National Renewable Energy Laboratory

Innovation for Our Energy Future

Advanced Power Electronic Interfaces for Distributed Energy Systems

Part 1: Systems and Topologies

W. Kramer, S. Chakraborty, B. Kroposki,
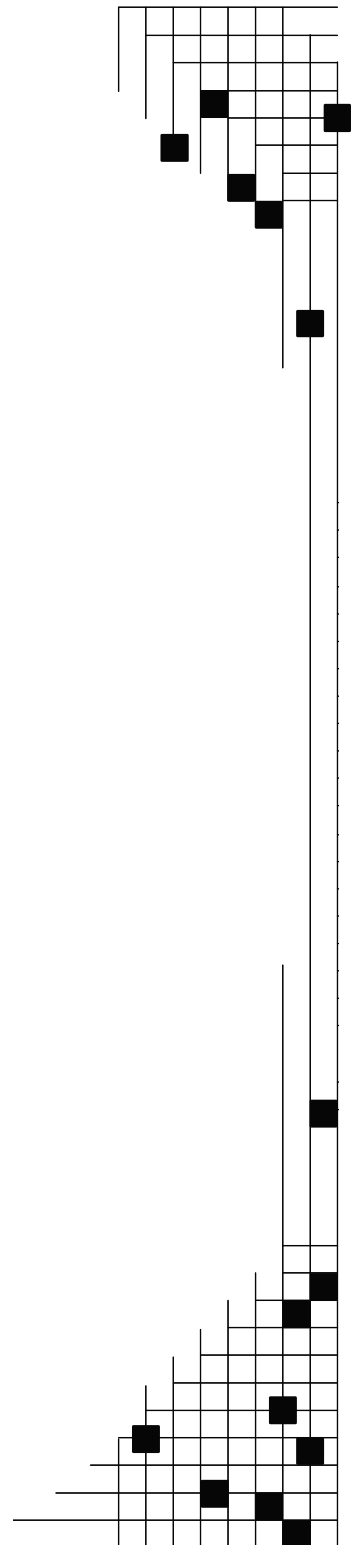and H. Thomas

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List of Acronyms

AC	Alternating current
ACE	Area control error
ACRDI	Active clamp resonant DC-link inverter
A/D	Analog to digital
AIPM	Advanced integrated power module
APEI	Advanced power electronics interface
BESS	Battery energy storage system
CAES	Compressed air energy storage
CAN	Controller area network
CCHP	Combined cooling, heating, and power
CHP	Combined heat and power
CPU	Central processing unit
CVT	Continuously variable transmission
DBC	Direct-bonded copper
DC	Direct current
DE	Distributed energy
DER	Distributed energy resource
DFIG	Doubly-fed induction generator
DG	Distributed generation
DSP	Digital signal processing
EMI	Electro-magnetic interference
EPS	Electric power system
ERCOT	Electric Reliability Council of Texas
FESS	Flywheel energy storage system
FOC	Field oriented controlled
FPGA	Field-programmable gate array
GTO	Gate turn-off thyristors
HC	Harmonic compensator
HFAC	High-frequency AC
HFLC	High-frequency link converter
IC	Internal combustion
IEEE	Institute of electrical and electronics engineers
IGBT	Insulated-gate bipolar transistor
IM	Induction machine
IPEM	Integrated power electronics module
ISO	Independent system operator
MCFC	Molten carbonate fuel cell
MCT	MOS-controlled thyristors
MPP	Maximum power point
MPPT	Maximum power point tracking
NEC	National electrical code
NREL	National Renewable Energy Laboratory
PAFC	Phosphoric acid fuel cell
PCB	Printed circuit board

|	
PCC	Point of common coupling
PDM	Pulse density modulation
PE	Power electronics
PEBB	Power electronics building block
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
PHEV	Plug-in hybrid electric vehicle
PI	Proportional-integral
PIER	Public interest energy research
PLL	Phase-locked-loop
PM	Permanent magnet
PR	Proportional resonant
PV	Photovoltaic
PWM	Pulse-width modulation
RPLI	Resonant-phase leg inverter
RPM	Revolutions per minute
RPS	Renewable portfolio standards
SCR	Silicon controller rectifier
SKAI	Semikron advanced integration
SMES	Superconducting magnetic energy storage
SOC	State-of-charge
SOFC	Solid oxide fuel cell
SPWM	Sine pulse-width modulation
UC	Ultra-capacitors
UL	Underwriters laboratories
V2G	Vehicle-to-grid
VAR	Volt-amperes reactive
VFD	Variable frequency drive
VRB	Vanadium redox battery
VSI	Voltage source inverter
ZVS	Zero voltage switching

Executive Summary

Several distributed energy (DE) systems are expected to have a significant impact on the California energy market in the near future. These DE systems include, but are not limited to: photovoltaics (PV), wind, microturbine, fuel cells, and internal combustion engines (IC engines). In addition, several energy storage systems such as batteries and flywheels are under consideration for DE to harness excess electricity produced by the most efficient generators during low loading. This harvested energy can be released onto the grid, when needed, to eliminate the need for high-cost generators. Inclusion of storage in the distributed generation system actually provides the user dispatchability of its distributed resources which generally are renewable energy sources, like PV and solar, having no dispatchability by their own. In the future, using hybrid electric vehicles along with the utility grid in the form of plug-in hybrid electric vehicles (PHEV) and vehicle-to-grid systems (V2G) will be a very promising option to be included in the DE classification. All of these DE technologies require specific power electronics capabilities to convert the generated power into useful power that can be directly interconnected with the utility grid and/or that can be used for consumer applications. Because of the similar functions of these power electronics capabilities, the development of an advanced power electronic interface (APEI) that is scalable to meet different power requirements, with modular design, lower cost, and improved reliability, will improve the overall cost and durability of distributed and renewable energy systems. This report presents a summary providing a convenient resource to understand the current state-of-the art power electronic interfaces for DE applications. It also outlines the power electronic topologies that are needed for an advanced power electronic interface.

This report focuses on commercially available DE systems and is organized into eight application-specific areas:

- Photovoltaic Systems
- Wind Systems
- Microturbine Systems
- Fuel Cell Systems
- Internal Combustion Engine Systems
- Battery Storage Systems
- Flywheel Systems
- Plug-In Vehicles.

Different power electronics topologies are discussed for each of these DE systems and a generalized topology is selected for understanding the control design. An interesting section on plug-in hybrid vehicles is also included in the report that can help to explain the new vehicle technologies that are viable to be included in the DE framework. Figure ES-1 shows a general block diagram of general power electronics interface for use with DE systems and can be subdivided into four major modules. These include: the source input converter module, an inverter module, the output interface module, and the controller module. The blue unidirectional arrows depict the power flow path for the DE sources whereas the red arrows show the bidirectional power flows for the DE storages. The input converter module can be either used with alternating current (AC) or direct current (DC) DE systems and is most likely to be specific for the type of energy source

or storage. The DC-AC inverter module is the most generic of the modules and converts a DC source to grid-compatible AC power. The output interface module filters the AC output from the inverter. The fourth major module is the monitoring and control module that operates the entire interface and contains protection for both the DE source and the utility at the point-of-common-coupling (PCC). Due to many inherent similarities in these modules, it is possible that a modular and scalable APEI could allow each of the energy source technologies to use the same power electronic components within their system architectures. The future requirements for modular design, such as standard interfaces, are also discussed. These requirements can lead to modular and flexible design of the power electronics converters for the DE applications.
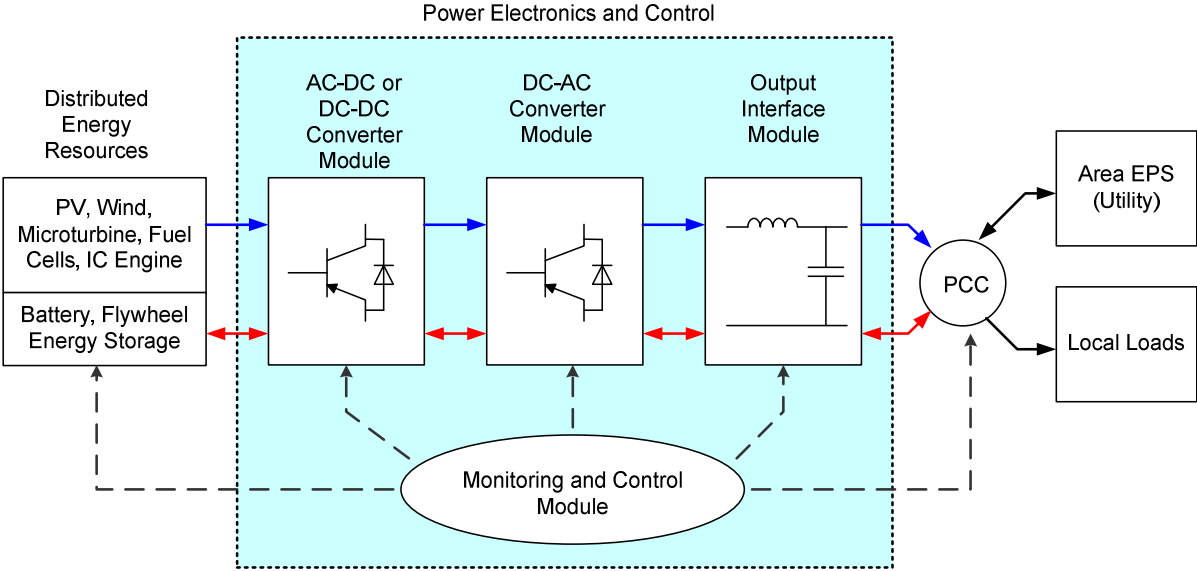
Figure ES-1. Proposed modular configuration for DE power electronics interface

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1 Introduction

Several distributed energy (DE) systems are expected to have a significant impact on the California energy market in near future. These DE systems include, but are not limited to: photovoltaics (PV), wind, microturbine, fuel cells, and internal combustion (IC) engines (Byron 2002). In addition, several energy storage systems such as batteries and flywheels are under consideration for DE to harness excess electricity produced by the most efficient generators during low loading. This harvested energy can be released onto the grid, when needed, to eliminate the need for high-cost generators. Inclusion of storage in the distributed generation system actually provides the user dispatchability of its distributed resources which generally are renewable energy sources, like PV and solar, having no dispatchability by their own. In the future, using hybrid electric vehicles along with the utility grid in the form of plug-in hybrid electric vehicles (PHEV) and vehicle-to-grid systems (V2G) will be a very promising option to be included in the DE classification. All of these DE technologies require specific power electronics capabilities to convert the power generated into useful power that can be directly interconnected with the utility grid and/or can be used for consumer applications. Because of similar functions of these power electronics interfaces, the development of scalable, modular, low cost, highly reliable power electronic interfaces will improve the overall cost and durability of distributed and renewable energy systems.

Although most DE systems are not new in a technological respect, they are receiving increased attention today because of their ability to provide combined heat and power, peak power, demand reduction, backup power, improved power quality, and ancillary services to the power grid. Out of all DE systems, the visibility of renewable energy sources are increasing significantly due to several state governments' adoption of Renewable Portfolio Standards (RPS) that require a certain percentage of energy be produced using renewable energy sources. A large factor in whether or not DE systems are installed is the initial capital cost. Although power electronics are the integral part of most of the DE technologies, in order to convert the power generated into useful power that can be directly used on the grid, they can cost up to 40% of the costs of a distributed energy system (Blazewicz 2005). Therefore, the improvement of the DE economics strongly requires decreased costs for the power electronics. Another important aspect to the life-cycle cost of the DE systems is reliability. Many of the power electronics used for DE applications have a low reliability rate, typically operating less than five years before a failure occurs. This rate can be improved with modern reliability testing techniques and needs to be fully examined to improve the economics of DE systems.

The current plans of the California Energy Commission Public Interest Energy Research (PIER) program are to implement projects to accelerate the use of DE systems, in part by addressing the cost and reliability of the common element of all of the distributed and renewable technologies: the power electronics interface. This objective is being accomplished through a recently announced Advanced Power Electronics Interface (APEI) initiative. The objectives of the APEI initiative include (Treanton 2004):

- Developing an architecture for standardized, highly integrated, modularized power electronics interconnection technologies that will come as close as possible to "plug-and-play" for distributed energy platforms;

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- Reducing costs and improving the reliability for DE and interconnections by developing standardized, high production volume power electronic modules; and

- Improving the flexibility and scalability for power electronic modules and systems to provide advanced functionality at a range of power levels.

The purpose of this report is to provide a consolidated resource describing the current state-of-the-art in power electronic interfaces for DE applications and outline possible power electronic topologies that will lead to a low-cost, reliable APEI.

1.1 General Topology

A generalized block diagram representation of power electronics interface associated with DE systems is shown in Figure 1. The power electronics interface accepts power from the distributed energy source and converts it to power at the required voltage and frequency. For the storage systems, bidirectional flow of power between the storages and the utility is required. Figure 1 illustrates a design approach to organize the interface into modules, each of which can be designed to accommodate a range of DE systems and/or storages. For this example, four major modules for a power electronics interface are depicted. They include the source input converter module, an inverter module, the output interface module and the controller module. The blue unidirectional arrows depict the power flow path for the DE sources whereas the red arrows show the bidirectional power flows for the DE storages.

The design of the input converter module depends on the specific energy source or storage application. The DE systems that generate AC output, often with variable frequencies, such as wind, microturbine, IC engine, or flywheel storage needs an AC-DC converter. For DC output systems like PV, fuel cells, or batteries, a DC-DC converter is typically needed to change the DC voltage level. The DC-AC inverter module is the most generic of the modules and converts a DC source to grid-compatible AC power. The output interface module filters the AC output from the inverter and the monitoring and control module operates the interface, containing protection for the DE and utility point-of-common-coupling (PCC).

The power electronic (PE) interface also contains some level of monitoring and control functionality to ensure that the DE system can operate as required. The monitoring and control module also contains protective functions for the DE system and the local electric power system that permit paralleling and disconnection from the electric power system. These functions would typically meet the IEEE 1547-2003 interconnection requirements (Basso and DeBlasio 2004), but should have the flexibility for modifications of the settings depending on the application or a utility's interconnection requirements. In addition, the monitoring and control module may also provide human-machine interface, communications interface, and power management. Monitoring functions typically include real-power, reactive power, and voltage monitoring at the point of the DE connection with the utility at the PCC. These functions are necessary because, in order to synchronize the DE system, its output must have the same voltage magnitude, frequency, phase rotation, and phase angle as the utility. Synchronization is the act of checking that these four variables are within an acceptable range before paralleling two energy sources.

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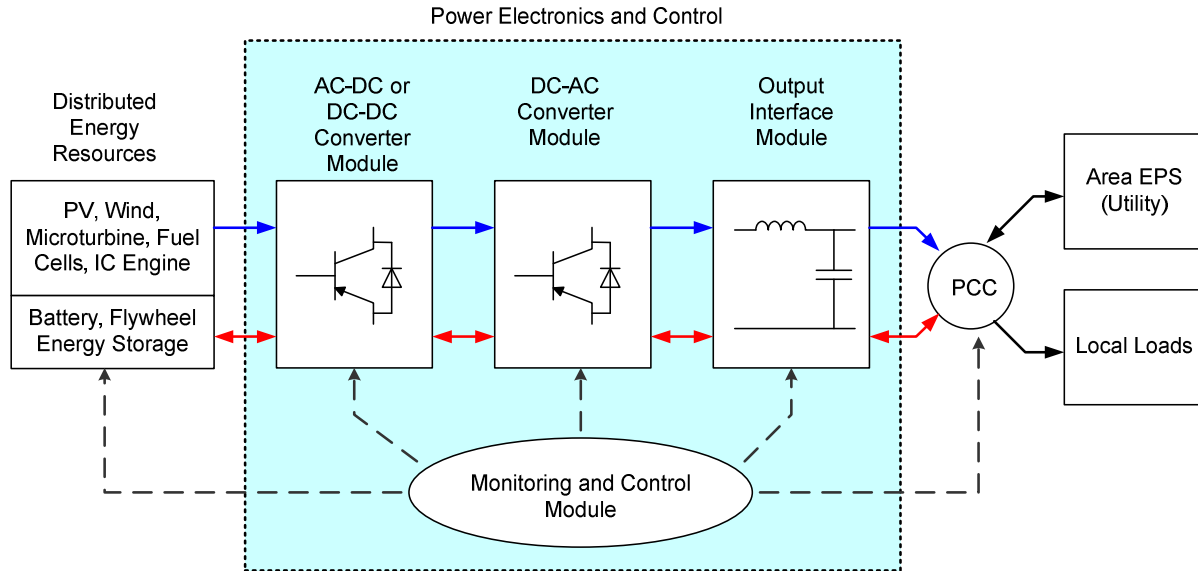
Figure 1. General block diagram of typical DE power electronic systems

Every power electronics circuit consists of different semiconductor devices fabricated with appropriate impurities (known as "doping") in order to achieve particular electrical properties such as conduction, resistance, turn on/turn-off times, power dissipation, etc. The fundamental power electronics device is the semiconductor-based switch, a technology that has existed for many decades, but is continuously being improved in terms of power density and reliability. In general, the term "power electronics" refers to the device switches (e.g., IGBT and SCR), and the various modules that they comprise. In power applications, these devices are most often used to convert electrical energy from one form to a more usable form. Benefits of power electronic devices include increased efficiency, lower cost, and reduced packaging size.

A rectifier is a power electronics topology that converts AC to DC. Rectifier circuits are generally used to generate a controlled DC voltage from either an uncontrolled AC source (i.e., microturbine, wind turbine) or a controlled AC source (i.e., utility supply) (Kroposki et al. 2006). When converting from a utility supply, a rectifier application is usually for linking DC systems or providing DC voltage for specific load applications such as battery regulators and variable frequency drive (VFD) inputs.

Some DE systems like photovoltaics and fuel cells produce DC power. In order to make this power useful for grid-tied applications, it must be converted to AC; therefore, inverters are used to convert DC to AC. Inverter circuits generate a regulated AC supply from a DC input. They are commonly found in systems providing standalone AC power, utility-connected DE systems, and on the motor side of a VFD.

There are a number of applications for DC-to-DC systems. These systems are used to convert the DC voltage magnitude from one level to another with or without galvanic isolation. They take an uncontrolled, unregulated input DC voltage and condition it for the specific load application. An example for such topology can be found in PV applications, where the dedicated DC-DC units are often designed to extract the maximum power output of the PV array.

AC-to-AC converters can be used convert the AC source voltage magnitude and frequency to a fixed amplitude and frequency, making it compatible with the utility grid. The AC-to-AC converters are not typically used in modern DE applications due to some inherent disadvantages. A summary of the different power converters that are used for DE applications are given in Table 1 (Shepherd et al. 2004; DeBlasio et al. 2006).

Table 1. Power electronics systems for different power conversions

Power Conversion	Common Module Names
AC-DC	Rectifier
DC-AC	Inverter
DC-DC	Boost, Buck, Buck-Boost, Chopper
AC-DC	Cycloconverter, Matrix Converter
AC-DC-AC	Back-to-Back Converter, Rectifier-Inverter

1.2 Report Structure

This report focuses on commercially available DE systems and is organized into eight application-specific areas:

- Photovoltaic Systems
- Wind Systems
- Microturbine Systems
- Fuel Cell Systems
- Internal Combustion Engine Systems
- Battery Storage Systems
- Flywheel Storage Systems
- Plug-In Vehicles.

Different power electronics topologies are discussed for each of these DE systems and a generalized topology is selected for understanding the control design. Based on these generalized power electronics topologies, a section on modular power electronics is presented based on the available power electronics devices and topologies. The future requirements for modular design (i.e., standard interfaces), which can lead to modular and flexible design of the power electronics converters for the DE applications, are also discussed in this section. An interesting section on plug-in hybrid vehicles is also included in this report that helps explain the new vehicle technologies that are viable to include in the DE framework. All the topologies described in this report are for the grid interconnected systems. Although some power electronic devices are used in off-grid applications for stand-alone applications or in village or hybrid power systems, those systems are not considered in this report.

2 Photovoltaic

2.1 General Description

Photovoltaic (PV) technology involves converting solar energy directly into electrical energy by means of a solar cell. A solar cell is typically made of semiconductor materials such as crystalline silicon and absorbs sunlight and produces electricity through a process called the photovoltaic effect. The efficiency of a solar cell is determined by its ability to convert available sunlight into usable electrical energy and is typically around 10%-15%. Therefore, to produce significant amount of electrical energy, the solar cells must have large surface areas.

Individual solar cells are usually manufactured and combined into modules that consist of 36 to 72 cells, depending on the output voltage and current of the module. The modules vary in size by manufacturer, but are typically between 0.5 to 1 m2 and generate around 100 W/m2 of energy during peak solar conditions for a 10% efficient module (Blaabjerg et al. 2004). Additionally, the modules can also be grouped together in various quantities and configurations (as discussed in the following section) to form arrays with unique voltage and current characteristics. The distinction between modules and arrays is important when considering power electronics interfaces, as power electronics manufacturers design their products using either module-centric or array-based approaches.

Figure 2 shows typical PV panels configured into arrays. For a PV system, the voltage output is a constant DC whose magnitude depends on the configuration in which the solar cells/modules are connected. On the other hand, the current output from the PV system primarily depends on the available solar irradiance. The main requirement of power electronic interfaces for the PV systems is to convert the generated DC voltage into a suitable AC for consumer use and utility connection. Generally, the DC voltage magnitude of the PV array is required to be boosted to a higher value by using DC-DC converters before converting them to the utility compatible AC. The DC-AC inverters are then utilized to convert the voltage to 60 Hz AC. The process of controlling the voltage and current output of the array must be optimized based on the weather conditions. Specialized control algorithms have been developed called maximum power point tracking (MPPT) to constantly extract the maximum amount of power from the array under varying conditions (Blaabjerg et al. 2004). The MPPT control process and the voltage boosting are usually implemented in the DC-DC converter, whereas the DC-AC inverter is used for grid-current control.

Figure 2. PV panels (NREL 2008)

2.2 Photovoltaic System Configurations

PV modules are connected together into arrays to produce large amounts of electricity. The array is then connected with system components such as inverters to convert the DC power produced by the arrays to AC electricity for consumer use. The inverter for PV systems performs many functions. It converts the generated DC power into AC power compatible with the utility. It also contains the protective functions that monitor grid connections and the PV source and can isolate the PV array if grid problems occur. The inverter monitors the terminal conditions of the PV module(s) and contains the MPPT for maximizing the energy capture. The MPPT maintains the PV array operation at the highest possible efficiency, over a wide range of input conditions that can vary due to the daily (morning-noon-evening) and seasonal (winter-summer) variations (Blaabjerg et al. 2004).

PV Systems can be structured into several operational configurations. Each configuration has the basic power electronic interfaces that interconnect the system to the utility grid. Figure 3 shows the configuration where a centralized inverter is used. This has been the most common type of PV installation in the past. PV modules are connected in series and/or parallel and connected to a centralized DC-AC converter. The primary advantage of this design is the fact that if the inverter is the most costly part in the installed PV system, this system has the lowest cost design because of the presence of only one inverter. The primary disadvantage of this configuration is that the power losses can be high due to the mismatch between the PV modules and the presence of

string diodes (Blaabjerg et al. 2004). Another disadvantage is that this configuration has a single point failure at the inverter; therefore, it has less reliability (Kjaer et al. 2005).
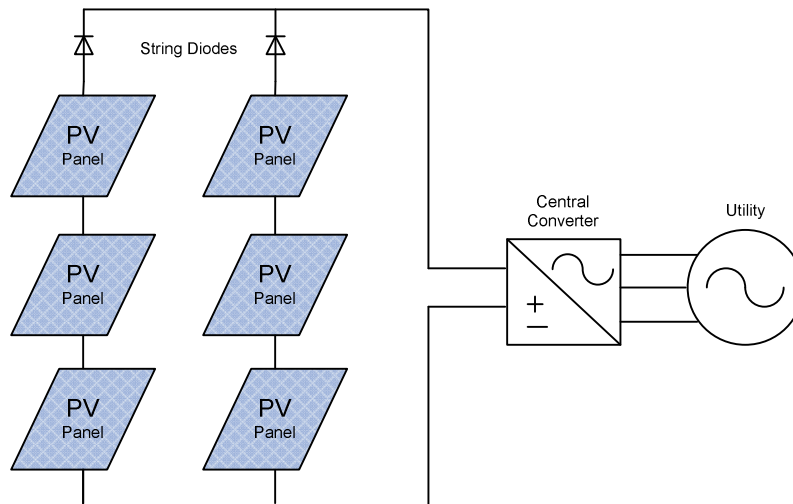
Figure 3. Centralized PV configuration

Figure 4 (a) shows the configuration of a string-array PV system. The series of PV panels are connected in the form of a single string. Typically, 15 panels are strung together in series and interconnected through the utility with one inverter per string. The primary advantage of this topology is that there are no losses associated with the string diodes and a maximum power point tracker can be applied for each string. This is especially useful when multiple strings are mounted on fixed surfaces in different orientations. The disadvantage to this configuration is the increased cost due to additional inverters (Blaabjerg et al. 2004; Kjaer et al. 2005).

The input voltage coming from the PV strings may be high enough to avoid the need for voltage amplification. As the cost of the PV modules is still rather expensive, voltage amplification can be added together with the string inverter in order to allow for fewer modules to be connected to the inverter. Multi-string inverters, a development of the string-inverter, have several strings that are interfaced with their own DC-DC converter for voltage boosting and are then connected to a common DC bus. A common DC-AC inverter is then used for utility interfacing. A multi-string PV system is shown in Figure 4 (b) (Kjaer et al. 2005).
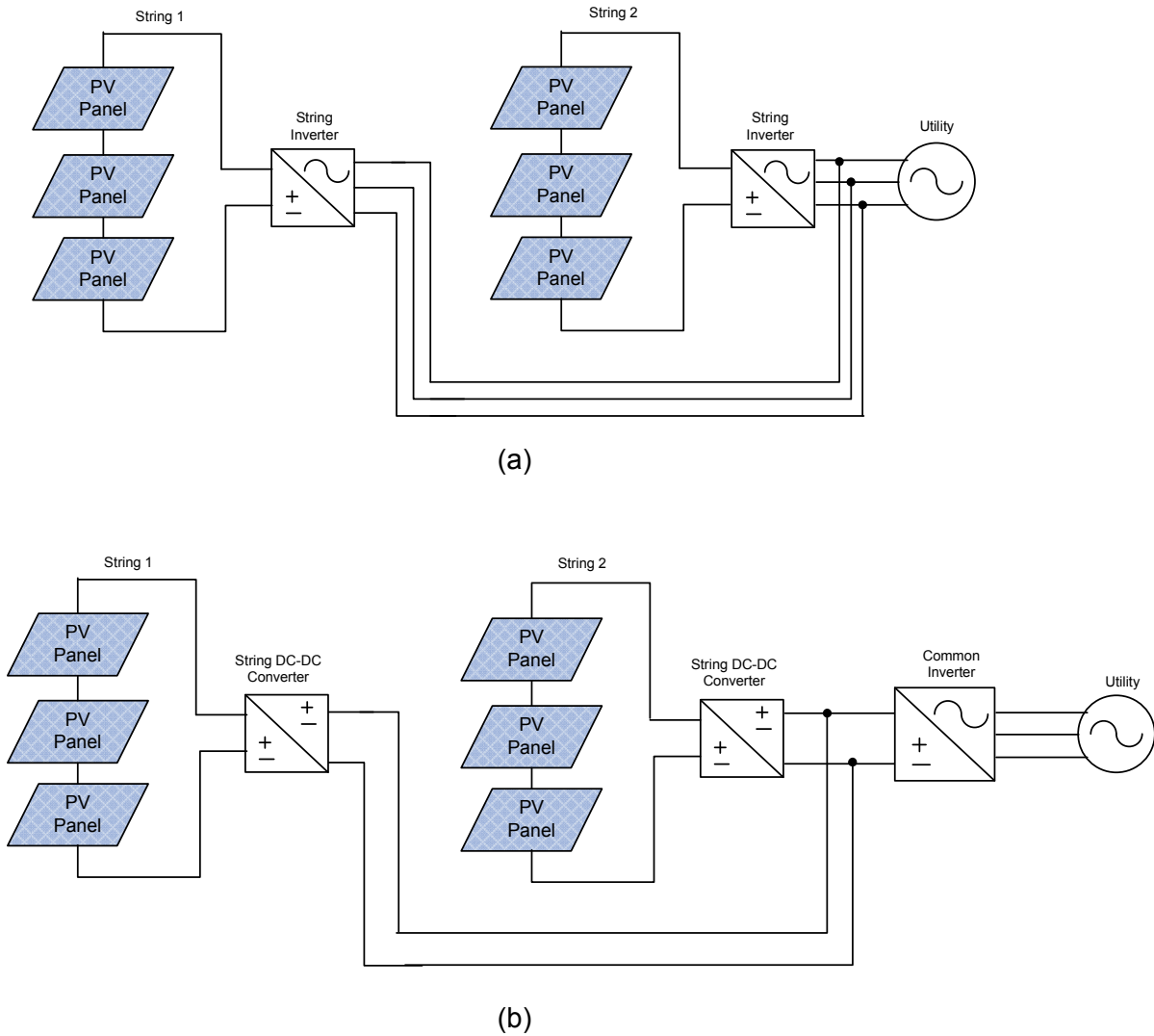
Figure 4 (a). PV panels in strings with individual inverters; (b). PV panels in a multi-string configuration

Figure 5 shows a configuration where each PV module has its own inverter. This design is also known as an AC-module. Advantages of this type of system are that it is easy to add modules because each module has its own DC-AC inverter and the connection to the utility is made by connecting the inverter AC field wirings together. There is also an overall improvement in system reliability because there is no single-point failure for the system (Blaabjerg et al. 2004; Kjaer et al. 2005; Islam et al. 2005). It is a highly flexible and configurable design topology; however, prior examples of this configuration are still more costly than the conventional PV systems because of the increased number of inverters. The power loss of the system is lowered due to the reduced mismatch among the modules, but the constant losses in the inverter may be the same as for the string inverter. The power electronics are typically mounted outside together with the PV panel and need to be designed to operate in an outdoor environment. The AC-module seems to be a promising option for future designs as it can be used as a plug-in device by individuals without specialized knowledge (Kjaer et al. 2005).
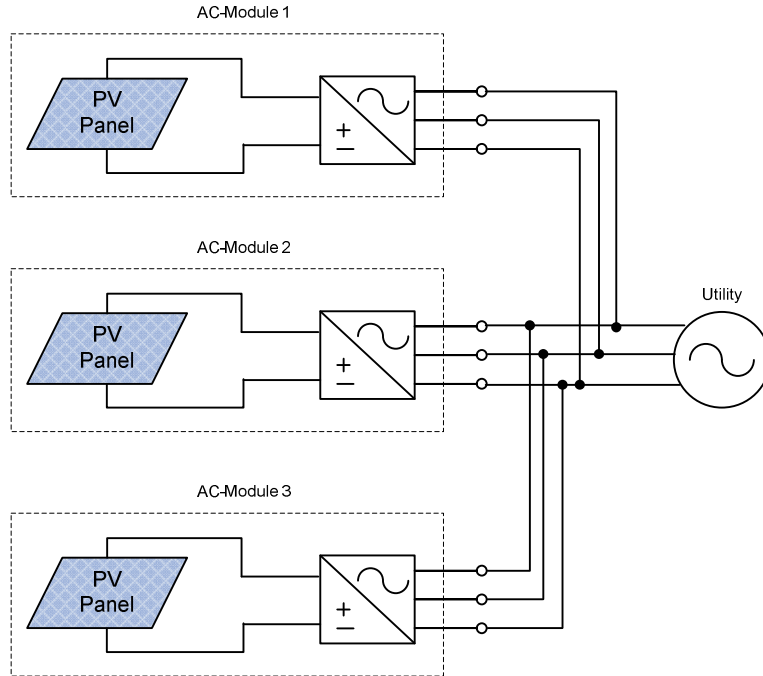
Figure 5. AC-Module power electronics configuration

2.3   Power Electronics Topologies

The power electronics topologies for the PV systems can be categorized on the basis of the number of power processing stages, the location of power decoupling capacitors, utilization transformers, and the types of grid interfaces (Carrasco et al. 2006). The basic classification based on the number of inverter output phases is presented next.

2.3.1   Single Phase – Single Stage

The most fundamental topology for a PV inverter is a single-phase, self commutated PV system as shown in Figure 6. The DC output of the PV array is connected across a filter capacitor. The capacitor is used to limit the harmonic currents in the array. The output of the capacitor connects to a full-bridge converter and the output of the converter is connected to an inductor, limiting the high frequency harmonics injected into the AC system. A synthesized AC output voltage is produced by appropriately controlling the switches and consists of a controlled series of positive and negative pulses that correspond to the positive and negative half cycles of a sinusoid. To enable operation at or near unity power factor, the switches are controlled in response to the measured PV array output voltage to produce the required AC output voltage. A phase-locked-loop (PLL) is utilized to synchronize the inverter output voltage to the grid voltage (Wasynczuk 1984). The PV array is then connected to the utility grid through an electrical isolation transformer. There are several drawbacks of this topology, one being that all of the modules are connected to the same MPPT device. This causes severe power losses during partial shadowing.

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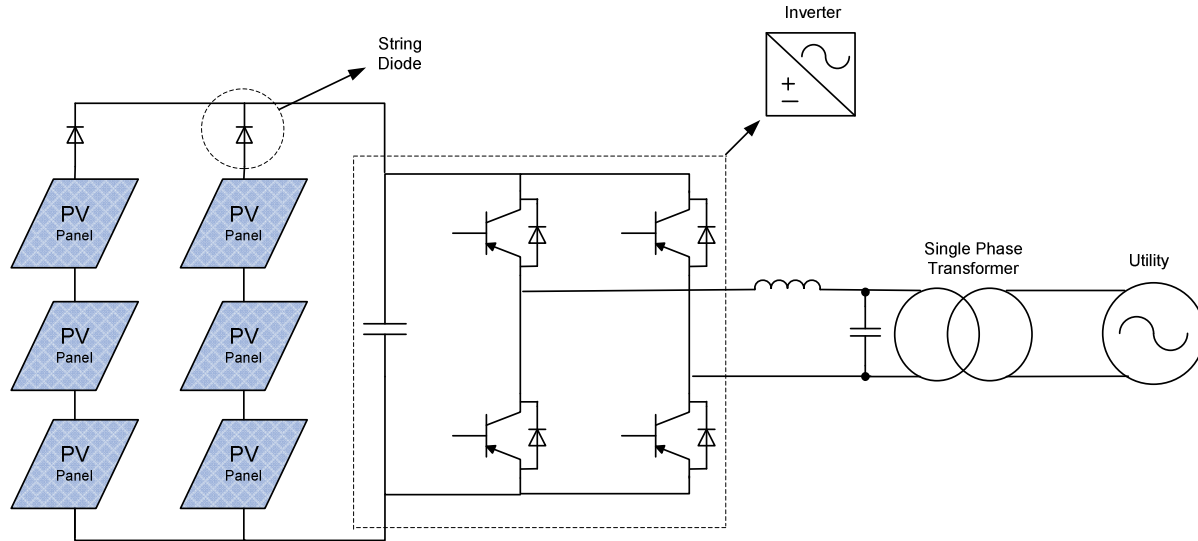
Figure 6. Single-phase single-stage PV power electronics

2.3.2 Single Phase – Multiple Stage

To avoid bulky, low-frequency transformers, which are regarded as a poor component mainly due to their relatively large size and low efficiency, the multiple stage (two-stage) conversion systems are widely used for PV generation. The most common two-stage topologies consist of a DC-AC grid-connected voltage source pulse width modulation (PWM) inverter with some kind of DC-DC PV connected converters. In general, the DC–DC converter performs the maximum power point tracking (MPPT) and, perhaps, voltage amplification (Kjaer et al. 2005). The DC–AC full-bridge inverter controls the grid current by means of PWM or "bang-bang" operation. A simple design for a multiple stage PV inverter is shown in Figure 7, which utilizes a high frequency transformer for a single phase connection to the grid (Mohan et al. 2003). The DC voltage input is inverted to produce a high frequency AC across the primary of the high frequency transformer. The transformer secondary voltage is rectified and the resulting DC output is interfaced with the line voltage through a line-frequency line-voltage-commutated thyristor inverter. Since the line current is required to be sinusoidal and in phase with the line voltage, the line-voltage waveform is measured to establish the reference waveform for the sinusoidal line current whose amplitude is determined by a peak power-tracking controller. The inverter can be controlled using current regulated controllers. Several topologies exist for single-phase, dual-stage grid connected inverters as can be found in Blaabjerg, Chen, and Kjaer's, "Power Electronics as Efficient Interface in Dispersed Power Generation Systems," and Kjaer, Pedersen, and Blaabjerg's "A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules."
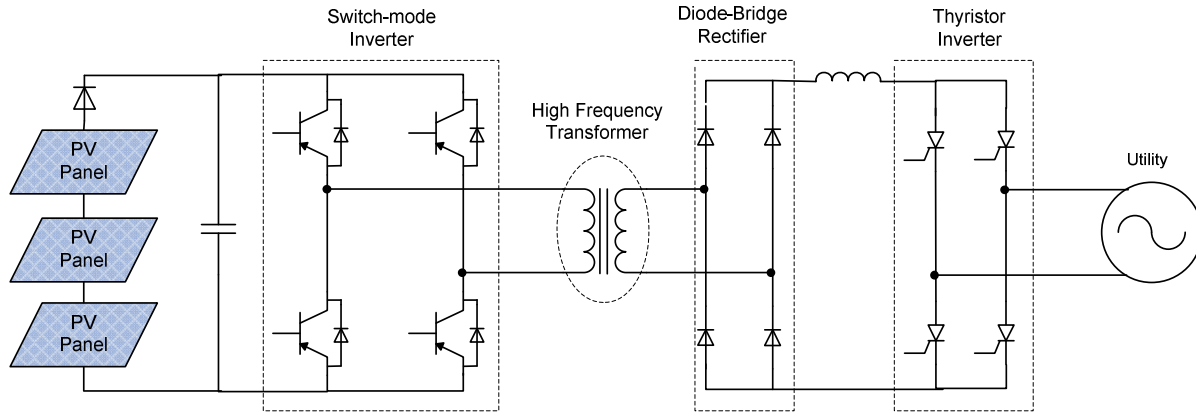
Figure 7. Single-phase multiple-stage PV power electronics

2.3.3 Three Phase

For larger systems over 10kW, three-phase inverters are most often used. All the configurations described for single-phase utility connection can be used for the three phase. Again, the isolation from the grid can be done either by using a line-frequency transformer or a high-frequency transformer. In the later case, an additional converter is required for converting DC from PV into high-frequency AC.

Figure 8 shows a typical topology for a three-phase PV inverter utilizing a line-frequency three-phase transformer. The DC output of the PV array is connected across a filter capacitor. The output of the capacitor connects to the input of a voltage-source three-phase inverter. The output of each phase of the converters is connected to an inductor and capacitor to limit the high-frequency harmonics injected into the AC system. A synthesized AC output voltage is produced by appropriately controlling the switches. A three-phase transformer is then used to connect the power to the utility.
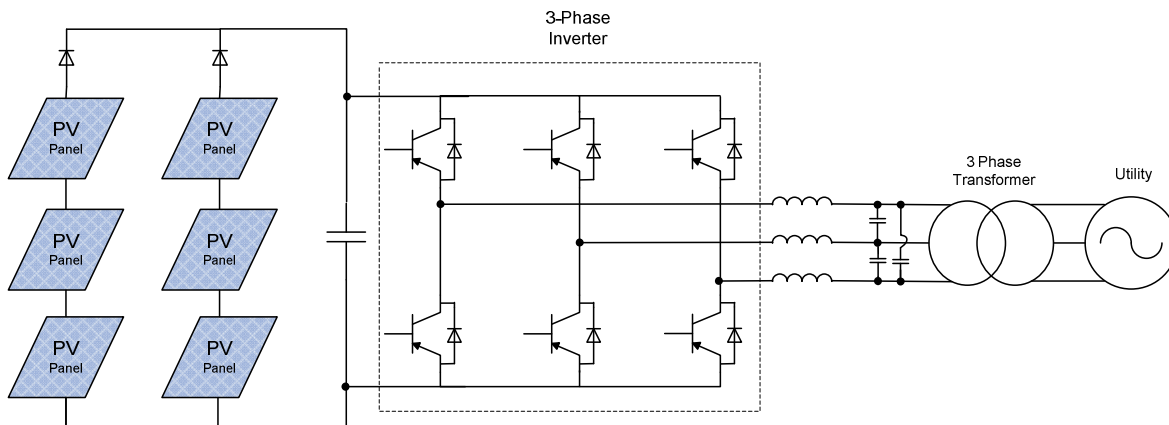
Figure 8. Three-phase PV topology with line-frequency transformer

Different configurations without transformers can be used for the PV system; however, such topologies are more for the European countries and Japan where system grounding is not mandatory for the PV inverters. In the United States, the National Electrical Code (NEC) Article

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690 requires that the PV modules be system grounded and monitored for ground faults when the maximum output voltage of the PV modules reaches a certain level (e.g., 50 V) (Kjaer et al. 2005). Only a few transformer-free, high-input voltage topologies that can be grounded both at the input and at the output are yet known. Modern inverters tend to use a high-frequency transformer for galvanic isolation. This technology results in entirely new designs, such as the printed circuit board (PCB) integrated magnetic components (Kjaer et al. 2005). One such design is shown in Figure 9, where the transformers are embedded in high-frequency DC-DC converters. Such a topology is also very useful for multi-string configurations, where each of the strings can be connected to a common DC bus and then converted to grid compatible AC by using a single DC-AC inverter.
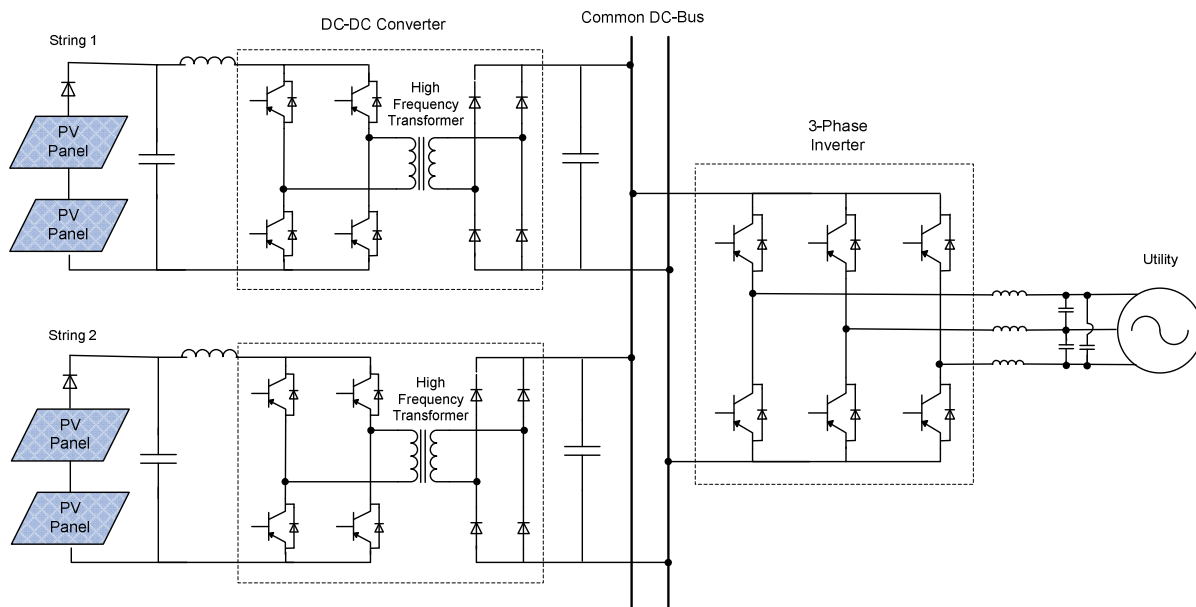
Figure 9. Multi-string PV topology with high-frequency transformer-based isolation

2.4 Generalized Power Electronics and Control

From the discussion in the previous subsection, it can be observed that the most generalized form of power electronics topology for the PV application is the DC-DC converter with embedded high-frequency transformer, along with the DC-AC inverter as shown in Figure 9. In general, the MPPT and voltage boost are done by the DC-DC converter controller. The power flow control to the utility and the sinusoidal unity power factor current-injection to the utility is produced by the DC-AC inverter controller. A simplified block diagram of the PV system with the power electronics and control is given in Figure 10.
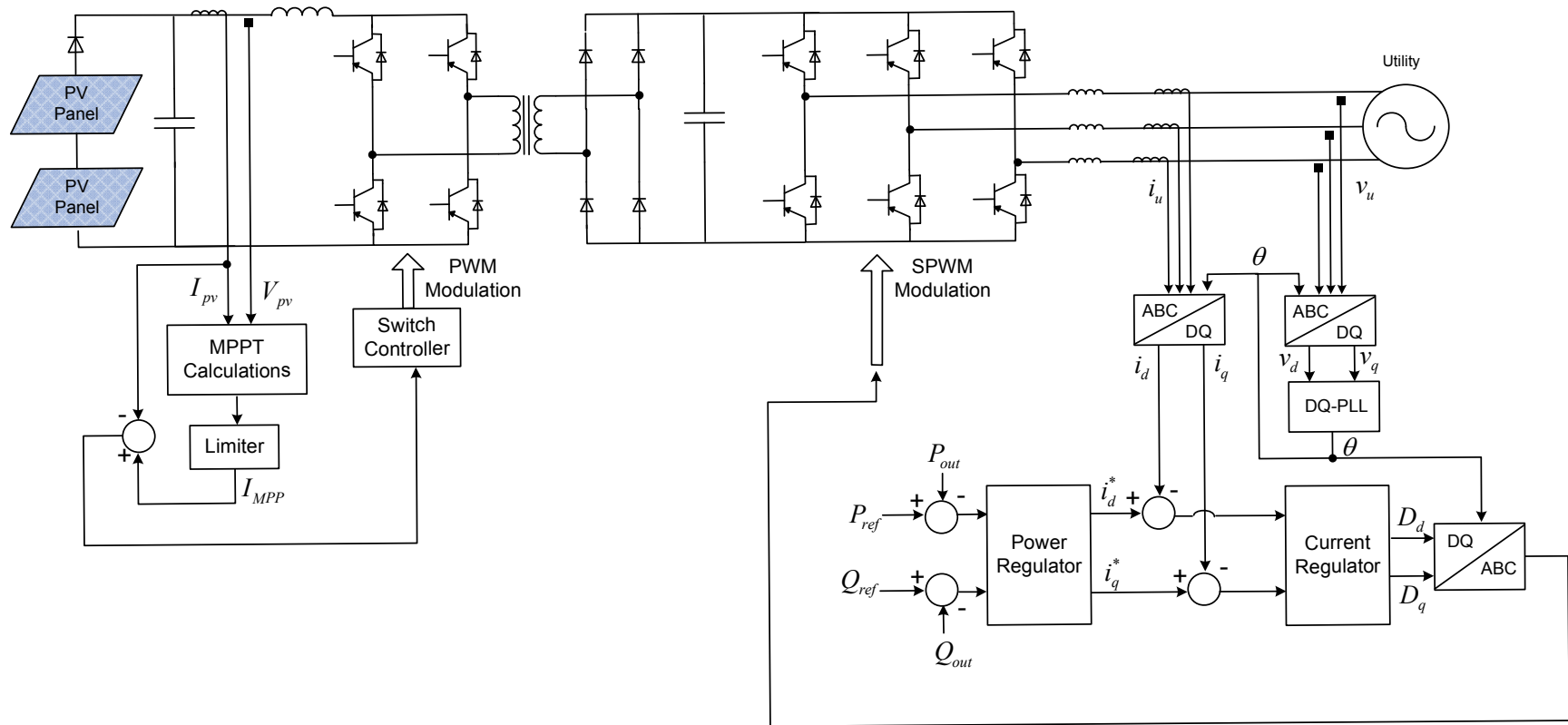
Figure 10. Generalized power electronics and control of a PV system

The power electronics circuits shown in Figure 10 consist of a DC-DC converter and a three-phase inverter. The DC-DC converter is based on current-source full-bridge inverter with an embedded high-frequency transformer and rectifier. As this inverter includes galvanic isolation between the PV string and the grid, the PV strings can be easily system-grounded and compatible with the NEC Article 690 requirements. The current-source input stage is beneficial since it reduces the requirement for the filter capacitor in parallel with the PV strings. Furthermore, the diodes included in the rectifiers are current-commutated, involving low-reverse recovery of the diodes and low voltage stress (Kjaer et al. 2005). The voltage from the PV string is first converted into a high-frequency AC; galvanic isolation with voltage boosting is accomplished through the use of a high-frequency transformer. The transformer secondary voltage is then rectified using a full-bridge diode rectifier. The rectified DC is then converted into grid compatible AC and connected to the utility by a three-phase voltage-source inverter.

Tracking the maximum power point (MPP) of a PV array is usually an essential part of a PV system. Over the years, many MPPT methods have been developed and implemented. These methods vary in complexity, required sensors, convergence speed, cost, range of effectiveness, implementation hardware, popularity, etc. The names of some of these methods are hill climbing, perturb and observe, incremental conductance, fractional open-circuit voltage, fractional short-circuit current, fuzzy logic and neural network control, ripple correlation control, current sweep, DC-link capacitor droop control, load-current or load-voltage maximization, and dP/dV or dP/dI feedback control. The detailed overview of these MPPT methods can be found in T. Esram and P. L. Chapman's "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques."

In Figure 10, a simple but effective method for the MPPT is shown. By measuring the string voltage and current, the PV array output power is calculated and compared to the actual PV array output power. Depending on the result of the comparison, the duty cycle is changed to control the input current for the current-source inverter, accordingly. This process is repeated until the maximum power point has been reached. Other types of MPPT controllers can also be developed within the same controller framework. Furthermore, additional controllers can be designed to control the amplitude of the high-frequency AC voltage at the primary of the transformer.

There are two basic control modes for the grid-connected inverters. One is constant current control; the other is constant power control. It is still debatable if an inverter should be allowed to regulate voltage during grid-connected operation. The current IEEE 1547 standard does not allow distributed generation to actively regulate voltage, while some people in the industry suggest that voltage regulation may have some positive impact on the grid (Ye et al. 2006). Control of the utility-connected inverter is shown with constant power control (see Figure 10). Many functions to manage practical issues are not shown in the diagram, such as the negative sequence regulation, d-q decoupling, etc. The inner central loop regulates current, and the other control loop regulates power. In some cases, the reactive power reference, Q_{ref}, could be a power factor reference. By controlling this reference, the injected current to the utility can be maintained at unity power factor. Also, a variation of the constant power control can be implemented to maintain the inverter DC bus voltage at a constant value. In that case, the active power P_{ref}, can be replaced with V_{dref}, and P_{out} can be replaced with V_{dout} so the DC voltage is regulated to the setpoint V_{dref}. The output of this outer control loop is the setpoint I^*_d, which is used as a reference signal to the current regulator. When DC bus voltage is increasing, meaning

the power from the primary source is increasing; it is charging the DC capacitor. In order to maintain the DC bus voltage, the i^*_d will be increased so that the power can be transferred to the inverter output. More details of d-q based controllers can be found in Appendix B.

3   Wind

3.1   General Description

Wind turbines convert kinetic energy in the wind into mechanical power that can be converted into electrical energy with a generator. Power is normally generated either with an induction generator or with a synchronous generator. Synchronous generators are typically interconnected to the grid through power electronics. Power output is typically between 10kW to 2.5 MW and wind power is captured using a blade that is connected to the rotor of a generator. The power is generated only when the wind blows. Like PV systems, there are no fuel costs, but periodic maintenance of the wind turbines is required (Farret and Simoes 2006). A 100 kW wind turbine is shown in Figure 11.

Figure 11. 100-kW wind turbine (NREL 2008)

3.2   Wind System Configurations

In the last two decades, wind energy has matured to a level of progress where it is has become widely accepted as a utility generation technology. The growth of the world-wide wind-turbine market in the last five years has been around 30% a year, and wind power is playing an increasingly important role in electricity generation. The main components of a popular wind turbine system are illustrated in Figure 12, including the turbine blades, gear box, generator, transformer, and potential power electronics (Chen and Blaabjerg 2006).
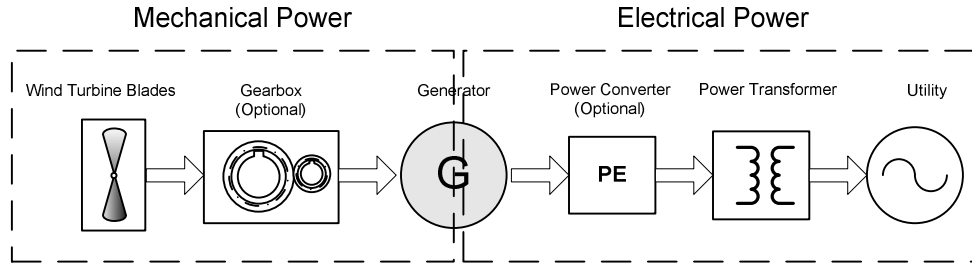
Figure 12. Main components of the wind generation system

Modern wind turbine technology can fundamentally be divided into three categories: 1) the systems without power electronics; 2) the systems with partially rated power electronics; and 3) the systems with full-scale power electronic for interfacing wind turbines (Chen et al. 2004).

Systems without power electronics use an induction generator. The wind turbine spins the rotor shaft of a squirrel cage-rotor induction generator connected directly to the grid without any power electronics (PE) interface. This wind turbine must operate at a constant speed (with an allowable variation of 1-2%) and adjusts the rotor speed by controlling the pitch of the wind turbine blades (Chen et al. 2004). The induction machine requires reactive power to operate that can be either supplied from the utility grid or by capacitors connected at the machine terminals. These machines cannot deliver any reactive power and generally require a soft-starter to reduce the inrush currents during start-up (Chen et al. 2004). Figure 13 shows the basic configuration of this design.
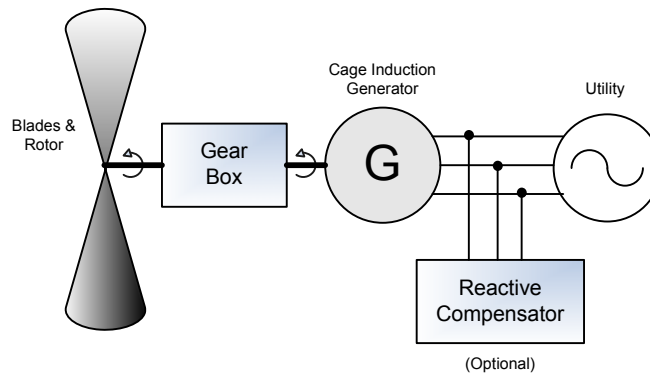
Figure 13. Direct connected induction generator power electronics configuration

Systems with partially rated power electronics, requires a wound-rotor induction machine where both the stator and rotor windings are accessible. Power from the spinning rotor (at slip frequency) is collected via slip rings. The output of the generator is passed through a PE based rectifier and inverter system, transforming the variable frequency into grid compatible AC power with the proper voltage and frequency. Figure 14 (a) shows a wind turbine system where the generator is a wound-rotor induction generator. An extra resistance controlled by power electronics is added in the rotor, giving a speed range of 2-4%. This solution also needs a soft starter and a reactive power compensator (Chen et al. 2004).

A medium-scale power converter with a wound rotor induction generator, known as doubly-fed induction generator (DFIG), is shown in Figure 14 (b). A power converter connected to the rotor

through slip rings controls the rotor currents. This design allows the wind turbine to have some amount of variable speed operation. 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. The solution is naturally a little bit more expensive compared to the classical solutions. The advantage of this design is that it provides reactive power compensation/production and increased energy capture from the wind. This arrangement allows the generator stator winding to be undersized by about 25%, with the power electronics making up the power difference from the rotor power (Chen et al. 2004).

(a)

(b)
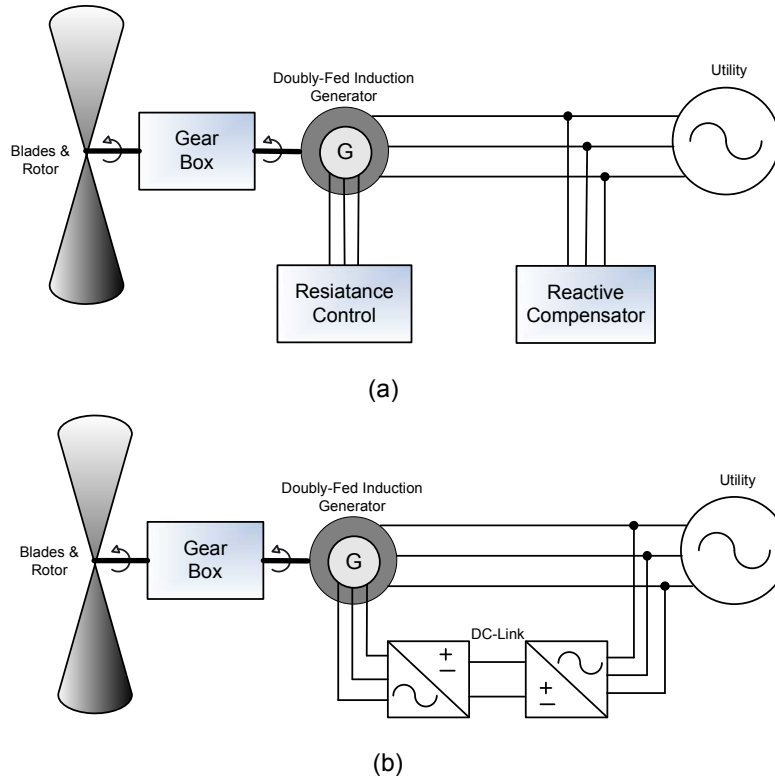
Figure 14. Induction generator with partially rated power electronics configuration (a) Rotor resistance controller, (b) Doubly-fed induction generator

A third type of wind turbine design is shown in Figure 15. The system uses full-scale power electronics for interfacing the wind turbine to the grid. The generating system uses a conventional or permanent magnet synchronous generator to convert the wind turbine power to a variable voltage, variable frequency output that varies with wind speed (Chen et al. 2004). A PE based rectifier and inverter are then used to convert the full rated output of the machine to power that is compatible with the utility system. This topology causes extra losses in the power conversion system, but it will provide additional power gain through the system's added technical performance. This design allows the wind turbine to operate in a variable speed mode, allowing more of the energy of the wind to be captured.
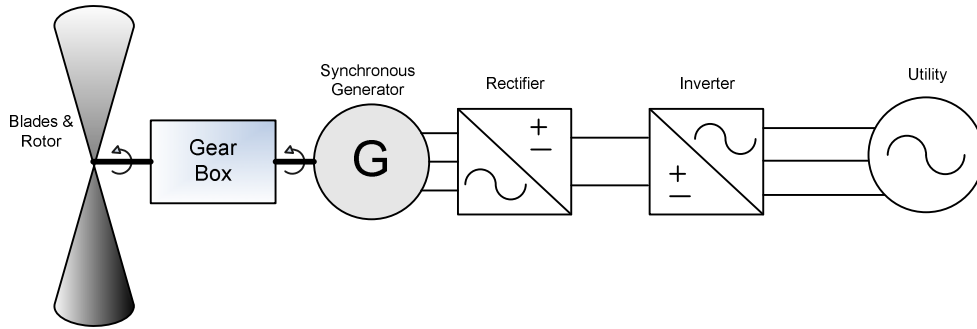
Figure 15. Synchronous generator power electronics configuration

3.3 Power Electronics Topologies

A typical power electronics topology that is used for a permanent magnet synchronous generator is shown in Figure 16. The three-phase variable voltage, variable frequency output from the wind turbine is rectified using a diode bridge. With the change in the speed of the synchronous generator, the voltage on the DC side of the diode rectifier changes. To maintain a constant DC-link voltage of the inverter, a step-up chopper is used to adapt the rectifier voltage. As viewed from the DC inputs to the inverter, the generator/rectifier system is then modeled as an ideal current source. This rectified output signal from the diode bride is filtered into a smooth DC waveform using a large capacitor (Carrasco et al. 2006). The DC signal is then inverted through the use of semiconductor switches into a three-phase, 60 Hz waveform. This waveform can then be scaled using a transformer to voltage levels required by the utility's AC system. The generator is decoupled from the grid by a voltage-sourced DC-link; therefore, this PE interface provides excellent controllable characteristics for the wind energy system. The power converter to the grid enables a fast control of active and reactive power. However, the negative side is a more complex system where more sensitive power electronic parts are required.
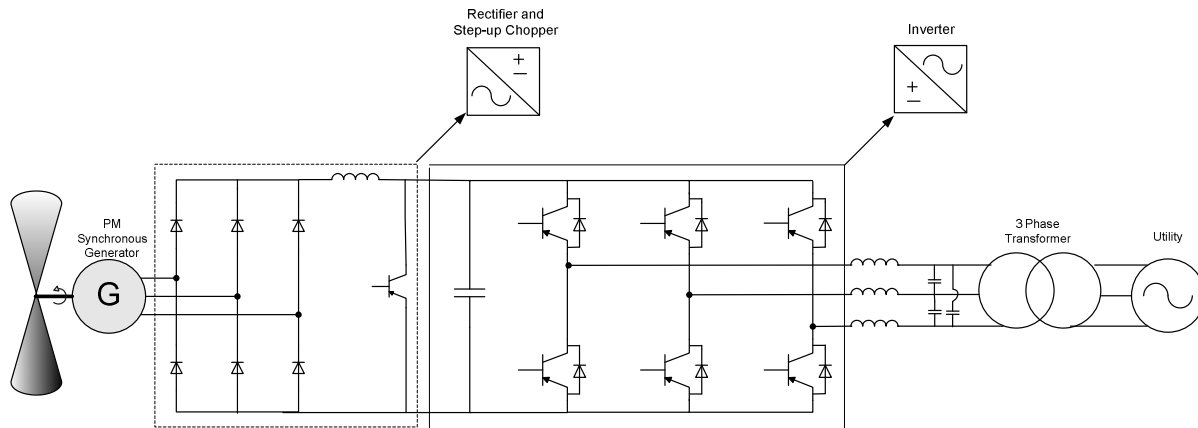
Figure 16. Synchronous generator power electronics topology

The power electronics required for the DFIG consists of an AC-DC-AC IGBT-based PWM converter. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at a variable frequency through the AC-DC-AC converter (Chen et al. 2004; Carrasco et al. 2006). A

typical DFIG electrical topology, as shown in Figure 17, uses a converter arrangement with back-to-back rectifier/inverter that shares a DC-link for power transfers. The AC side of the rectifier is connected to the rotor of the induction machine via slip rings; the output of the inverter is tied to the utility grid. This system can be classified as variable-speed constant frequency. The DFIG configuration is usually used in wind generators greater than 1 MW. Another PE based topology includes modular multilevel matrix converter designs. These designs can improve efficiency and are currently being developed (Erickson et al. 2004), but have not been implemented in commercial products.
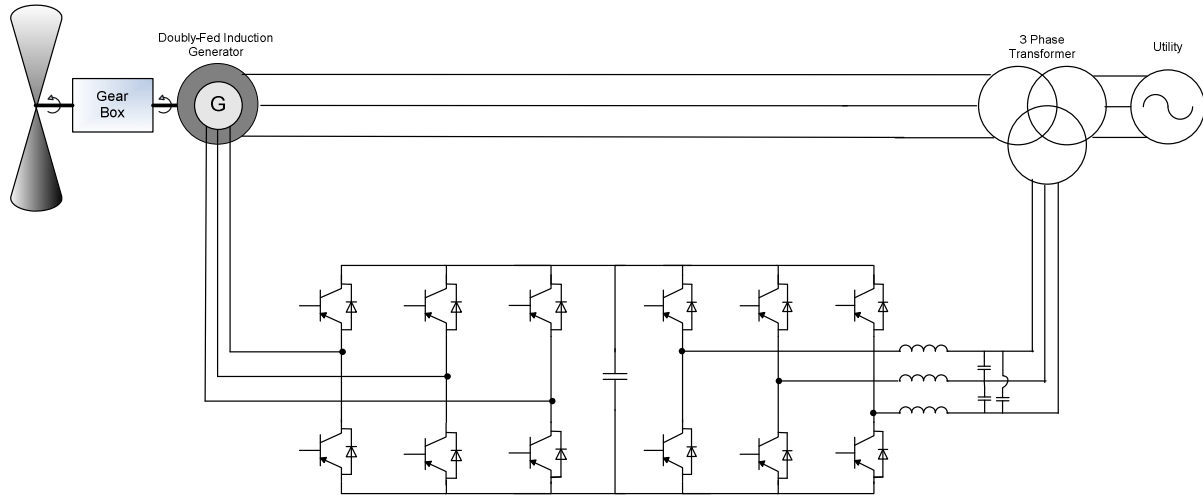
Figure 17. Power electronics AC-DC-AC converter for doubly-fed generator

3.4 Generalized Power Electronics and Control

From the discussion in the previous subsection, it can be observed that the most generalized form of power electronics topology for the wind energy application is the back-to-back rectifier/inverter connection which provides the improved power flow control as well as increased efficiency. The voltage-fed converter scheme used in such systems is shown in Figure 18. A PWM-based IGBT bridge rectifies the variable-frequency variable-voltage power from the wind generator. The rectifier also supplies the excitation needs for the induction generator. The inverter topology is identical to that of the rectifier, and it supplies the generated power at 60 Hz to the utility grid (Simoes and Farret 2004).
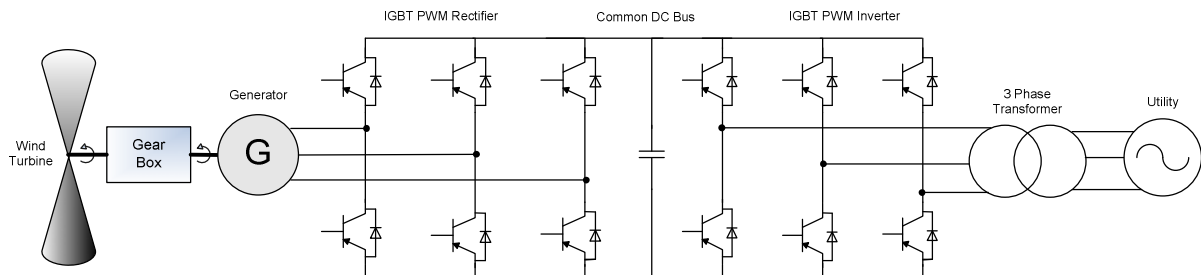
Figure 18. Generalized power electronics converter for wind systems

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This general structure is suitable for any type of wind energy systems. For the PM synchronous generator, as discussed in Figure 16, the rectifier and boost converter can be replaced by the PWM rectifier to achieve the same level of control. Similarly, for the induction generator based wind system, this power electronics topology is necessary for utility connection. Based on the control design for the back-to-back PWM converter system, various advantages can be obtained such as (Simoes and Farret 2004):

- The line-side power factor is unity with no harmonic current injection (satisfies IEEE 519);

- Wind generator output current is sinusoidal;

- There are no harmonic copper losses;

- The rectifier can generate programmable excitation for the induction generator based system;

- Continuous power generation from zero to the highest turbine speed is possible;

- Power can flow in either direction, permitting the generator to run as a motor for start-up (required for vertical turbine). Similarly, regenerative braking can quickly stop the turbine; and

- Islanded operation of the system is possible with a start-up capacitor charging the battery.
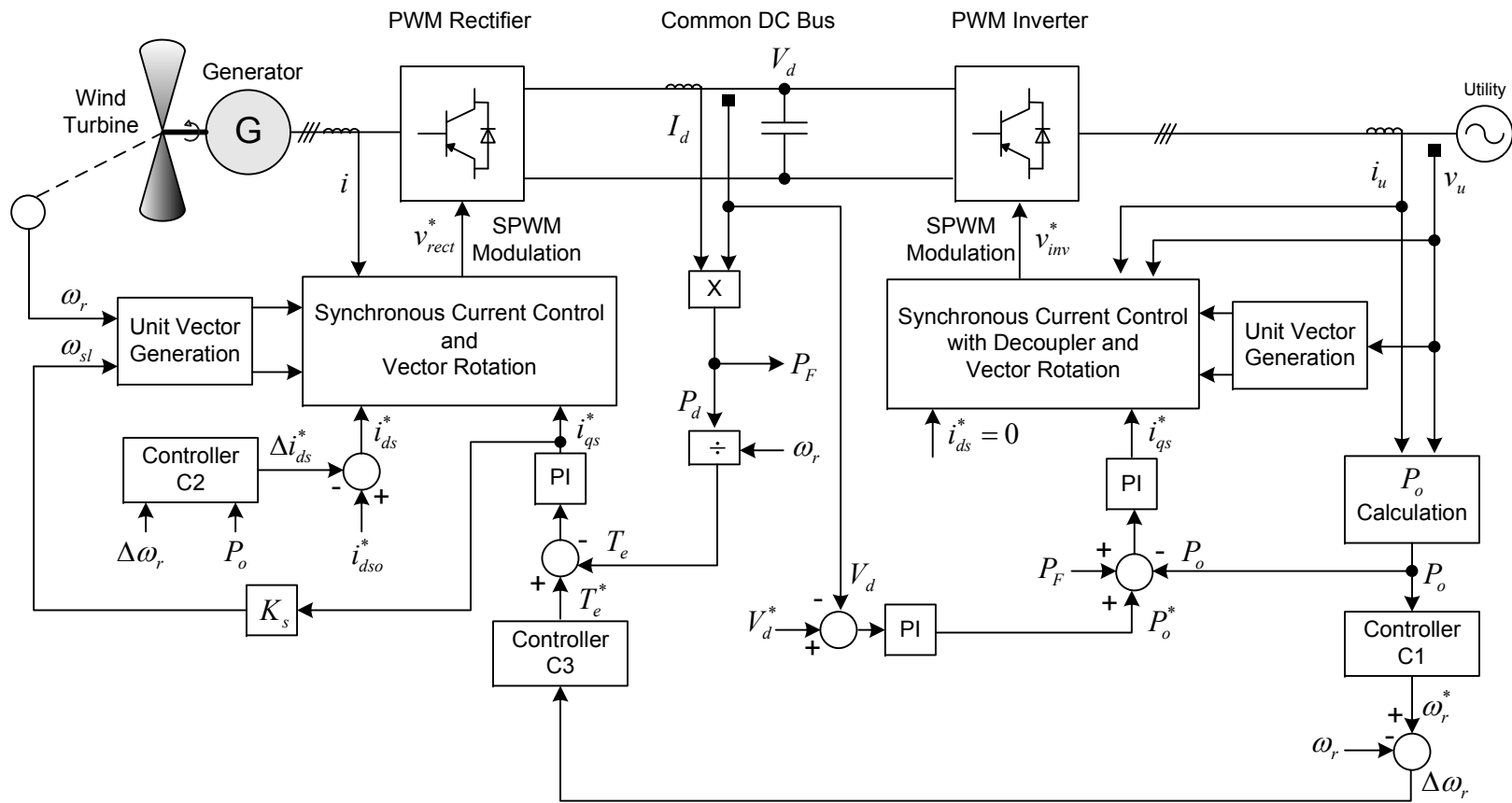
Figure 19. Control block diagram for double PWM converter with induction generator

To understand the importance of the double PWM converter based PE system for wind energy applications, a specialized control approach based on a squirrel-cage induction generator must be discussed. Similar controllers can be designed for other types of generators. Figure 19 shows the control block diagram of an induction generator with a double PWM converter-fed wind energy system that uses the power circuit shown in Figure 18. The induction generator and inverter output currents are sinusoidal due to the high frequency of the pulse-width modulation and current control as shown in the figure. The induction generator absorbs the lagging reactive current, but the reactive current is always zero on the line side; that is, the line power factor is unity. The rectifier uses indirect vector control in the inner current control loop, whereas the direct vector control method is used for the inverter current controller (Simoes and Farret 2004).

Vector control permits fast transient response of the system. Intelligent controls, such as a fuzzy-logic-based vector control, can be used to enhance three important characteristics in this system: 1) adaptive searching of the best generator speed command to track the maximum extractable power from the wind (by controller C1); 2) improving the generator efficiency by reducing generator rotor flux when the optimum generator speed set-up is attained in steady-state (by controller C2); and 3) robust control of the speed loop to overcome possible shaft resonances due to wind gusts and vortex (by controller C3) (Simoes and Farret 2004).

For a particular wind velocity (V_w), there is an optimum setting of generator speed (ω^*_r). The speed loop control generates the torque component of induction generator current, balancing the developed torque with the load torque. The variable-voltage variable-frequency power from the super-synchronous induction generator is rectified and pumped to the DC-link. The DC-link voltage controller regulates the line power Po (i.e., the line active current) so that the link voltage always remains constant. A feed-forward power signal from the induction generator output to the DC voltage loop prevents transient fluctuation of the link voltage (Simoes and Farret 2004).

With the DC-link bus voltage fixed, the induction generator can be excited with ids, as the rated flux is established in the induction generator. Next, a speed reference is commanded to rotate the turbine with the minimum turbine speed required to catch power from wind; the controller C3 is always working. The flow of wind imposes a regenerative torque in the induction generator. Of course, the power generation is not optimum yet, but the slip frequency becomes negative and the power starts to flow from the turbine towards the line side. As the power starts to flow to the line side, the DC-link voltage loop control can be gradually commanded to a higher value than the peak value of the line-side voltage (typically, 75% higher). After the DC-link voltage is established at its new higher value, the system is ready to be controlled by controllers C1 and C2 (Simoes and Farret 2004).

The IGBT PWM-bridge rectifier that supplies lagging excitation current to the induction generator also rectifies the variable-frequency variable-voltage power generated by the induction generator. The DC-link power is inverted to 60 Hz and fixed voltage AC is fed to the utility grid at unity power factor through an IGBT PWM inverter. The line-power factor can also be programmed to lead or lag by static volt-amperes reactive (VAR) compensation, if desired. The generator speed is controlled by indirect vector control, with synchronous current and torque control in the inner loops. The induction generator flux is controlled in open loop by control of the ids current, but under normal conditions, the rotor flux is set to the rated value for fast transient response. The line-side converter is also vector-controlled using direct vector control

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and synchronous current control in the inner loops. The output power P_o is controlled to control the DC-link voltage V_d. Since an increase of P_o causes a decrease of V_d, the voltage loop error polarity has been inverted. The details of the vector control and the specialized controllers can be found in Simoes and Farret's, "Renewable Energy Systems: Design and Analysis with Induction Generators." Additional control functions such as monitoring grid power, protection, and islanding can also be incorporated into the line-side converter.

4 Microturbines

4.1 General Description
Microturbines were developed and customized for customer-site electric user applications by the industry through improvements in auxiliary power units originally designed for aircrafts and helicopters. The output power of typical microturbines is between 30 kW and 400 kW. These are used for distributed electrical power generation or in combined cooling, heating, and power (CCHP) systems (Farret and Simoes 2006).

Microturbines can burn a variety of fuels including natural gas, gasoline, diesel, kerosene, naphtha, alcohol, propane, methane, or digester gases. The majority of commercial devices presently available use natural gas as their primary fuel (Farret and Simoes 2006). Modern microturbines have dramatically progressed with advanced components such as inverters, heat exchangers (recuperators), power electronics, communications, and control systems.

In most configurations, the turbine shaft spinning at up to 120,000 rpm drives a high-speed generator. The high-frequency output from the generator is first rectified and then converted to AC power. The systems are capable of producing power at around 25-30% efficiency by employing a recuperator that transfers heat energy from the exhaust stream back into the incoming air stream. The systems are air-cooled, and some even use air bearings, eliminating water and oil systems. Microturbines are appropriately sized for commercial buildings or light industrial markets for combined heat and power (CHP) or power-only applications (Staunton and Ozpineci 2003). A typical microturbine system is shown in Figure 20.

Figure 20. Microturbine (NREL 2008)

4.2 Microturbine System Configurations
The shaft construction defines many important characteristics of the microturbine that eventually influence the required power electronics and control system. There are two primary types of shaft construction: single-shaft and split-shaft (Farret and Simoes 2006). In a high-speed, single-

shaft design, the compressor and turbine are mounted on the same shaft and the alternator rotates at speeds of 90,000 to 120,000 revolutions per minute (rpm). The microturbine drives a high-frequency generator that may be either synchronous or asynchronous (Staunton and Ozpineci 2003). The caged rotor design in asynchronous (or induction) generators tends to make it a less costly alternative to synchronous generators (Zarringhalam and Kazerani 2004). Synchronous generators contain a magnetic rotor that is designed to use either rare earth permanent magnets or coils with additional hardware for delivering current (e.g., slip rings, brushes). Although asynchronous generators are somewhat rare in the industry for microturbine applications, they are gaining more popularity in other distributed generation systems such as wind energy (Staunton and Ozpineci 2003).

In conventional low-speed gas turbine applications, synchronous generators have an advantage as they can be connected directly to the grid if speed is properly regulated. This is generally not the case in high-speed microturbine applications. For all generator types, the generated three-phase high-frequency voltage, typically in the range of 1000 Hz to 3000 Hz, must be converted to line frequency before the generated power becomes usable for the consumers and/or for the utility (Staunton and Ozpineci 2003). Figure 21 shows a general diagram for a microturbine generator system along with a power converter (Mansir 2005). The power converter essentially converts high-frequency AC to 60 Hz AC. The power converter can also be designed to provide valuable ancillary services to the consumer and/or to the power grid. These services may include voltage support, sag support, static VAR compensation, load following, operating reserve, backup supply, and/or start-up power for the microturbine or other local microturbines (Staunton and Ozpineci 2003).
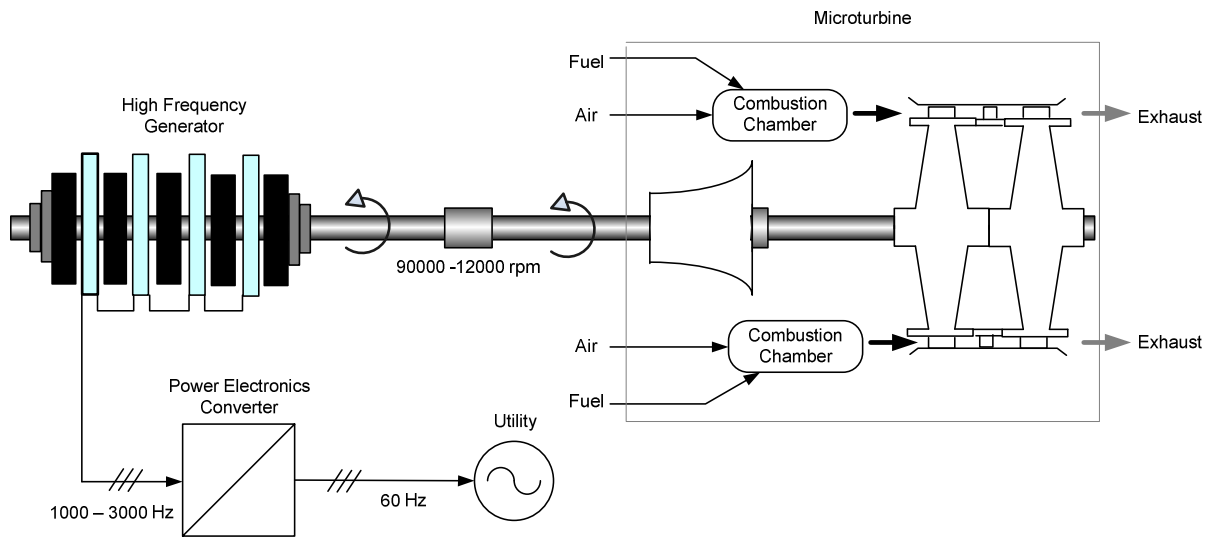
Figure 21. Basic microturbine and power electronics configuration

The single-shaft, high-speed microturbine system can be of different configurations depending on the power converter. The most common power converter topology that is used for connecting microturbines to the grid is the DC-link converter. The high-frequency power from the generator must be converted to DC first either by using a diode-bridge passive rectifier or a self-commuted active rectifier. The DC-link is then used to construct three phase voltages at 60 Hz using a DC-

AC inverter. Figure 22 shows a microturbine generator feeding power to the utility by DC-link converter.
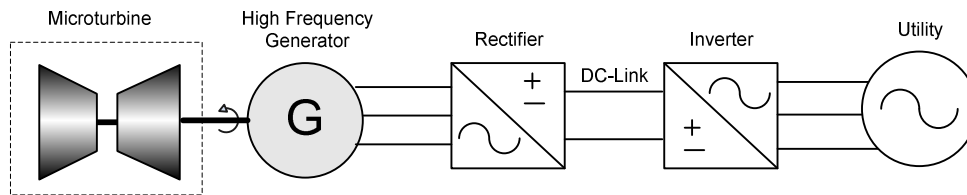
Figure 22. Microturbine configurations with DC-link power converters

Another type of high-interest power conversion system is the high-frequency link converter (HFLC). Figure 23 shows a microturbine generator feeding three-phase power to a rectifier and the DC is then fed to a high-frequency, single-phase inverter so that a compact, high-frequency transformer can be used. The secondary of the transformer feeds an AC-AC converter that takes the single-phase, high-frequency voltage to produce a three-phase voltage at the frequency and phase needed to make a direct connection to the grid (Staunton and Ozpineci 2003). Although the HFLC requires a higher number of parts, the circuit provides several advantages, including: the use of a transformer for robust isolation; the use of compact, high-frequency transformers; easier addition of other isolated loads and supplies via additional windings and taps; and elimination of the need for static transfer switches (Staunton and Ozpineci 2003). No microturbine manufacturer is presently marketing generation systems using HFLC, but it is certainly a configuration of future interest due to the smaller size of the converters, less passive elements, as well as other advantages of the high-frequency AC (HFAC) based system.
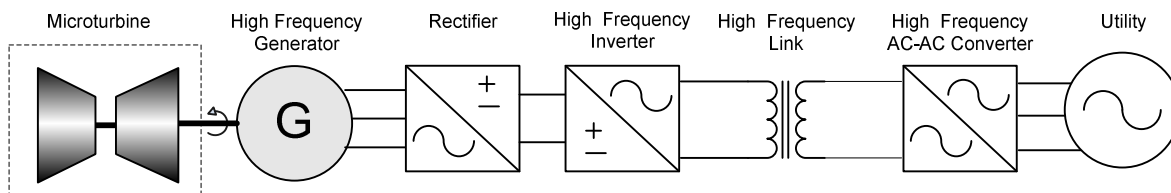
Figure 23. Microturbine configurations with an HFAC-link power converter

The shortcomings of the AC-DC-AC conversion units are large physical dimensions, heavy weight, and excessive volume/foot-print of the DC-link component, such as the DC capacitor (and if applicable, the inductor), and the low reliability of the DC capacitor. To overcome these problems, a cycloconverter or a matrix converter can be used to connect the microturbine generator to the grid instead of using a rectifier and an inverter (Staunton and Ozpineci 2003). These converters, as shown in Figure 24, directly convert AC voltages at one frequency to AC voltages at another frequency with variable magnitude. For this reason, they are also called "frequency changers". The disadvantages of these converters are that they have higher number of switches compared to the DC-link approach, and they do not have a DC or AC link to store energy. Without energy storage in the converter, any fluctuations at either side of the converter will directly influence the other side. Additionally, unlike the DC-link converter or the HFLC, it is not possible to connect a battery or any other power source to these converters (Staunton and Ozpineci 2003). A cycloconverter or matrix converter can still be used for microturbines with the high-frequency link inverter. Instead of converting the generator voltage to DC and then to high-

frequency AC, a cycloconverter or matrix converter can directly convert the three-phase AC voltage to a single-phase high-frequency AC voltage (Staunton and Ozpineci 2003).
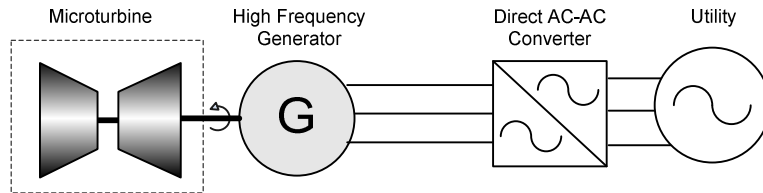
Figure 24. Microturbine configurations with direct AC-AC converter

Whereas the above discussions are based on the single-shaft high-speed microturbines, the split-shaft microturbines are very different in terms of design and electrical power output. The split-shaft design has a power wheel on a separate shaft and transfers its output to a conventional generator using a gear reducer (Farret and Simoes 2006). This system employs the conventional technology of the two-pole generator sets running at 3600 rpm. Although manufacturers claim that this type of microturbine does not need PE, it requires synchronizing equipment and relays for connection to the utility grid, and the gear reducer and lubrication systems require maintenance. Of the two turbines, one is a gasifier turbine driving a compressor and another is a free-power turbine driving a generator at rotating speed of 3600 rpm (Farret and Simoes 2006). As in conventional power plants, a two-pole permanent magnet generator running at constant speed can be directly connected to the utility distribution network after it is synchronized to the utility.

4.3 Power Electronics Topologies

Based on the discussion presented in the previous subsection, there are two basic power electronics topologies that can be used for the microturbine system. The first topology involves two converters with a common DC bus, one for converting high-frequency AC output from the microturbine to the DC; the second is for DC-AC conversion to get 60 Hz utility compatible AC. The second topology for the microturbine system is the direct AC-AC frequency changer in form of cycloconverter or matrix converter. As the HFLC topology is still only a concept, it is not included in this discussion.

A bidirectional power electronics converter that allows motoring and regeneration control of the high-frequency generator is shown in Figure 25 (a). The self-commuted active rectifier is used for AC-DC conversion. Figure 25 (b) shows a more simplified scheme where the generator voltage is rectified by a passive diode bridge and delivered to an inverter tied to the utility. The scheme provided by Figure 25 (a) is more flexible as it provides the starting-up features but it requires very fast devices and signal processing. On the other hand, the scheme in Figure 25 (b) requires standard power electronics devices, at the expense of an auxiliary mechanical start-up on the shaft for bringing the turbine to the optimal generation speed range. Most commercial turbines are constructed with a front-end rectifier as shown in Figure 25 (b) for lower cost and less complexity (Farret and Simoes 2006).

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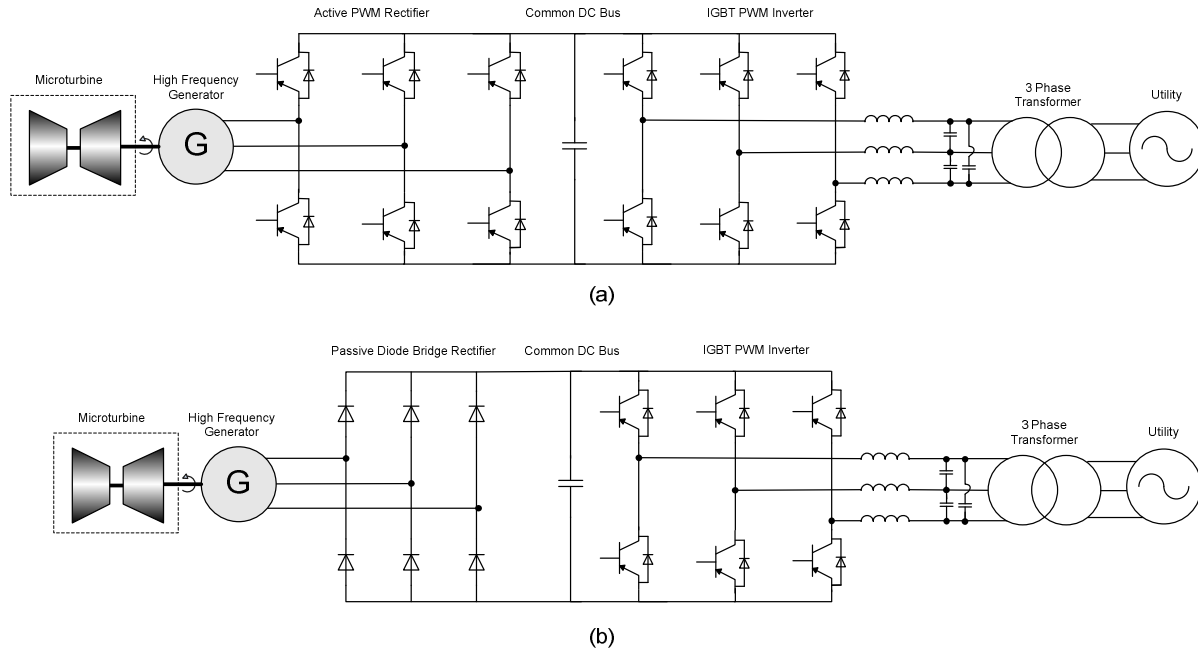
Figure 25. DC-link based power electronics topologies with (a) Active rectifier; (b) Passive rectifier

As mentioned in the previous subsection, the main limitations of the AC-DC-AC conversion unit are the large physical dimensions, weight, and excessive volume/foot-print of the DC-link component (i.e., the DC capacitor and the inductor, if applicable) and the low reliability of the DC capacitor. A direct AC–AC cycloconverter or matrix converter can be used for the microturbine and utility interface as an alternative to the conventional AC–DC–AC converter. The matrix converter based microturbine system, shown in Figure 26, eliminates the DC-link components and inherently resolves the size, weight, and reliability issues (Nikkhajoei and Iravani 2005). The main drawback of the matrix converter is the requirement for on-off controlled, bidirectional switches which are currently realized through back-to-back connection of IGBTs. This may result in higher switching losses than that of an AC–DC–AC conversion system (Nikkhajoei and Iravani 2005). Additionally, the DC capacitor of an AC–DC–AC topology provides suitable electrical terminals to interface an energy storage unit. The matrix converter, due to its inherent topology, eliminates such an option; therefore, other provisions are to be made if energy storage has to be included as an integral part of the microturbine system. Also, without energy storage in the converter, any fluctuations at either side of the converter will directly influence the other side.

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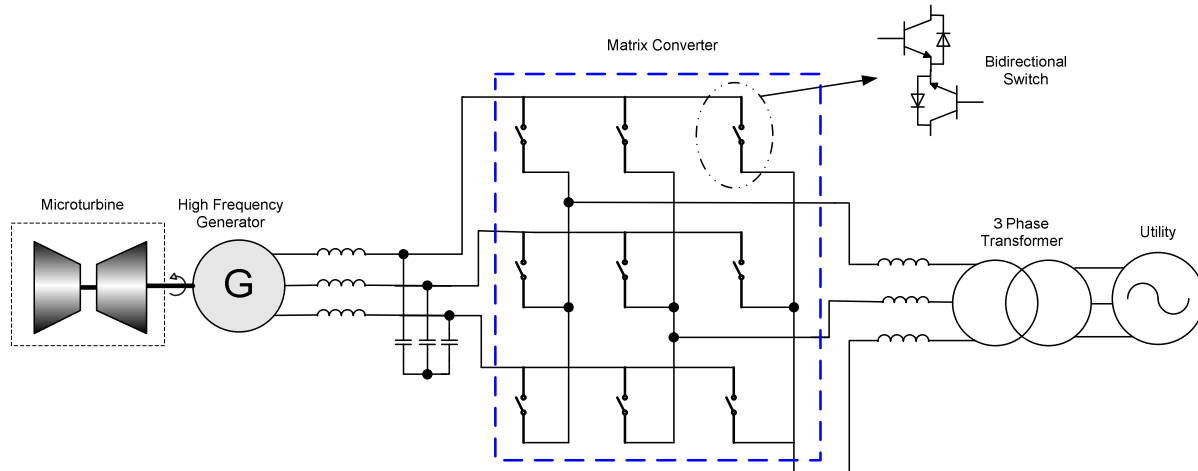
Figure 26. Direct AC-AC conversion by matrix converter

4.4 Generalized Power Electronics and Control

Based on the discussion in the previous subsections, it can be observed that the most generalized and versatile form of power electronics topology for the microturbine application is the back-to-back rectifier/inverter connection which provides the improved power flow control as well as increased efficiency. The voltage-fed converter scheme used in such a system is shown in Figure 27. A PWM-based IGBT bridge rectifies the high-frequency AC from the microturbine generator. The rectifier can also supply the needs for start-up and eliminates the requirement of a gear-box. The inverter topology is identical to that of the rectifier, and it supplies the generated power at 60 Hz to the utility grid.

The life span of a microturbine is closely related to the range and rapidity of its temperature changes. The total efficiency is optimal at a certain temperature and speed, which makes the microturbine more economical if it always runs at the optimum point (Farret and Simoes 2006). The purpose of the control system is to produce the demanded power while maintaining the optimal temperature and speed characteristics. In the stand-alone mode, the control system must maintain a constant voltage and be frequency insensitive to variations in the load power; therefore, a very fast control loop is required for stand-alone systems. This faster control is achieved at the expense of higher thermal variations in the machine, reducing its lifespan (Farret and Simoes 2006).
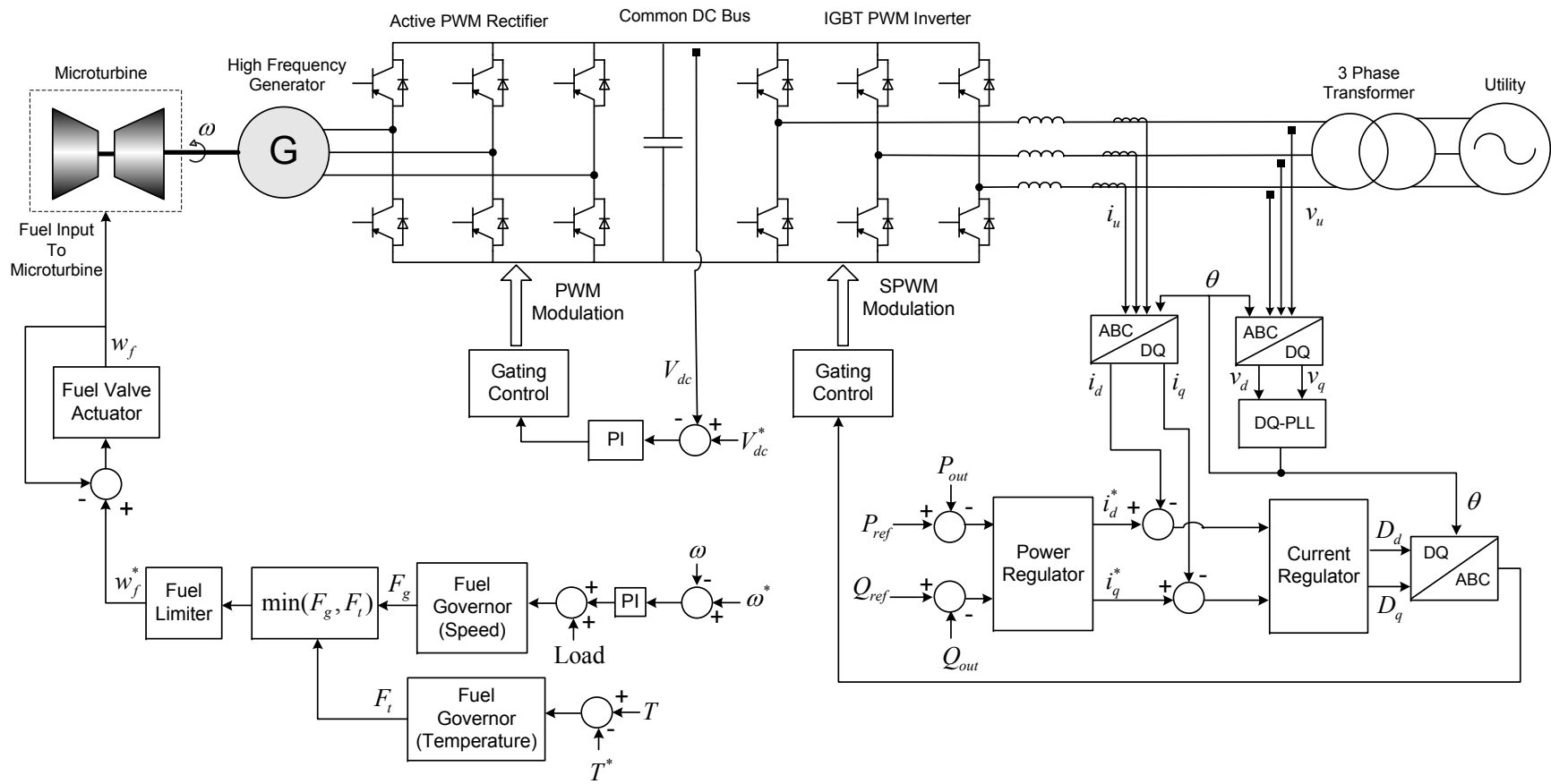
Figure 27. Generalized power electronics and control of a microturbine system

When a microturbine is connected to the grid, the gas turbine provides heat and power at a constant level to a local load. If the power demand in the local power grid increases to a higher value than the microturbine's maximum output, the additional power needed is provided by the utility. The microturbine usually runs at its optimum under a full load. Since the control system does not need to react to sudden changes, all control actions can be done slowly and the thermal fluctuations inside the gas turbine are minimized (Farret and Simoes 2006).

Three basic control loops can be designed for the control of the microturbine and associated power electronics system. The first control loop works to maintain the generator speed, whereas the other two loops maintain the rectifier DC-link voltage and the power flow control by the inverter (Bertani et al. 2004).

The speed control loop's operation depends on several microturbine system components, such as: fuel governor response, temperature rise time, valve position, combustion chamber response, time delay of the combustion chamber, compressor discharge, and turbine expansion (Farret and Simoes 2006). A simplified scheme for the generator speed control is shown in Figure 27. The control system consists of a normal speed regulator that tries to maintain a predefined reference speed (ω*). Such speed may not be the optimal for lower power loads, but the regulator tries to maintain the speed by controlling the fuel input to the turbine. It is very difficult to increase the speed without reducing the power load for a short moment and a very complex control must consider all of those variables. The upper performance limit is the limitation of the fuel injectors, and the maximum amount of fuel that can be injected is based on temperature limitations (Farret and Simoes 2006). The fuel demand is the input of a nonlinear transfer function representing the dynamics of the fuel valve actuator system; the output from the valve actuator system is the fuel input required for rotating the turbine shaft at the reference speed (Bertani et al. 2004).

The second control loop (shown in Figure 27) works as the DC-link voltage regulator. A reference DC-link voltage is set and the rectifier is controlled to follow the set-point. It consists of a PI regulator, acting on the Vdc error ($= V_{dc}^* - V_{dc}$) that provides the pulse-width modulation signal output required for the three-phase rectifier switches.

The control of the utility connected inverter, as shown in Figure 27, is developed with constant power control (Ye et al. 2006). Many functions to deal with practical issues are not shown in the diagram, such as the negative sequence regulation, DQ decoupling, etc. The power loops are on top of the current loops. In some cases, the reactive power reference Q_{ref} could be a power factor reference. By controlling this reference, the injected current to the utility can be maintained at unity power factor. Also, a variation of the constant power control can be implemented to start-up the microturbine generator. The output of the control system is the high-frequency sine PWM signals for the voltage-source inverter switches. More details of d-q based controller can be found in Appendix B.

5 Fuel Cells

5.1 General Description

Fuel cells that are currently being developed can be used as possible substitutes for the internal combustion engine in vehicles as well as in stationary applications for power generation. A fuel cell is an electro-chemical device which produces electricity without any intermediate power conversion stage. The most significant advantages of fuel cells are low emission of green house gases and high power density. The energy density of a typical fuel cell is 200 Wh/l, which is nearly ten times that of a battery (Blaabjerg et al. 2004). The efficiency of a fuel cell is also high, in the range of 40% to 60%. If the waste heat generated by the fuel cell is used for cogeneration, the overall efficiency of such a system could be as high as 80% (Blaabjerg et al. 2004). A typical stationary fuel cell system is shown in Figure 28.

Figure 28. Stationary fuel cell system (NREL 2008)

Fuel cells can be classified into five different categories based on the electrolyte chemistry: proton exchange membrane fuel cell (PEMFC); solid oxide fuel cell; molten carbonate fuel cell; phosphoric acid fuel cell; and aqueous alkaline fuel cell. In these kinds of fuel cells, PEMFCs are being rapidly developed as the primary power source in movable power supplies and distributed generation (DG), because of their high energy density, low working temperature, and firm and

simple structure (Xu et al. 2004). Table 2 provides a summary of various fuel cell types and corresponding characteristics (Distributed Utility Associates 2003).

Table 2. Summary of typical fuel cell characteristics for DE applications

Electrolyte Material	Operating Temp (Warm-up Time)	Anticipated Applications	Comments
Proton Exchange Membrane (PEMFC)	80 $^{\circ}$C (relatively short)	Stationary and vehicle	Minimum contamination and material problem
Alkaline (AFC)	Approx. 100 $^{\circ}$C (relatively short)	Space program	Susceptible to contamination, very expensive
Phosphoric Acid (PAFC)	Approx. 100 $^{\circ}$C (medium)	Stationary	Higher temperature and longer warm up time makes unsuitable for vehicles
Solid Oxide (SOFC)	1000 $^{\circ}$C (long)	Stationary	High temperature create material problems, steam generation could increase efficiency by cogeneration
Molten Carbonate (MCFC)	600 $^{\circ}$C (long)	Stationary	Same as SOFC

For the PEM type of fuel cell, hydrogen and oxygen gas are fed into the fuel cell. The fuel cell *anode*—a negative connection that conducts electrons those are freed from pressurized hydrogen molecules—typically has etched channels that uniformly distribute the pressurized hydrogen gas over the surface of a catalyst. The *cathode* is the positive connection of the fuel cell that carries electrons back from the external circuit to the catalyst, where it combines with hydrogen ions and oxygen, forming the water that is the byproduct of the fuel cell. The electrolyte is the proton exchange membrane, a specially treated material that allows the conduction of positively charged ions while not allowing electrons to pass through it. There is a catalyst material that facilitates the reaction of oxygen and hydrogen. The catalyst is usually made of a platinum powder coated on a carbon paper or cloth. The catalyst is porous to maximize the surface area that can be exposed to the hydrogen and oxygen. The platinum coated side of the catalyst faces the electrolyte. Figure 29 below shows a graphic of a proton exchange membrane fuel cell(PEMFC). The reaction described takes place in one cell, resulting in approximately 0.7 volts cell potential. Multiple cells can be placed in series, often called as a stack, to increase the DC voltage output (Distributed Utility Associates 2003).
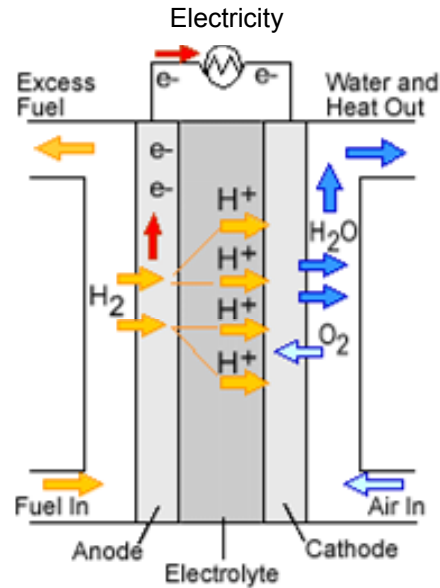
Figure 29. Proton exchange membrane fuel cell

A number of engineering problems need to be overcome before PEMFCs can be widely adopted for stationary power purposes. Most of these systems use expensive materials and have a low mean time before failure (Distributed Utility Associates 2003). The use of impure hydrogen causes the deterioration of electrolyte and catalyst materials, which can lead to replacement of the entire fuel cell after limited operation. One of the biggest technical barriers to widespread adoption of PEMFCs is the development of safe hydrogen distribution and storage systems. Hydrogen has a low energy/volume ratio compared to other fuels. Innovative research is being conducted to obtain and store hydrogen such as wind-electrolysis, thermo-chemical production, chemical hydride storage, etc (Levene et al. 2006).

5.2   Fuel Cell System Configurations

Fuel cells are similar to PV systems in that they produce DC power. 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.

The simplest form of fuel system configuration, as shown in Figure 30, consists of a fuel system stack followed by the DC-AC converter. If the isolation or a high ratio of the voltage conversion is required, a transformer is usually integrated into the system. The main drawback for this configuration is that the low-frequency transformer placed at the output of the inverter makes the system very bulky and expensive (Blaabjerg et al. 2004).
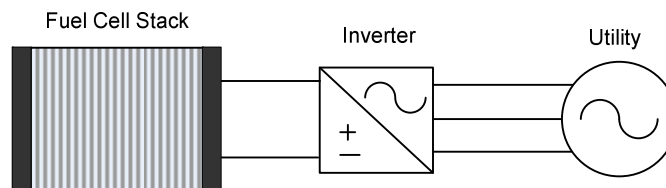
Figure 30. Fuel cell system configuration with a single inverter

A DC-DC converter is usually put between the fuel cell and the inverter, as shown in Figure 31. The DC-DC converter performs two functions: 1) it acts as the DC isolation for the inverter; and 2) it produces sufficient voltage for the inverter input so that the required magnitude of the AC voltage can be produced (Blaabjerg et al. 2004). The inverter can be single-phase or three-phase depending on the utility connection.
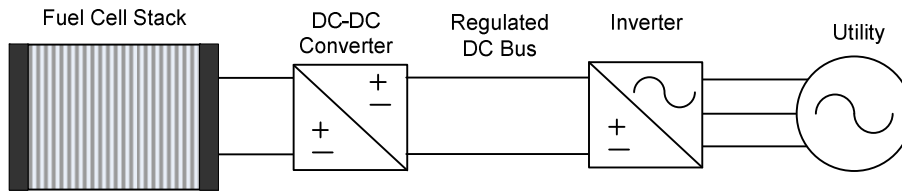
Figure 31. Fuel cell system configuration with cascaded DC-DC and DC-AC converters

Another possible configuration of the system includes a high-frequency DC-AC inverter which converts the fuel cell DC voltage into a high-frequency AC voltage. A cycloconverter is then used to change the high-frequency voltage into a power-frequency AC voltage, as shown in Figure 32 (Blaabjerg et al. 2004). This way, the power conversion is more direct than with a conventional DC bus structure with an isolated DC-DC converter. Moreover, the topology supports bidirectional power flow and is suitable for power conditioning systems that double as active filters (Nikkhajoei and Iravani 2005). This topology is more relevant for the single-phase utility connection.
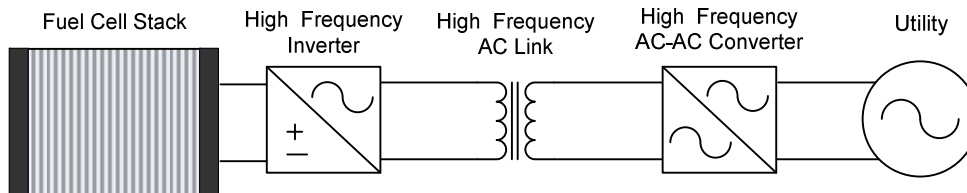
Figure 32. Fuel cell system configuration with cascaded DC-AC and AC-AC converters

5.3   Power Electronics Topologies

The power electronics topologies for fuel cell systems are varied and are based on the number and types of cascaded stages in the conversion systems. Two such topologies that can be used with fuel cells for supplying consumer loads and for utility connection include cascaded DC-DC and DC-AC converters (DC-link) and cascaded DC-AC and AC-AC converters (high-frequency link). There are also many recently developed and/or proposed circuit configurations for fuel cell applications, including a Z-source converter that combines functionality of DC-DC boost and Voltage-Source Inverter (VSI) (Blaabjerg et al. 2004).

5.3.1 Cascaded DC-DC and DC-AC Converters (DC-Link)

Many topologies can be used for DC-DC converters and DC-AC inverters, including hard-switching and soft-switching circuits (Blaabjerg et al. 2004; Cheng et al. 2001). The classical DC-DC converter, the H-bridge type forward converter shown in Figure 33 (a), is a well-developed and proven technology. However, in order to reduce the switching loss, soft-switching PE such as the H-bridge series-resonant converter shown in Figure 33 (b) can be used. Whereas

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the hard-switching forward converter requires a very accurate bi-polar waveform or current mode control to prevent the transformer from experiencing saturation and causing extra losses (Cheng et al. 2001), the main advantages of the resonant converter are its inherited short-circuit protection and the fact that the transformer has no saturation problems. Figure 33 (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 Figure 33 can also be replaced with half bridge diode rectifiers (Blaabjerg et al. 2004).

(a)

(b)

(c)
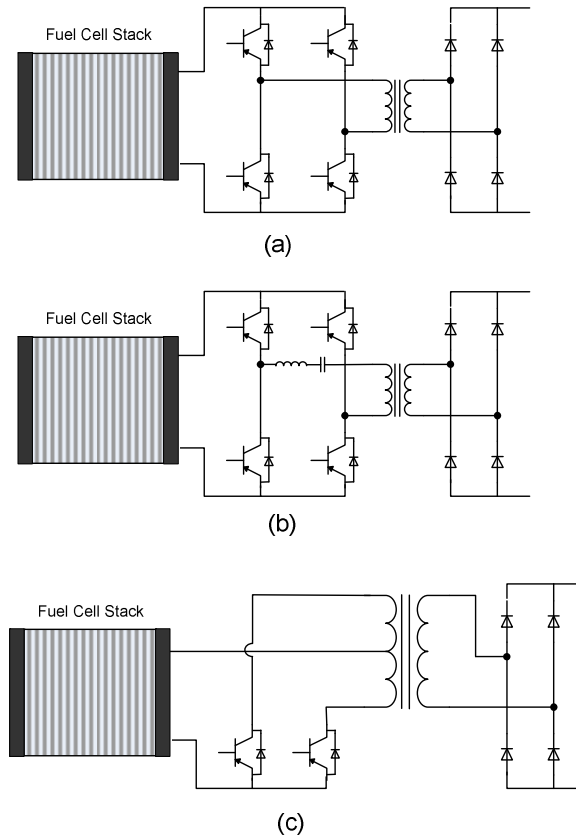
Figure 33. Isolated DC-DC converters (a) H-bridge;
(b) Series-resonant H-bridge; (c) Push-pull

Various three-phase inverters can be used for three-phase utility connections. Figure 34 shows two popular inverter topologies for fuel cell applications. The hard-switching three-phase VSI, as shown in Figure 34 (a), is well proven design and the converter is widely used in industrial applications; however, it suffers from switching loss (Blaabjerg et al. 2004). The resonant-phase leg inverter (RPLI) is shown in Figure 34 (b) and is an improvement to the hard-switching inverter with zero-voltage switching (Cheng et al. 2001). A modified variable-frequency modulation can further improve the soft-switching range. The active clamp resonant DC-link inverter (ACRDI) is an improvement to the classical resonant DC-link inverter where the DC-link voltage is twice as 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, causing some reliability issues (Cheng et al. 2001).

(a)

(b)
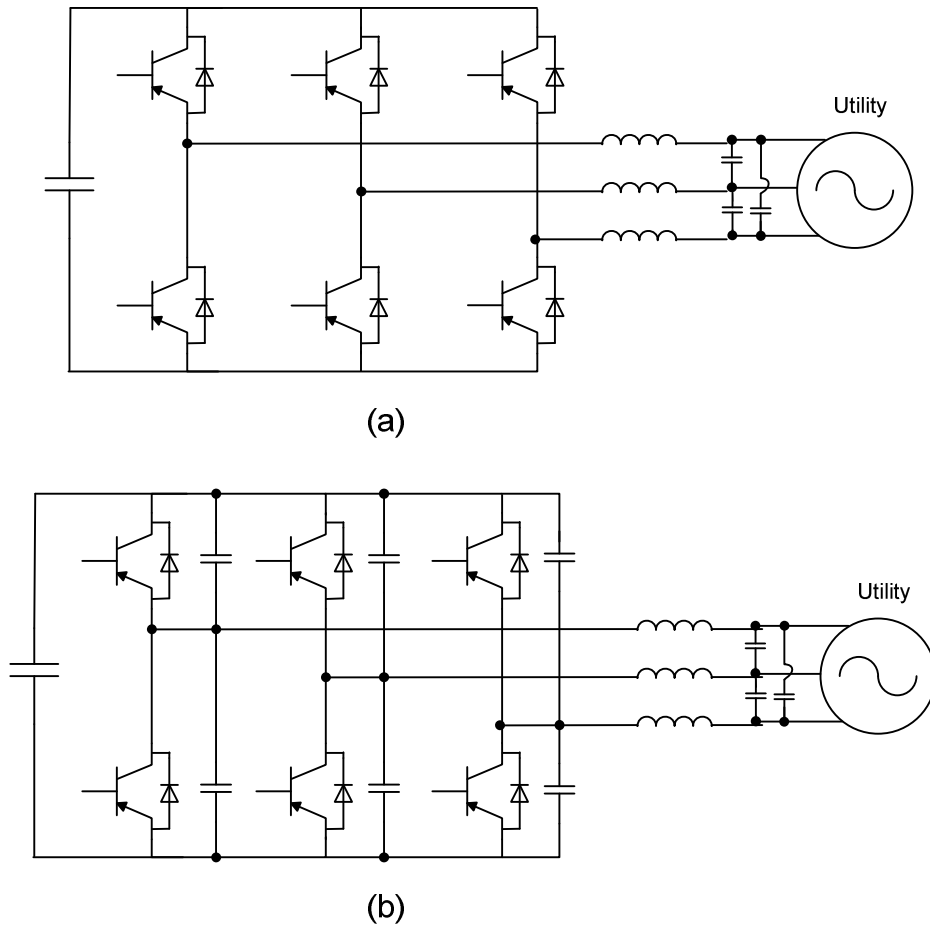
Figure 34. Three-phase inverters (a) Hard-switching inverter; (b) Resonant-phase leg inverter

A power conditioning system for a fuel cell with a DC-DC converter and a DC-AC inverter can be constructed with a combination of the converters discussed above. An example of a fuel cell system with power electronics interfacing into a three-phase utility system is shown in Figure 35, where an isolated DC-DC bridge converter and a three-phase hard switching voltage-source inverter are used.
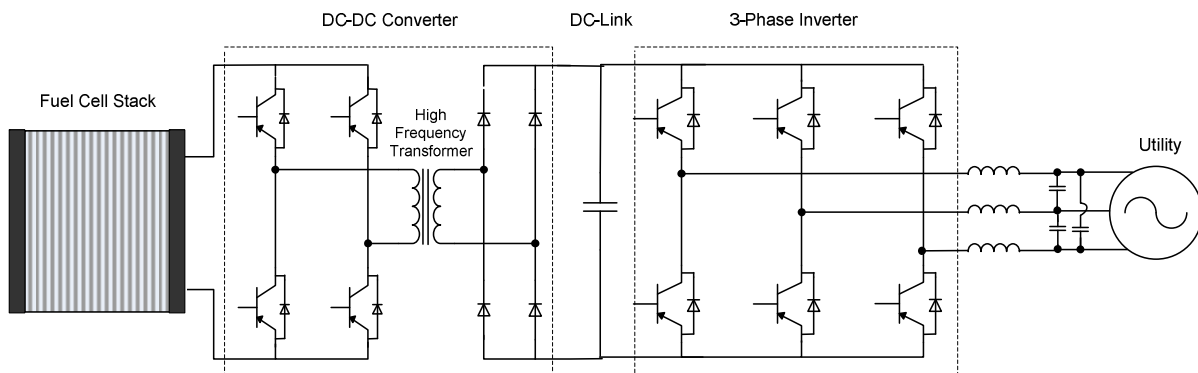
Figure 35. Cascaded DC-DC and DC-AC converter topology (DC-link)

5.3.2 Cascaded DC-AC and AC-AC Converters (High Frequency Link)

For residential power systems, a medium power fuel cell is used. This application can use a compact DC-AC converter with required galvanic isolation. The high-frequency link power conversion technique is attractive for this application because a high-frequency link direct DC-AC converter which consists of a high-frequency inverter, a cycloconverter, and a high-frequency transformer between them provides a possible way to build a compact direct DC-to-AC converter without the DC-link capacitor. The advantage of this approach provides a high power conversion efficiency due to the reduced number of conversion steps (Song et al. 2004). High-frequency-based PE topologies are mainly used in single-phase systems. Three-phase cycloconverters require a large number of devices, which results in higher costs, more switching losses, and increased system complexity.

The conventional cascade topology, as described in the previous subsection, is a DC-DC forward converter with a DC-AC inverter. This configuration actually has three stages of power conversion: DC-AC in the forward converter primary, DC in the rectification for the DC bus, and then DC-AC in the inverter. The cascaded conversion would appear to have redundancy, especially since the topology adds a DC bus that must be filtered. A few topologies exist for cascaded DC-AC and AC-AC cycloconverter for the fuel cell applications (Nikkhajoei and Iravani 2005; Ye et al. 2006). In the future, the possibility of using matrix converters as the AC frequency changer will probably introduce more high-frequency link topologies for the fuel cell systems.

One high-frequency topology for the fuel cell system is shown in Figure 36. In this circuit, the forward converter is replaced with a simple square-wave inverter that produces a high-frequency link at the transformer. The internal rectifiers and DC bus filtering have been eliminated; the output inverter is replaced with an AC–AC converter that processes the high-frequency link and delivers the AC at utility frequency. The PWM cycloconverter concept is used for the control of an AC-AC converter which reduces some of the complexities of cycloconverter control (Nikkhajoei and Iravani 2005).
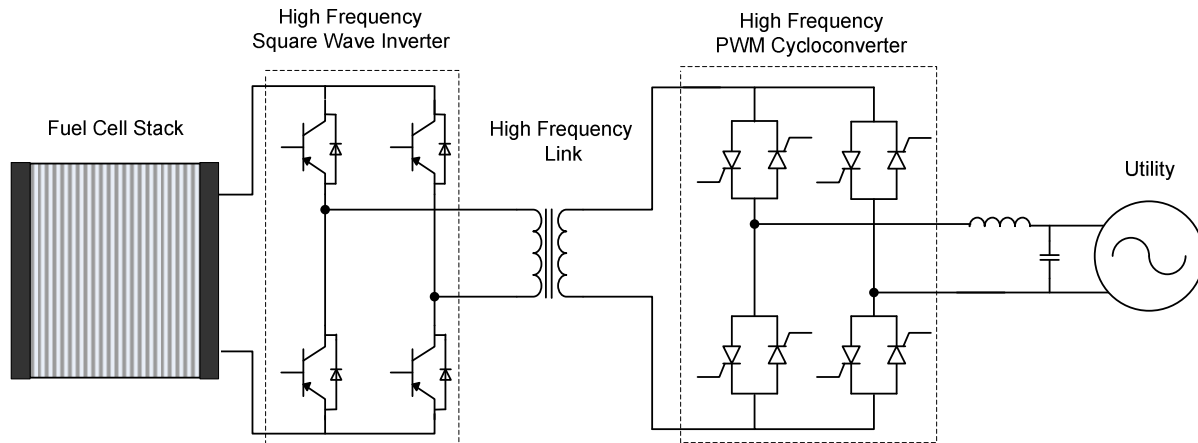
Figure 36. Cascaded DC-AC and AC-AC converter topology (high-frequency link)

5.4 Generalized Power Electronics and Control

From the discussion in the previous subsections, it can be observed that the most generalized form of power electronics topology for the fuel cell system is the DC-DC converter with an embedded high-frequency transformer and the DC-AC inverter as shown in Figure 35. In general, the voltage boost and isolation are done by the DC-DC converter. The power flow control to the utility, as well as the sinusoidal unity power factor current injection into the utility, is obtained by the DC-AC inverter controller. A simplified block diagram of the PEM fuel cell system with the power electronics and control is given in Figure 37.

The PEM fuel cell uses hydrogen as input fuel and produces DC power at the output of the stack. The performance of the stack is expressed by the polarization curve, giving the relation between stack terminal voltage and load current. It is evident from Tanrioven and Alam's, "Modeling, Control and Power Quality Evaluation of a PEM Fuel Cell Based Power Supply System for Residential Use" that the cell voltage decreases almost linearly as the load current increases. Therefore, the output voltage should be regulated at a desired value. To keep the polarization characteristic at a constant level, additional parameters such as cell temperature, air pressure, oxygen partial pressure, and membrane humidity also need to be controlled (Tanrioven and Alam 2004).

The control of a utility connected inverter, as shown in Figure 37, is developed with constant power control (Ye et al. 2006). The controller works similarly as described in the photovoltaics section of this report. The power loops are on the outer level of the current loops, and in some cases, the reactive power reference Q_{ref} could be a power factor reference. By controlling this reference, the injected current to the utility can be maintained at unity power factor. The output of the control system is the high-frequency sine PWM signals for the voltage-source inverter switches. More details of d-q based controller can be found in Appendix B.
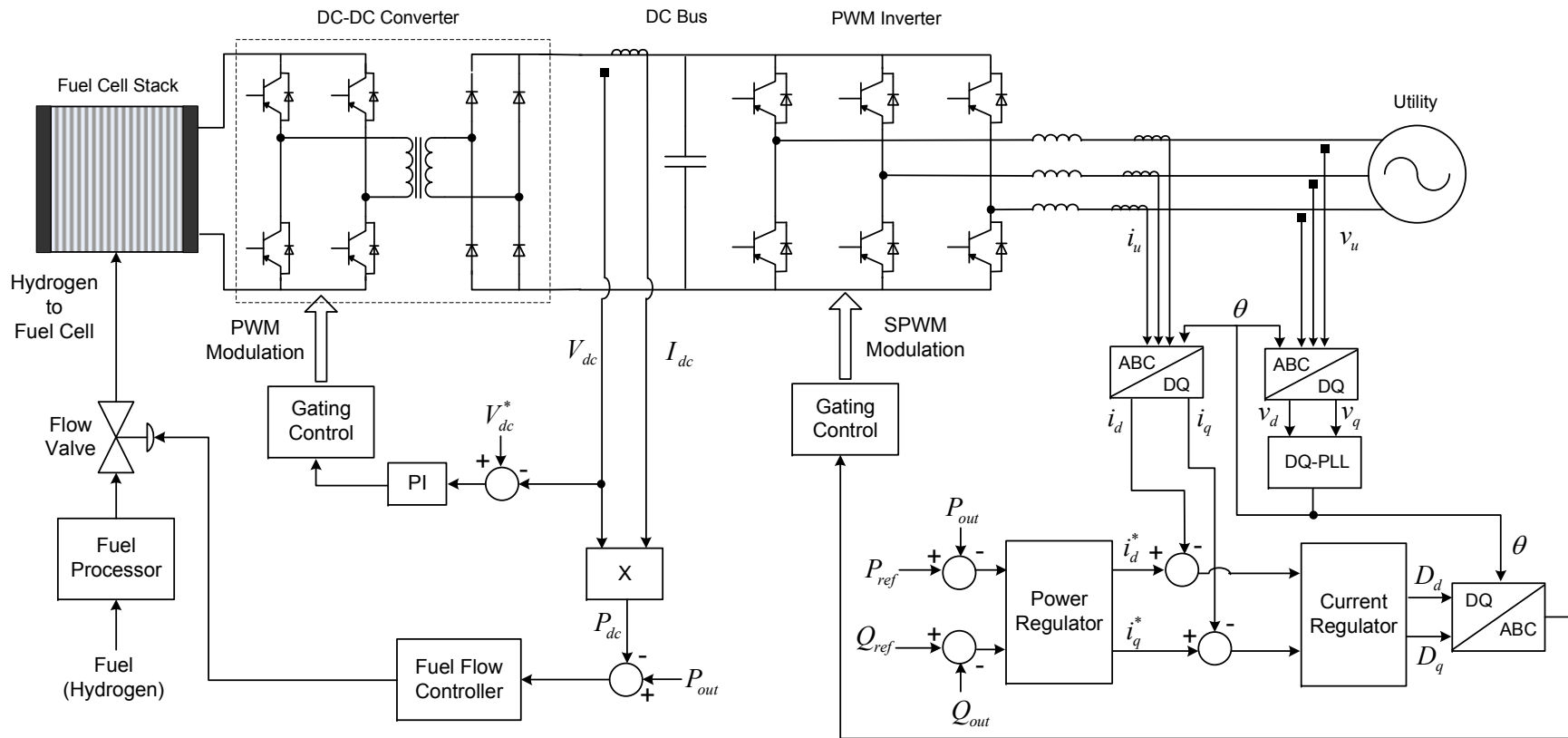
Figure 37. Generalized power electronics and control of a PEM fuel cell system

When the active power reference is increased, drawing more power from the fuel cell with constant hydrogen flow rate reduces the fuel cell output voltage, which in turn decreases the DC bus voltage (Tanrioven and Alam 2004). The DC-link voltage regulator tries to maintain the constant DC-voltage by changing the PWM switching pattern of the single-phase high-frequency inverter embedded in the DC-DC converter. For the steady state power adjustment, power changes must be followed by a proper hydrogen flow rate control as shown in Figure 37. It is important to remember that the response of the fuel cell is much slower than electric load response, especially when the load power changes abruptly. The chemical reaction of the PEMFC cannot keep up with the fast changes of the load demand. The use of power electronics converters mitigates this problem to some extent. Employing high-power density ultra-capacitors (UC) and/or battery storage system is required in some cases, especially when the fuel cell is used for supplying power in the islanded mode to some local loads.

6 Internal Combustion Engines

6.1 General Description

Internal combustion (IC) engines burn liquid or gaseous fuels to convert chemical energy into mechanical energy in the form of moving pistons. The pistons then spin a shaft and convert the mechanical energy into electrical energy via an electric generator. The electric generator is usually of synchronous or induction type, and is typically connected directly to the electric power system without any additional interconnection devices. The IC engines can be of either spark ignition types that use natural gas, propane, or gasoline; or compression types that use diesel or heavy oil (Farret and Simoes 2006). Natural gas is the preferred fuel for stationary power generation; however, IC engines can also utilize propane or liquid fuels for combustion. The compression type diesel cycle engines can operate on diesel or heavy oil, or they can be set up in a dual-fuel configuration that burns primarily natural gas with a small amount of diesel pilot-fuel. Current IC engines offer low initial costs, easy start-up, proven reliability when properly maintained, and good load-following characteristics. Emissions from IC engines have been reduced significantly in the last several years by exhaust catalysts and through better design and control of the combustion process. IC engines are well suited for standby, peaking, and intermediate applications, and for combined heat and power (CHP) in commercial and light industrial applications of less than 10 MW.

For spark ignition engines, fuel and air are mixed together before entering into the combustion cylinder, whereas in diesel units, the air and fuel are introduced separately with fuel being injected after the air being compressed. The combustion cylinder is closed at one end and contains a moveable piston. The fuel-air mixture is then compressed as the piston moves toward the top of the cylinder. Close to the time when the piston reaches the top of its stroke, a spark is introduced to ignite the mixture (in a non-spark diesel engine, the mixture is self-ignited by the compression alone). The pressure of the hot, combusted gases drives the piston down into the cylinder. The translational energy in the moving piston is then translated to rotational energy by a crankshaft. As the piston reaches the bottom of its stroke, an exhaust valve opens to expel the exhaust gases. Almost all commercial IC engines, which are used for power generation, are four-stroke and operate in four cycles (intake, compression, combustion, and exhaust). Figure 38 shows a typical IC engine-generator system. Both diesel (compression ignition) and natural gas (spark ignition) engines are widespread, but it is becoming increasingly hard to site diesel generators, especially in larger sizes, due to emissions regulations. Most installed natural gas units are stoichiometric, though newer units, especially in larger sizes, focus on lean-burn technology which allows for increased efficiency and lower emissions from the combustion chamber. Current engine research mainly focuses on increased efficiency and lower emissions (Farret and Simoes 2006).

Figure 38. Internal combustion engine-generator systems (NREL 2008)

6.2 IC Engine System Configurations

Typically, most IC engines are interconnected to the utility through a fixed speed synchronous generator that has protective relays. In automotive applications, it has been shown that the torque curve of a diesel engine is optimized for high power versus speed performance over the range of 1000 to 3600 rpm. But for power generation and direct utility connection, the generator speed must be constant for 60 Hz systems, depending on the number of generator poles. Therefore, conventional IC engines don't utilize the full speed range of the engine on the application or removal of electrical loads. Using a power electronics interface with an IC engine offers the advantage of having variable speed operation of the IC engine, which in turn optimizes fuel usage for varying loads (AI-Khayat et al. 2002). The engine speed can be controlled in response to load changes to optimize the combined efficiency of the engine and generator. Additionally, the power electronics also provides the flexibility of adding different storage systems, especially for the islanded mode of operation.

Figure 39 shows a variable speed IC engine-generator configuration that allows the integration of synchronous generators, or even the asynchronous induction generator, to the utility. The generator converts mechanical energy from the IC engine to a variable voltage, variable frequency output that varies with engine speed. The rectifier and inverter are then used to convert

the output of the generator to a power that is compatible to the utility system (AI-Khayat et al. 2002; Van Tichelen and Weyen 1998). For the induction generator, a reactive power compensator may be required.
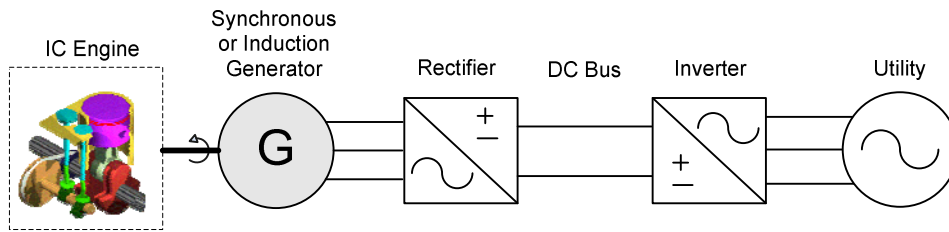
Figure 39. Variable speed IC engine configuration with power electronics

Another solution for using a medium scale power converter with a wound rotor induction generator is shown in Figure 40 (Kawabata et al. 2001). 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. This type of induction generator is known as a doubly-fed induction generator (DFIG). The solution is a bit more expensive compared to the classical solutions. The advantage of this design is that it provides reactive power compensation/production and increased energy capture from the IC engines. This arrangement allows the generator stator winding to be undersized by about 25% with the power electronics making up the power difference from the rotor power.
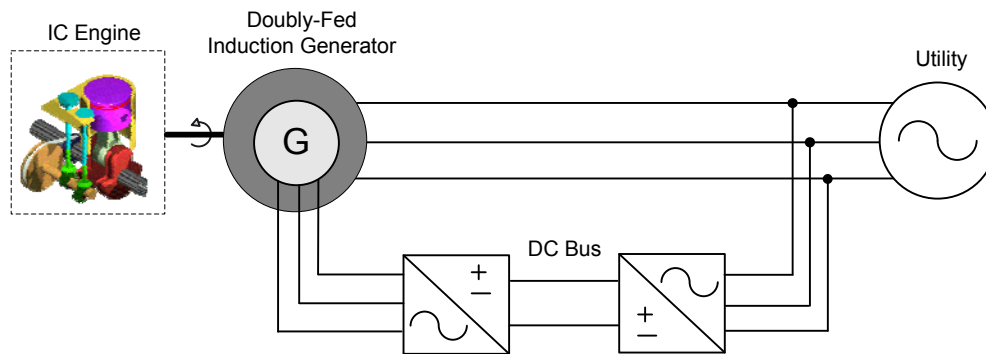
Figure 40. IC engine configuration with DFIG and partially rated power electronics

6.3   Power Electronics Topologies

A typical power electronics topology that is used for an IC engine with permanent magnet synchronous generator is shown in Figure 41. The three-phase variable voltage, variable frequency output from the IC engine is rectified using a diode bridge. This rectified output signal from the diode bride is filtered into a smooth DC waveform using a large capacitor. The DC signal is inverted to 60 Hz AC using a three-phase voltage-source inverter. This three-phase 60 Hz waveform can then be scaled using a transformer to voltage levels required by the utility AC system. The transformer also provides isolation required for the utility connection. Instead of passive rectifier, a bidirectional, self-commutated active rectifier using IGBT switches can also

be used, allowing regeneration. Additionally, the requirement of reactive power for the induction generator can be satisfied by this bidirectional converter.
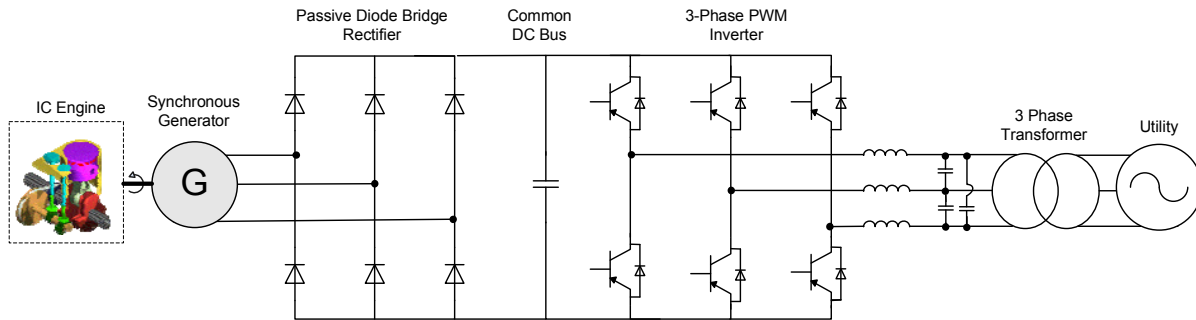
Figure 41. Synchronous/Induction generator with DC-link power electronics topology

The power electronics required for the DFIG consists of an AC-DC-AC IGBT-based pulse width modulated (PWM) dual converter. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC-DC-AC converter. A typical DFIG electrical topology, as shown in Figure 42, uses a converter arrangement with back-to-back rectifier/inverter that shares a DC-link for power transfer. The AC side of the rectifier is tied to the rotor of the induction machine via slip rings; the inverter is tied to the fixed-frequency utility grid.
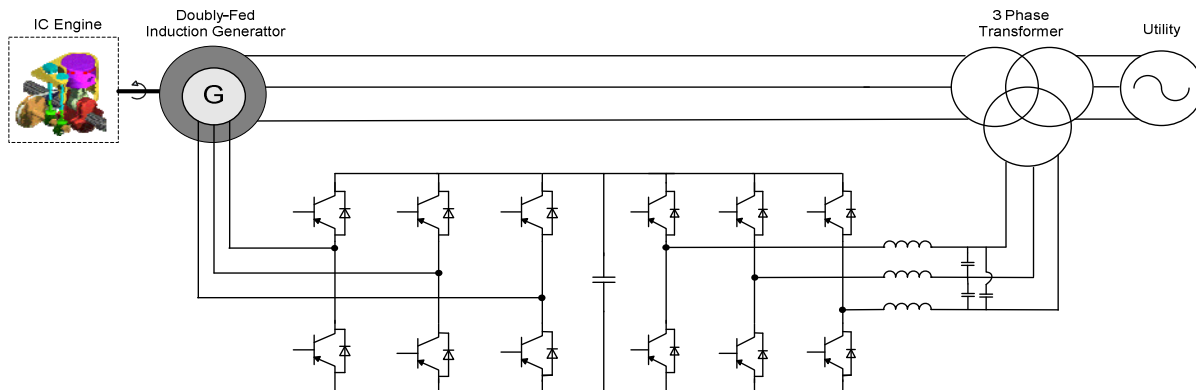
Figure 42. DFIG Power Electronics Topology with AC-DC-AC Converters

Although a variable speed IC engine with synchronous/induction generator offers better performance in terms of fuel efficiency, it does not respond as well as a conventional IC engine generator to sudden changes in load because of the engine inertia and power margin, especially during islanded operation (Stott et al. 2007). During such a condition, the DC-link voltage would collapse unless there was some form of energy storage. A power electronics topology used with a variable speed IC engine and energy storage is given in Figure 43. The AC-output of the generator is rectified into DC and is fed to a DC-DC boost converter. A DC-energy storage system is connected to the DC bus using a bidirectional, full-bridge DC-DC converter. Then a three-phase voltage-source inverter is used for utility connection. The addition of the energy storage module allows for a seamless transition to power local loads directly from the IC engine generator in case of grid failure (Lasseter 2006).
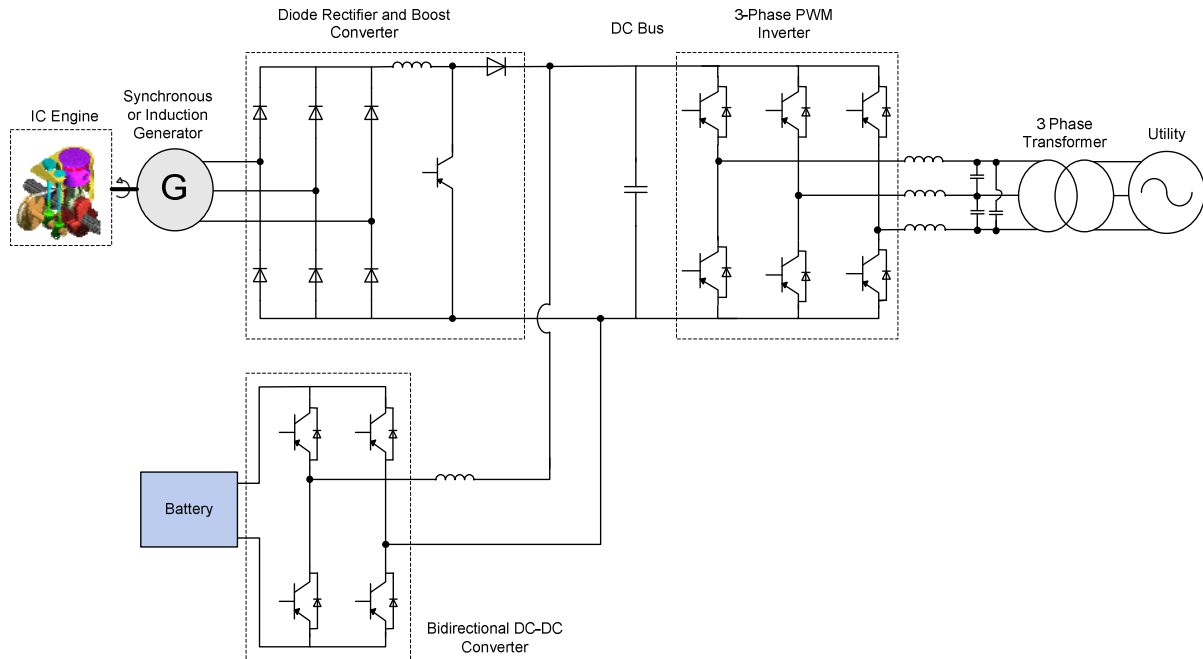
Figure 43. Power electronics configuration for hybrid IC engine-battery system

6.4 Generalized Power Electronics and Control

From the discussion in the previous subsections, it can be observed that the most generalized and versatile form of power electronics topology for the IC engine-synchronous generator application is the back-to-back rectifier/inverter connection which provides the improved power flow control as well as increased efficiency. The voltage-fed converter scheme used in such a system is shown in Figure 44. A PWM-based IGBT bridge rectifies the AC from the generator. The inverter topology is identical to that of the rectifier, and it supplies the generated power at 60 Hz to the utility grid.
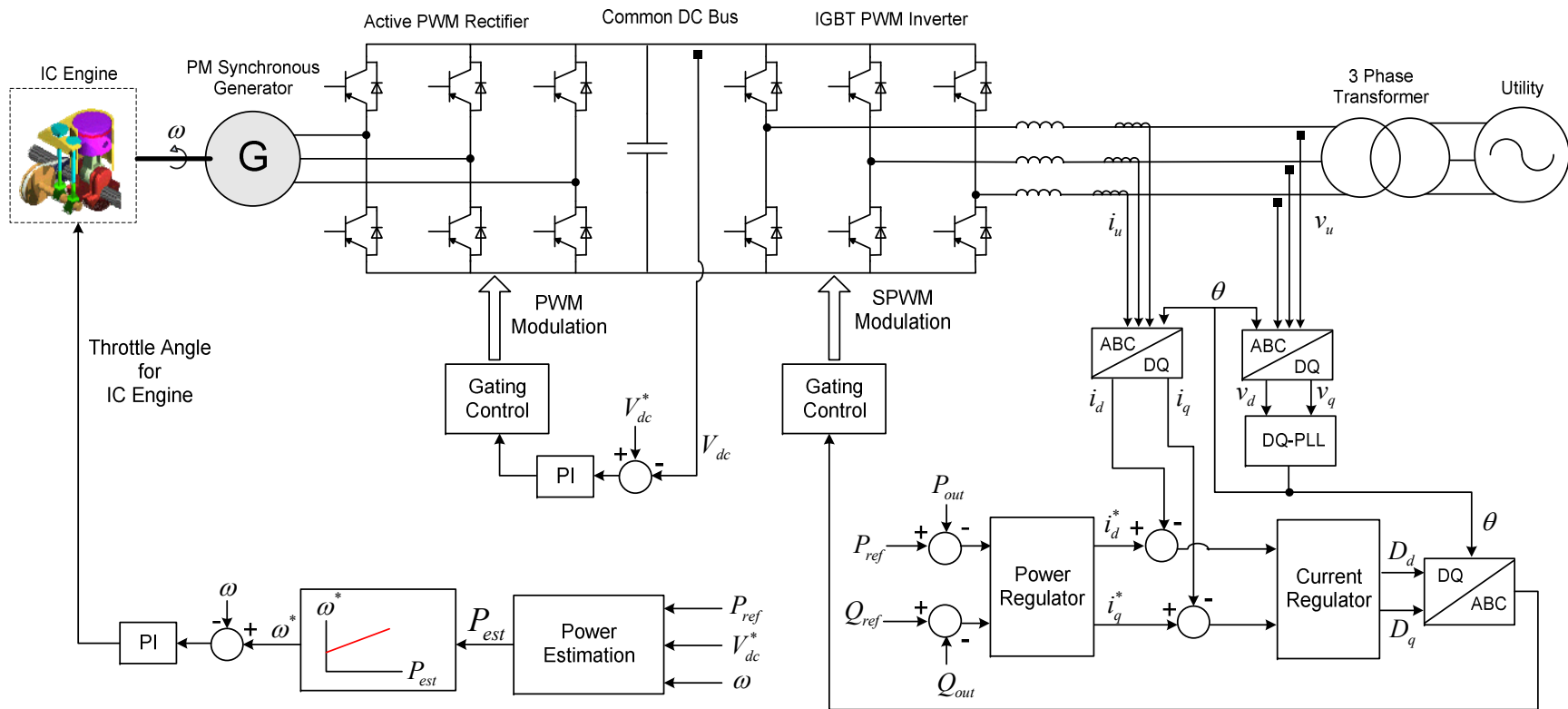
Figure 44. Generalized power electronics and control of an IC engine and permanent magnet synchronous generator system

A typical variable-speed IC engine is most often a four-stroke, spark-ignited, air-cooled type, where speed/power is controlled via a carburetor throttle. These engines commonly have one or two cylinders and are available in 3-25 Hp ratings. With few exceptions, these engines are rated at 3600 rpm (Ryan and Lorenz 2000). Attached to the IC engine is a three-phase permanent magnet synchronous generator. These generators are ideally suited for the task of electro-mechanical power conversion as they offer small size, low weight, and high efficiency. In addition, they are usually designed with a high pole number and a short stack so that they may be mounted directly to the IC engine without the need for bearings or brushes (Ryan and Lorenz 2000).

Three basic control loops can be designed for the control of the IC engine-generator and associated power electronics system. One of the control loops works to maintain the generator speed, whereas the other two control loops are developed for maintaining the rectifier DC-link voltage and the power flow control by the inverter.

The control of the utility connected inverter, as shown in Figure 44, is developed with constant power control (Ye et al. 2006). Many functions to deal with practical control issues are not shown in the diagram, such as the negative sequence regulation, DQ decoupling, etc. The inner control loop regulates current, and the outer control loop regulates power. In some cases, the reactive power reference Q_{ref} could be a power factor reference. By controlling this reference, the injected current to the utility can be maintained at unity power factor. The output of the control system is the high-frequency sine PWM signals for the voltage-source inverter switches. More details of d-q based controller can be found in Appendix B.

When the active power reference is increased, the inverter draws more power from the DC bus, decreasing the DC bus voltage. The DC-link voltage regulator, as shown in Figure 44, tries to maintain the constant DC voltage by changing the PWM switching pattern for the three-phase controller rectifier switches.

The speed control loop for an IC engine operates by changing the throttle angle so that the engine runs in its optimized fuel usage point for varying loads (Ryan and Lorenz 2000). Whenever there is a change in the power reference, the inverter supplies that power to the utility by changing its sine pulse width modulation (SPWM). That power comes from the DC bus, changing the DC bus voltage. The DC bus voltage regulator tries to maintain that voltage fluctuation based on the voltage reference by changing PWM signals to the controlled rectifier. The input power for the rectifier comes from the generator, which is powered by the IC engine; therefore, any fluctuations in the power demand causes the change in the speed of the generator, and the IC engine may run outside its optimized fuel usage region due to the speed variation. The power estimation block tries to estimate the new operation point for power generation that can be produced by the IC engine based on the load demand (P_{ref}), DC bus voltage reference (Vdc^*), and current speed (ω). All these parameters are important to define the power-speed characteristics and limits of the IC engine-generator system, so that the new output power from the IC engine follows operational limits in the power-speed plane. Inside the power and speed operating region of the IC engine, a mapping of power-to-speed is defined by either system identification or by non-linear methods (Farret and Simoes 2006). For a particular estimated power, the mapping system outputs the corresponding reference speed (ωr^*), and the control loop changes the actual speed of the IC engine to follow that reference by varying the throttle angle.

7 Battery Storage

7.1 General Description

To optimize the utility grid's efficiency, the largest system generators need to be operated at rated capacity at all times. These generation systems are also referred to as base loaded plants and include large hydroelectric, nuclear, and coal fired plants. During a typical daily cycle, customer usage of the grid fluctuates. At times of heavy usage, or peak-loading, additional low-efficiency utility generators (oil or gas-fired generators) are added to the grid in order to support the increased load. These low-efficiency generators are expensive to operate due to high fuel costs. Several energy storage systems are under consideration to harness excess electricity produced by the most efficient utility generators during low loading. This harvested energy can be released onto the grid, when needed, to eliminate the need for high-cost generators. Inclusion of storage in the distributed generation system actually provides the user dispatch capability of its distributed resources, which generally are renewable energy sources like PV and solar, having no dispatchability on their own. During periods of low demand, excess generation can be used to charge an energy storage device. The stored energy can then be used to provide electricity during periods of high demand.

There are a variety of technologies that can be used to store energy on the utility power system, including: lead-acid, nickel-electrode, and sodium-sulfur modular batteries; zinc-bromine, vanadium redox, and polysulfide-bromide flow batteries; superconducting magnetic energy storage (SMES); flywheels; electrochemical capacitors (ultracaps); compressed air energy storage (CAES); pumped hydro; and production and storage of gases such as hydrogen (to run fuel cells or hydrogen IC engines) (EPRI-DOE 2003). Of these technologies, batteries and flywheels are commonly integrated at the distribution system level and are commercially available.

The emphasis of this section will be on energy storage in batteries and some prevalent grid-tied interconnections that can be used to maximize system efficiency. Battery banks connected to the grid are generally either lead-acid or flow batteries. Lead-acid batteries consist of electrodes of lead metal and lead oxide immersed in an electrolyte consisting of 35% (by weight) sulfuric acid in water. This electrolyte solution produces electrons, creating energy flow through the external circuit.

Lead-acid batteries are the prevalent form of electrical energy storage in use today. They have a commercial history of well over a century, and are being applied in every area of the industrial systems, including: telecommunication, emergency power, and auxiliary power in stationary power plants. Because of their low cost and ready availability, lead-acid batteries always become the default choice for energy storage in new applications. This popularity comes despite many perceived disadvantages, including low specific energy (W-h/kg) and specific power (W/kg), short cycle life, high maintenance requirements, and environmental hazards (EPRI-DOE 2003). A grid-tied lead acid storage system is shown in Figure 45.

Figure 45. Lead-acid energy storage (NREL 2008)

Deep-cycle batteries are designed to be discharged down as much as 80% time after time, with 85%-95% efficiency. All lead-acid batteries supply about 2.14 V per cell (12.6 V to 12.8 V for a 12 volt battery) when fully charged. Flow batteries work in a similar fashion as lead-acid batteries, but the electrolyte is stored in external containers and circulated through the battery cell stack as required. This external reservoir of rechargeable electrolyte can be as large as needed and situated where convenient. Because of the high energy density and relatively low cost of zinc, rechargeable zinc battery technology has long been considered attractive for large-scale energy storage systems. Similarly, flow batteries are recognized as a favorable technology for large systems because they are eminently scalable and allow a great deal of flexibility in system design. The zinc-bromine flow battery is a combination of these two technologies, with significant potential for use in large scale utility applications (EPRI-DOE 2003). The Vanadium Redox Battery (VRB) is also a flowing-electrolyte battery (or "flow battery"). For flow batteries, aqueous liquid electrolyte is pumped from storage tanks through reaction stacks where chemical energy is converted to electrical energy (discharge), or electrical energy is converted to chemical energy (charge). There are a limited number of manufacturers of sodium sulfur (NaS) batteries for utility applications (EPRI-DOE 2003). There are also five common battery technologies that use the nickel-electrode: nickel-iron (NiFe), nickel-cadmium (NiCd), nickel-hydrogen (NiH2),

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nickel-metal hydride (NiMH), and nickel-zinc (NiZn). Of these, NiCd, NiMH, and lithium ion are the most common and well-known for low voltage consumer electronics.

7.2 Battery Storage System Configurations

All of the battery technologies, discussed in the previous section, produce DC that must be converted to AC to connect to the utility. The individual battery cells are generally connected in different configurations in series and/or parallel to achieve the required voltage and current outputs. The power conditioning systems, including inverters and DC-DC converters, are often required for the battery energy storage systems (BESS) in order to supply normal customer load demand or send electricity into the grid. The most unique aspect to power electronics for energy storage is that they must be bidirectional, that is both taking power (during charging) and providing power (during discharge) from/to the grid. Unlike PV and fuel cell inverters, however, BESS inverters are not expected to consider the peak power operations. They only provide the power level demanded by the system that can be sustained by the battery.

The simplest form of battery energy storage system configuration, as shown in Figure 46, consists of a battery system followed by the DC-AC converter. If the isolation or a high ratio of the voltage conversion is required, a transformer is usually integrated into the system. The current at full operating power determines the rating of the inverter. The current, in turn, is dependant on the BESS voltage at full operating power, which varies substantially from no-load to full load, and is at its lowest level under full operating power. The main drawback for this configuration is that the low-frequency transformer placed at the output of the inverter makes the system very bulky and expensive (Ponnaluri et al. 2005). The inverter can be of single-phase or three-phase depending on the utility connection.
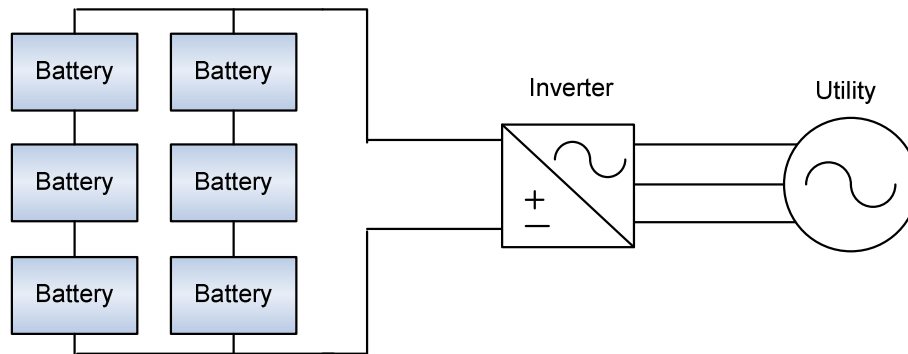
Figure 46. BESS configuration with single inverter

A DC-DC converter is often used between the BESS and the inverter, as shown in Figure 47. The DC-DC converter must be bidirectional and is mainly utilized to produce sufficient voltage for the inverter input so that the required magnitude of the AC voltage can be generated (Ponnaluri et al. 2005). Additionally, in some power electronic topologies, high-frequency transformers are used in DC-DC converters for galvanic isolation.
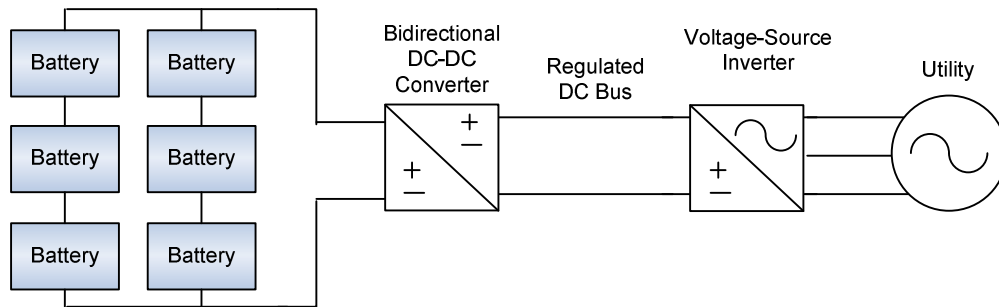
Figure 47. BESS configuration with cascaded DC-DC and DC-AC converters

Additionally, the battery storage system is very common to use with other types of energy sources in form of hybrid systems. When using with renewable sources, such as wind or PV, the BESS can offset the daily and seasonal intermittency of the primary energy, smooth-out load fluctuations, damp out utility transients, and facilitate islanding operation. In Figure 48, one such hybrid system is shown where the BESS is included in wind energy system. The battery is integrated into the DC bus of the wind system by using a bidirectional DC-DC converter. These hybrid systems can be of various types, depending on the primary source of energy and the type of BESS integration.
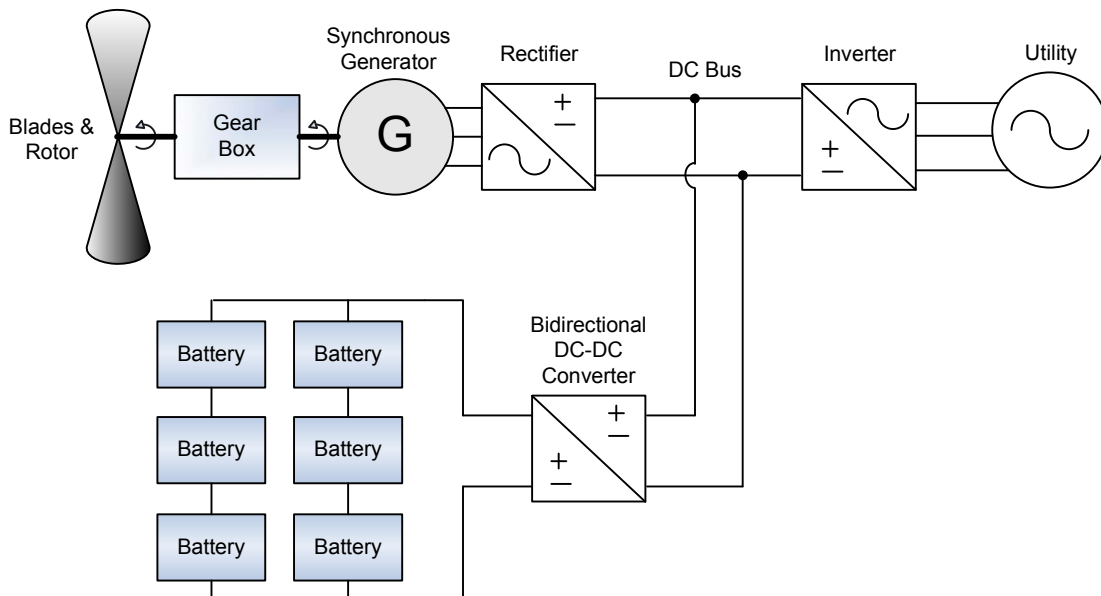
Figure 48. Hybrid system configuration with BESS and wind energy system

7.3   Power Electronics Topologies

The power electronics topologies for the battery energy storage systems can be of different types based on the number of cascaded stages in the conversion systems, types of converters, presence of galvanic isolation, and utility connection.

The most fundamental topology for utility connection of the BESS is the single-stage, self-commutated voltage-source inverter as shown in Figure 49. While the DC output of the battery system is connected across a filter capacitor, the capacitor itself is used to limit the harmonic

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currents in the battery. The output of the capacitor connects to a voltage-source inverter (VSI) (Ponnaluri et al. 2005; Leung and Sutanto 2000). Depending on the utility connection, the inverter can be single-phase or three-phase. The output of the inverter is then connected to a low-pass filter to prevent high-frequency harmonics injected into the AC system. A synthesized AC-output voltage is produced by appropriately controlling the switches and consists of a controlled series of positive and negative pulses that correspond to the positive and negative half cycles of a sinusoid.

(a)

(b)
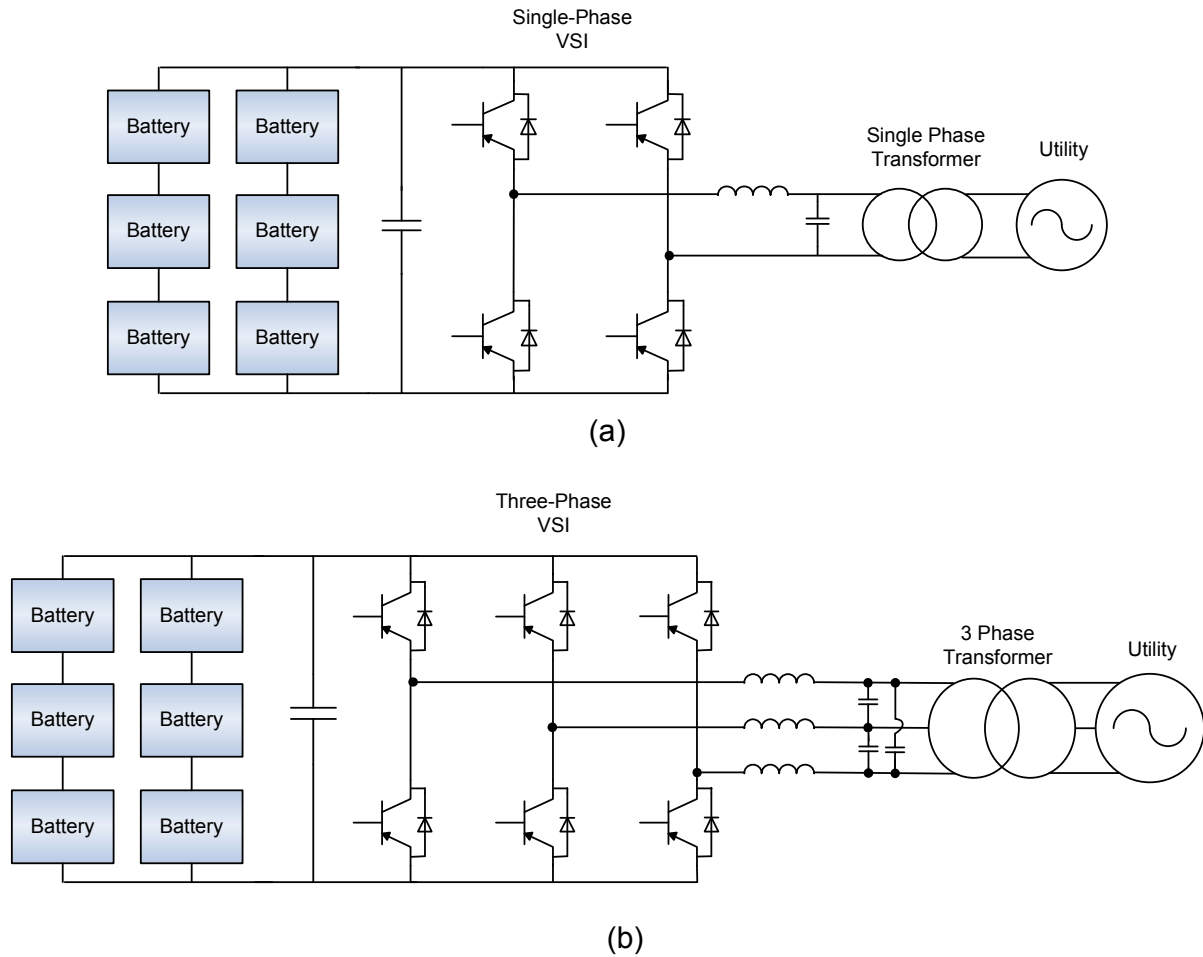
**Figure 49. Single-stage power electronics topologies with (a) Single-phase inverter;
(b) Three-phase inverter**

The most common two-stage topology for the BESS consists of a DC-AC grid-connected voltage source PWM inverter with a bidirectional DC-DC converter. The DC-AC full-bridge inverter controls the grid current by means of pulse width modulation (PWM), known as a "bang-bang" operation. A simple design for a two-stage power electronics topology, as shown in Figure 50, incorporates a full-bridge DC-DC converter that can operate with any voltage and current polarity. The voltage polarity and amplitude can be set irrespective of the current direction (Mohan et al. 2003).
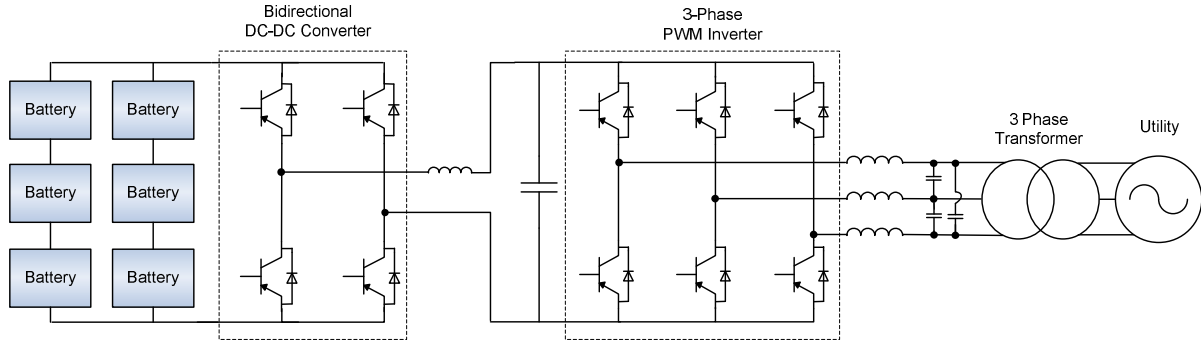
Figure 50. Cascaded power electronic topologies with DC-DC and DC-AC converters

All of the power electronics topologies discussed so far do not provide isolation. For utility connection, a line-frequency transformer is used for galvanic isolation. To avoid the bulky, low-frequency transformers (regarded as poor components mainly due to their relatively large size and low efficiency), several bidirectional isolated DC-DC converter topologies have been developed (Inoue and Akagi 2007; Li et al. 2003; Jain et al. 2000). One such topology (see Figure 51) can provide galvanic isolation between the output terminals from the input terminals, and can step up and down its output voltage by using a high-frequency transformer.
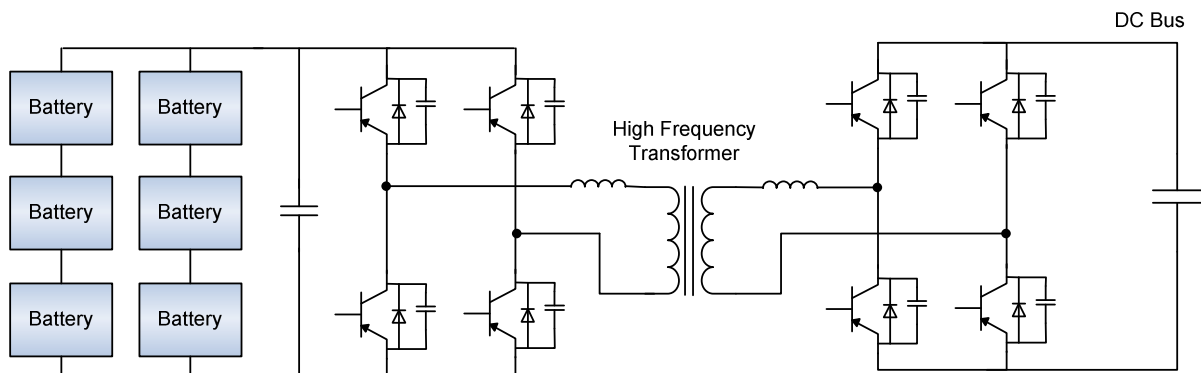
Figure 51. Bidirectional isolated DC-DC power electronics topology

7.4 Generalized Power Electronics and Control

From the discussion in the previous subsections, it can be observed that the most generalized form of power electronics topologies for the battery energy storage systems is the bidirectional DC-DC converter cascaded with the DC-AC three-phase inverter as shown in Figure 52.

There are different modes of operation for the BESS connected to the utility. The BESS can either send power to the utility by discharging or it can receive power from the utility to charge itself (Chiang et al. 1998). The operation mode control block, as shown in Figure 52, decides the charging/discharging operation for the BESS. The control design for power electronic systems is different for charging and discharging modes. Based on the mode in which the battery is operating, the control signals from charging or discharging blocks are connected to the power electronics system by the selector switches Sw1 and Sw2.

The operation mode control block is designed based on a simple charge-discharge schedule of the BESS. The BESS can send the power to the utility during the peak-load period (i.e., from 6 p.m. to 10 p.m.) only if the voltage of BESS is greater than the nominal value (V_b,nom). During the discharge mode—based on the present voltage (V_b) and the state-of-charge (SOC) of the BESS—the P_{ref} signal determines the amount and rate of discharge to be generated. The BESS can be charged any other time, provided the SOC of the battery is smaller than the maximum storage capacity (SOCmax). The switch control signal is generated based on a lookup table. According to the design, the signal "0" means no charge/discharge, "1" means discharging, and "2" indicates charging. This signal simultaneously controls switches Sw1 and Sw2. Based on the status of this signal, the power electronics converters are either connected to the charging block or the discharging block. Other charge-discharge schedules can also be programmed in the operation mode control depending on the application.

When the mode of operation for the BESS is charging, the power flows from the utility to the battery system through power electronic converters. The DC-DC converter determines the voltage at the battery terminals (V_b) based on which the battery is charged. The battery voltage regulator generates the PWM pattern based on the reference battery voltage (V_b*) (coming from operation mode control) such that the (V_b) follows this reference voltage. For the proper control, the DC-DC converter requires a constant DC input. The DC-AC converter works as the controlled rectifier and the controller maintains the DC bus voltage (Vdc) at a preset value. This control design is a variation of the constant power control (Ye et al. 2006). Instead of using the active power reference, a DC bus voltage is regulated while the input to the inverter acts as a constant power source to represent the prime mover. In this case, the output of the DC bus regulator is proportional to the active power.
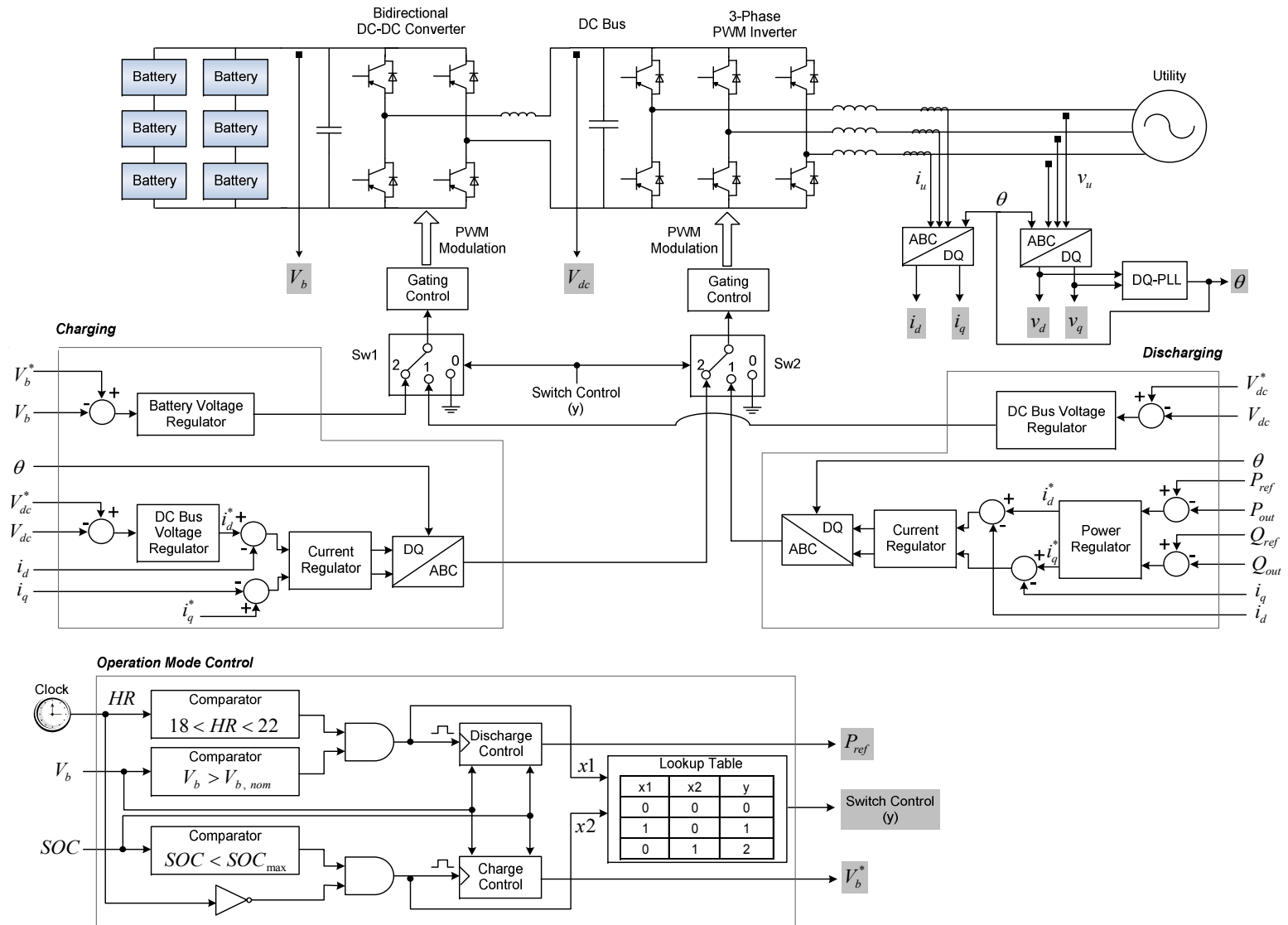
Figure 52. Generalized power electronics and control of a battery energy storage system

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During discharge mode, the power flows from the BESS to the utility. In this mode, the DC-DC converter maintains the DC bus voltage for the inverter, and the grid connected inverter controls the active and reactive power flow. The control of the utility connected inverter, as shown in Figure 52, provides constant power control (Ye et al. 2006). Many control functions to deal with practical issues are not shown in the diagram, such as the negative sequence regulation, DQ decoupling, etc. The inner control loop regulates current, and the outer control loop regulates power. In some cases, the reactive power reference, Q_{ref}, could be a power factor reference. By controlling this reference, the injected current to the utility can be maintained at unity power factor. The output of the control system is the high-frequency sine PWM signals for the voltage-source inverter switches. More details of d-q based controller can be found in Appendix B. When the active power reference is increased, the inverter draws more power from the DC bus, thereby decreasing the DC bus voltage. The DC-link voltage regulator, as shown in Figure 52, tries to maintain the constant DC voltage by changing PWM switching pattern for the three-phase controller rectifier switches.

8 Flywheels

8.1 General Description

Flywheels are very popular as energy storage due to the simplicity of storing kinetic energy in a spinning mass. For approximately 20 years, it has been a primary technology used to limit power interruptions in motor/generator sets where steel wheels increase the rotating inertia, providing short power interruptions protection and smoothing of delivered power (Carrasco et al. 2006). Flywheel energy storage system (FESS) works on the same principle: it stores energy in the form of the kinetic energy of a spinning mass. Conversion from kinetic to electric energy is accomplished by electromechanical machines. Many different types of generator machines are used in flywheel systems, such as permanent magnet machines, induction machines, and switched reluctance machines (Carrasco et al. 2006; da Silva Neto et al. 2003). The key design element is to match the decreasing speed of the flywheel during discharge and the increasing speed during charging with a fixed frequency electrical system. Along with electromechanical machines, two methods are used to match system frequencies, mechanical clutches, and power electronics. The basic operation of a flywheel can be summarized as follows: When there is excess in the generated power with respect to load demand, the difference is stored in the flywheel that is driven by the electrical machine operating as a motor. On the other hand, when a fluctuation in delivered power is detected in the loads, the electrical machine is driven by the flywheel and operates as a generator supplying the extra energy needed.

FESS often utilizes power electronics that convert and regulate the power output from the flywheel. As the motor/generator draws mechanical energy from the rotor during discharge, the rotor slows down, changing the frequency of the AC electrical output. The output must be converted to DC or to constant-frequency AC power. When power electronics is used, the variable frequency AC output of the flywheel alternator is rectified, providing a DC-voltage and current. The primary purpose of the power electronics system is to couple the fixed-frequency AC-electrical grid with the variable-speed flywheel as well as to invert, regulate, and provide the proper wave form for providing power to the grid. By reversing the process, the power electronics are also able to draw power from the AC utility connection and drive the flywheel motor to spin up and recharge the flywheel.

Typical flywheel systems are intended for standby power applications. The energy storage assembly is designed to operate at high speeds (typically >10,000 RPM) to achieve its highest energy storage density (Wh/kg). The motor/generator rotor is mounted on a shaft which is integral to the flywheel. An active lift magnet system supports the shaft axially. Two active magnetic bearing systems provide support at the ends of the shaft for frictionless and maintenance-free operation. The flywheel rotor assembly rotates in a low-pressure environment to reduce drag loss. The flywheel is typically connected to at three-phase motor/generator. A sectional view of a commercially available flywheel energy storage system is shown in Figure 53 (Rojas 2007).
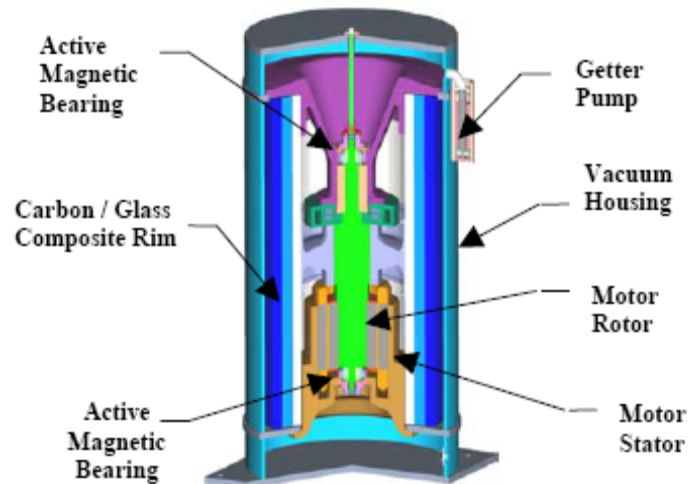
Figure 53. Flywheel energy storage module

8.2 Flywheel Storage System Configurations

The flywheel energy storage systems (FESS) can be classified into two categories. The first technology is based on low-speed flywheels (up to 6000 rpm) with steel rotors and conventional bearings. The second involves more recent high-speed flywheel systems (up to 60000 rpm) that are available commercially and make use of advanced composite wheels that have a much higher energy and power density than steel wheels. This technology requires ultra-low friction bearing assemblies, such as magnetic bearings (Carrasco et al. 2006).

Flywheels can be used together with batteries to reduce the number of discharge cycles of the batteries to extend useful life of the batteries. Flywheels can also be used together with emergency generators to provide temporary power during the changeover to emergency power. The primary use of flywheels for distributed energy applications is to provide voltage and frequency regulation for utilities. The major electrical components of a flywheel energy storage system include a bidirectional inverter, variable-speed motor drive, and controller. An electronic control module controls the power electronics to operate in charge, discharge, or standby modes.

The most common configuration for supplying flywheel energy to the grid is the back-to-back converter as shown in Figure 54 (a) (Lazarewicz and Rojas 2004). The variable frequency AC output of the flywheel generator is first converted to DC power. The DC bus is then connected to a DC-AC converter for connection to the grid. During charging, the grid-connected converter works as a rectifier while the generator-connected converter works as the inverter. During discharge, the two converters exchange their roles to supply power from FESS to the utility. In this configuration, multiple flywheel systems, as shown in Figure 54 (b), can be connected to the grid via the DC bus to provide frequency, voltage regulation, and backup power for customer loads. Multiple flywheels tied together can provide higher energy storage capacity which will provide higher power levels (Lazarewicz and Rojas 2004).
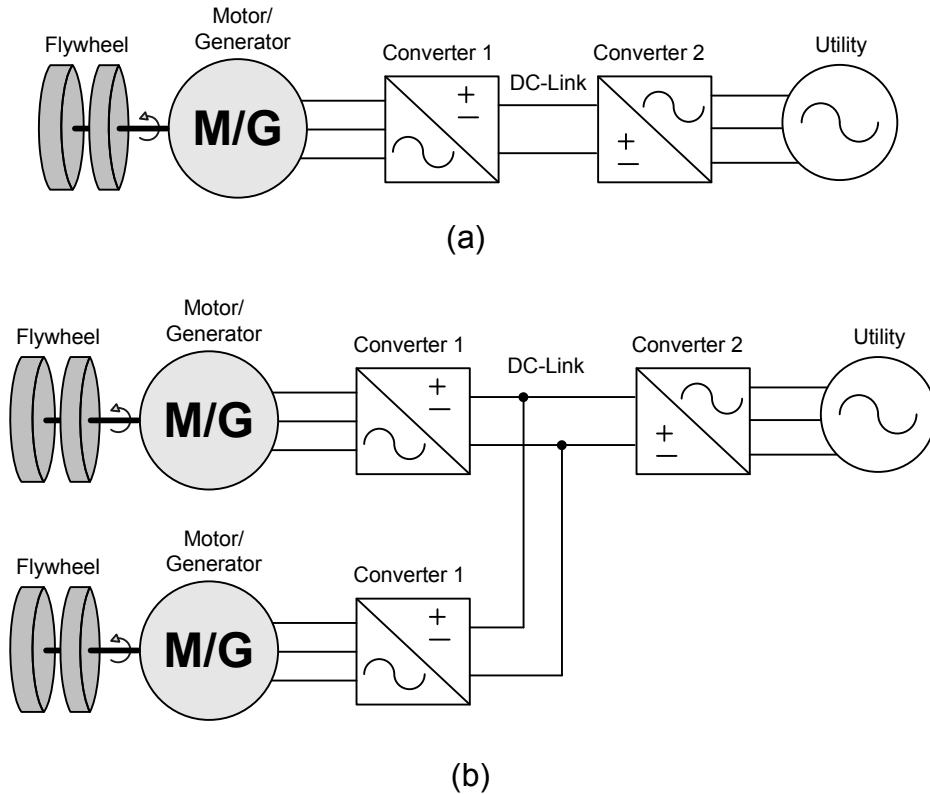
Figure 54. FESS with back-to-back DC-link converters (a) Single system; (b) Multiple systems

In Alan and Lipo's, "Induction Machine Based Flywheel Energy Storage System," a field oriented controlled (FOC) induction machine-based FESS consists of a 20 kHz high-frequency AC link (HFAC-link) and back-to-back pulse density modulated (PDM) converters. The 20 kHz HFAC-link and PDM technology, as shown in Figure 55, provides a convenient means for power management in a multi-terminal converter distribution system, offers flexibility in voltage level changes, and allows single stage power conversion. Such an HFAC-link distribution system is especially attractive for isolation and power density sensitive applications (Alan and Lipo 2003).
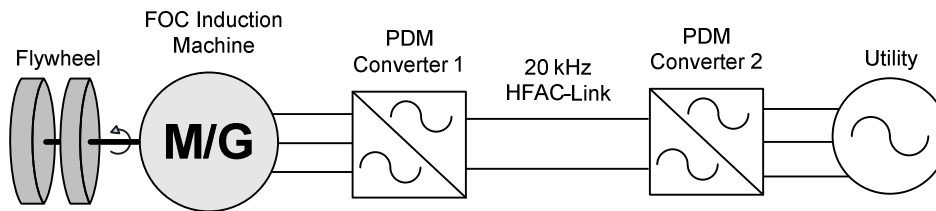
Figure 55. FESS with back-to-back HFAC-link PDM converters

Similar to the battery energy storage system, flywheel systems can be used in-tandem with the other renewable distributed energy (DE) sources to smooth out load fluctuations; damp-out voltage sags and frequency variations. As flywheel systems are capable of tens of thousands of cycles, they are the optimum solution for highly cyclic applications where electrochemical batteries are not beneficial. FESS can be used together with batteries to reduce the number of discharge cycles on the batteries to extend useful life of the batteries. In Figure 56, one such

hybrid system is shown where the FESS is included in a wind energy system (Cimuca et al. 2006). The flywheel is integrated into the DC bus of the wind system by using a bidirectional AC-DC converter. These hybrid systems can be of various types, depending on the primary source of energy and the type of FESS integration.
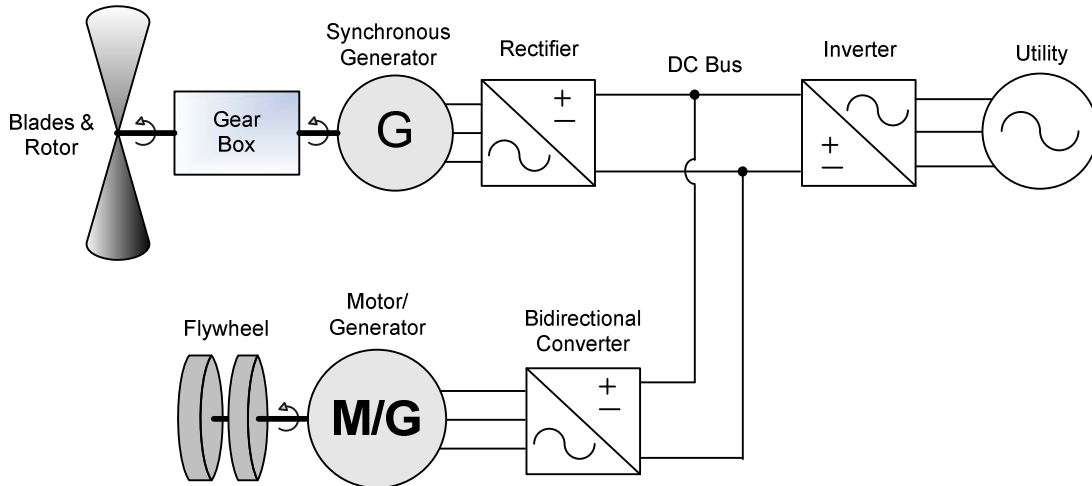
Figure 56. Hybrid system configuration with FESS and wind energy system

8.3 Power Electronics Topologies

The most common power electronics topology for the FESS consists of a DC-AC grid-connected converter and a bidirectional AC-DC flywheel converter, having a common DC bus. During discharge, the flywheel converter works as the rectifier and the grid converter works as the inverter to control the grid current by means of PWM. During charging, the rectification and inversion processes are reversed and the power flows from the utility to the flywheel. Depending on the utility connection, the utility converter can be of single-phase or three-phase. A simple design for a back-to-back converter topology is shown in Figure 57. Galvanic isolation is provided by the three-phase transformer connected to the utility converter.
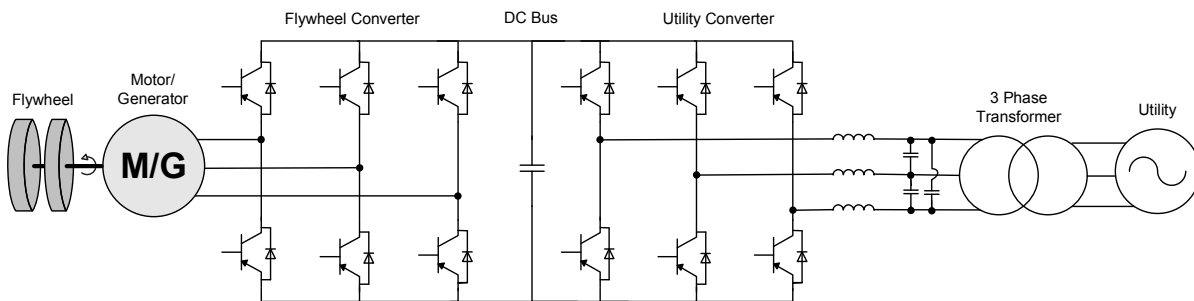
Figure 57. DC-link based power electronic topology

One modification of the conventional DC-link based topology, as described in Weissbach, Karady, and Farmer's, "A Combined Uninterruptible Power Supply and Dynamic Voltage Compensator Using a Flywheel Energy Storage System," is an additional DC-DC boost converter that is included between the flywheel and the DC-link (see Figure 58). A switch is included in the topology that is closed during charging to bypass the boost converter. This

topology can be useful in such cases where the transformer connection is not mandatory for galvanic isolation.
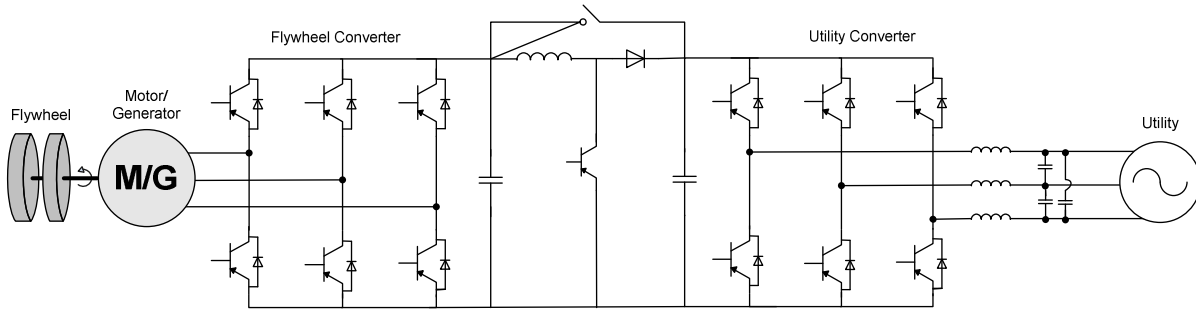
Figure 58. DC-link based power electronic topology with additional boost converter

The topology developed in Alan and Lipo's, "Induction Machine Based Flywheel Energy Storage System" is based on an FOC induction machine based FESS fed from a 20 kHz HFAC-link and back-to-back PDM converters. The technology provides reduced switching losses due to the utilization of the zero voltage switching (ZVS) technique. The design for the HFAC-link based back-to-back converter topology is shown in Figure 59.
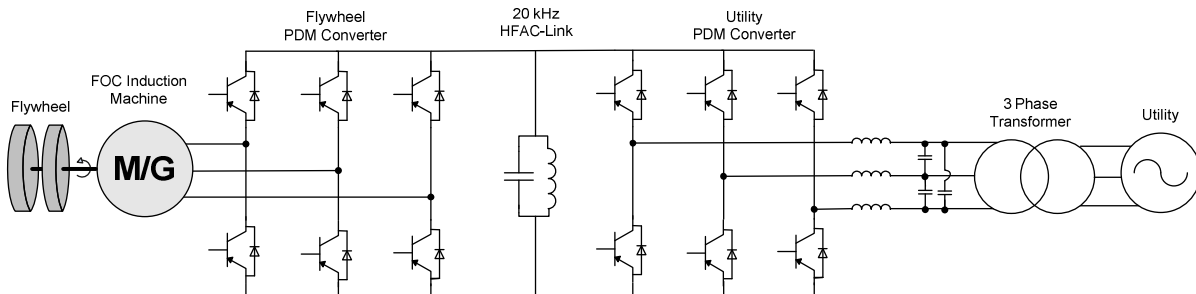
Figure 59. HFAC-link based power electronic topology

8.4 Generalized Power Electronics and Control

From the discussion in the previous subsections, it can be observed that the most generalized from of power electronics topology for the flywheel application is the back-to-back rectifier/inverter connection which provides the improved power flow control as well as increased efficiency. The voltage-fed converter scheme used in such a system is shown in Figure 57; the power electronics and controls for the FESS are shown in Figure 60. The control for the system is designed for two main functions: DC bus voltage regulation and power flow control.

The induction machine (IM) associated with the flywheel operates using a rotor flux-oriented control approach. The torque control is used for the FESS induction machine. Based on the d-axis current from the induction machine, stator flux is estimated, which is then compared with the reference flux command that is generated from the machine speed. Often, a flux weakening mode of operation is required for the IM to match the flywheel and IM speed. The error in the reference and estimated flux is then fed to the flux controller which generates the reference d-axis current. To regulate the DC-link voltage, a voltage controller is used to output the power signal (ΔP) required for maintaining this voltage at the reference value (Vdc*). If P_{ref} is the

power expected from the FESS, the reference value of the active power exchanged between the FESS and the DC-link is determined by $P^* = (P_{ref} - \Delta P)$. Based on this power signal, the reference torque is computed. The reference q-axis current is then computed based on the reference torque computation. More control design details can be found in Cimuca, Saudemont, Robyns, and Radulescu's "Control and Performance Evaluation of a Flywheel Energy-Storage System Associated to a Variable-Speed Wind Generator."

The control of the utility connected inverter, as shown in Figure 60, is developed with constant power control (Ye et al. 2006). Many functions to deal with practical control issues are not shown in the diagram, such as the negative sequence regulation, DQ decoupling, etc. The power loops are on the outer level and generate the reference current signals for the current controller. Then the inner current control loops are implemented to generate the duty cycle for the PWM converter connected to the utility. In some cases, the reactive power reference Q_{ref} could be a power factor reference. By controlling this reference, the injected current to the utility can be maintained at unity power factor. The output of the control system is the high-frequency sine PWM signals for the voltage-source inverter switches. More details of d-q based controller can be found in Appendix B.
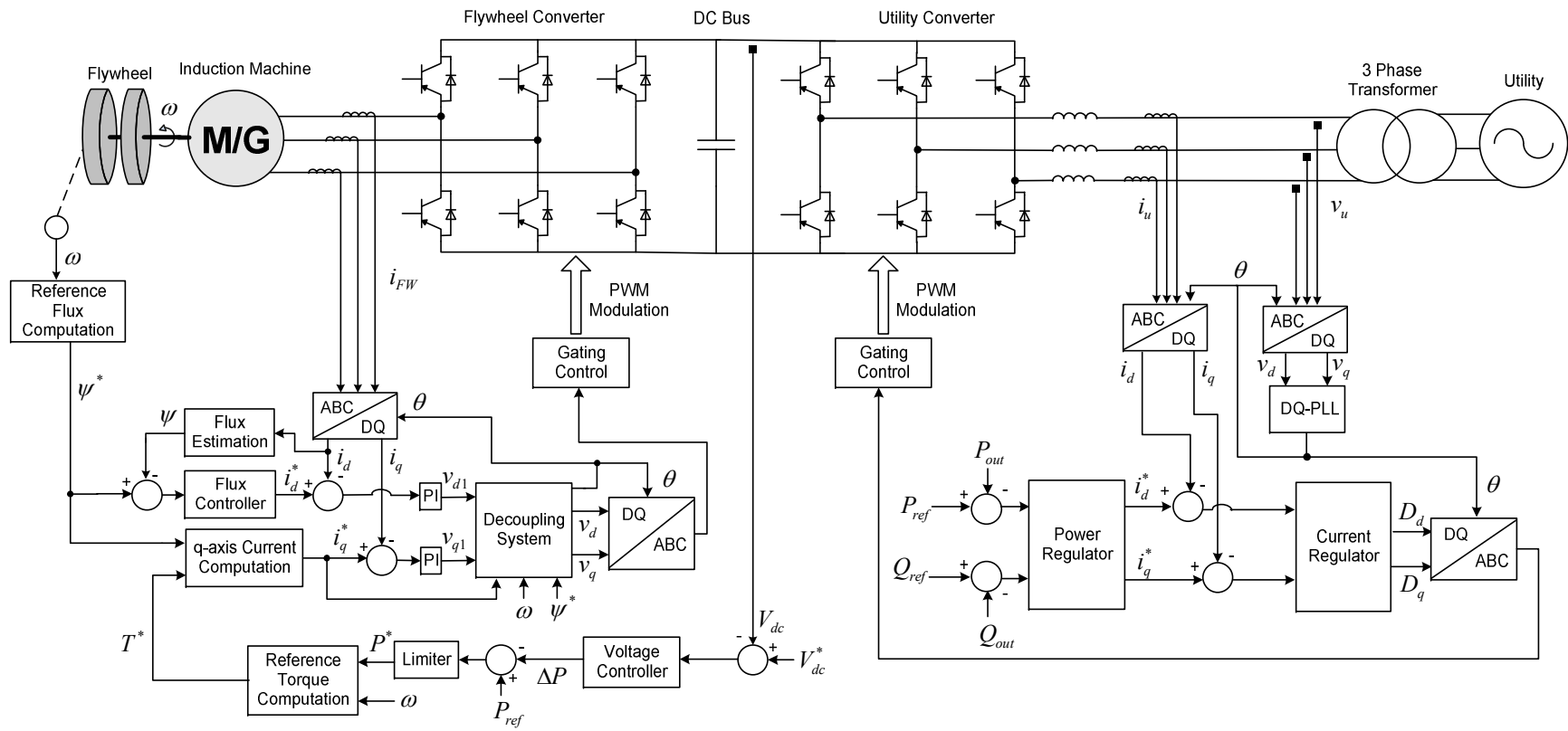
Figure 60. Generalized power electronics and control of a flywheel energy storage system

9 Plug-in Vehicles

9.1 General Description

Plug-in hybrid vehicles can be classified into different categories such as electric vehicles (EV), hybrid electric vehicles (HEV), plug-in hybrid vehicles (PHEV), and plug-in fuel cell vehicles (PFCV). A typical electric vehicle has a battery pack connected to an electric motor and provides traction power through the use of a transmission. The batteries are charged primarily by a battery charger that receives its power from an external source, such as the electrical utility. The primary advantage of an EV is that the design is simple and has a low part count. The primary disadvantage is that the driving range of the vehicle is limited to the size of the battery and the time to re-charge the battery can be 15 minutes to 8 hours, depending on how far the vehicle was last driven, the battery type, and charging method.

Typical PHEV batteries can be charged with a battery charger that receives its power from the utility; however, it can also be charged through the use of the on-board internal combustion engine and generator. The best PHEV designs are those that allow the vehicle to operate on electric power only, reducing the amount of time that the engine runs. When the vehicle is not operating, the battery can be charged through the use of a battery charger that is "plugged in" to the electrical utility or other energy source to charge the on-board battery. A PHEV normally has a larger battery pack than an HEV. The advantage of a PHEV over an HEV is that the battery is charged from an external source and can allow the vehicle to run longer on electric power instead of engine power, reducing engine fuel consumption.

In a PFCV, a battery pack and a fuel cell that are connected to an electric motor that provides traction power to the wheels through a transmission. The batteries can be charged with a battery charger that receives its power from the utility, or it can be charged with the fuel cell. Examples of plug-in vehicle prototypes are shown in Figure 61.

The GM Chevrolet Volt shown in Figure 61 (d) is a series HEV prototype that uses an electric driveline for traction. The design is reported to have a 40 mile battery-only range which can be extended using the on-board engine driven generator (http://www.chevrolet.com/electriccar/).

The 2006 Toyota Prius PHEV shown in Figure 61 (c) was converted to operate as a plug-in vehicle. The vehicle includes a standard Prius driveline, a lithium ion battery, and on-board battery charger (Markel et al. 2007).

The Ford Edge PFCV, as seen in Figure 61 (a), is prototype vehicle that includes a proton exchange membrane (PEM) fuel cell with a 5,000 psi hydrogen fuel tank, 336 volt lithium-ion battery pack, and electrically powered drive train. The vehicle, presented in Washington, D.C. in January of 2007, is a hybrid vehicle that uses the on-board fuel cell to charge the batteries when their state of charge drops below a pre-determined level. The prototype vehicle also has an on-board charger that can be plugged into a 110 or 220 VAC. The vehicle has a battery-only range of 25 miles and the on-board storage tank has enough capacity to allow the vehicle to travel 200 miles using the PEM fuel cell (http://media.ford.com/newsroom/release).

(a)

(b)

(c)

(d)

**Figure 61. Plug-in prototypes (a) Ford Edge PFCV; (b) AC Propulsion Tzero V2G EV;
(c) Toyota Prius PHEV; (d) GM Chevrolet Volt**

9.2   Plug-in Vehicle System Configurations

According to the Electric Power Research Institute (EPRI), more than 40% of U.S. generating capacity operates at a reduced load overnight, and it is during these off-peak hours that most PHEVs would be recharged. Recent studies show that if PHEVs replace half of all vehicles on the road by the year 2050, only an 8% increase in electricity generation (4% increase in capacity) will be required (http://www.epri-reports.org/Otherdocs/PHEV-Primer.pdf). PHEVs that are Vehicle-to-Grid (V2G) capable allow these vehicles' batteries to deliver power back to the utility. When the battery is being charged, the amount of DC power delivered to the battery is regulated according to a charge profile based on the type of battery technology. When the vehicle provides power back to the grid, the DC power is converted to a fixed frequency AC output, and the amount of current that is drawn from the battery is either fixed or variable depending on the complexity of the power electronics and control strategies that are used. V2G technology is a promising future alternative to increase the amount of distributed generation that can be used during peak hours. On-going demonstrations are being conducted by utilities such as PG&E and Xcel Energy to allow utilities and customers to evaluate this new technology (http://www.xcelenergy.com/XLWEB/CDA/0,3080,1-1-1_15531_46991-41555-0_0_0-0,00.html).

The simplest, most typical form of an EV configuration is shown in Figure 62. This configuration consists of a battery system and a motor controller that supplies power to the motor, which in-turn supplies power to the wheels for traction. Many of today's EVs use a permanent magnet-electric motor that can also act as a generator to recharge the batteries when the brakes are applied, also known as "regenerative braking." During regenerative braking, the motor acts as a generator, providing power back to the batteries while slowing down the vehicle. When the vehicle must be stopped quickly, or if the batteries are at full charge, friction brakes are used. Most EV systems also utilize an on-board battery charger to recharge the batteries using utility power.
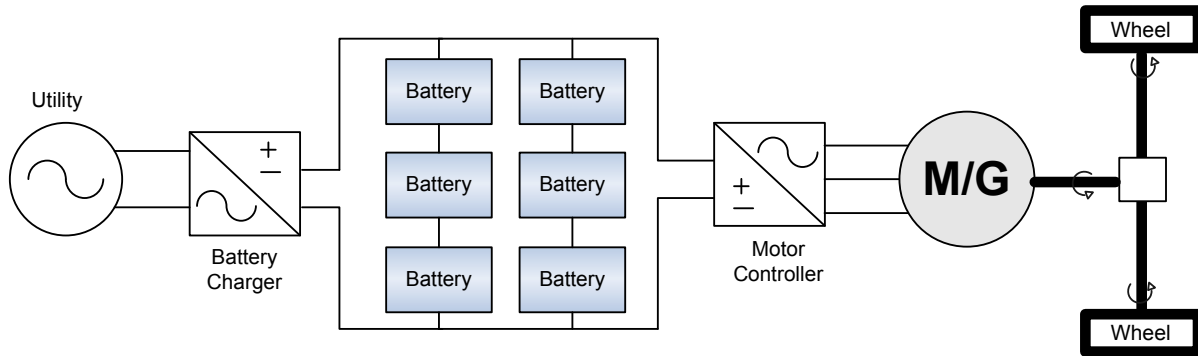
Figure 62. Typical EV configuration

Figure 63 shows a typical parallel HEV configuration. A number of HEVs are in production and are available for purchase, include the Toyota Prius, Toyota Highlander Hybrid, Toyota Camry Hybrid, Lexus RX 400h, Lexus GS450h, Honda Insight, Honda Civic Hybrid, Honda Accord Hybrid, Silverado, Saturn Vue, and Ford Escape. The components that make up a typical HEV include a battery pack, motor controller, motor/generator, internal combustion engine, and transmission and driveline components. The primary power electronics (PE) in an HEV include a DC-AC motor controller which provides three-phase power to a permanent magnet motor.

The Toyota Prius HEV configuration, as shown in Figure 64, uses a permanent magnet (PM) motor, PM generator, and gasoline engine feed into a planetary gear set. The system operates with a continuously variable transmission (CVT) where the gear ratio is determined by the power transfer between the generator and motor (Jahns and Blasko 2001). The batteries on the standard Prius are charged using the on-board PE. There is no provision to charge the batteries externally.
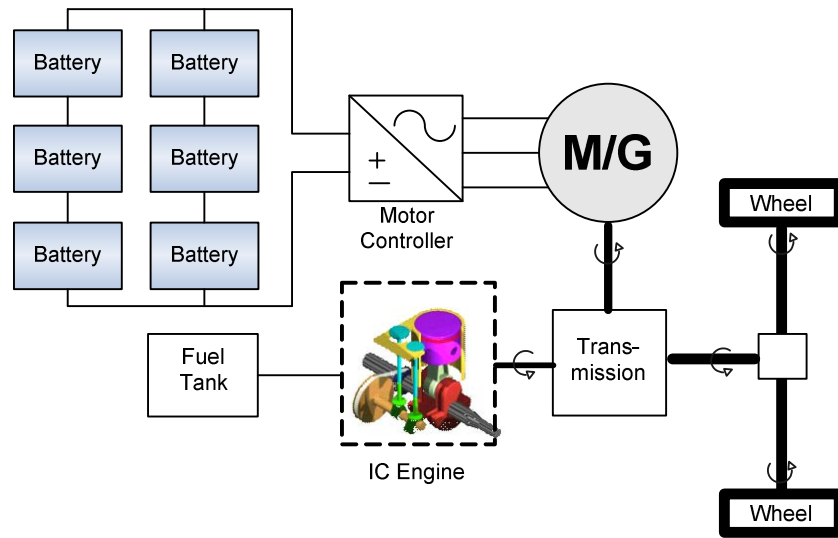
Figure 63. Typical parallel HEV configuration
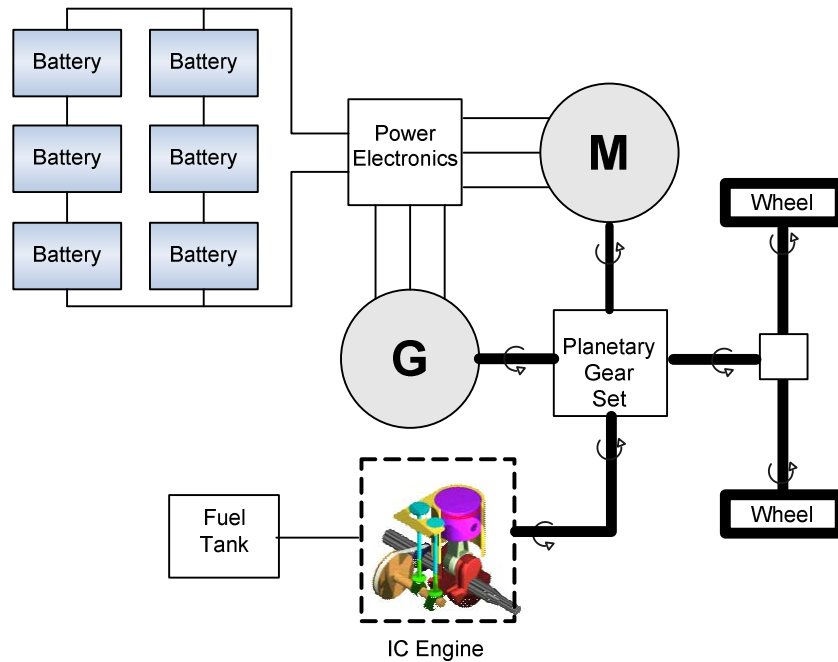
Figure 64. Prius HEV configuration

A comparison of fuel economy for various HEVs using a standard testing drive cycle (SAE J1634) is given in Figure 65 (Karner and Francfort 2007).
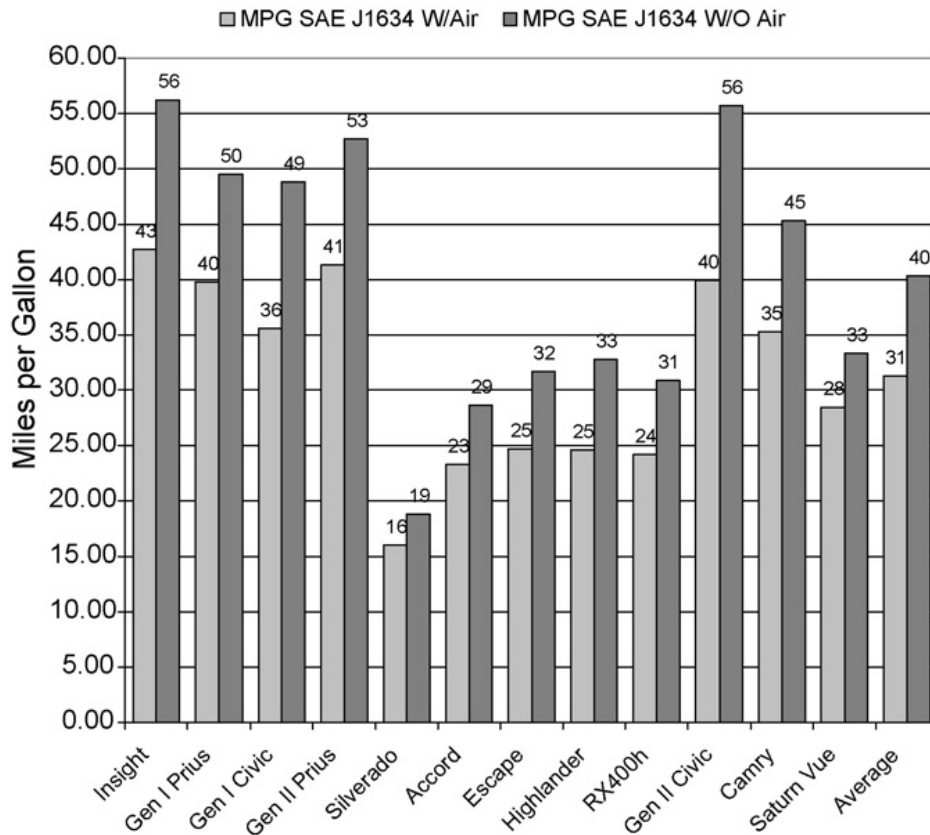
Figure 65. HEV fuel mileage comparison (Karner and Francfort 2007)

For plug-in vehicles, batteries are charged when they are not being driven. This is normally accomplished through a utility connected AC-DC converter to obtain DC power from the grid. The batteries can also be charged directly from a solar resource using a DC-DC converter, or from a wind source using an AC-DC or DC-DC converter depending on the type of power that is available from the wind resource.

In PHEVs or PFCVs, charging the batteries with an external source allows the electric motor to run more often on the batteries, thus reducing the amount of fuel used. A PHEV is basically an HEV with a larger battery pack that can be charged using a battery charger. Energy flow is unidirectional as power is taken from the utility to charge the battery pack. While a typical Prius HEV configuration is shown in Figure 64, there are a few companies who convert hybrid vehicles like the Toyota Prius to add plug-in capability (see Figure 66).

The battery voltage for most converted PHEVs are maintained at the same voltage level (typically 200-400 VDC) as the original design and battery modules are added in parallel to increase the energy capacity of the battery pack. This allows the motor to run more often than the original HEV design. The size of the electric motor for PHEV designs is expected to vary from about 10kW to as high as 100 kW for standard automobile applications. Some of the PHEV conversion companies include: CalCars, Energy CS, Hymotion, Electrovaya, and Hybrids Plus—most of whom use lithium batteries.
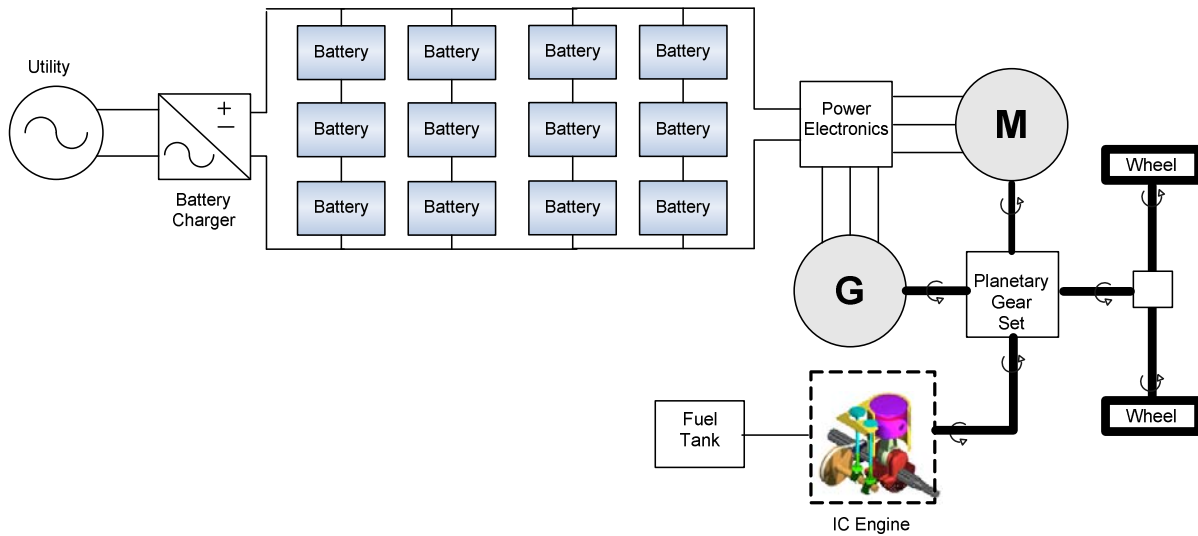
Figure 66. Prius PHEV configuration

Prototype fuel cell vehicles are currently under development; a typical fuel cell vehicle (FCV) configuration is shown in Figure 67. Most vehicles utilize a pressurized 5,000 to 10,000 psi tank on-board to store the hydrogen. The hydrogen and conditioned air are fed into a PEM stack, and fuel is provided by a pressurized hydrogen fuel tank. As the fuel flow increases, the DC output current increases. The DC output from the stack is fed into a DC-DC converter to a DC power bus. Connected to the DC bus is a battery pack and motor controller. The configuration is very similar to the electric vehicle configuration in which a motor/generator provides the mechanical power for traction. The on-board batteries allow the energy to be stored during regenerative braking and provide peak power to the motor controller during vehicle acceleration. In field-tests, over 800,000 miles have been placed on a fleet of various fuel cell vehicles. The demonstration showed that the vehicles were performing between 52%-58%, efficiency with distances ranged between 100 to 190 miles (Wipke et al. 2007).
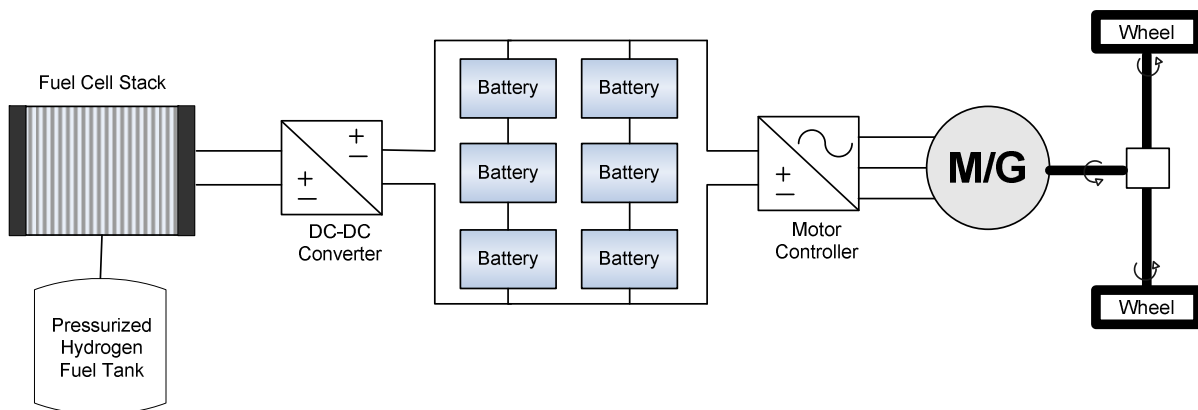
Figure 67. Fuel cell vehicle configuration

In a typical PFCV configuration, as shown in Figure 68, the batteries are charged using an on-board utility connected battery charger. This configuration typically uses a larger battery pack than an FCV to give the vehicle a longer driving range under electric power. The fuel cell

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produces DC power which is boosted to a higher voltage using a DC-DC converter. Batteries connected to the bus are used to allow the fuel cell stack to operate at more constant operating conditions. The motor controller draws its power from the DC bus and provides three-phase power to the motor/generator. Regenerative braking is also used and the power is stored by the battery pack for later use. An on-board battery charger is connected to a single phase utility connection to allow the batteries to be recharged when the vehicle is parked.
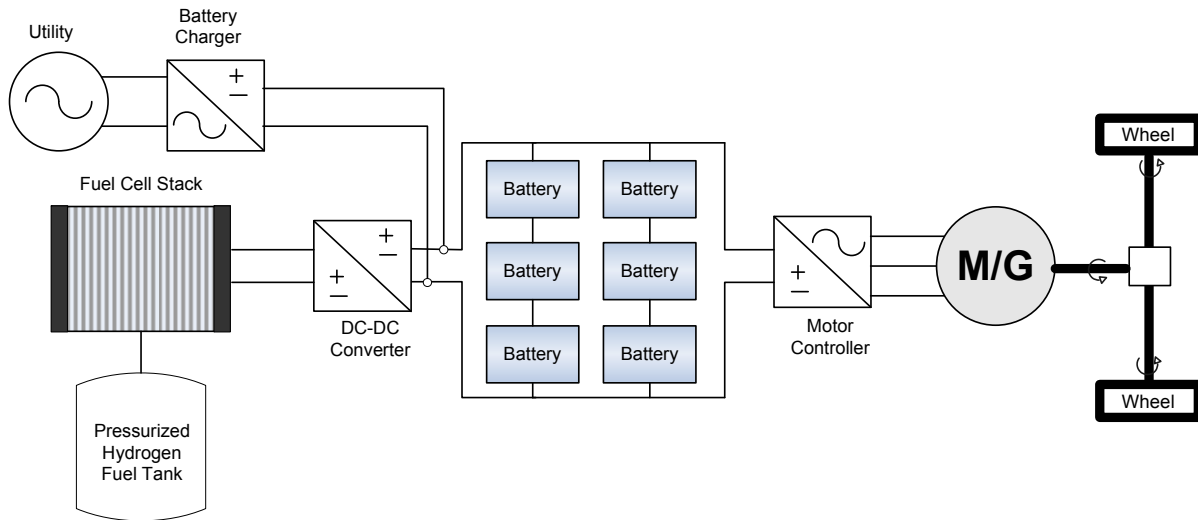
Figure 68. PFCV configuration

A plug-in vehicle can also be designed to provide power for standby power applications such as back up power to a home. For EVs, the amount of energy (watt-hours) that can be provided is limited to the size of the on-board energy storage device. For PHEVs and PFCVs, the amount of energy is limited to not only the battery pack size but also the amount of fuel that is on board. Control systems can be designed that will cycle the engine or fuel cell on and off to keep the batteries within a specified state of charge range; however, the vehicle needs to either be located outside or have provisions to allow the exhaust to be vented outside from an enclosed space, providing sufficient ventilation for both exhaust and cooling requirements for the PHEV.

In a study conducted by Parks, as documented in the "Costs and Emissions Associated with Plug-In Hybrid Electric Vehicles Charging in the XCEL Energy Colorado Service Territory" technical report, the researchers concluded that the actual electricity demands associated with PHEV charging are quite modest compared to normal electricity demands. Replacing 30% of the vehicles currently in the Xcel Energy service territory with PHEVs with a 20 mile all-electric range, 39% of their miles would be derived from electricity increasing their total load by less than 3%.

A very large penetration of PHEVs into society would place increased pressure on peaking units if charging is completely uncontrolled. There is a large natural coincidence between the normal system peaks and when significant charging would occur during both the summer and winter seasons. At today's electrical rates, the incremental cost of charging a PHEV fleet in overnight charging will range from $90 to $140 per vehicle per year. This translates to an equivalent production cost of gasoline of about 60 cents to 90 cents per gallon (Parks et al. 2007). Further

study is needed to determine the effects of battery life, state of charge control, driving range, life, and any associated replacement costs. An excellent review of current PHEV research and technologies can be found in the DOE milestone report, "Plug-In Hybrid Vehicle Analysis" (Markel et al. 2006).

9.3 Vehicle-to-Grid System Configurations

A PHEV can only charge its batteries using AC power, typically provided by a utility grid; however, as discussed, EVs, HEVs, and PFCVs can also be designed to send power back to the grid. A vehicle with this type of technology is defined as being vehicle-to-grid (V2G) capable.

All of the technologies, as discussed in the previous section, utilize a battery pack that produces DC power that must be converted to AC power in order to connect to the utility for V2G applications. The individual battery cells are generally connected in different series and/or parallel configurations to achieve the required voltage and current outputs. The power conditioning systems include inverters and motor controllers. The unique aspect to power electronics for V2G vehicles is that they must be bidirectional, that is, both taking power from the grid during charging and providing power to the grid during discharge.

The proposed use of V2G vehicles for distributed energy applications is to provide voltage and frequency regulation, spinning reserves, and electrical demand side management. If used in large numbers, V2G vehicles have the potential to absorb excess electricity produced by renewables (e.g., wind power) when the grid is operated at low load conditions—studies show that PHEVs could be a significant enabling factor for increased penetration of wind energy (Short and Denholm 2006). Controls can be developed that would allow an operator to dispatch these renewable resources through the use of the vehicle's battery when they are needed by the utility. During periods of low demand, the driver can use excess generation to charge the on-board batteries which can then be used by to run an electric motor, offsetting fuel consumption. A set of fleet vehicles that are parked at a company's facility could potentially be used to provide electricity during periods of high demand to offset the facility's electrical demand charges. Such a system is referred to as an independent system operator (ISO). A proposed wireless configuration for ISO control is shown in Figure 69.
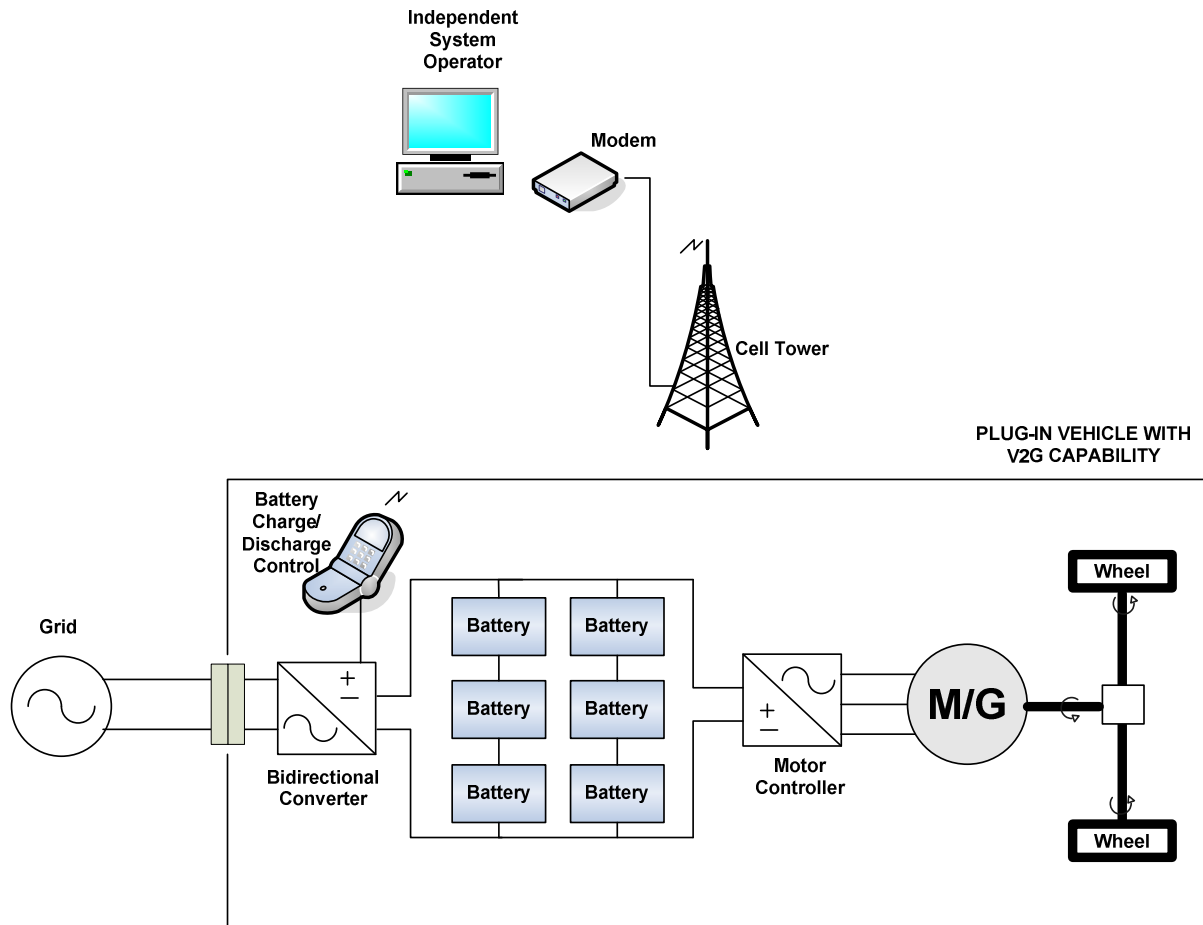
Figure 69. ISO controlled V2G

Each V2G capable vehicle must have three required elements: 1) a power connection to the grid for electrical energy flow; 2) control or logical connection necessary for communication with grid operators; and 3) precision metering on-board the vehicle (Tomi´c and Kempton 1998). The configuration shown in Figure 69 shows the power electronics being controlled using a wireless cell connection to communicate with the V2G capable vehicles. While V2G-capable cars could provide peak power or serve as a demand-response resource, their economic values do not generally justify the expense. These services are needed for just a few hours each year; therefore, the potential revenue from providing these services is limited. Current research documented by Lentendre and Denolm in their, "Public Utilities Fortnightly" report suggests that the most promising markets for V2G power are for those services that the electric industry refers to as ancillary services.

V2G vehicles typically use a high-power, high-energy battery pack and a bidirectional inverter and controller. An electronic control module controls the power electronics to operate in charge, discharge, or standby modes. Typical V2G vehicles utilize either a nickel metal hydride or a lithium-ion battery pack. Similar to the battery and flywheel energy storage systems, a V2G system can be used in-tandem with the other renewable DG sources to smooth out load fluctuations and damp out voltage sags and frequency variations. A concern using batteries for this application is the state-of-charge of the batteries must be controlled within a given range to

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avoid premature life degradation of the electrochemical batteries. Limiting the state-of-charge range will limit the system's power duration, thus limiting its usefulness for this highly cyclic control requirement.

A promising V2G configuration for supplying battery energy to the grid is the integrated motor controller/inverter shown in Figure 70. This configuration shows a utility connection using the same power electronics that are used for the motor controller, eliminating the need for a separate battery charger (Brooks 2002).
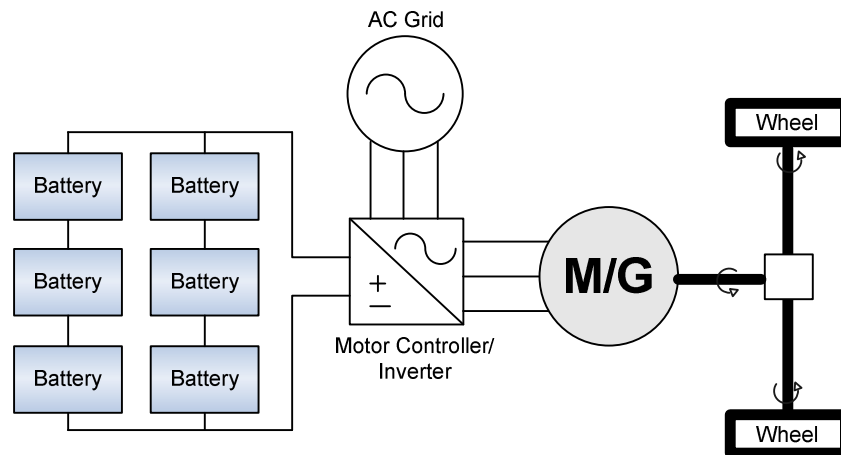
Figure 70. PE configuration with V2G

V2G power electronics (PE) provide bidirectional power either from or back to the grid. With proper power electronics, these vehicles can provide regulation services, a spinning reserve, or provide power back to the utility during high demand periods and charge their vehicle's backup during low demand times. A V2G vehicle can be designed that will provide regulation services by absorbing or providing power back to the utility to match generation with the load. A grid operator could provide commands to V2G-capable vehicles to allow the vehicles to absorb or produce power in order to keep the utilities area control error (ACE) low. ACE is a measure that indicates the deviation of the generation in a power system area from the load. The ACE is generally controlled by managing individual generators within that control area so that it complies with the National Electric Reliability Council and the area's governing electricity council's prescribed acceptable limits (Hirst and Kirby 1998; Kirby 2004).

At today's gas prices in the United States, a vehicle that can provide regulation services is expected to provide the highest return to the V2G owner (Tomi´c and Kempton 1998; Lentendre and Denholm 2006). An annual revenue estimate for a 10kW V2G capable vehicle could provide between $920 to $1,117 for spinning reserves and $2,497 to $3,285 for regulation for the PJM and Electric Reliability Council of Texas (ERCOT) territories (Lentendre and Denholm 2006). State-of-charge regulation, battery life, power capacity, energy capacity, and available power connection will be critical factors in the design of these vehicles. The number of battery discharges, charges, and state-of-charge control directly effects battery life. It is expected that with today's battery technology, designing a vehicle that can provide spinning reserve capability will be easier than a vehicle that provides regulation. The number of charges, discharges, energy capacity, and range of state-of-charge control will be less for V2Gs that provide spinning reserve

over V2Gs that are used for regulation services that will require deeper discharges and more frequent operations.

9.4 Power Electronics Topologies

The schematic for Semikron's Advanced Integrated Power Module (AIPM) motor controller PE topology, commercially available for sale, has been used some of the automaker's prototype vehicles (see Figure 71); a photograph of the packaged PE is shown in Figure 72. The AIPM uses six insulated-gate bipolar transistors (IGBT), a DC-link capacitor, integrated current sensors, temperature sensors, and a driver board that are all mounted on a heat sink. The AIPM uses pressure contact technology for a compact design, improved thermal performance, and high reliability. Integrating the DC-link capacitors in the design reduces internal inductance and allows higher bus voltages to be used. Integrating the DC-link capacitor also allows less capacitance to be used for a smaller, more reliable design. The AIPM can be purchased with either 600 volt or 1200 volt rated IGBTs. The packaging allows heat to be removed through the use of either water cooled or air cooled heat sinks. Together with a controller board, the AIPM can be controlled using a driver board with an integrated digital signal processing (DSP) controller. Customer supplied software can be downloaded the AIPM's DSP to allow the AIPM to act as a motor controller.

The AIPM controller board provides all the interface circuitry for gate drives, voltage, current, and temperature measurements, fault protection, isolation, and a DSP for on board integrated control. The controller board uses a DSP with a clock speed of 40MHz and includes a 32K flash memory, a 16 channel 10 bit analog-to-digital converter, and motor control peripherals (Curtis 2004).
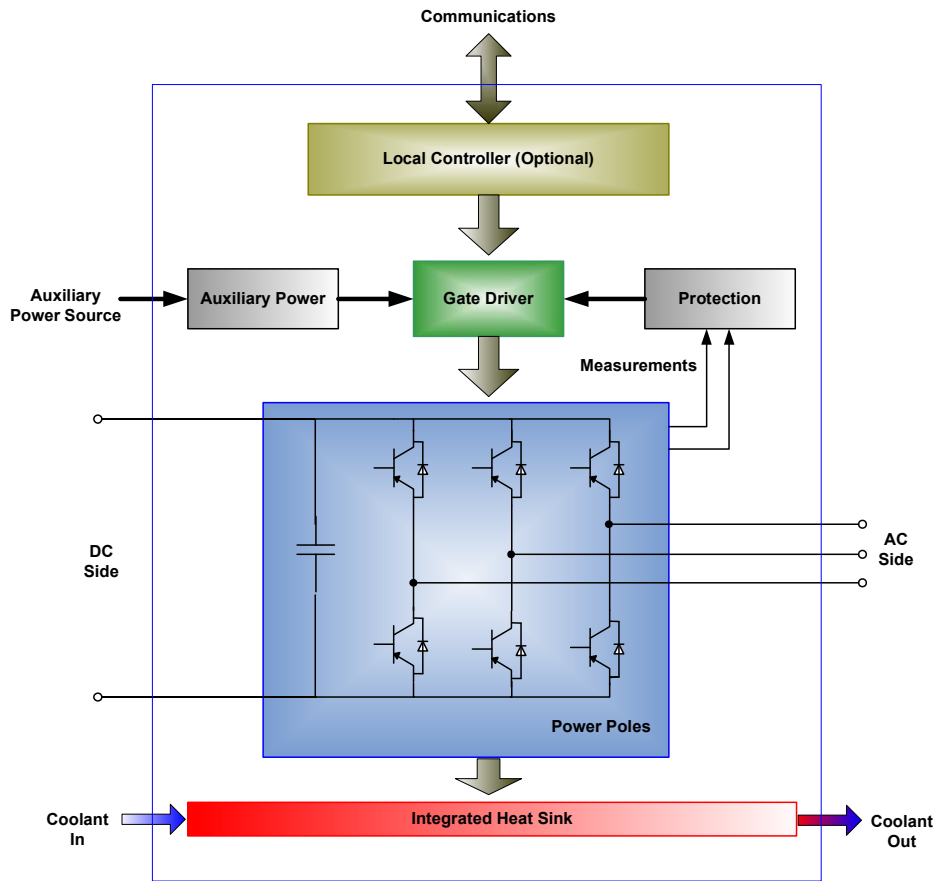
Figure 71. General AIPM PE schematic
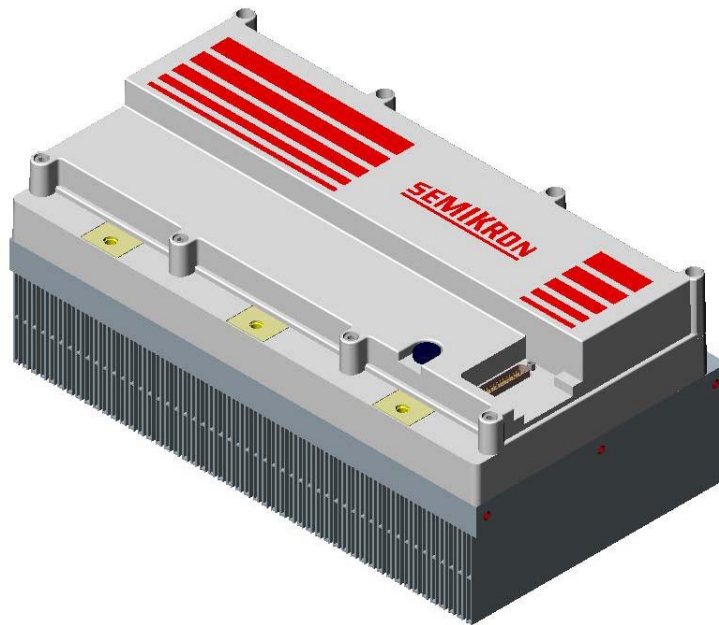
Figure 72. Air-cooled AIPM package

A commercially available V2G power electronics topology that can be purchased from AC Propulsion Systems is shown in Figure 73 (www.acpropulsion.com/technology/.htm). The unique feature of this system is that the same PE switching stage can be used for both motor control and battery charging as well as for providing power to the utility. A photograph of the system is given in Figure 74 (www.acpropulsion.com/technology/.htm).
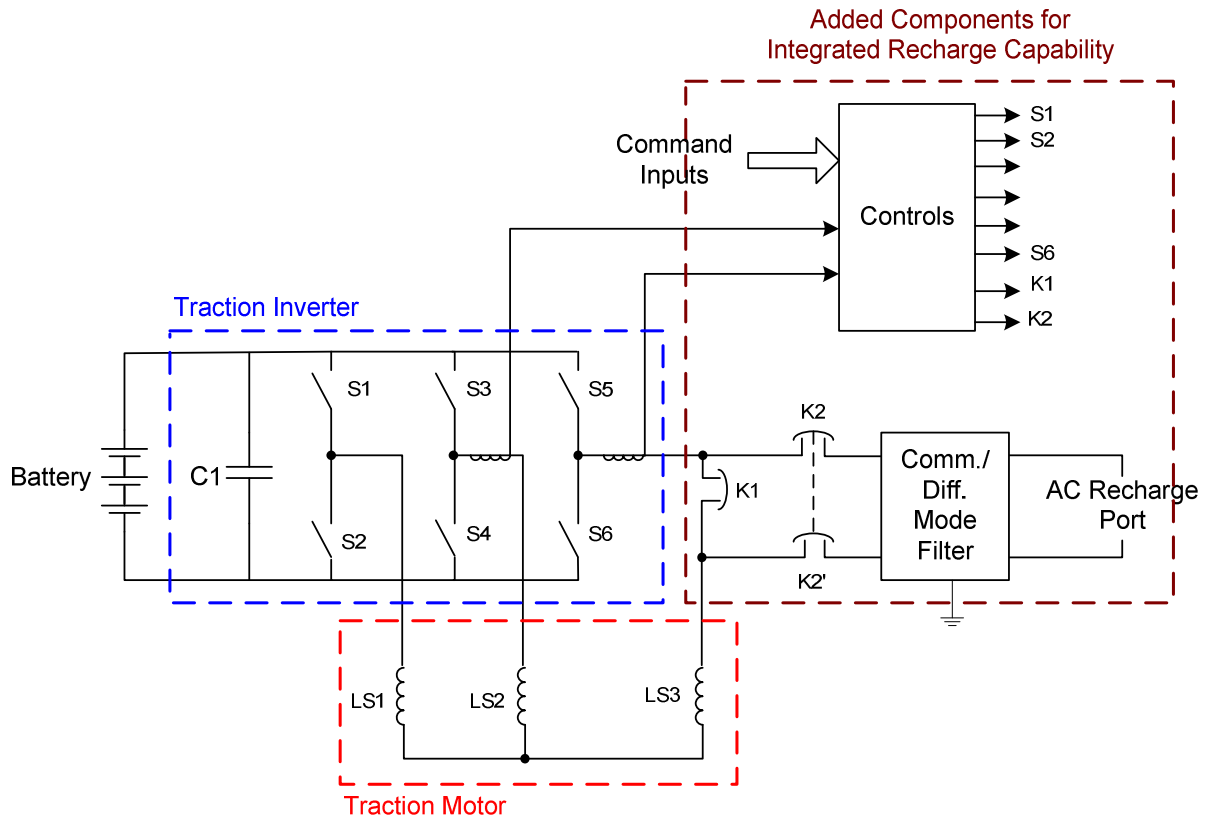
Figure 73. AC propulsion V2G model AC-150 electrical schematic

The AC Propulsion Systems' AC-150 drive system is rated at 150 kW (200 HP). The system uses a 20 kW bidirectional grid power interface that allows the drive to be used for distributed generation, selling grid ancillary services, and using vehicles to provide uninterruptible backup power to homes or businesses. The system includes a digital interface for instrumentation and recharge control, and an integrated DC bus power port for the connection of other DC power sources. The system is designed to operate as an induction motor controller with traction control and regeneration. The PE allow it to operate as a battery charger or V2G interface to the utility grid (Brooks 2002). The system reuses the power switches of the propulsion inverter (which drive the traction motor) as the power switches for a grid-tied inverter, using the motor windings as the inductors needed for the grid-tied inverter. This provides a bidirectional, high-power interface to the electric power grid with no extra power components beyond what is needed for propelling the vehicle. In addition to operating as a battery charger to convert AC grid power to DC for charging the battery, the system can operate in reverse to convert DC power from the vehicle's battery, generator, or fuel cell into AC power at the grid frequency. The AC power from the vehicle can then be used to power stand-alone loads or can be fed back into the grid.

Safety systems similar to those used with small distributed generation systems prevent the vehicle from feeding power into the grid when grid power is not available (Brooks 2002).

Figure 74. AC propulsion V2G model AC-150 electronic package

A general modular PE topology for DER and V2G is given in Figure 63. All vehicles with V2G capability must meet the IEEE Standard 1547 that specifies the type, production, and commissioning tests that must be performed to demonstrate that the utility interconnection functions properly (http://grouper.ieee.org/groups/scc21/1547/1547_index.html).

10 Modular Power Electronics

10.1 General Description

Power electronics (PE) can account for up to 40% of the costs of a typical distributed energy resource (DER) system, and they are often the least reliable part in the whole system design. Therefore, from the commercialization perspective, the key business needs for DER power electronics are reducing costs and improving reliability. Associated with these cost and reliability issues, three major technology challenges exist when discussing power electronics for DER applications (Blazewicz 2005):

- There is a lack of standardization and interoperability among power electronic components and systems. This increases the cost of manufacturability and reduces volume and reliability.

- Power electronic devices must be modular and scalable. This will simplify applications and designs, leading to increased use; higher production volumes will lower costs and improve performance.

- Current research focuses on power electronic subsystems and components rather than the DER system package. Improvements in the system package are the greatest need for the DER.

Power Electronics Building Block (PEBB) is a broad concept towards designing modular PE systems that incorporate the integration of power devices, gate drives, and other components to functional blocks (Hingorani 2003). By integrating them into building blocks, a designer addresses the device stresses, switching speed, switching losses, and thermal management with functional specifications that relate to the performance requirements of a broad set of applications (Hingorani 2003). Adoption of functional building blocks that can be used for multiple applications results in high volume production, and reduced engineering effort, design testing, onsite installation, and maintenance work for specific customer applications. The value of integration can be enhanced with the standardization of interfaces of the building blocks, control, or protections requirements.

PE devices have evolved tremendously from their familiar plastic package form towards integrating more components into a module. The module package initially combined discrete switching devices to form a half bridge, then evolved to include H-bridge circuits, three-phase bridges (six-packs), and, more recently, gate drives and sensors. Integrated power electronic modules (IPEMs), such as the Semikron Advanced Integration (SKAI) modules or PM1000 by American Superconductor, have also recently come on the market (Treanton et al. 2006). This approach, along with the power electronic devices, combines the dc-link filter capacitors, current and temperature sensors, gate drivers, heat sink and the digital signal processing (DSP) controller into a single highly optimized module (Mookken 2006). The DSP-based local controller can communicate with a higher level controller through different communication interfaces.

When designing PE systems, new IPEMs allow designers to use a building-block approach with software and wiring, defining the function of each identical block. The versatility of the module for different applications also facilitates the economics of production. Additionally, the fact that the module integrates many of the subcomponents means that the user is getting a fully

integrated and tested package—a package that is already qualified to meet some of the stringent specifications and, therefore, highly reliable (Mookken 2006). All of the advantages to using IPEMs in power electronics design make them very exciting candidates for addressing the reliability, modularity, scalability, and standardization issues for the DER applications. A simple modular design of wind energy power electronics system, shown in Figure 75, uses two IPEMs to form back-to-back converters. Each of these IPEMs consists of six power electronics switches in the form of a three-phase bridge, along with the DC bus filters, gate drivers, sensors, and local controller.
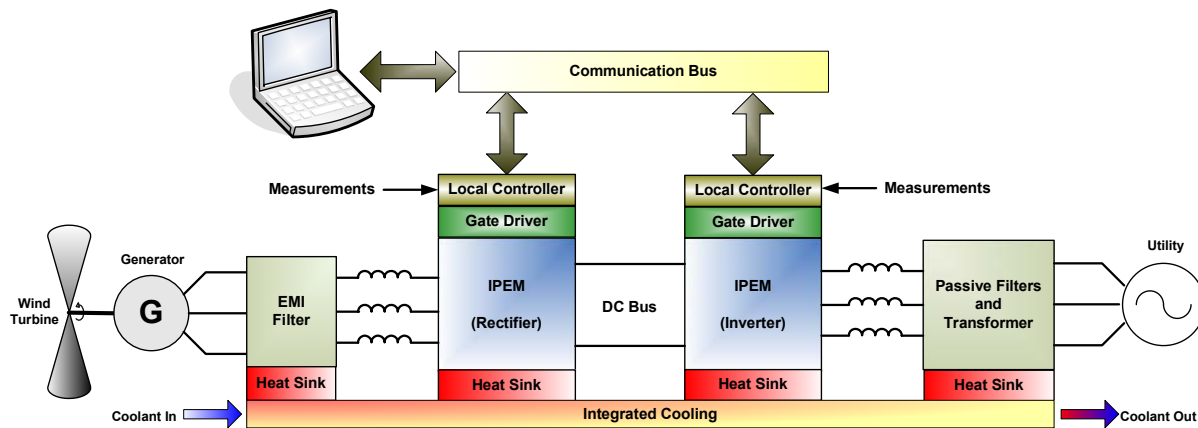
Figure 75. Modular power electronics design for wind energy system

10.2 Development of Advanced Power Electronics Interfaces (APEI)

From the previous sections of this report on various distributed energy resource (DER) technologies, it is evident that power electronics are essential components for converting generated power into useful power which can be directly interconnected to the utility grid. Because of the similar functions of these power electronics capabilities, the development of an advanced power electronic interface (APEI) that is scalable to meet different power requirements, with modular design, lower cost, and improved reliability, will improve the overall cost and durability of distributed and renewable energy systems. In this subsection, the present power electronics devices and topologies that can lead to modular design of the power electronics converters for the DER are discussed.

10.2.1 Integrated Power Electronics Modules

Integrated power electronic modules (IPEM) that have recently come on the market consists of power electronic devices, dc-link filter capacitors, current and temperature sensors, gate drivers, heat sinks, and optional digital signal processing (DSP) controllers are combined into a single highly optimized module (Mookken 2006). The inherent advantages provided by the IPEMs are: a shorter time to market, easier system design and assembly, a reduced number of components, and economical, standard interface design and reliability.

The power electronics devices can be configured in different ways inside the IPEM. Some manufacturer's products are based on half-bridge power modules, where each half-bridge can be considered a PEBB with their own hardware controller (or hardware manager) and sensors. Also, an IPEM with three-leg, six switches configurations is also available in the market (Treanton et al. 2006). In any case, it is important to note that the IPEM concept goes beyond power module

structures; it also includes the integration of sensing and control with the implementation of auxiliary functions. The structure of a representative IPEM is shown in Figure 76 (Treanton et al. 2006; Mookken 2006).
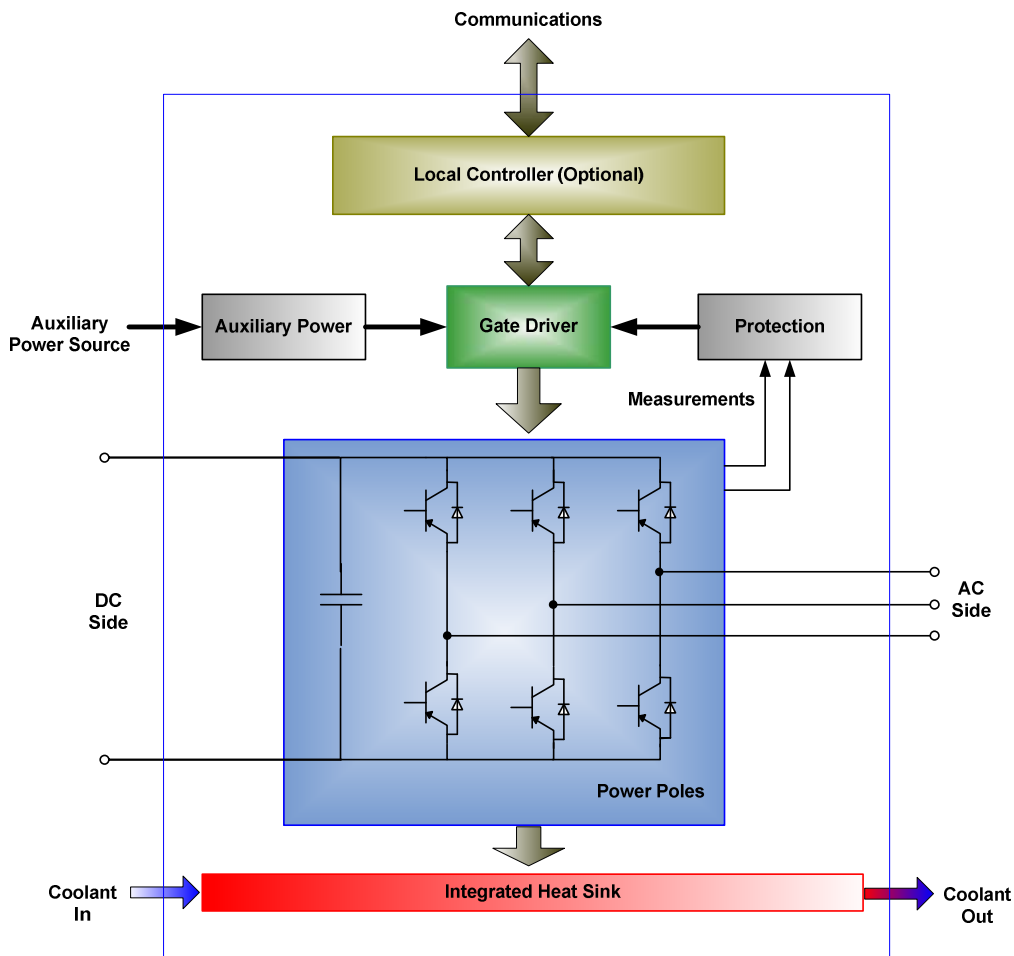
Figure 76. Typical integrated power electronics module

This particular IPEM consists of six IGBT switches arranged in a three-phase bridge configuration. Having a common heat sink, the DC bus filter capacitor, voltage and current sensors, auxiliary power supply, and gate drivers are all included inside the IPEM. A local DSP controller can also be included inside IPEM for application level of control. The DSP-based local controller can communicate with a higher level controller through different communication interfaces.

Novel packaging and assembly techniques can result in higher reliability within the modules. For example, pressure contact technology can be used to eliminate the large solder interfaces typically seen between the direct-bonded copper (DBC) and the module base plate. Greater reliability is also achieved by using an aluminum-nitrite (AlN) substrate rather than the less-expensive alumina (Al2O3) (Mookken 2006). Although the modules are highly integrated, the underlying technology (off-the-shelf products) lends itself to the development of several standard configurations such as different heat sinks, additional output sensors, and a wide selection of switching devices to populate the module.

10.2.2 Generalized Modular PE Topologies for DER

Different distributed energy systems require various power electronics topologies for converting the generated power to the utility compatible power. The photovoltaic (PV) and fuel cell systems generate DC power which needs to be converted to single- or three-phase AC for utility connection. Additionally, an isolated DC-DC converter is often used before the DC-AC inverter in order to avoid bulky line frequency transformers for isolation and voltage boosts. Wind microturbine systems generate variable frequency AC output which must be converted into 60 Hz AC for utility connection. The use of a back-to-back converter is the most efficient way to utilize the generated power. Typically, most internal combustion (IC) engines are interconnected to the utility through a fixed-speed synchronous generator that has protective relays. But as discussed in Section 6 of this report, using a power electronics interface with an IC engine offers the advantage of having variable speed IC engine operation, which in turn optimizes fuel usage for varying loads. A back-to-back voltage source converter is the most suitable choice for IC engine applications. Inclusion of storage in the distributed energy system actually provides the user with dispatch capability of its distributed resources, which are generally renewable energy sources like PV and wind, having no dispatch ability on their own. The stored energy can then be used to provide electricity during periods of high demand. Depending on the type of storage, PE converters are required for utility connection. The most unique aspect to power electronics for energy storage is that they must be bidirectional, both taking power from the grid during charging and providing power for the grid during discharge. For the battery energy storage system (BESS), a bidirectional DC-DC converter followed by a DC-AC inverter is the most general choice, whereas the flywheel system can utilize a back-to-back converter for utility connection. A diagram showing the use of IPEM with different distributed generation system is given in Figure 77.
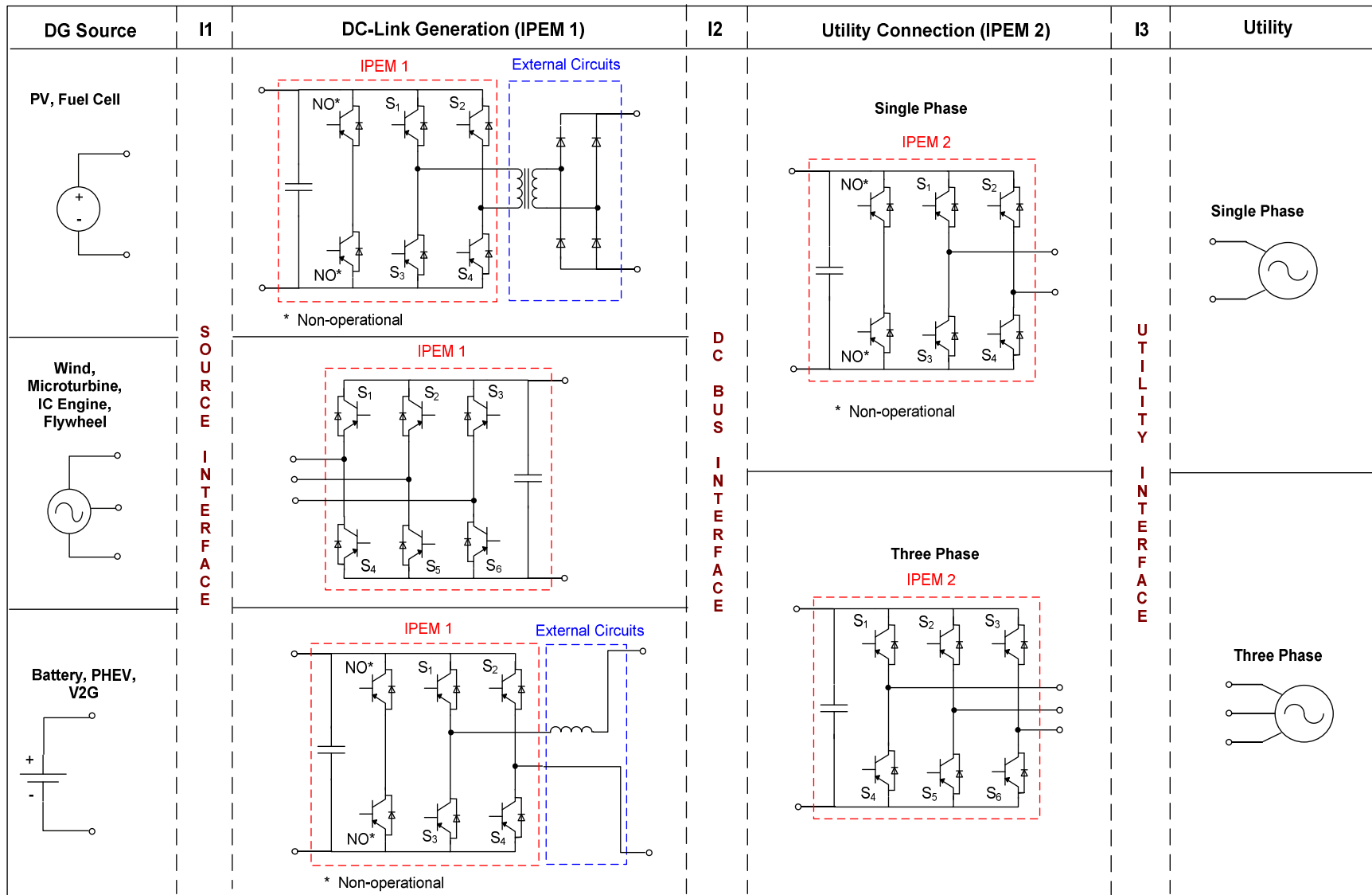
Figure 77. Generalized IPEM-based power electronics for different distributed energy systems

In Figure 77, two IPEMs are used for the distributed energy systems. As discussed in the previous subsection, each IPEM includes the six IGBTs along with gate drivers and sensors. In some cases, additional hardware components are required for designing the converter. Also, three power interfaces that are essential for the operation of the complete system are shown in Figure 77. The source interface for such systems typically consists of EMI filters and the utility interface, including line frequency filters. The DC bus filter may also be required if the capacitor inside the IPEM is not sufficient. The DC-AC inverter can be single- or three-phase, depending on the utility connection type.

The most generalized form of power electronics topology for the PV and fuel cell system is the DC-DC converter with an embedded high-frequency transformer and a DC-AC inverter (see Figure 77). In both of these applications, the IPEM based solution is not optimal, as one-third of the switches are not used in the H-bridge configuration. However, the IPEM's hardware commonalities and short system development time can provide significant cost savings (Mookken 2006).

For sources like wind, microturbines, and IC engines that generate variable frequency AC, the most generalized and versatile from of power electronics topology is the back-to-back rectifier/inverter connection. This topology provides improved power flow control and increased efficiency. The voltage-fed converter scheme used in this system is shown in Figure 77. Because the back-to-back converter scheme is inherently bidirectional, the same topology can be used with the flywheel energy storage system as well. In such power electronic topologies, line-frequency transformers are often included in the utility interface for galvanic isolation.

For battery energy storage systems (BESSs), the most generalized form of power electronics topology is the bidirectional DC-DC converter cascaded with the DC-AC inverter (see Figure 77). The full-bridge DC-DC converter can operate with any voltage and current polarity. Additionally, the voltage polarity and amplitude can be set irrespective of the current direction, providing bidirectional power flow (Mohan et al. 2003). Again, in this topology, a line-frequency transformer is often included in the utility interface for galvanic isolation.

10.2.3 Controller for APEI Systems

Based on the power electronics topologies, as shown in Figure 77, controllers can be designed for the APEI systems (the detailed control designs can be found in the respective sections of this report). These control functions are to be implemented for the APEI systems by either using the local DSP controller or by utilizing a higher level controller. A summary of general control functions for DG applications are shown in Table 3, along with the associated variables. The nomenclature for these variables can be found in the corresponding sections of the report.

Table 3. Generalized Control Functions with IPEM Based Power Electronics for Different Distributed Energy Systems

DG Sources	IPEM 1		IPEM 2		Additional Control	
	Control Objective	*Control Variables*	*Control Objective*	*Control Variables*	*Control Objective*	*Control Variables*
PV	Maximum peak power tracking	V_{PV}, I_{PV}	Power flow P, Q to Grid	$P_{ref}, Q_{ref},$ v_u, i_u	N.A.	N.A.
Wind	Generator speed, current and flux	$\omega_r, P_o, \Delta\omega_r, i,$ i^*_{dso}, I_d, V_d	DC bus voltage and unity p.f. current to utility	$V_d, I_d, V^*_d,$ v_u, i_u	N.A.	N.A.
Microturbine	DC bus voltage	V^*_{dc}, V_{dc}	Power flow P, Q to Grid	$P_{ref}, Q_{ref},$ v_u, i_u	Fuel usage	$\omega^*, \omega, Temp^*,$ $Temp, Load$
Fuel Cell	DC bus voltage	V^*_{dc}, V_{dc}	Power flow P, Q to Grid	$P_{ref}, Q_{ref},$ v_u, i_u	Fuel usage	$V_{dc}, I_{dc},$ v_u, i_u
IC Engine	DC bus voltage	V^*_{dc}, V_{dc}	Power flow P, Q to Grid	$P_{ref}, Q_{ref},$ v_u, i_u	Fuel usage	$P_{ref}, V^*_{dc}, \omega$
Battery Charge	Battery terminal voltage	V^*_b, V_b	DC bus voltage	$V^*_{dc}, V_{dc}, i^*_q,$ v_u, i_u	Operational mode	$Time, V_b, SOC$
Battery Discharge	DC bus voltage	V^*_{dc}, V_{dc}	Power flow P, Q to Grid	$P_{ref}, Q_{ref},$ v_u, i_u		
Flywheel	Generator torque, speed and DC bus voltage	$V^*_{dc}, V_{dc}, \omega,$ i_{FW}, P_{ref}	Power flow P, Q to Grid	$P_{ref}, Q_{ref},$ v_u, i_u	N.A.	N.A.

10.3 Requirement of Standard Interfaces

In traditional centralized digitally controlled power electronics systems, construction, debugging and maintenance of the PE systems are complicated and difficult due to the lack of standardization and modularization. The difficulties also increase because of the strong dependence of control design on system hardware. The concept of power electronics building blocks (PEBB) provides a way to hardware standardization of PE systems. Based on PEBB concept, and as discussed in the previous subsection, the new integrated devices are feasible for distributed energy applications. Additionally, the standardization in PE requires standardizing of the power flow and signal distribution network, which in turn allows for an open-architecture distributed controller approach. The standardization of communication interface allows partitioning of power electronics systems into flexible, easy-to-use, multifunctional modules or building blocks, which can significantly ease the task of system integration. By using control software that is functionally divided into hierarchical levels, and by standardizing interfaces between levels, the application software becomes independent of the hardware specifications of power stage. As long as there are standardized support interfaces between levels, products from different vendors can communicate and work with each other (Guo et al. 2001). Furthermore, if both sides of an interface support device self-identification and system resources assignment, then the so-called "plug-and-play" implementation is feasible for future APEI systems.

10.3.1 Power Interfaces

A simplified block diagram for the power electronics for the different DER systems is shown in Figure 78. The following characteristics should be made available for designing the standardized power circuits:

- Each IPEM should have two ports: a DC-Port and an AC-Port.

- Both ports for the IPEM are to be bidirectional and should be able to work in a buck or boost mode.

- Device ratings for the IPEMs are limited by manufacturer datasheets; therefore, for high power applications, paralleling of the converters are necessary.

- The wiring will be based on the operational power.

- Filters, transformers, and other external circuit designs will be dependent of the operational power. It is always possible to design the circuit for higher power and use it for low power applications, but there will be obvious drawbacks, including an inefficient design and higher cost.

- For single-phase applications, the utility connected IPEM (i.e., IPEM 2) will only use four switches. However, the IPEMs offer cost savings thanks to the commonality of the hardware and short development time for the system.

- Combining multiple sources and/or storages can be done using the DC bus. In such cases, a single IPEM can be used for DC-AC inversion (Khersonsky and Robinson 2003).
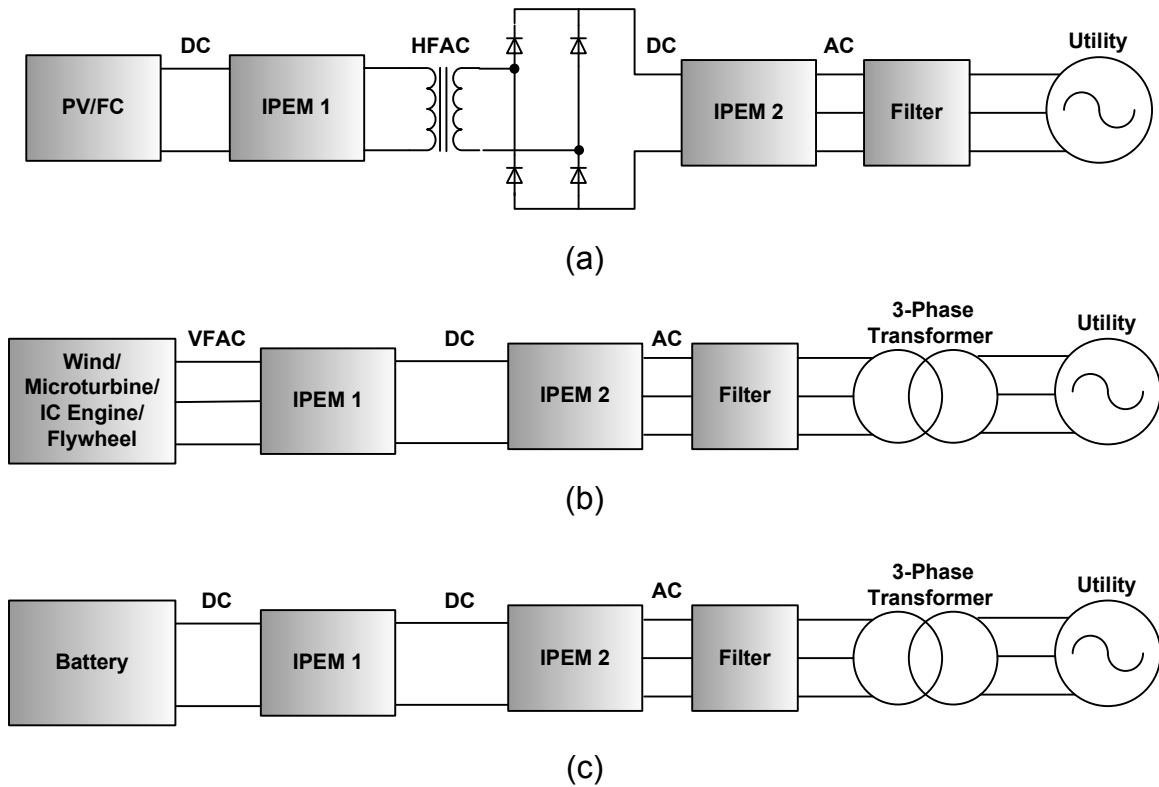
Figure 78. Block diagrams of power electronics for (a) DC sources; (b) Variable frequency AC sources and storages; (c) DC storages

10.3.2 Control Interfaces

Control of today's medium and high-power converters is primarily based on a centralized digital controller that has several drawbacks, including the large number of point-to-point signal links that connect power stage and sensors on one side with the centralized controller to the other (Celanovic 2000). Additionally, the signals in typical PE systems are of different formats and are transmitted through a variety of physical media. This makes the standardization and modularization of PE systems and subsystems very difficult (Celanovic 2000). The standardization in power electronics requires standardizing the power flow and signal distribution network, which in turn allows for an open-architecture distributed controller approach. The standardization of communication interface allows partitioning of power electronics system into flexible, easy-to-use, multifunctional modules or building blocks, which should significantly ease the task of system integration. By using control software that is functionally divided into hierarchical levels, and by standardizing interfaces between levels, the application software becomes independent of the hardware specifications of the power stage.

For the modular design of PE for distributed generation applications, the control of the PE system can be functionally divided into hierarchical architecture as shown in Figure 79. The controller that is the inherent part of the IPEM is defined as the local controller. In literature, the local controller is often called a hardware manager (Celanovic 2000; Rosado et al. 2003). The higher level controller, defined as the application manager, is external to the IPEM and establishes the main mission functions of the PE system. In order to achieve the goals required at the system control level, some standard control functions must be performed inside the

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applications manager. If more than one application is combined, in a hybrid system with different DER sources for example, a higher level system manager is required that coordinates the operation while maintaining the system data bus for communicating with the individual application managers.
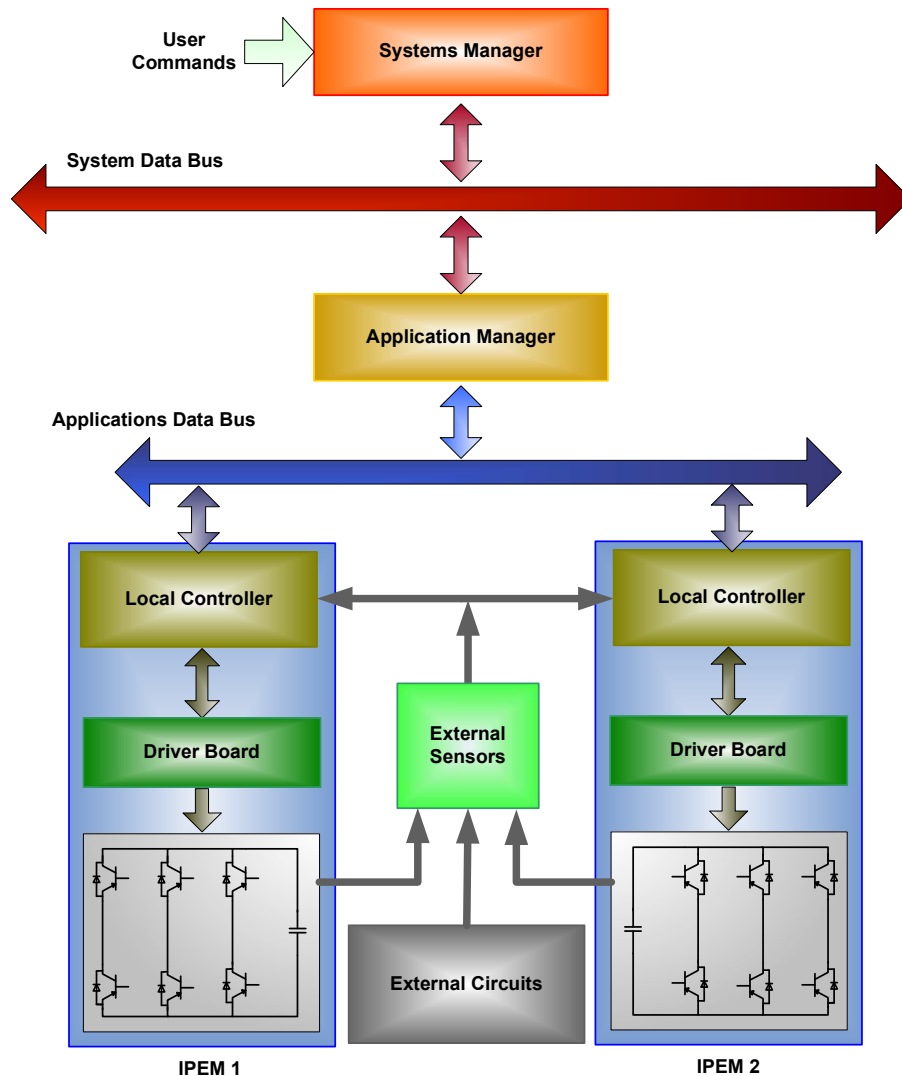
Figure 79. Hierarchical division of control functionality for IPEMs

The local controller is designed to provide control and communication functions for the IPEM it is associated with. It is designed to support all module specific control tasks, making the module specific functions (i.e., soft switching) invisible to the application manager. As the IPEM's built-in DSP module provides enough calculation capabilities to carry out the voltage and current control inside the local controller in addition to the PWM generation for the switches, it is preferable to so implement the control at this level. From a generalized evaluation of different converters, it can be found that there is a set of common functions they all share; these common functions are related to the lower levels as well (Rosado et al. 2003). For DER applications, the PWM generation at the lower level always relates to either voltage or current control for the

particular converter; therefore, it is desirable to achieve these controls inside the local controller to make the system more modular.
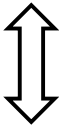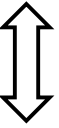
In addition, the local controller can be used for over-current protection and indication; current, voltage and temperature sensing with A/D conversion; and communication of PWM, status, and measurements. Some IPEM manufacturers also offer the IPEM without the DSP controller, which in turn provides the user the flexibility to choose a suitable controller according to the application requirements. In such cases, it is required to define the interfaces for the local controller in order to maintain the modularity and standardization for the IPEM system.

The application manager is the external controller that provides the functions to control the main mission of the power electronics system. For example, in microturbine applications, the power circuit consists of two IPEMs connected in a back-to-back formation with a common DC bus. The application manager operates the individual local controllers in such a way that the source IPEM (IPEM1) works for the DC-link voltage control and the utility IPEM (IPEM2) controls the power flow to the grid. In order to achieve these goals required at the system control level, some standard control functions must be performed in the application manager. The application manager controls the local controller through standard interfaces. It also controls the communications data bus for the local controllers.

The top-level system manager performs the controls tasks at the system level, including responding to users' commands, coordinating performances between different applications, and monitoring system execution. Additionally, the system manager can also be utilized to determine the mode of operation for each of the DER system individually so that the issues related to islanding and energy cost optimization can be resolved.

The input-output signals and control interfaces for a typical IPEM hierarchical controller are summarized in Table 4. For this IPEM, it is assumed that the local DSP controller is outside the power electronics module and is connected to the power electronics module through a connector. Furthermore, it is assumed that the external sensors are connected directly to the local controller's analog input ports. It is also assumed that the connection between the local controller and the applications manager follow the typical IPEM manufacturers' controller area network (CAN) interface (Treanton et al. 2006). Different open architecture communications protocols can also be used as will be discussed later. Both the system manager and application manager are developed in a central processing unit (CPU) and named as external controllers in the table. All the measurement signals are routed to the external controllers via the local controller.

Table 4. Input-Output Signals and Control Interfaces of a Hierarchical Controller in an IPEM

IPEM	Interface 1	Local Controller (LC)	Interface 2	External Controllers (EC) and External Sensors (ES)

Inputs:
• PWM signals (5V CMOS level)
• Enabling signals
 	
Outputs:
• DC bus voltage
• Phase currents
• Heat sink temperature
• Fault signals
  1. Excessive switch current
  2. Phase over-current
  3. DC bus over-voltage
  4. Power supply under-voltage
  5. Over-temperature at heat sink
	⇕
	
	D-sub 25 pin connector with ribbon cable
		Inputs:
		• Phase currents
		• Phase voltages
		• DC bus voltage
		• Heat sink temperature
		• Relay sense signals
		• Encoder inputs
		• Zero-crossing detection
		• Fault signals from IPEM
		• System operation mode signals from EC
		• Protection signals from EC
		
		Outputs:
		• Gate drive PWM signals
		• Communication signals for IPEM
		• Enabling signals to IPEM
		• PWM status signals to EC
		• Fault signals for EC
			⇕
			
			Measurement signals from sensors to analog input of DSP
			
			⇕
			
			Control signals from external controller by CAN or asynchronous serial
				Inputs:
				• Measurement signals from LC
				• Measurement signals from ES
				• Encoder signals
				• Fault signals
				• User Inputs
				• PWM status signals
				
				Outputs:
				• Reference voltage and current signals to LC
				• Communication signals for external data bus
				• Relay contactor signals
				• Protection signals to LC
				• System operation mode signals to LC

The communication between the IPEM and local DSP controller is obtained through a connector. If the DSP controller is inside the IPEM, this communication interface is not available to the user. The application manager and the system manager are generally implemented in CPU. The communications between the local controller and the CPU is typically achieved by a CAN or an asynchronous serial using fiber optics. According to Rosado, Wang, Boroyevich, and Wachal's, "Control Interface Characterization of Power Electronics Building Blocks (PEBB) in Utility Power System Applications," it can be observed that the bandwidth of the analog type signals depends on the number of signals, the switching frequency, and the number of bits representing the duty cycle—analog signals that are not directly related to the switching frequency may require a lower bandwidth. On the other hand, the channel bandwidth requirement for the digital type signal depends on the number of signals, the ratio of the sampling period to the transmission time, the sampling frequency, and the number of bits representing the variables. In most of the APEI applications, the CAN communication is sufficient for data transmission as it can support up to 1 Mbit/s bit rate at network lengths below 40 meters. But using IPEMs for other types of applications such as active filtering may require new communication protocols as described in "A New Control Architecture for Future Distributed Power Electronics Systems," and "Control Interface Characterization of Power Electronics Building Blocks (PEBB) in Utility Power System Applications."

11 Conclusions and Recommendations

Different distributed energy (DE) systems require various power electronics topologies for converting generated power in to utility compatible power. The photovoltaic (PV) and fuel cell systems generate DC power which needs to be converted to single- or three-phase AC for utility connection. The wind, microturbine systems generate variable frequency AC output which needs to be converted into 60 Hz AC for utility connection. Typically, most internal combustion (IC) engines are interconnected to the utility through a fixed-speed synchronous generator that has protective relays. However, using a power electronics interface with an IC engine offers the unique advantage of having variable speed operation of the IC engine, optimizing fuel usage for varying loads. Inclusion of storage in the distributed energy system actually provides the user dispatch capability of its distributed resources. Stored energy can then be used to provide electricity during periods of high demand. Depending on the type of storage, power electronics (PE) converters are required for utility connection. The most unique aspect to PE for energy storage is that they must be bidirectional, both taking power from the grid during charging and providing power to the grid during discharge. For battery energy storage systems (BESS), a bidirectional DC-DC converter followed by a DC-AC inverter is the most general choice, whereas the flywheel system has a back-to-back rectifier and inverter that can be utilized for utility connection.

On the downside, PE can account for a significant part of the total capital cost of a typical DE system, and they are often the least reliable part in the whole system design. Therefore, from the commercialization perspective, the key business needs for DER power electronics are reducing costs and improving reliability. In Figure 80, a representative chart is given that compares the average PE costs in terms of the percentage of total capital costs for four DE systems. It is evident from the figure that PE can contribute up to 40% of the total capital cost.
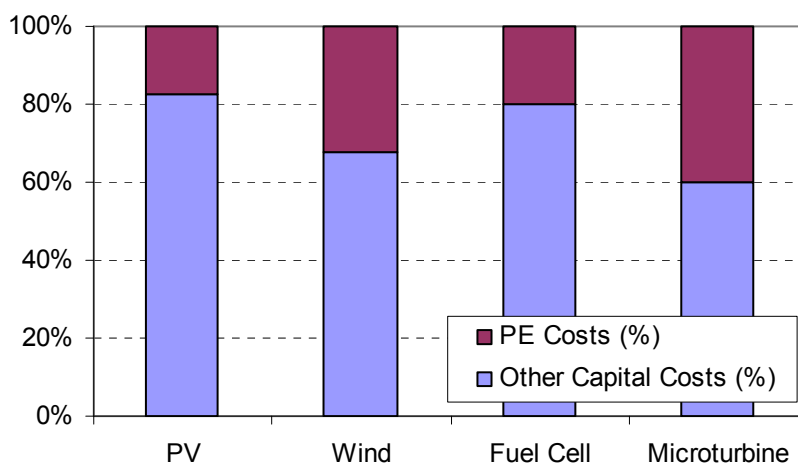
Figure 80. PE costs compared to total capital costs for DE systems

As discussed in detail, this report cites that there are many PE topologies that are being used by the distributed energy resource community. A list of current DE technology vendors that produce power electronic interfaces is provided in Appendix A. As discussed in this report, though most of the PE designs are specific to the DE technology, they possess some common functionality

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across the technologies. It is therefore feasible to design a modular and scalable advanced power electronics interface (APEI) that will allow each of the energy source technologies to use the same power electronic components within their system architectures. This will allow for cost reductions due to high volume production of the power electronic interface modules. This modular block approach will also help manufacturers to use their products without sacrificing their intellectual property.

In addition to the inherent advantages provided by the PE, such as improvement of operating efficiencies and power quality, volt-amperes reactive (VAR) support and voltage regulations, and the reduction of distributed energy fault currents, modular PE can provide the following features and capabilities:

- A crosscutting, standardized interface for utility grid-tie and smart grid DE applications
- Scalability
- Modularity
- High reliability with a mean time between failures of at least 10 years
- Low cost and manufacturability in high volume
- Ways to address, improve, and lower costs for UL certification.

As previously mentioned, the key barriers for advanced PE interfaces include cost and reliability. Based on the expertise of Semikron, a rough break down of the costs for each of the components in an inverter is given in Figure 81. Though the actual percentage values can vary among different manufacturers, the figure provides a solid basis to help illustrate the relative costs between design elements. It can be observed that the highest cost items are sensors, followed by switches, capacitors, and the bus bars.
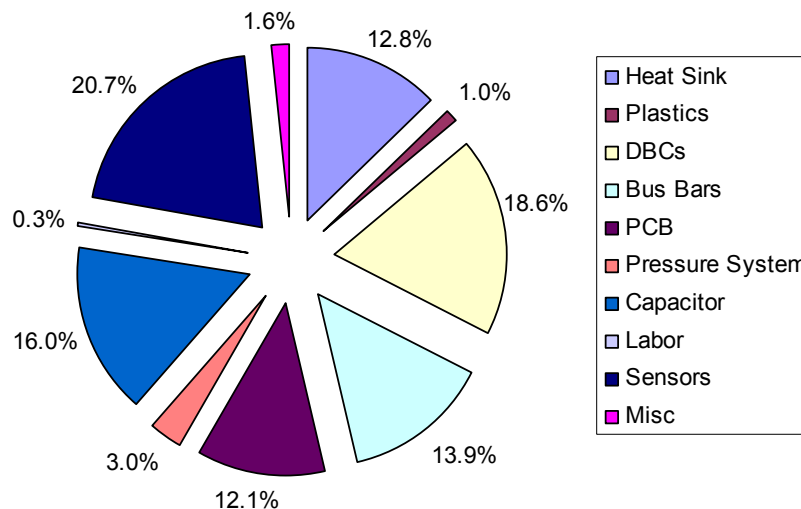
Figure 81. Estimated component cost distribution for Semikron's 200 kW inverter

The goal of a modular system design is to prevent redesign requirements for different DE applications, enabling high-volume production and reduce costs. On the reliability perspective,

the fact that the module integrates many of the subcomponents means that the user is getting a fully integrated and tested package, a package that is already qualified to meet some of the stringent specifications and, therefore, highly reliable. The integrated power electronics module (IPEM) based on back-to-back converter topologies has been presented in this report as a viable PE interface that can operate with different DE systems with small or no modifications. However, to reach the goal of modularity, some challenges must be overcome first. One challenge lies in defining the power and communication interfaces. The power connection interfaces must be simple enough for the common consumers to accomplish installation. Standardization is also required for the communication interfaces between modules, packages, and controllers. IEEE standards do not currently address this issue, so there is no standard for communication between different products.

To have complete modular APEI systems, the control software must be functionally divided into hierarchical levels. Additionally, interfaces must be standardized between levels so that the application software becomes independent of the power stage hardware specifications, allowing products from different vendors to communicate and work with each other. Furthermore, if both sides of an interface support device self-identification and system resources assignment, then the so-called plug-and-play implementation is feasible for future APEI systems. Further research and development is necessary to expand requirements and implement technologies associated with interconnecting modular, inverter-based interface technologies.

California Energy Commission's PIER Program has started the APEI Initiative to achieve these technological milestones. The APEI Initiative is a coordinated plan to develop a modular architecture for standardized, highly integrated, modularized power electronics interconnection technologies that will come as close to "plug-and-play" as possible for distributed energy resource (DER) platforms.

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13 Glossary

13.1 List of Acronyms

AC	Alternating current
ACE	Area control error
ACRDI	Active clamp resonant DC-link inverter
A/D	Analog to digital
AIPM	Advanced integrated power module
APEI	Advanced power electronics interface
BESS	Battery energy storage system
CAES	Compressed air energy storage
CAN	Controller area network
CCHP	Combined cooling, heating, and power
CHP	Combined heat and power
CPU	Central processing unit
CVT	Continuously variable transmission
DBC	Direct-bonded copper
DC	Direct current
DE	Distributed energy
DER	Distributed energy resource
DFIG	Doubly-fed induction generator
DG	Distributed generation
DSP	Digital signal processing
EMI	Electro-magnetic interference
EPS	Electric power system
ERCOT	Electric Reliability Council of Texas
FESS	Flywheel energy storage system
FOC	Field oriented controlled
FPGA	Field-programmable gate array
GTO	Gate turn-off thyristors
HC	Harmonic compensator
HFAC	High-frequency AC
HFLC	High-frequency link converter
IC	Internal combustion
IEEE	Institute of electrical and electronics engineers
IGBT	Insulated-gate bipolar transistor
IM	Induction machine
IPEM	Integrated power electronics module
ISO	Independent system operator
MCFC	Molten carbonate fuel cell
MCT	MOS-controlled thyristors
MPP	Maximum power point
MPPT	Maximum power point tracking

NEC	National electrical code
NREL	National Renewable Energy Laboratory
PAFC	Phosphoric acid fuel cell
PCB	Printed circuit board
PCC	Point of common coupling
PDM	Pulse density modulation
PE	Power electronics
PEBB	Power electronics building block
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
PHEV	Plug-in hybrid electric vehicle
PI	Proportional-integral
PIER	Public interest energy research
PLL	Phase-locked-loop
PM	Permanent magnet
PR	Proportional resonant
PV	Photovoltaic
PWM	Pulse-width modulation
RPLI	Resonant-phase leg inverter
RPM	Revolutions per minute
RPS	Renewable portfolio standards
SCR	Silicon controller rectifier
SKAI	Semikron advanced integration
SMES	Superconducting magnetic energy storage
SOC	State-of-charge
SOFC	Solid oxide fuel cell
SPWM	Sine pulse-width modulation
UC	Ultra-capacitors
UL	Underwriters Laboratories
V2G	Vehicle-to-grid
VAR	Volt-amperes reactive
VFD	Variable frequency drive
VRB	Vanadium redox battery
VSI	Voltage source inverter
ZVS	Zero voltage switching

13.2 Definitions

Distributed energy (DE) – Electric power sources located at or near the point of use or load center. DE includes both distributed generation and distributed energy storage. The generation sources include a range of technologies, such as photovoltaics, wind turbines, fuel cells, microturbines, combustion turbines, reciprocating engines, gas- and steam-powered turbines, stirling engines, biomass systems, and solar thermal systems. Distributed energy storages include technologies such as batteries and flywheels. Related systems and supporting technologies for DE include power electronics and control technologies.

Flexibility – The ease with which a system or component can be modified for use in applications or environments other than those for which it was specifically designed. For interconnection systems, the ability to adapt to: new types of DE prime movers, emerging storage platforms, provide new functionality (e.g., ancillary services), integrate into diverse distribution systems, and/or adapt to new communications protocols.

Full Bridge – Mainly used in association with single phase rectifiers, DC-DC converters, and inverters. Four power electronics devices are setup in forms of two legs in parallel, where each of the legs consists of two devices in series as shown in Figure GL-1(b). Based on the input/output connections and the type of power electronics devices, the same circuit can be used as rectifiers, DC-DC converters, or inverters. In literature, "full bridge" is often referred to as "H-bridge" due to the similarity in shape.

Half Bridge – Denotes that only two of the power electronics devices are present in the topology. For the half-bridge inverters, two capacitors of equal values are generally placed in the DC bus of the inverter as shown in Figure GL-1(a).
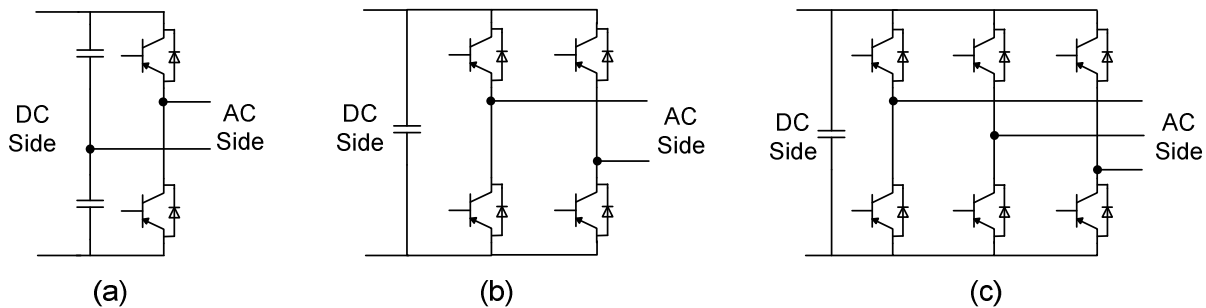
Figure GL-1. Power Electronic Topologies (a) Half Bridge, (b) Full Bridge/H-Bridge, (c) Three-Phase Bridge

Modularity – A modular architecture that divides the interconnection system into discrete components (building blocks), each performing standard functions like: DE control, power conversion, voltage regulation, power quality, protection, synchronization, communications/control with load, metering, dispatch, and area EPS communications and support.

Plug and play – An approach in which hardware and software work together to automatically configure devices and assign resources. This allows hardware changes and additions without large-scale adjustments or modifications. The goal is to be able to plug in a new device and immediately use it, without complicated or significant setup modifications or adjustments.

Power Electronics Devices – Every power electronics circuit consists of different semiconductor devices fabricated with appropriate impurities (known as "doping") in order to achieve particular electrical properties such as conduction, resistance, turn on/turn-off times, power dissipation, etc. There are several types of power electronics devices that are available, such as: diodes, thyristors, metal–oxide semiconductor field-effect transistors, Gate Turn-off Thyristors (GTO), Insulated Gate Bipolar Transistors (IGBT), MOS-controlled Thyristors (MCT), etc. Power semiconductor devices, even diodes, are more complicated in structure and

operational characteristics than their low-power counterparts. The added complexity arises from the modification made to the simple low-power devices to make them suitable for high-power applications.

Reliability – The ability of a system to perform a required function under stated conditions for a stated period of time.

Scalability – The ability to incrementally add functional capacity to a system without replacing it completely. For example, an interconnection system designed for a certain power level could be increased by adding additional like systems in series or parallel.

Three-Phase Bridge – For the three phase rectifiers and inverters, six power electronics devices are generally setup in the form of a bridge where three legs are placed in parallel. Each leg consists of two power electronics devices in series as shown in Figure GL-1(c). Again, based on the input/output connections and the type of power electronics devices, the same circuit can be used as rectifiers or inverters.

Appendix A. Representative DE Manufacturers

Company Name	PV	Wind	Fuel Cell	Micro turbine	Generator	Energy Storage	Generic
ABB		X					
Aerovironment	X	X	X		X	X	X
Alpha Technologies	X						
AlliedSignal Power Systems				X			
American Superconductor		X			X		X
Ballard Power Systems Corporation			X				
Beacon Power Corporation	X					X	
Bowman Power Systems				X			
Capstone Turbine Corp				X			
Caterpillar/Altorfer					X		
Cummins					X		
Detroit Diesel					X		
DuPont USA					X		
Eaton Corporation					X		

Company Name	PV	Wind	Fuel Cell	Micro turbine	Generator	Energy Storage	Generic
Elliott Microturbines							
Enerpro							X
Fronius USA, LLC	X						
FuelCell Energy Inc			X				
GE Energy	X	X			X	X	
GridPoint	X					X	
UTC Fuel Cells			X				
Ingersol-Rand Energy System					X		
International IFR Rectifier							X
Kohler						X	
Magnetek	X	X	X				
Northern Power		X			X	X	X
One Cycle Controls							X
ONSI							
Open Energy Corp	X						

Company Name	PV	Wind	Fuel Cell	Micro turbine	Generator	Energy Storage	Generic
OutBack Power Systems	X						
Powerex							X
Princeton Power Systems	X	X					
PV Powered LLC	X						
Rolls-Royce Fuel Cell Systems		X	X		X		
SatCon Power Systems							
Semikron Inc.							X
Sharp Corporation	X						
Siemens Westinghouse		X					
SMA America	X						
SmartSpark Energy Systems							
Solectria Renewables, LLC	X					X	
Southwest Windpower		X					

Company Name	PV	Wind	Fuel Cell	Micro turbine	Generator	Energy Storage	Generic
SunPower Corp.	X				X		
UQM Technologies, Inc.							
Xantrex Technology Inc.	X	X				X	
Youtility		X	X		X		X

Appendix B. DQ and Utility Inverter Control

B.1   General Description

It can be seen from the previous sections of this report that the control of the grid connected inverter is very important for the operation of DER systems in the utility connected mode. There are two basic control modes for the grid-connected inverters as used in this report: 1) constant power control; and 2) the DC bus voltage control. The DC voltage control is basically a variation of the constant power control. Instead of using the active power reference, the DC bus voltage is regulated, while the input to the inverter is a constant power source to represent the prime mover. In this case, the output of the DC bus regulator is proportional to the active power. When the DC bus voltage is increasing, meaning the power from the prime mover is increasing, it is charging the DC capacitor. In order to maintain the DC bus voltage, the power will be transferred to the inverter output (Ye et al. 2006).

The control strategy applied to the grid-side converter consists mainly of two cascaded loops. There is usually a fast internal current loop that regulates the grid current, and an external voltage loop that controls the DC-link voltage. Rather than an external voltage loop, there may be an external power loop that controls the power flow. The current loop is responsible for power quality issues and current protection; thus, harmonic compensation and dynamics are the important properties of the current controller. The DC-link voltage controller is designed for balancing the power flow in the system. The power flow controller controls the flow of active and reactive power to the utility. These external controllers usually aim for system stability and have slow dynamics (Teodorescu et al. 2006).

In the previous sections of this report, the controls of the utility connected inverters are achieved in simple d-q reference frame based controllers. But controllers designed in different reference frames are also presented in literature like Blaabjerg et al.'s, "Overview of Control and Grid Synchronization for Distributed Power Generation Systems." Also, the inner current control can be utilized for compensating for low-order harmonics. Moreover, the d-q based controls can also be different based on the control design as described in (Pogaku et al. 2007).

B.2   D-Q Based Control

B.2.1 Basics of D-Q Theory

Axis transformation from the three-phase stationary a-b-c to direct-quadrature (d-q) axis happens in the form of either the two-phase stationary ds-qs or the two-phase rotating frame d-q. This is an integral part of generalized electrical machines theory where all three-phase machines can be considered two-phase primitive machines with fixed stator windings and rotating rotor windings. The complexity of coupled electrical quantities can be simplified by utilizing those axis transformations, which in turn greatly reduces the complexities in transient modeling and simulation of those machines.

Based on those axis transformations, the concepts of vector control of the electrical machines, especially for the induction machines, are a step forward. The technique of field-oriented or vector-control allows an algebraic transformation that converts the dynamic structure of the AC machine into a separately excited, decoupled control structure with independent control of flux and torque. The principles of field orientation originated in West Germany in the work of Hasse and Blaschke at the technical universities of Darmstadt and Braunschweig and in the laboratories

of Siemens AG (Bose 2002). The concepts of axis transformation are not only useful for the machines but also incorporated into different fields such as inverter controls and active filtering.

Understanding the basic principles of d-q theory is necessary in order to understand control of three-phase voltage-source inverters. The following discussion draws on voltage transformation, but other variables like flux and current can also be transformed similarly. Figure B-1 shows distribution of the three stationary axes a, b, and c, 120° apart from each other. Cartesian axes are also portrayed in Figure B-1, where qs is a horizontal axis aligned with phase a, and a vertical axis rotated by –90° is indicated in the figure by ds.
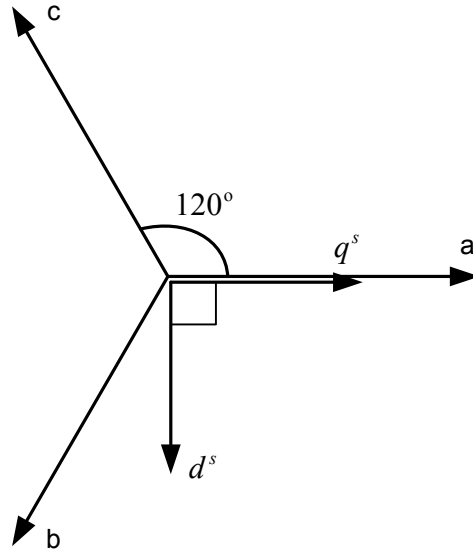
**Figure B-1. Distribution of three-phase and quadrature stationary axes**

Three-phase voltages varying in time along the axes a, b, and c can be algebraically transformed onto two-phase voltages, varying in time along the axes ds and qs, using the transformation given in this equation:

$$\begin{bmatrix} v_q^s \\ v_d^s \\ v_0^s \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\sqrt{3}/3 & \sqrt{3}/3 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

The inverse of such a transformation can also be obtained to transform the quantities back from two-phase to three-phase, as shown in the following equation:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -1/2 & -\sqrt{3}/2 & 1 \\ -1/2 & \sqrt{3}/2 & 1 \end{bmatrix} \begin{bmatrix} v_q^s \\ v_d^s \\ v_0^s \end{bmatrix}$$

Synchronous reference frame control, also called d-q control, uses a different reference frame that rotates synchronously with the grid voltage as shown in Figure B-2. The reference frame control variables become DC values; thus, filtering and controlling can be easier to achieve.
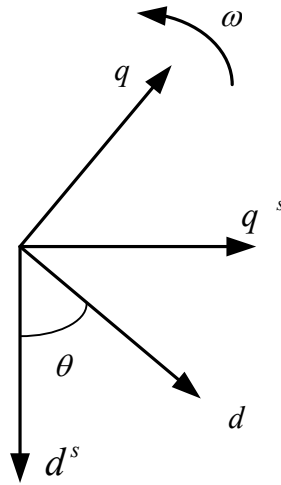
Figure B-2. Quadrature stationary and synchronous reference frames

The following equation takes a two-phase quadrature system along the stationary frame and transforms it onto a two-phase synchronous frame:

$$\begin{bmatrix} v_q \\ v_d \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_q^s \\ v_d^s \end{bmatrix}$$

The reverse operation, taking a two-phase synchronous frame and transforming it into a two-phase quadrature system along the stationary frame, is shown in the following equation:

$$\begin{bmatrix} v_q^s \\ v_d^s \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_q \\ v_d \end{bmatrix}$$

The θ angle is considered to be the instantaneous angular position of the voltage where the reference frame will be aligned.

Figure B-3 shows simplified block diagrams representing transformations from three-phase to d-q synchronous frame.
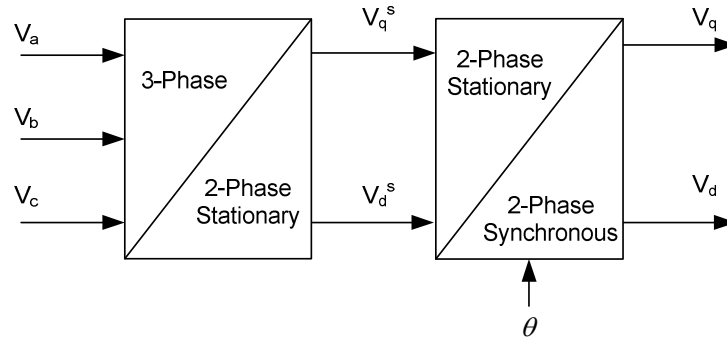
Figure B-3. Transformation from three-phase to synchronous reference frame

B.2.2 Synchronous Frame Control of Utility Inverter

The controller of a utility inverter can typically be divided into three different parts. First is an external power control loop that, according to the droop characteristics set for the real and reactive powers, generates the set points for the magnitude and frequency of the fundamental component of the inverter output voltage (Pogaku et al. 2007). The second and third parts of the control system are the voltage and current controllers, which are designed to reject high-frequency disturbances and provide sufficient damping for the output filter. The block diagram of the utility inverter and controls is shown in Figure B-4.
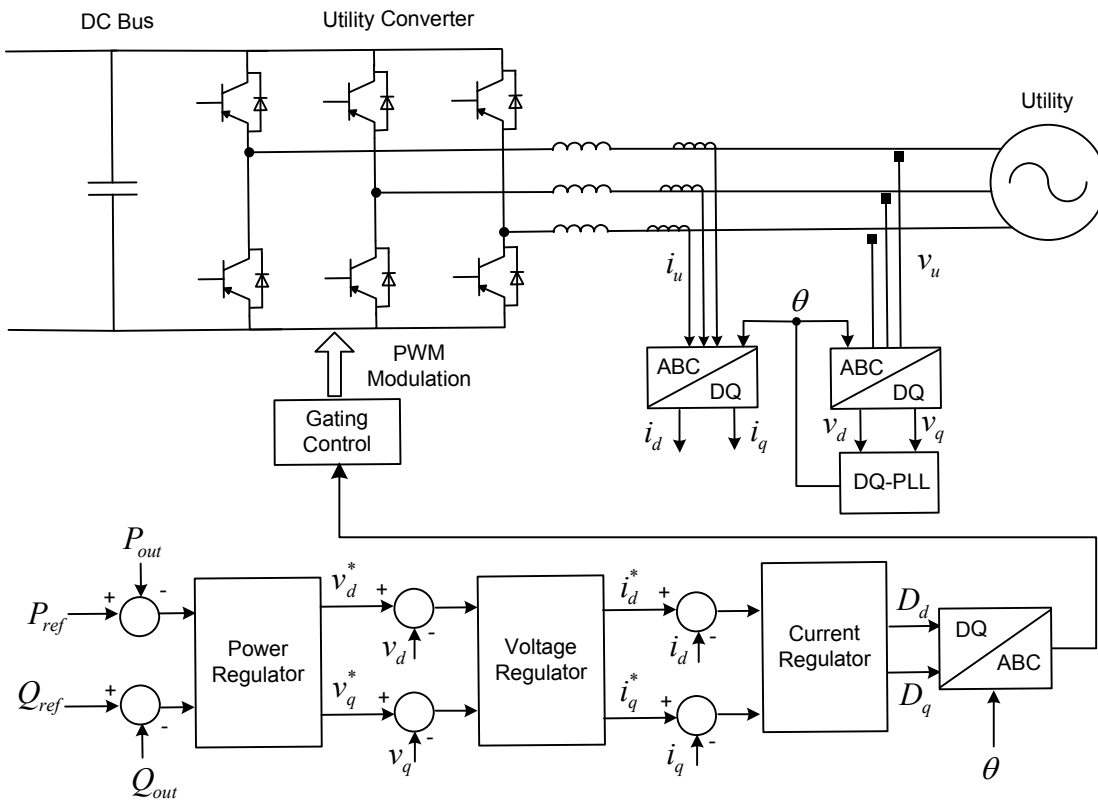

Figure B-4. Block diagram of utility inverter and controls in d-q reference frame

The droop control for the inverters is developed to mimic the governor of a synchronous generator (Pogaku et al. 2007). In a conventional power system, synchronous generators will share any increase in the load by decreasing the frequency according to their governor droop characteristic. The same principle is implemented in inverters by decreasing the frequency of reference voltage when there is an increase in the load. Similarly, reactive power is shared by introducing a droop characteristic in the voltage magnitude. The block diagram for the droop control is shown in Figure B-5.
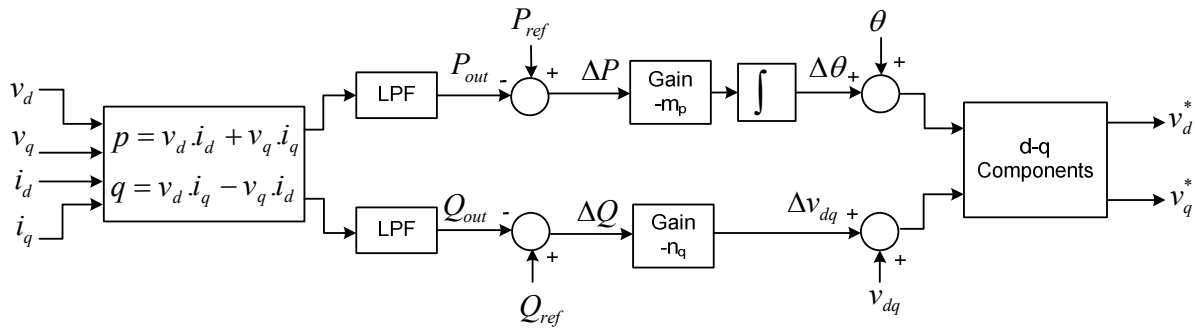
Figure B-5. Block diagram of droop power controllers

As shown in Figure B-5, instantaneous active and reactive power components are first calculated from the measured output voltages and currents. The instantaneous power components are then passed through low-pass filters to obtain the average real and reactive powers. The real power flow through the inverter is obtained by introducing an artificial droop in the inverter frequency. This mimics the governor and inertia characteristics of conventional generators and provides a degree of negative feedback (Pogaku et al. 2007). For instance, if the power drawn from a generator increases, then the rotation of its voltage slows and its angle retards. To share the reactive power between the inverter and the utility, a droop is introduced in the voltage magnitude. The droop gains mp and nq can be calculated using the predefined range of frequency and voltage magnitude variations (Pogaku et al. 2007).

Figure B-6 shows the voltage controller block diagram, including all feed-back and feed-forward terms. Output voltage control is achieved with a standard proportional-integral (PI) controller. The current controller block diagram, including all feed-back and feed-forward terms, is also shown in Figure B-6. Output filter inductor current control is achieved with a standard PI controller. The terms C and L in Figure B-6 denote the capacitor and inductor values, respectively, of the line frequency filter at the inverter output. The fundamental voltage and currents become DC quantities in the d-q control structure; therefore, the PI controllers are used as they give satisfactory behavior when regulating DC variables (Pogaku et al. 2007; Marwali and Keyhani 2004). Additionally, as the controlled current has to be in phase with the grid voltage, the phase angle used by the abc-dq transformation has to be extracted from the grid voltages.
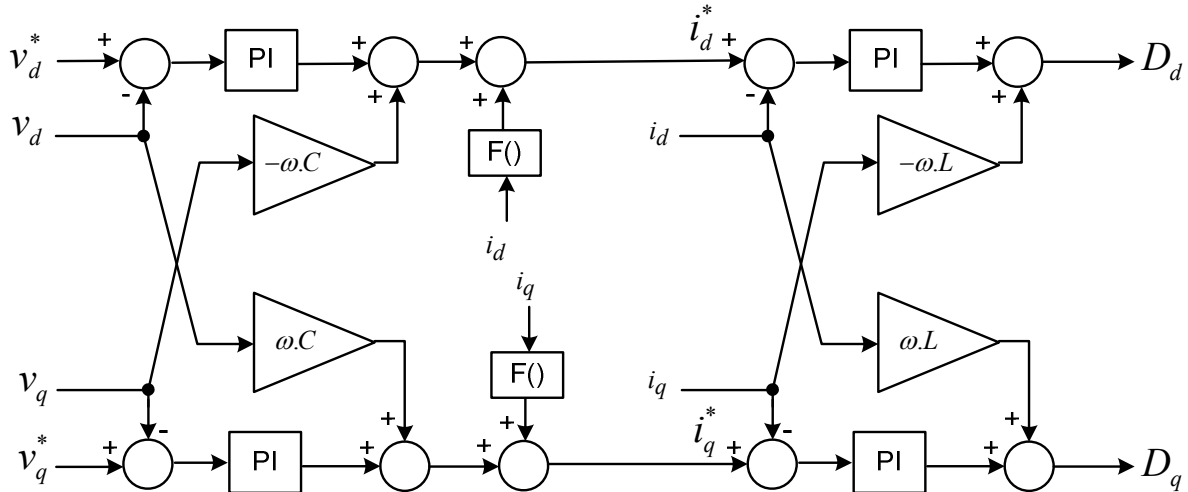
Figure B-6. Block diagram of d-q based voltage and current controllers

B.3   Other Control Methods

The cross-coupling terms and feed-forward are usually used in the synchronous or d-q reference frame for improving the performance of PI controllers (see Figure B-6). In any case, with all of these improvements, the compensation capability of the low-order harmonics in the case of PI controllers is very poor, standing as a major drawback when using it in grid-connected systems (Teodorescu et al. 2006). If the current controller has to be immune to the grid voltage harmonic distortion, harmonic compensator for each harmonic order should be designed (Teodorescu et al. 2006). Additionally, under unbalanced conditions, harmonic compensators for both positive and negative sequences of each harmonic order are necessary. Therefore, the complexity and computational burden of the control scheme makes the implementation very difficult.

B.3.1 Stationary ds-qs Reference Frame Control

The control loops can also be implemented in the stationary reference frame, as shown in Figure B-7. In this case, the grid currents are transformed into a stationary reference frame using the a-b-c to ds-qs transformation. Since the control variables are sinusoidal in this reference frame, PI controllers are not suitable for removing the steady-state errors. Proportional resonant (PR) controllers have gained a large popularity in the last decade in current regulation of such grid-tied systems. In the stationary frame control approach, harmonic compensation can be easily achieved by cascading several generalized integrators tuned to resonate at the desired frequency. Additionally, the harmonic compensator (HC) works on both positive and negative sequences of the selected harmonic; thus, only one HC is necessary for a harmonic order (Teodorescu et al. 2006).
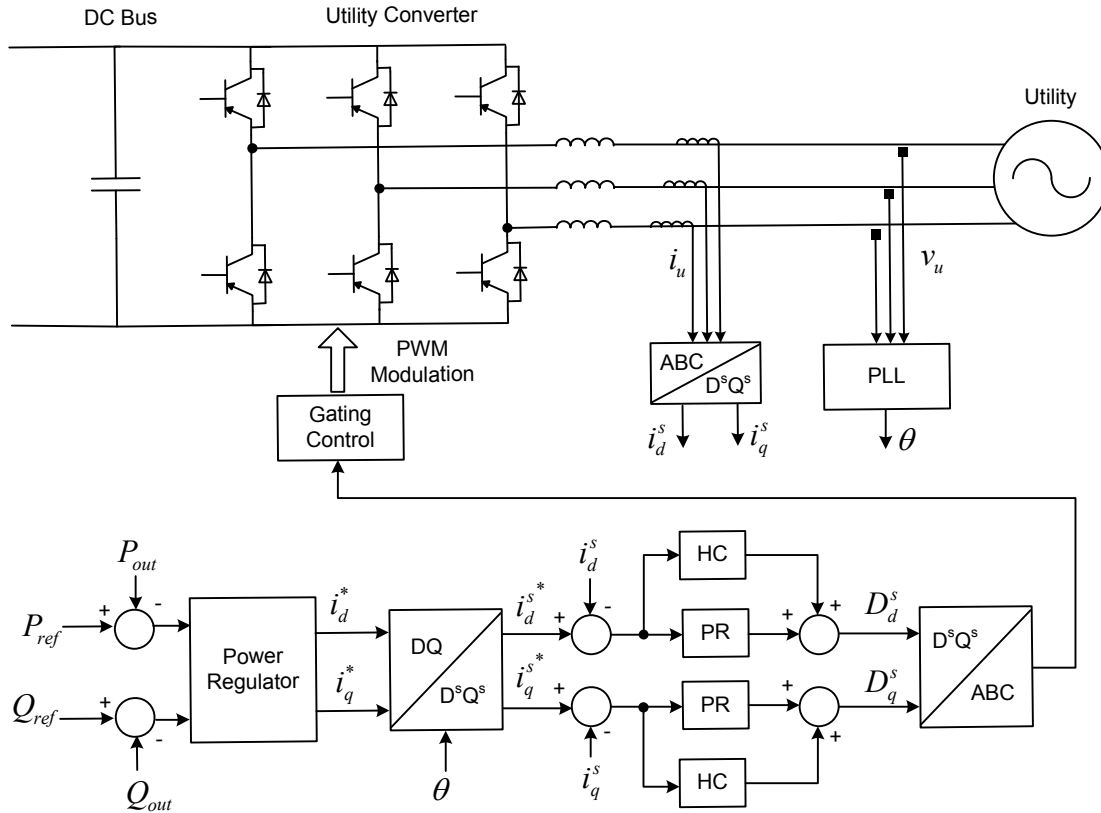
Figure B-7. Block diagram of utility inverter and controls in stationary ds-qs frame

B.3.2 Stationary a-b-c Reference Frame Control

In a-b-c reference frame approach for utility inverter, the type of three-phase connections (i.e., delta, star, with or without isolated neutral, etc.) is to be considered when designing the controller. In any case, three independent controllers can be designed for current control. Typically, nonlinear controllers like hysteresis or dead-beat controls are preferred due to their high dynamics. It is well known that the performance of these controllers is proportional to the sampling frequency; hence, high speed digital systems such as digital signal processors (DSP) or field-programmable gate array (FPGA) are used (Teodorescu et al. 2006). A possible implementation of a-b-c control is depicted in Figure B-8, where each of the current references is compared with the corresponding measured current, and the error goes into the controller. Since both hysteresis and dead-beat controller have very fast dynamics, there is no concern about the low-order harmonics when the control structure uses such controllers. In any case, the current waveform will contain harmonics at the switching and sampling frequencies order; therefore, line frequency filters are required at the output of the inverter (Teodorescu et al. 2006).
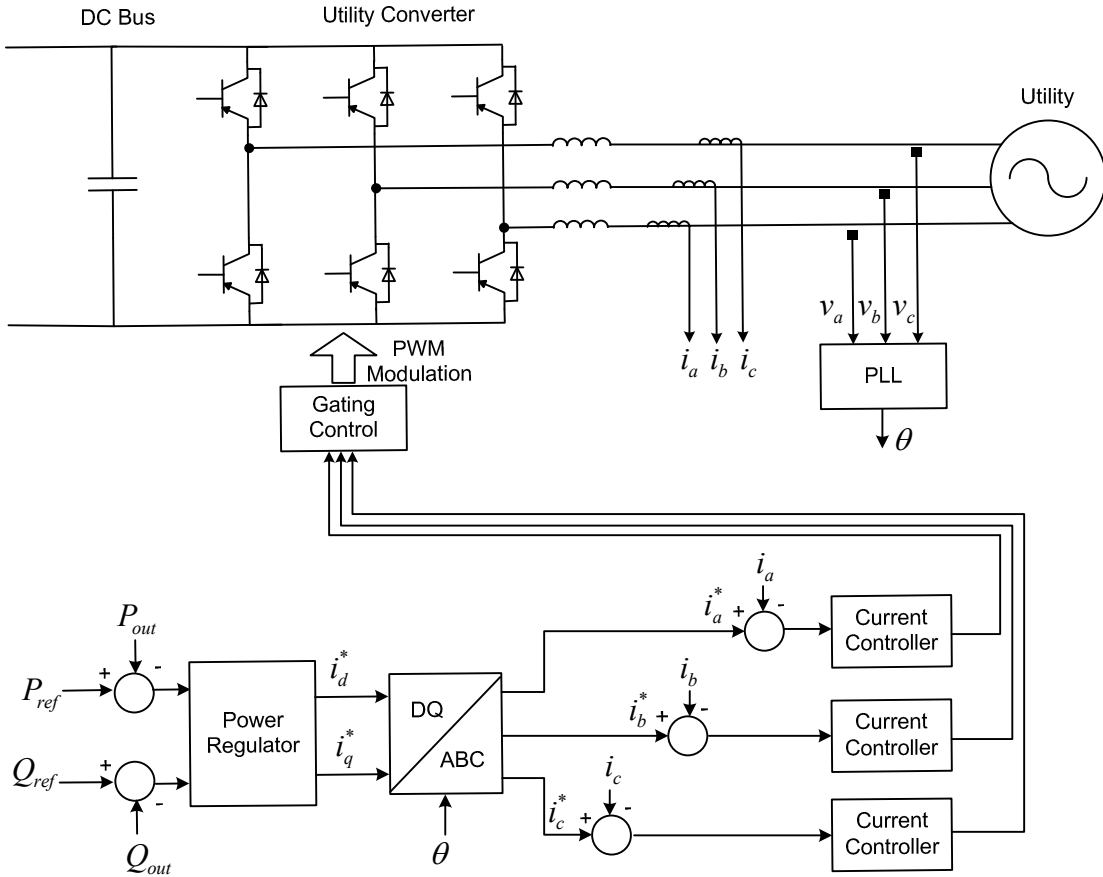
Figure B-8. Block diagram of utility inverter and controls in stationary a-b-c frame

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14. ABSTRACT *(Maximum 200 Words)*
This report presents a summary of the state-of-the-art power electronic interfaces for distributed energy applications. It also outlines the power electronic topologies needed for an advanced power electronic interface. The report focuses on commercially available distributed energy systems, including photovoltaic, wind, microturbine, fuel cell, internal combustion, battery storage, flywheel storage, plug-in hybrid and vehicle-to-grid systems. Different power electronics topologies are discussed for each of these systems, and a generalized topology is selected for understanding the control design.

15. SUBJECT TERMS
advanced power electronic interface; APEI; distributed energy; distributed power; California Energy Commission; CEC; National Renewable Energy Laboratory; NREL

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