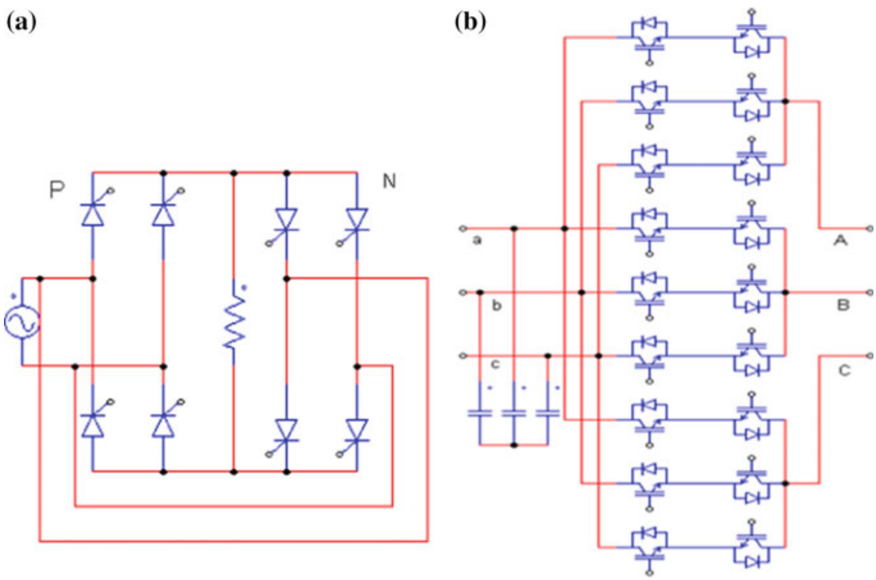


Fig. 7.14 **a** Single-phase cycloconverter, **b** Three-phase matrix converter

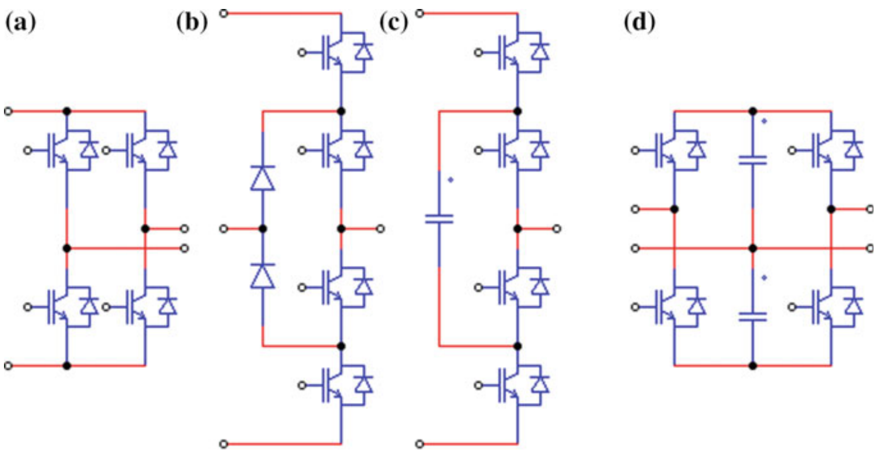


Fig. 7.15 Neutral Point Diode Clamped (NPC) three-level legs: **a** H-bridge inverter, **b** NPC, and **c** flying capacitor multilevel legs, **d** ac-dc-ac power stage conversion with two dc-link midpoint connections (single-phase to single-phase power converter)

The VSI and CSI are part of the Indirect Conversion Topology. The Cycloconverter (Fig. 7.14a) and matrix converter (Fig. 7.14b) takes part of the Direct Conversion Topology (Fig. 7.11). The VSI are divided in multilevel VSI and 2-level VSI [16, 17]. The multilevel inverter (MLI) topologies are based on Neutral Point Diode Clamped, Cascaded H-Bridge, and Flying Capacitor [16] (Fig. 7.15).

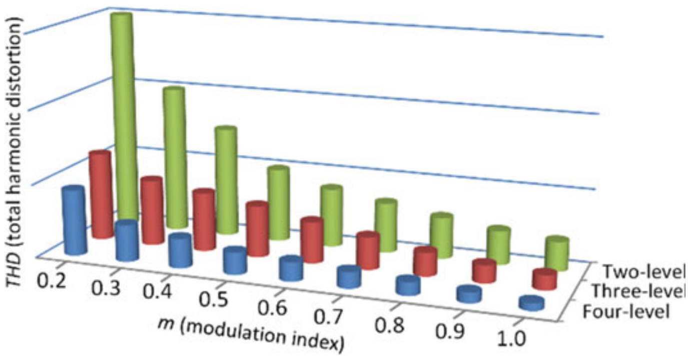


Fig. 7.16 *THD* comparison of the conventional power converter (2 level) and MLI (3, 4 levels) function on the modulation index

The cascade H-bridge inverter has the minimum components for a given number of levels. By connecting in series several H-bridge inverters (Fig. 7.15a), the cascade multilevel H-bridge inverter is obtained. Due to the high number of clamped diodes (Fig. 7.15b) of the NPC, this type of inverter is limited to three-level.

The flying capacitors—MLIs (Fig. 7.15c) contain the capacitors instead of diodes and are balancing on phase buses. The challenge is to balance the DC-link. These MLIs are used in order to obtain a sinusoidal output voltage from different DC sources like *PV*, *fuel cells* or *battery*. The CSI are divided in Load Commutated Inverter and PWM-CSI [16, 17].

In the Fig. 7.16, related to power quality issue, a comparison of the total harmonic distortion (*THD*) function on the amplitude-modulation ratio (modulation index, $m_a = V_m/V_t$ the ratio between the sinusoidal amplitude or the control signal and the carrier voltage as triangular waveform) for two-level and MLI (three, and four-level) waveforms is shown.

From the Fig. 7.16 it could be noted that with number of levels increasing the *THD* decreases. For each level, the *THD* decrease as the modulation index reaches 1 (one) value [8]. The explanation consists of output voltage waveform improving as the number of level increases. These applications are appropriate for *wind energy conversion* due to the high voltage (6.6 kV) and power ratings (1–40 MW) at low switching frequency (below 1 kHz).

7.6.2 Topologies of the DC-DC Static Power Converters

In the Fig. 7.17, the basic configuration of the boost DC-DC power converter is shown. The main disadvantage is that it cannot provide galvanic isolation. In addition, the wide variation in amplitude between input and output puts a strain on the static

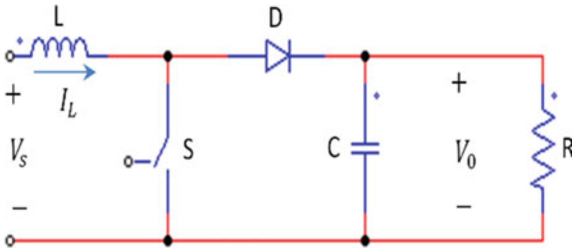


Fig. 7.17 Step-up DC-DC power converter without isolation

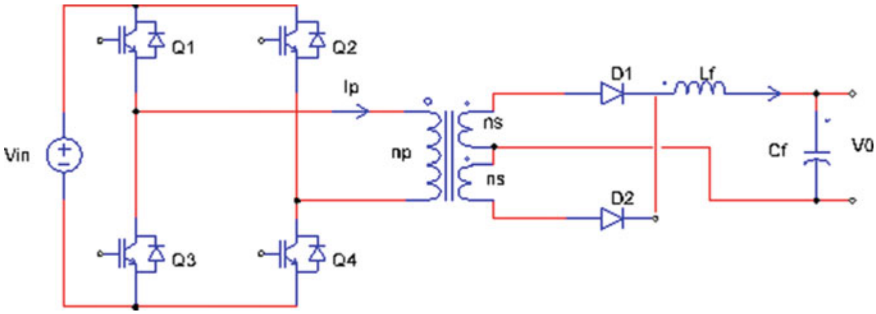


Fig. 7.18 Boost full bridge DC-DC converter with isolation

power device. If galvanic isolation is required, the boost full bridge converter is often employed (Fig. 7.18). For galvanic isolation and a high gain factor, several solutions could be used: full bridge, push-pull, forward power converter or half-bridge power converter.

From the above mentioned isolated power converter the full bridge is preferred for ability to transmit high power By using this type of power converter, the voltage applied to power transistors and the flow current through it are not very high compared with the other isolated power converter. The push-pull and forward power converters are used in high power applications. Compared with the DC-DC half-bridge power converter, the rated current across the devices and the ratio of the transformer are reduced to half. The full bridge power converter assures the low input-output currents and no voltage variation. The full bridge converter topology is preferred in the techniques of pulse width modulation with zero-voltage switch (ZVS).

7.6.3 DC-DC Full Bridge Converter with Multiple Secondary Windings [5]

This topology uses a transformer with multiple secondary devices connected in series (Fig. 7.19). This topology is able to obtain zero voltage switching, leading to a high

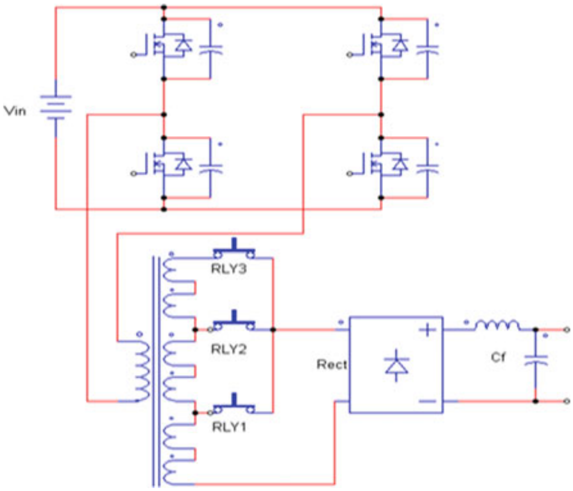


Fig. 7.19 Full bridge DC-DC converter with multiple secondary windings

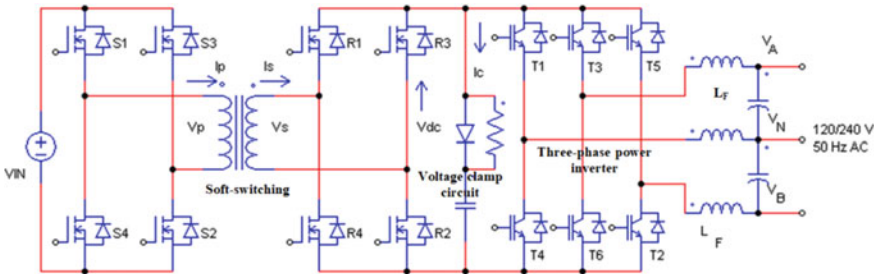


Fig. 7.20 DC-DC soft switching without DC-link

efficiency. This converter allows operation either at constant current or constant voltage; therefore, high flexibility is obtained. The electromechanical relays are used in the secondary transformer windings to control the voltage amplification, allowing appropriate adjustment to the conversion ratio (Figs. 7.20, 7.21, 7.22 7.23, 7.24, 7.25 and Table 7.1).

Remarks in order to provide galvanic isolation or to use the soft-switching techniques the number of components would increase; therefore, the efficiency of the power conversion decreases) [19]; the adequate topology can be chosen only by the designer of the power converters with strong skills. In order to assure a high output voltage despite of low input one, the DC-DC high boost converter is chosen if galvanic isolation is not required.

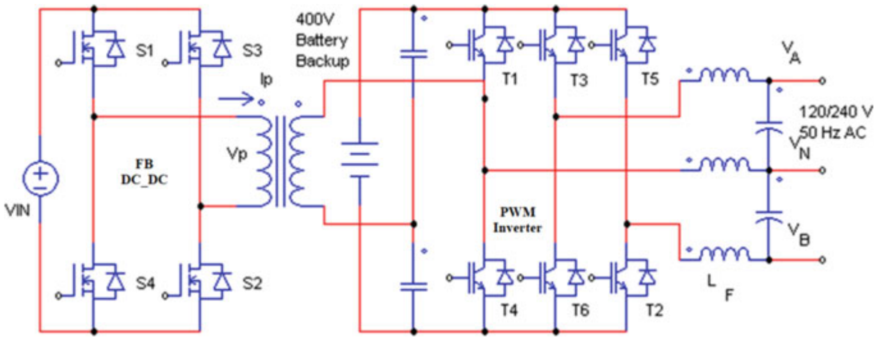


Fig. 7.21 DC-DC voltage doubler

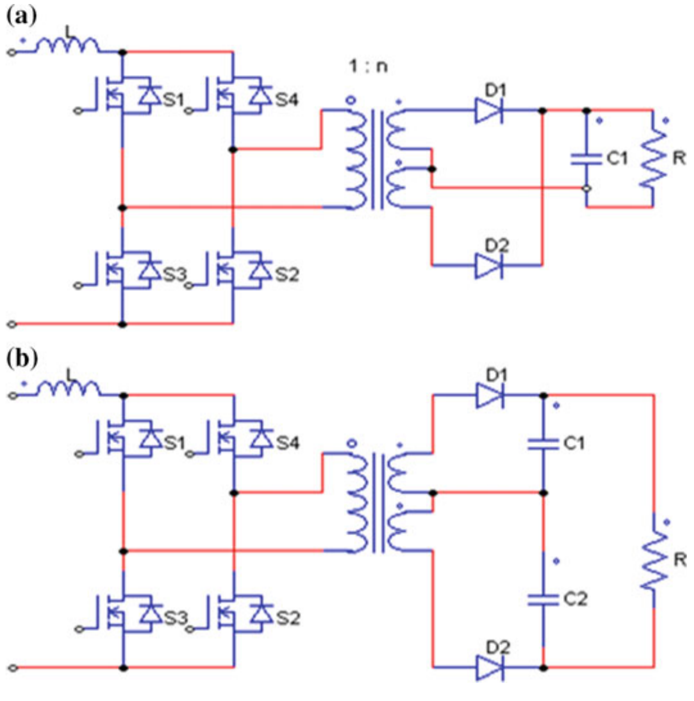


Fig. 7.22 Current injection DC-DC converter, **a** conventional, **b** with voltage doubler

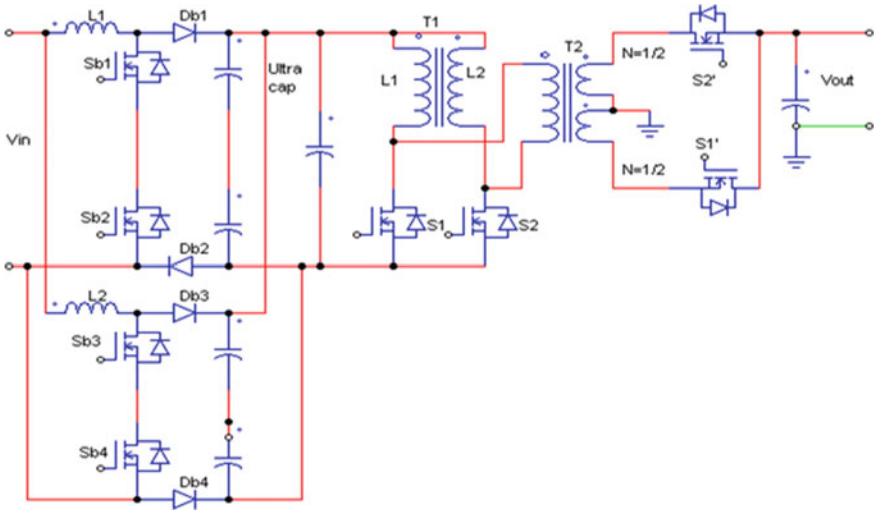


Fig. 7.23 Converter with wide input range

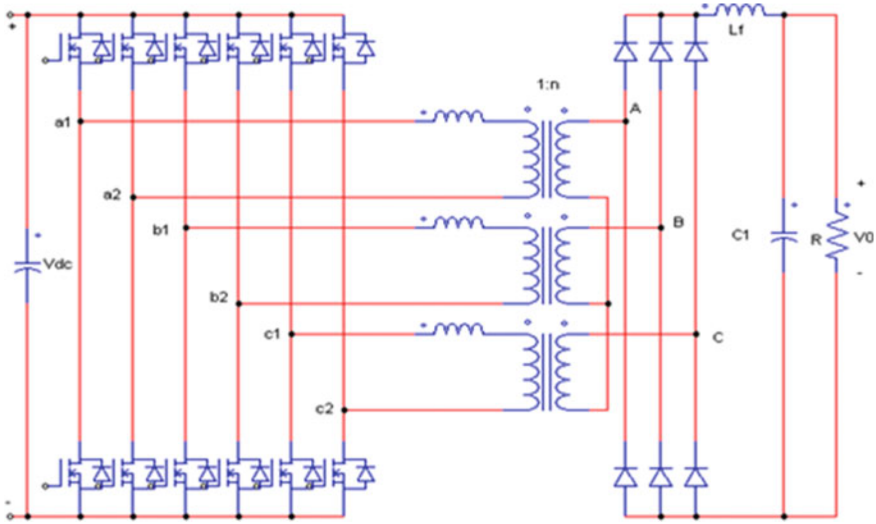


Fig. 7.24 Converter with multiple phases

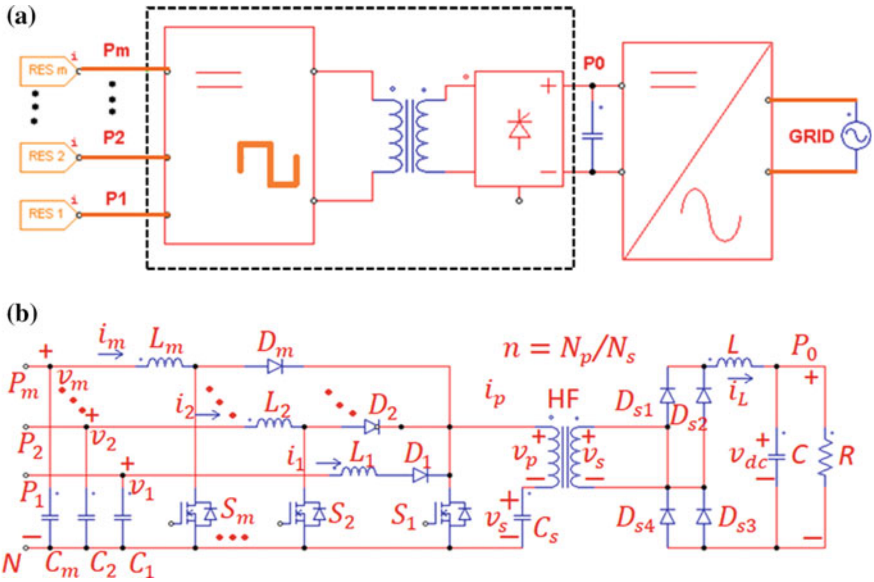


Fig. 7.25 Multiple RES integration into the utility grid: **a** principle, **b** DC-DC converter [16]

Table 7.1 Comparison between different DC-DC converter topologies [18]

Topologies	Advantages	Disadvantages
Boost	Low components, elementary design and control	The inexistence of electrical isolation feature
Full-bridge (FB)	Galvanic isolation; implementation of soft-switching methods (high efficiency); high power	
FB with secondary winding	Electrical isolation; implementation of soft-switching methods (low switching stress); fitted to adjustable transformer-ratio (reduced leakage inductance)	
Soft-switching	Electrical isolation; soft-switching; without DC link capacitor	DC link capacitor is missing (necessary clamp circuit, slow dynamical response)
Voltage doubler	Isolation; implementation of soft-switching methods; due to the reduced leakage inductance the transformer size is reduced; the output current has low ripple	Complex control

(continued)

Table 7.1 (continued)

Topologies	Advantages	Disadvantages
Isolated three-phase transformer	Electrical isolation; based on the soft-switching; use of delta—star connection (additional boost, reduced leakage inductance); high frequency current ripple; modularity	Very complex
Current injection	Electrical isolation; contains a voltage doubler (reduced leakage inductance);	Large inductors required
Converter with wide input range	Electrical isolation; reduced current ripple; independent constant output voltage while input voltage may vary; sizing of the semiconductor devices for low current rating	Very complex
Converter with multiple phases	Galvanic isolation; transformer's secondary star connection allows high output voltage; interleaved connection allows the converter to be controlled so that symmetrical output waveforms are obtained; high efficiency (zero voltage and current switching for a wide variation range), low transformer ratio, high modularity, high frequency of the output signal ripple (the switching frequency is 6 times higher than of the single-phase power inverter). Therefore, the significant reduction of the output filter take place	Complexity of designing a control for 12 static soft-switching devices
Multiport DC-DC RES integration	Electrical isolation, low-cost, simple, minimum components, simultaneous power management of multiple RES, high efficiency	

7.7 Wind Power Conversion Systems

The well-known purpose of the wind power turbines is to extract from the wind kinetic energy the corresponding power. The used generators are synchronous or asynchronous induction. Therefore, the three-phase voltage system can be generated. In order to connect to the grid, the power grid converter should be inserted.

The considered power converter interfaces are as follows:

- The first power interface between the electrical generator and the DC link with variable voltage can be realized through an *active power rectifier*.
- The second power interface between the variable DC voltage provided by the electric generator and the DC link with constant voltage requirement. This task can be performed by using a *unidirectional DC-DC power converter*. Usually, to assure the required voltage level of the power inverter *a step-up (boost) converter* is necessary.

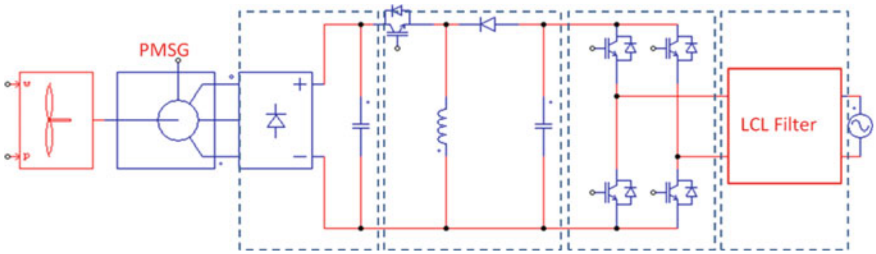


Fig. 7.26 Diode rectifier based wind power converter [20]

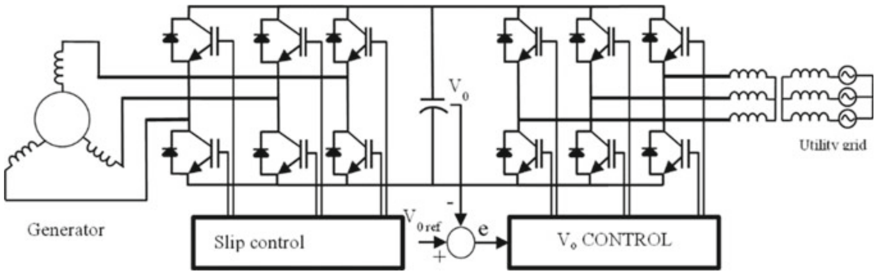


Fig. 7.27 Wind generator with variable speed and constant frequency

– The third power interface is located between battery and DC-link with constant voltage. In order to assure charging and discharging states of the battery a *bidirectional buck-boost* power converter topology is necessary;
– The fourth power interface between the constant voltage DC-link and the AC grid is provided by a three-phase power inverter.

This view provides a basis for different wind power systems design studies.

In the first stage, the wind power conversion is performed through AC generator (Induction generator or permanent magnet synchronous generator) and the appropriate AC-DC power converter (rectifier).

The main types of the AC-DC power converters are: diode rectifier based converter (Fig. 7.26), back to back (Fig. 7.27), back to back converter for connecting wind turbine based on DFIG generator to the three-phase grid (Fig. 7.28), matrix converter (Fig. 7.14b), cycloconverter (Fig. 7.14a), multilevel converters (Fig. 7.15), and Z-source converter (Fig. 7.29).

The power plant in Fig. 7.27 shows a wind generator based on induction machine and frequency inverter. The DC link voltage control of the voltage source converter will maintain the DC link voltage at a constant value. The inverter connected to the generator controls the slip of the generator and adjusts it according to the wind speed or power requirement. The back to back power converter maintain the machine's cos φ power factor independent of the power supply. The same configuration can also be used with synchronous machines.

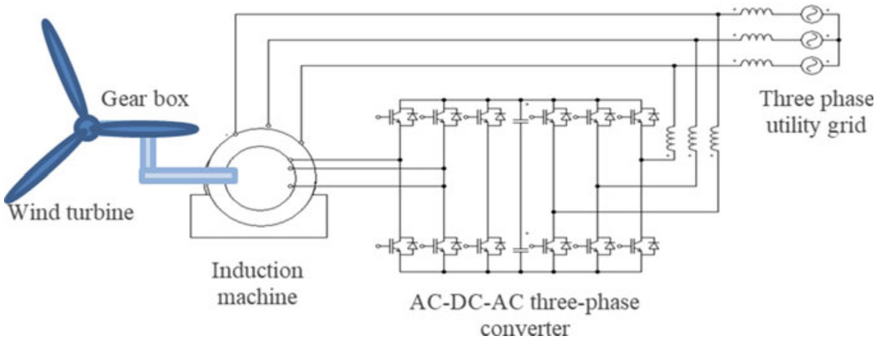


Fig. 7.28 Double-fed induction generation system based on back-to-back converter

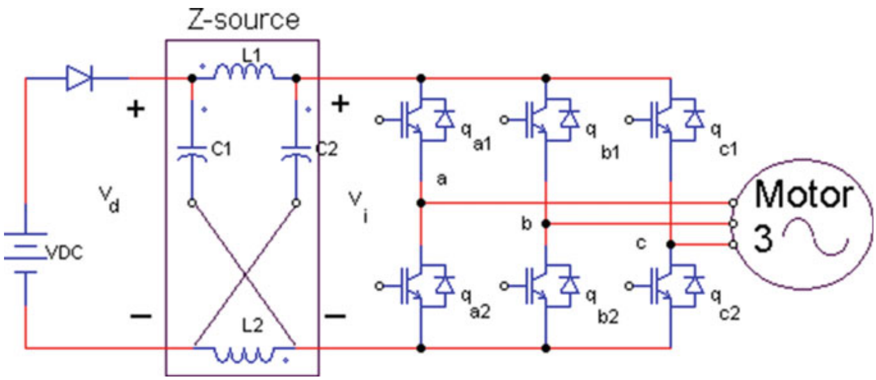


Fig. 7.29 Z-source power converter

The Z-source power converter is an impedance fed power converter. The DFIG cannot be used due to the unidirectional feature of the Z-source power converter. The Z-source power inverter operates both buck voltage mode (by decresing the modulation index) and boost mode (by increasing the modulation index). The low cost Z-source power inverter has high efficiency, it is simple and reliable with wide voltage output range [21].

Neutral-Point-Clamped *multilevel inverter* (*MLI*) has low harmonic content due to delivered three-phase voltages (Fig. 7.30) [22]. The switching losses are low (switching frequency is lower than 500 Hz. Due to the operation at fundamental frequency the reactive power flow is not necessary for switching devices.

Figure 7.31 illustrates the direct network connection of rotating generators without additional power electronics or compensation elements. This configuration can only be considered for high power systems that already include a relatively large fossil fuel generator or a battery system capable of controlling and stabilizing the utility network and providing the necessary reactive power.

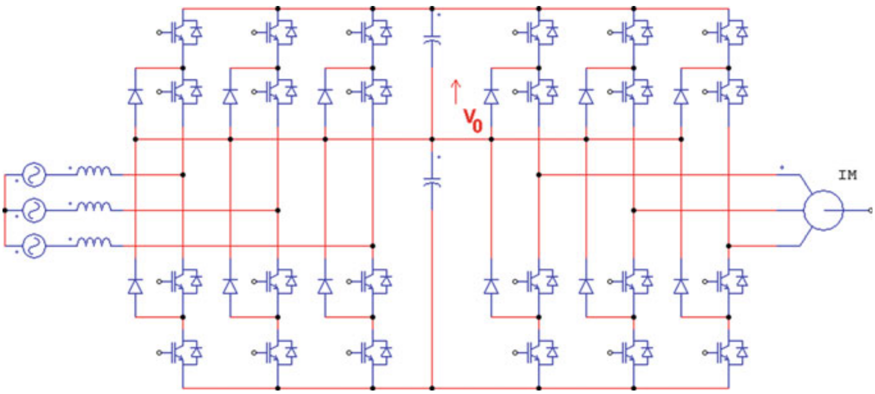


Fig. 7.30 Three-levels MLI: diode clamped

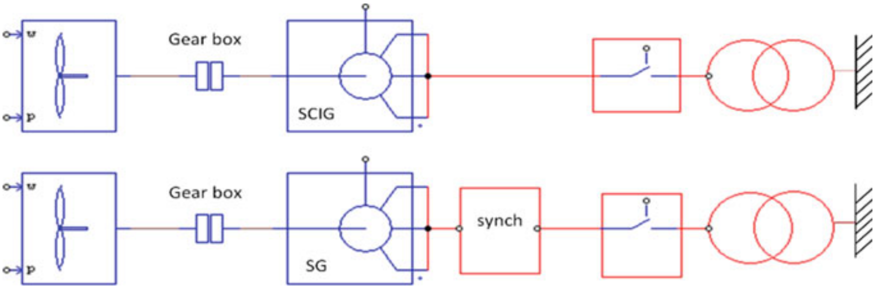


Fig. 7.31 Direct connection to the utility network of asynchronous/synchronous generators

The types of wind power systems can be classified according to: (1) *fixed or constant* including the asynchronous (squirrel cage) generator (SCIG) or synchronous generator (Fig. 7.31). The asynchronous machine absorbs reactive power for magnetization purposes and produces the active power. Therefore, the reactive power should be inserted through the adequate compensator (Fig. 7.32) [23]; (2) variable speed induction generator, based on the *wound rotor induction generator* (*WRIG*). The active pitch control and reactive power components are added to this type (Fig. 7.33) [23]; (3) *Doubly fed induction generator system* (*DFIG*): the rotor side is grid-connected by means of the AC-DC-AC power converter. The advantage of using DFIG system is the size decreasing of the power converter to 40% of power. The rest of 60% goes directly to the utility network. No additional reactive power compensation is necessary (Fig. 7.33). The pitch control, voltage ride-through and fast voltage recovery are included; (4) *Full power conversion*. The induction generator is connected through *back-to-back* power converter designed at full power (Fig. 7.27). Figure 7.32 illustrates the various possibilities for applied power electronics and compensation devices together with rotary generators. They allow modern systems to function in the following ways:

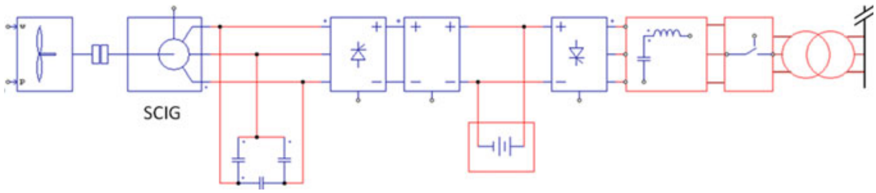


Fig. 7.32 Grid connection with frequency converter and DC link power converter

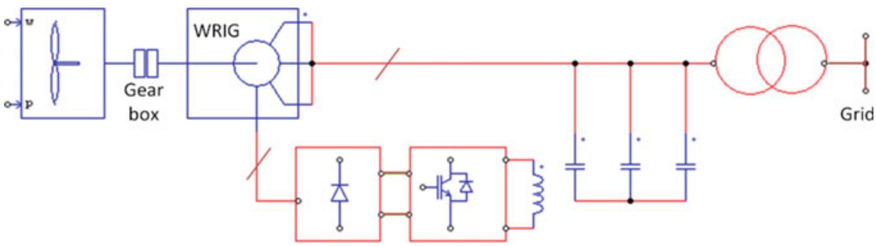


Fig. 7.33 Grid connection with WRIG

(1) grid control or grid forming;
(2) grid connected or grid feeding;
(3) grid supporting.

The *grid forming* (microgrid can be in island operation mode) power system control both the active and reactive power according to the loads such that the voltage and frequecny of the utlity grid are assured adequately. In the case of an asynchronous generator, capacitor batteries may be used to meet the demand for excitation of the reactive power generator required by its own system. The grid will therefore be exempted from the reactive power demand and in principle such a system will be able to control and work alone in the grid.

In order to stabilize the fluctuating voltage generated by the variable speed generator at a continuous and constant voltage value the DC-DC power converter is used. The first advantage is the simple connection of the rectifier and the inverter. The second advantage is the possibility of using a battery in the DC-link circuit.

Grid-feeding power converter delivers the appropriate active and reactive power to fulfill the requirements of the power dispatch [24]. Moreover, the power converter compensates power flow fluctuations and the load variations in the feeder.

Grid-supporting power converter is used to extract maximum active power from the power source, and to improve the power quality [10, 24].

If the inverter can operate in *grid control mode*, the battery can be used as a safety supply for short network interruptions, but also for balancing the energy fluctuations produced, for example from a wind turbine.

In order to generate sinusoidal voltage, even with low quality inverters, LC or LCL filters can be used at the inverter output.

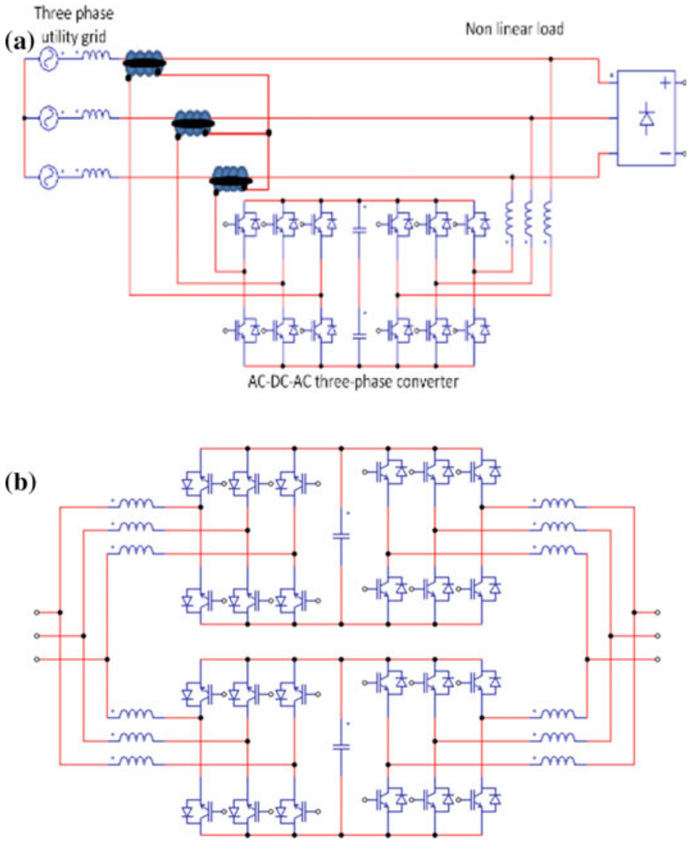


Fig. 7.34 BB power converter as **a** active power filter, **b** parallel connection

In wind power conversion systems the *back-to-back* (*BB*) power converter can be connected in series or parallel as active filters (Fig. 7.34a). The nonlinear three-phase load is supplied by means of the BB power converter from the main grid.

The parallel connection of the BB power converters is the used as the solution for high power manipulation (Fig. 7.34b). Moreover, the quality of the output and input signals are improved [10]. Depending on the power inverter characteristics, such a system can deliver the requested reactive power in the control-grid mode or to succesfully perform the reactive power balance in the grid support mode.

Using an asynchronous generator without a battery system, but along with a frequency converter, the bidirectional power converters are necessary. In this situation, the reactive power across the utility network to the generator and the active power from the generator to the network must be transferred simultaneously. The cost of the power electronic converters increases as the power increases.

7.8 Photovoltaic Power Conversion System

The photovoltaic panels are considered as power source by converting energy from sunlight to electrical power. The photovoltaic panels consist of photo cells connected in modules or arrays. Advanced Power Converter Systems should include solutions to power system challenges being a right pathway for increasing in depth and fast penetration of the RES (Renewable Energy Sources) into power system. They actively support the utility network parameters: voltage and frequency, are more robust tor grid disturbances, and actively monitor and control the microgrid via communications.

The existing installed *photovoltaic* (*PV*) power systems, the near future capacity development planning of the PV power systems and the necessity of growing of the power distribution systems conduct to finding the emergent solution of adapting the electrical parameters of the PV power systems to the utility network [12]. The photovoltaic modules delivers the DC voltage. Therefore, the power conversion system consists mainly of the series connected MPPT (maximum power point tracking) controlled step-up DC-DC power converter with grid-connected power inverter. The PV systems with backup power (battery) will add a vidirectional dc-dc power converter for charging/discharging the battery bank.

The low efficiency of the solar energy conversion (11–18%) through the PV module or array is compensated by introducing high efficiency power inverter.

7.8.1 Transformerless Inverters

The topolgies are classified as it follows: full bridge totpology, half-bridge topology **(NPC Based Inverter Structures)**, DC side decoupling and AC side decoupling [25, 26].

7.8.2 Full Bridge Topology

The *High Efficiency Reliable Inverter Concept* (*HERIC*) concept is used by Sunways (2.7–5 kW commercialized power inverter). The topology of the power inverter consists of a bipolar PWM H-bridge (or FB-full bridge) and a bypass branch formed by two IGBTs connected back to back. The HERIC invertor is presented in Fig. 7.35 [25]. The lower switches S4 (S2) are force commutated at high frequency. Instead, there is a grid frequency commutation of the upper switches S1 (S3). On the AC side, the purpose of the bypass switching is to improve the current mode voltage changes. By switching ON the S+ (S−) switches the zero output voltage states are obtained (the H bridge state is switched OFF).

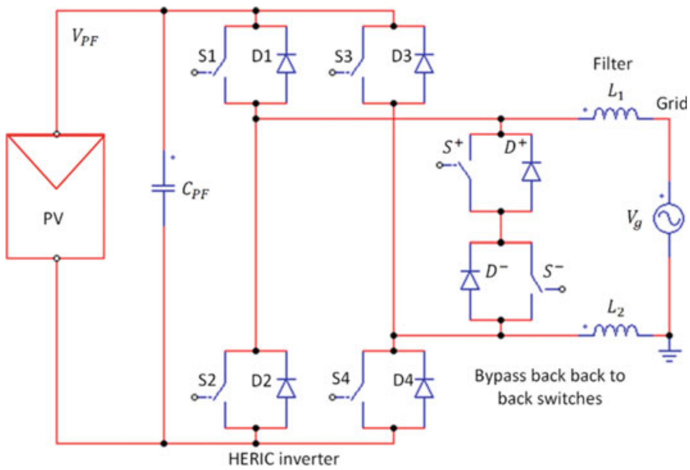


Fig. 7.35 HERIC topology of the power inverter (Sunways) [19]

Different FB HERIC inverter topologies have been developed: REFU Solar Inverter (11/15 kW) [27], FB-DCBP (Ingeteam) Inverter (2.5/3.6/6 kW) introduces of DC bypass in FB power inverter topology, *Full-Bridge Zero Voltage Rectifier-Inverter,* FB-ZVR.

For the several kilowatts, the photovoltaic generators are connected to the DC-module converter. The DC-module converters are series or parallel connected to one phase or three-phase power inverter. Up to 10 kW the string inverters collect the energy from the PV strings. For the [10, 27] kW range, the multiple PV strings connected to the common DC link through DC-DC converters supply the energy to the multi-string inverter. For the delivered power more than 30 kW the three-phase central inverter converts the power from the PV strings into the AC grid. Therefore, the power inverters for PV energy conversion are module level (AC and DC), string, multi-string, and central. String, multistring, and modular concept power inverters are the used types in the single-phase PV power systems [27]. In the three-phase topology of the PV systems the central inverter is used.

Half bridge topology (NPC Based Inverter Structures) classification: NPC Half Bridge Inverter (made by Danfoss Solar Inverter) with series TripleLynx (three-phase in power range of [10, 15] kW, *Conergy NPC Inverter* (patented by Conergy in string inverter IPG in power range of [2–5] kW), *oH5*—there is an optimized technology of the H5 power inverter, multilevel power inverter connected to the grid, *HRE*—high reliable and efficient power inverter, *HR-ZVR*—hybrid zero voltage rectifier configuration.

A DC fault current in the transformerless power inverter topology can take place; therefore, diminishing the personal safety (Fig. 7.36). Taking into account the above mentioned remark, the DC Residual Current Monitoring Unit (RCMU) is necessary. The classical RCDs are sensitive only to AC fault currents. The German safety

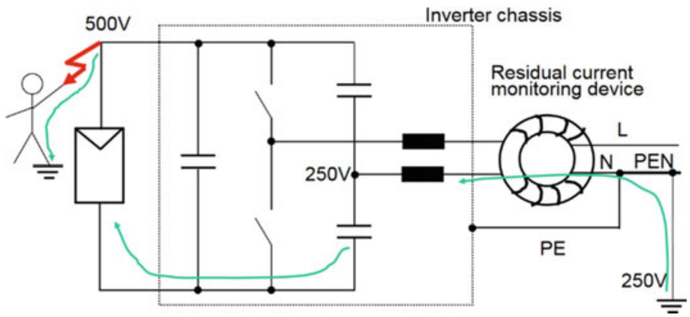


Fig. 7.36 Transformerless power inverter topology [28]

Standard DIN VDE 0126, requires an automatic AC disconnect interface, redundancy and one-fault tolerance; anti-islanding (the test is specified in UL 1741), DC current injection. The standard specify the RCMU test.

7.9 Case Study: AC Microgrid

In order to achieve the above mentioned objectives, a generic block diagram of the grid power inverter delivering the energy from RES, with local load connected at Point of Common Coupling (PCC) is proposed in Fig. 7.37. Microgrids are island systems for local utility or energy distribution systems and contain at least one distributed power source and a corresponding load.

The energy sources of a microgrid can be disconnected and reconnected to utility grid. For the *grid-connected mode*, the hybrid topology of the RES integration is shown in Fig. 7.38 [29].

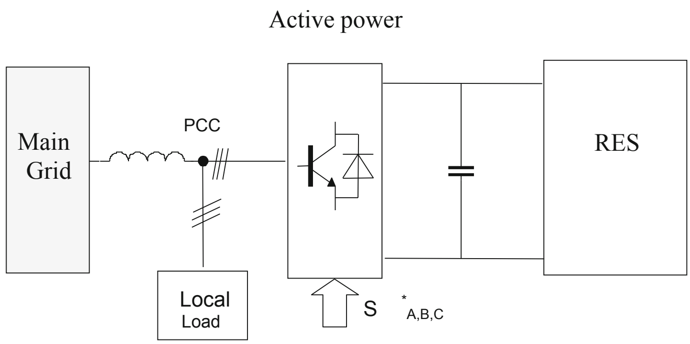


Fig. 7.37 RES integration into the main grid through the power inverter

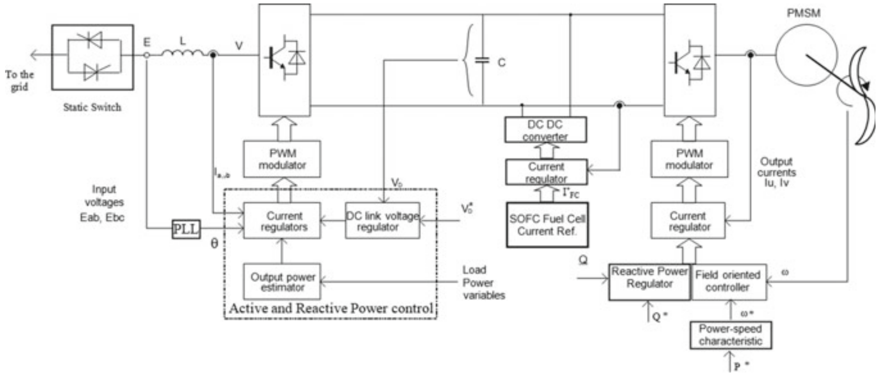


Fig. 7.38 Hybrid topology for RES integration [29]

The RES consists of the wind turbine and solide oxide fuel-cell generation system (Fig. 7.38). The proposed power conversion system derives from the all ready past research of the author [29]. The improvements consists of power loop integration in the inverter utillity grid, only one DC voltage converter is involved, and robust grid synchronization algorithm has been involved.

The control scheme is in cascaded manner [29], as depicted in Fig. 7.38. Another contribution is the transformation of the hybrid topology into a microgrid by adding a voltage controller.

Distributed generation (DG) concept is embedded in the proposed block diagram, the RES is closely exploited to the PCC in which the loads (consummers) are connected. This topology allows to avoid the expansion of the power transmission system [30]. Recently, in order to increase the reliability and to avoid the blackouts the intentional islanding concept has been introduced [30–32].

The features of the Microgrid should include two operation modes (island mode of operation and grid connected) and smooth transfer between them [30].

Intentional islanding is very helpful during disturbances on the power grid. In this manner, the local consummers can be supplied locally by the existing RES [29]. The control techniques used in distributed generation are as follows: voltage control for island operation mode and current control for grid-connected operation mode.

For the grid-connected mode the control task is to deliver current references for the system by using the measured inverter voltages and desired power levels. By using the power balance concept, the grid power inverter provides the currents into the main grid, and controlling the DC link voltage.

In the islanding mode of operation the system is disconnected from the utility; therefore the voltage is no longer regulated by it. The control needs to actively regulate the voltage of the Local Load. The control can work by using the voltage regulation through current compensation.

The inverter controllers have been generally inspired by control techniques of motor drives that are typically balanced loads. However, a distributed generation inverter needs to operate in an ambient with a broader degree of variability [26]: steady state and transient imbalances in the utility grid voltage [26, 27] and, in case of stand-alone mode, persistent imbalance in loads due to single-phase distribution circuits. Under such conditions the system requires implementation of more complicated controllers [29].

In conclusion, the main requirements on the utility network converter can be summarized as follows:

1. Adjustable power factor operation
2. Low input current harmonics
3. Optimization of the system's reactive components
4. Energy optimization (maximize the use of the available power)
5. Maintain a continuous supply with voltage and frequency within required limits
6. The system with full-scale converter must be easily adapted to different grid requirements.

7.9.1 Pulse Width Modulation Strategies

Fourth types of pulse width modulation techniques have been simulated and numerically implemented on DS1104 platform:

(1) sinusoidal PWM;
(2) third harmonic insertion;
(3) space vector-PWM;
(4) optimized modulation.

By using Matlab Simulink programming environment, the simulation results are provided [33]. In order to reduce the total harmonic distortion factor and to increase the power converter efficiency various pulse width modulation techniques were studied: sinusoidal PWM (Fig. 7.39a), space vector PWM (Fig. 7.39b), third harmonic insertion (Fig. 7.39b), optimized modulation (Fig. 7.39c), and the zero sequence signal generation by the adequate Simulink modulator and the generated signal by simulation (Fig. 7.40a,b).

The experimental results obtained through the dSpace platform are presented as follows (Figs. 7.41, 7.42, 7.43, 7.44, 7.45).

7.9.1.1 Sinusoidal PWM

See Figs. 7.41 and 7.42.

7.9.1.2 Third Harmonic Insertion

See Figs. 7.43 and 7.44.

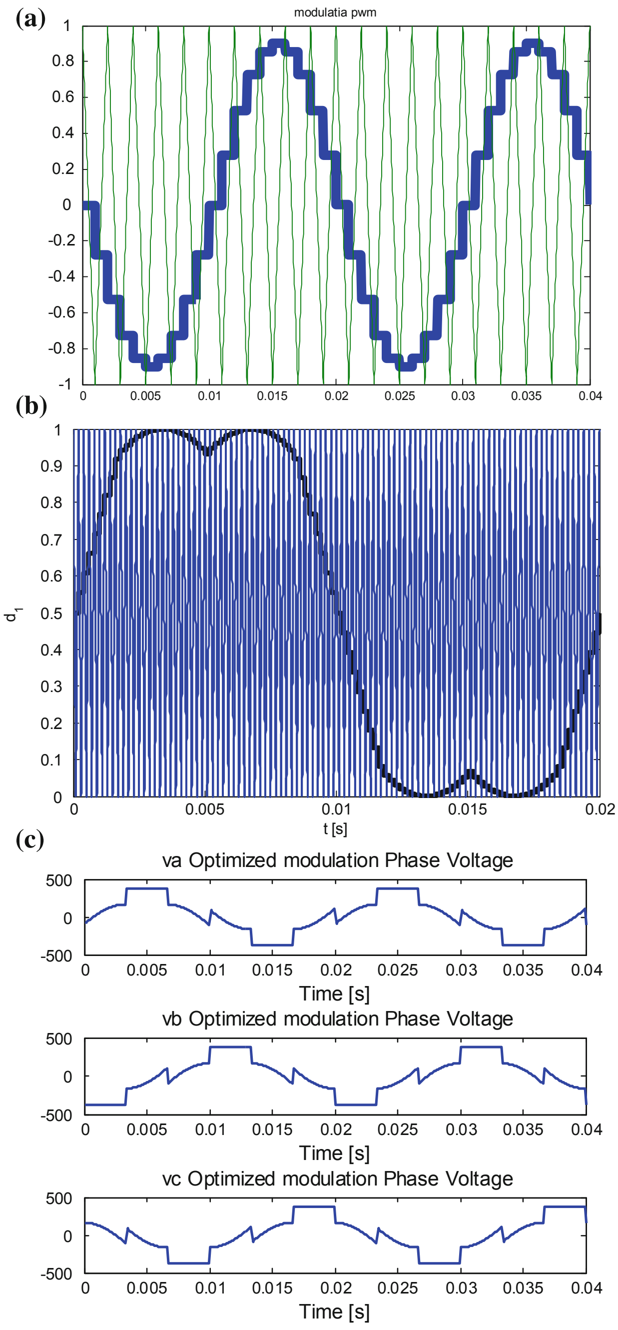


Fig. 7.39 **a** Simulation results: sinusoidal PWM, **b** SV-PWM, **c** optimized modulation

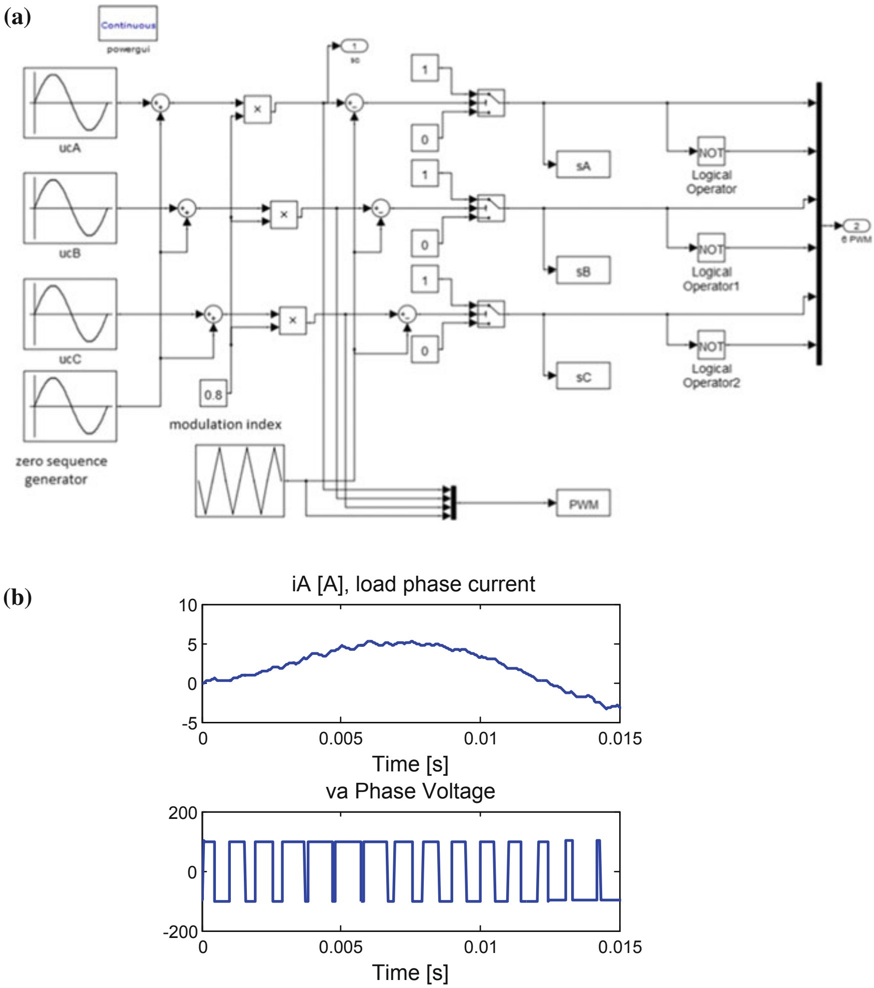


Fig. 7.40 **a** Zero sequence signal generation by the adequate Simulink modulator, **b** and the generated signal by simulation on RL load

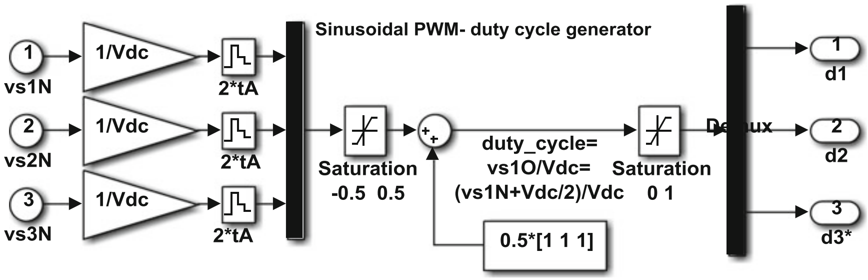


Fig. 7.41 Sinusoidal PWM modulator

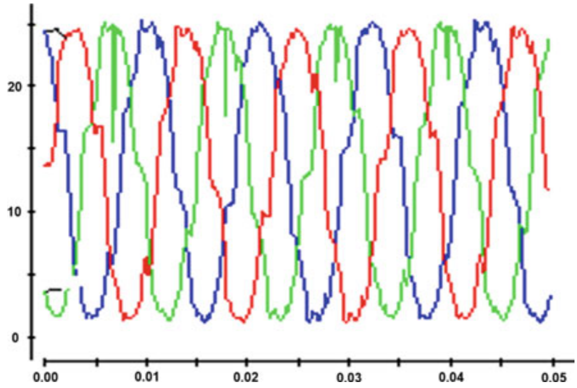


Fig. 7.42 The experimental modulated voltages

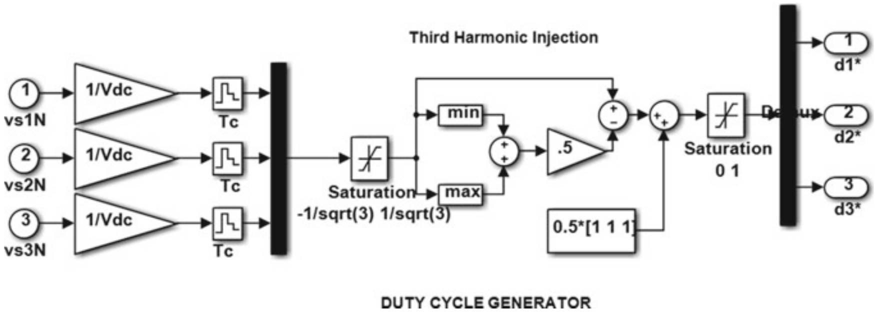


Fig. 7.43 Third harmonic injection modulator

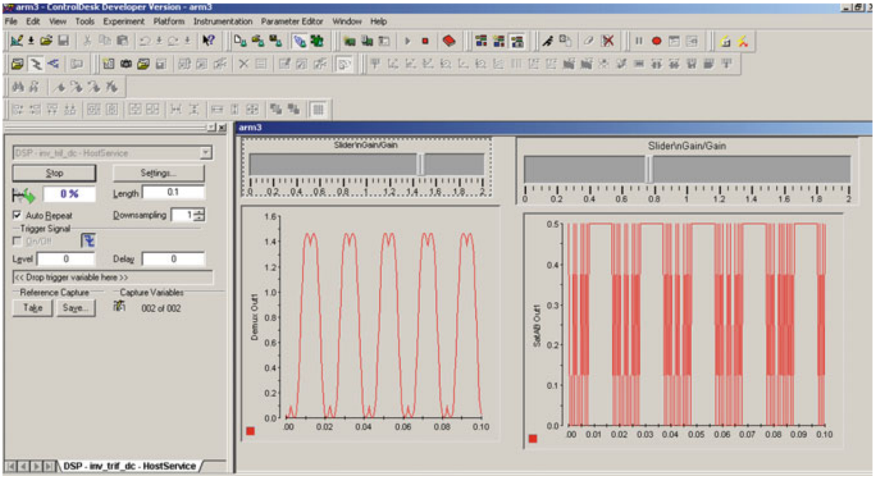


Fig. 7.44 The generated duty cycles by using dSpace platform

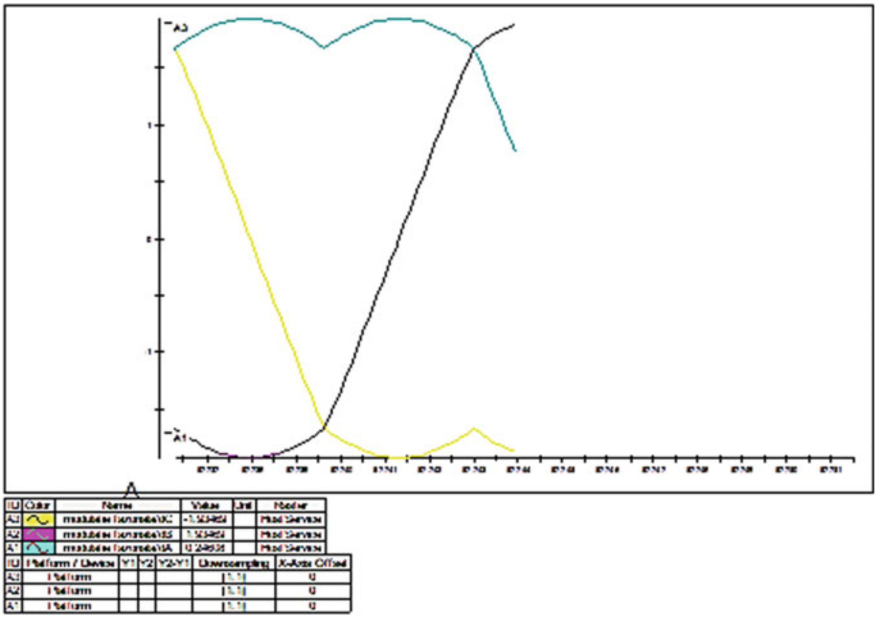


Fig. 7.45 The generated duty cycles for SVM-PWM, transient behaviour

7.9.2 Space Vector PWM

See Fig. 7.45.

7.9.3 Simulation Results on the Proposed Topology

From the simulation results, both the active current and reactive current regulators can be concluded that are correct tuned. The DC-link voltage controller assures the voltage regulation on the DC link capacitor and fast rejection of the perturbation. Unity power factor operation and bidirectional power flow are demonstrated in the Figs. 7.46, 7.47.

7.10 Conclusions

The chapter presents an overview of the power converters used in AC microgrids. The specific power topologies for both wind power and sunlight power integration are presented. The requirements imposed by the adequate standards are discussed.

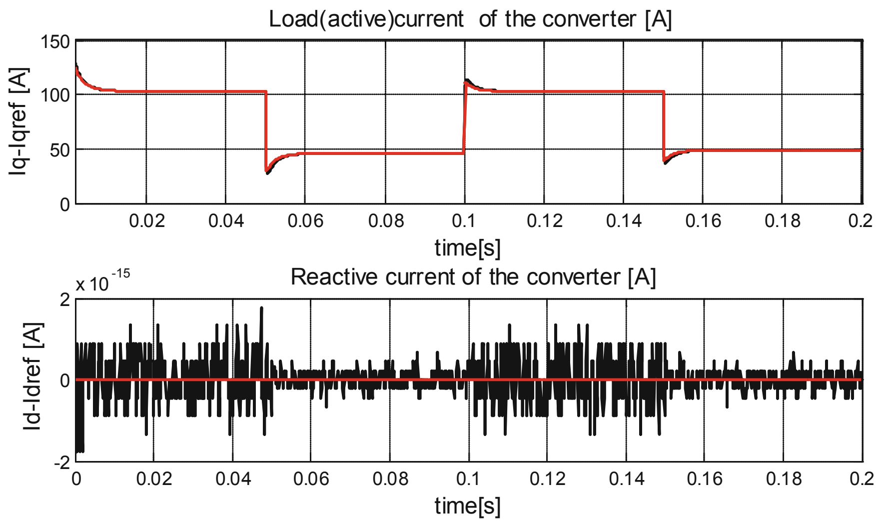


Fig. 7.46 Test on current regulators: active currents, and reactive currents (reference and the feedback current)

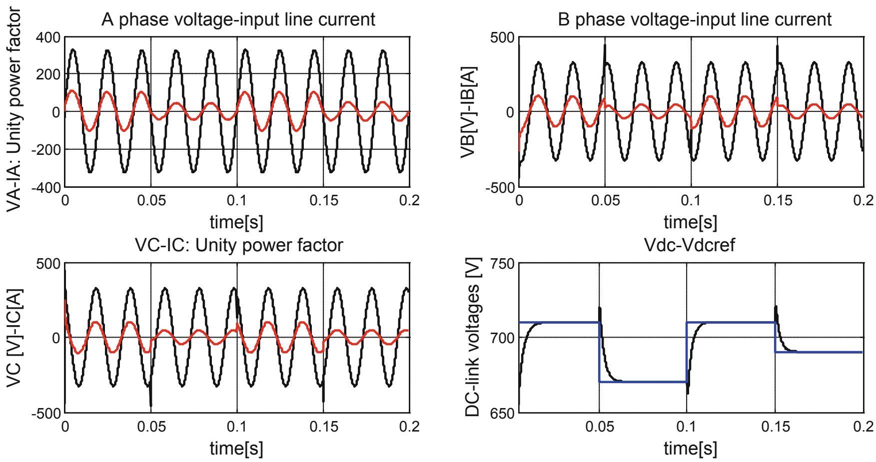


Fig. 7.47 Unity power factor operation and the DC link voltage controller

One solution as AC microgrid has been proposed. The main modulation techniques have been simulated and practical implemented by means of dSpace platform.

The chapter addresses the technical challenges of network interconnection to meet the requirements of utilities, including power quality, system stability and dynamic performances.

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