# Benefits of Power Electronic Interfaces for Distributed Energy Systems

Benjamin Kroposki, *Senior Member, IEEE*, Christopher Pink, *Member, IEEE*, Richard DeBlasio, *Senior Member, IEEE*, Holly Thomas, *Member, IEEE*, Marcelo Simões, *Senior Member, IEEE*, and Pankaj K. Sen, *Senior Member, IEEE*

***Abstract*—With the increasing use of distributed energy (DE) systems in industry and its technological advancement, it is becoming more important to understand the integration of these systems with the electric power systems. New markets and benefits for DE applications include the ability to provide ancillary services, improve energy efficiency, enhance power system reliability, and allow customer choice. Advanced power electronic (PE) interfaces will allow DE systems to provide increased functionality through improved power quality and voltage/volt–ampere reactive (VAR) support, increase electrical system compatibility by reducing the fault contributions, and flexibility in operations with various other DE sources, while reducing overall interconnection costs. This paper will examine the system integration issues associated with DE systems and show the benefits of using PE interfaces for such applications.**

***Index Terms*—Distributed energy (DE), distributed generation (DG), fault current, interconnection, interface, inverter, microgrid, power electronics (PE), power quality.**

## I. Introduction

DISTRIBUTED energy (DE) systems, also called distributed generation (DG), are energy systems located at or near the point of use. Typically ranging from 1 kW to 10 MW, they can provide both electricity and in some cases heat. There are a wide variety of potential benefits to DE systems both to the consumer and the electrical supplier that allow for both greater electrical flexibility and energy security [1]. For the customer, these benefits include: reduced price volatility, greater reliability, and improved power quality. There are many potential benefits for the energy supplier, such as released line capacity, reduced transmission and distribution congestion, grid investment deferment and improved grid asset utilization, and the ability of the DE system to provide ancillary services, such as voltage support and stability, volt–ampere reactive (VAR) support, and contingency reserves. Depending on economics, there are a wide variety of applications for DE systems: backup and emergency power, base load power, and peaking power in addition to offering a combined heat and power (CHP) option if the customer has a use for the thermal heat generated by the DE system.

In order to increase the usefulness of DE systems and reduce potential impacts, power electronic (PE) interfaces can be used to integrate DE with the existing electrical power system. PE interfaces offer unique capabilities over traditional interconnection technologies. As the price of PE and associated control systems decrease, these types of interconnection interfaces, along with their benefits, will become more prevalent in use with all types of DE systems. This paper examines system integration issues and discusses the benefits of using PE interfaces for a variety of DE applications.

Manuscript received September 25, 2006; revised November 16, 2007; accepted December 30, 2007. Date of publication August 3, 2010; date of current version August 20, 2010. This work was supported at National Renewable Energy Laboratory by the Department of Energy under Midwest Research Institute (MRI) Contract DE-AC36-99GO10337 and by the California Energy Commission under Technology Partnership Agreement 500-03-011. The work of Dr. Simões and Dr. Sen was supported by the National Science Foundation Power Systems Engineering Research Center. Paper no. TEC-00461-2006.

B. Kroposki, C. Pink, R. DeBlasio, and H. Thomas are with the National Renewable Energy Laboratory, Golden, CO 80401 USA (e-mail: benjamin_kroposki@nrel.gov; christopher_pink@nrel.gov; richard_deblasio@nrel.gov; holly_thomas@nrel.gov).

M. G. Simões and P. K. Sen are with the Colorado School of Mines, Golden, CO 80401 USA (e-mail: msimoes@mines.edu; psen@mines.edu).

Digital Object Identifier 10.1109/TEC.2010.2053975

## II. Types of DE Systems

DE systems may be powered by either fossil or renewable fuels. This section summarizes the most common types of DE systems on the market. More thorough discussions on the details of each DG technology are available on [2] and [3].

### A. Reciprocating Internal Combustion Engines

Reciprocating internal combustion (IC) engines burn fossil fuel to convert chemical (or heat) energy to mechanical energy from moving pistons. The pistons then spin a shaft and convert the mechanical energy into electrical energy via an electric generator. Those engines can be of either spark ignition type using natural gas, propane, or gasoline, or compression types that use diesel fuel or heavy oil. The electric generator is usually synchronous or induction type, and is typically connected directly to the electric power system without any additional interconnection device.

### B. Gas Turbines

Gas turbines, like IC engines, mix fossil fuel with air to create thermal (or heat) energy. High temperature, high-pressure air is the medium of heat transfer and air is allowed to expand in the turbine; thereby converting the heat energy into mechanical energy that spins a shaft. The shaft is connected to a series of reduction gears that spin a synchronous generator that is directly connected to the electric power system. Again for large systems, there is not an additional interconnection device.

### *C. Microturbines*

Microturbines work on a very similar principle to gas turbines as discussed earlier. Microturbines can burn a variety of fuels, including natural gas, gasoline, diesel, kerosene, naphtha, alcohol, propane, methane, and digester gas. The majority of commercial devices presently available use natural gas as the primary fuel. In a typical microturbine, a permanent magnet generator (PMG) spins at high speeds (80 000 r/min is typical) and produces electricity at a very high frequency. Hence, the generator cannot be connected directly to the grid. The high-frequency voltage is rectified to dc and a PE-based inverter is then used to convert the dc electricity to ac power compatible with the electric power system.

### *D. Fuel Cells*

Fuel cells work by the chemical reaction of combining hydrogen and oxygen to form electricity and water [4]. There are several different types of fuel cells currently available, including phosphoric acid, molten carbonate, solid oxide, and proton exchange membrane (PEM). Fuel cells produce dc power. This is again converted via an inverter to ac power that is compatible with the electric power system.

### *E. Photovoltaic Systems*

Photovoltaic (PV) systems convert solar energy into electricity. PV modules produce dc power. Like fuel cells, the dc power is the converter into ac power compatible with the electric power system by a PE inverter.

### *F. Wind Systems*

Wind turbines convert wind energy (kinetic or mechanical) into electrical energy. There are three basic types of wind turbine technology currently used for interconnecting with electric power systems. 1) In the first type called an induction machine, the wind turbine spins the rotor shaft of a standard cage-rotor induction generator connected directly to the grid without any PE interface. The induction machine requires VARs to operate. These can either be supplied by the utility power system or by capacitors connected at the machine terminals. These machines cannot deliver any reactive power. 2) The second type of design uses a double-fed induction generator (DFIG) and requires a wound-rotor design. In this case, power from the spinning rotor (at slip frequency) is collected via slip rings. Since this power is not produced at a voltage and frequency that is compatible with the electric power system, it is passed through a PE-based rectifier and inverter system, which transforms it into grid compatible ac power. This arrangement allows the generator stator winding to be undersized by 25%–30% with the PE making up the power difference from the rotor power. However, the cost of PE adds to the total cost of such a design. 3) The third type of wind turbine design 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. 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 electric power system. The last two designs (involving PE) allow the wind turbine to operate in a variable speed mode that can improve the overall wind power capture ability of the turbine.

### *G. Energy Storage*

Energy storage technologies are classified according to the total energy, time, and transient response required for their operation. It is convenient to define storage capacity in terms of the time that the nominal energy capacity can cover the load at rated power. Storage capacity can be then categorized in terms of energy density requirements (for medium- and long-term needs) or in terms of power density requirements (for short and very short term needs). Energy storage enhances DE systems overall performance in three ways. First, it stabilizes and permits DE to run at a constant and stable output, despite load fluctuations. Second, it provides the ride through capability when there are dynamic variations of primary energy (such as those of sun, wind, and hydropower sources). Third, it permits DE to seamlessly operate as a dispatchable unit. Moreover, energy storage can benefit power systems by damping peak surges in electricity demand, countering momentary power disturbances, providing outage ride-through while backup generators respond, and reserving energy for future demand.

Battery systems store electrical energy in the form of chemical energy. There are a wide variety of battery technologies. Akhil and Kraft [5] gives a good description of battery types and Gyuk *et al.* [6] presents and overview of battery projects in the U.S. Batteries are dc power systems that require PE to convert the energy to and from ac power. Many utility connections for batteries have a bidirectional charger/inverter, which allows energy to be stored and taken from the batteries.

Supercapacitors, also known as ultracapacitors, are electrical energy storage devices, which offer high-power density and extremely high-cycling capability. Recent technology improvements enabled supercapacitors to be an interesting option for short-term high-power applications, although most research has focuses on automotive and traction drives, regenerative energy systems, and medical and telecommunication equipment [7], there have been some studies looking at the use of supercapacitors with wind systems [8].

Flywheel systems have recently regained consideration as a viable means of supporting critical load during grid power interruption because of their fast response compared to electrochemical energy storage. Advances in PE and digitally controlled fields have led to better flywheel designs that deliver a cost-effective alternative in the power quality market. Typically, an electric motor supplies mechanical energy to the flywheel and a generator is coupled on the same shaft that outputs the energy, when needed, though a PE converter. It is also possible to design a bidirectional PE system with one machine that is capable of motoring and regenerating operations.

## III. Interconnection Interfaces

As briefly identified earlier, the electric output of DE systems can be connected to the electrical power system via three basic interconnection interfaces [9], [10].

### A. Synchronous Generator

Synchronous generators are rotating electric machines that convert mechanical power to electrical power. In a synchronous machine, a prime mover (like a turbine) turns the rotor that induces a voltage on the stator winding. A magnetic field is produced in the rotor by either a dc field current or by a permanent magnet. The electrical frequency of the induced voltage depends on the speed of rotation of the generator. When connected to an electric power system, the synchronous generator must run at a constant speed called "synchronous speed" and generate voltages corresponding to the supply frequency. Synchronous generators are used with most reciprocating engines and most high power turbines (gas, steam, and hydro).

### B. Induction Generator

Like synchronous generators, an induction generator is a rotating electrical machine that converts mechanical power into electrical power. Both machines have similar stator construction. The rotor in the induction generator, however, is different and no dc field current is needed for operation. There are two types of rotor designs available: cage rotor and wound rotor. Induction generators are typically only used in wind turbines and some low-head hydro applications. The advantage of the cage-rotor induction generator is the lower cost compared to a synchronous generator, but induction generators require a supply of VARs either from capacitors, from the electric power system, or from PE-based VAR generators to operate. The DFIG discussed earlier has added advantages, however, is more expensive.

### C. Power Electronics

The PE interface can be used to connect any type of DE system to an electric power system. PE-based inverters are used in microturbines, fuel cells, PV systems, some wind turbines, and energy storage systems. The types of PE interface used to connect these DE systems to the electric power system will be described in the following. Because of unique properties of PE interfaces, they can also be used to interconnect reciprocating engines that would normally be interconnected with only a synchronous or induction generator. When used with engines or wind turbines, the output of the electric generators is rectified to dc then converted to ac using an inverter.

## IV. PE INTERFACES

The study of PE devices, along with their control systems, is a very dynamic discipline. By taking advantage of technological innovations in semiconductor materials, and microprocessor (or digital-based) control systems, PE is creating devices that enhance energy generation and delivery systems. The versatility and reliability of lower cost devices combined with advances in circuit topologies and controls has resulted in technologies that replaced what has been traditionally done by electromagnetic and electromechanical systems. With the development of solid-state-based packages, PE devices can now convert almost any form of electrical energy to a more desirable and usable form. This is why PE-based systems are ideal for DE systems. Another benefit of PE is their extremely fast-response times. PE interfaces can respond to power quality events or fault conditions within in the subcycle range. This high-speed response can enable advanced applications, such as the operation of intentional islands (microgrids) for high-reliability applications and reducing fault level currents of DG, features that do not exist today.

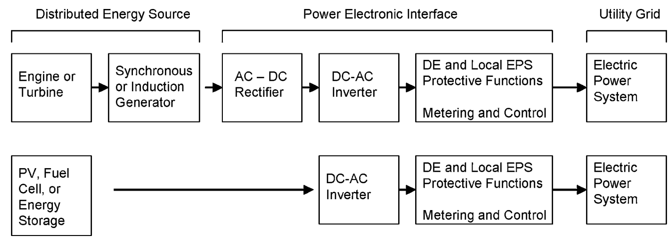

Fig. 1. DE system and PE interface block diagram.

### A. Properties and Attributes of PE Interface

The PE interface has several characteristics. It contains the necessary circuitry to convert power from one form to another. This may include both a rectifier and an inverter or just an inverter. The inverter is compatible in voltage and frequency with the electric power system to which it will be connected and contain the necessary output filters. The PE interface can also contain protective functions for both the DE system and the local electric power system that allow paralleling and disconnection from the electric power system. These functions would typically meet the IEEE Standard 1547 interconnection requirements [11], but can be set more sensitive depending on the situation and utility interconnection requirements. The PE interface will also contain some level of metering and control functionality. This will ensure that the DE system can operate as designed. Fig. 1 shows a block diagram of the DE system and PE interface.

### B. Components of PE

Typically, PE devices found in power systems are comprised of four basic categories of components: 1) semiconductor switches; 2) switch gating and controls systems; 3) inductive components; and 4) capacitive components. The inductive and capacitive components are used to dynamically store energy for circuit power flow dampening, filtering, and transformation. Switch gating and controls turn ON and OFF the semiconductor devices so that the circuit provides the desired power conversions, ancillary services, and protective functions in an efficient and stable manner.

Innovations and improvements in semiconductor switch designs have been the driving force for the advancements and implementation of PE interfaces. Their operation can be evaluated analogous to a switch, which essentially "opens" or "closes" based on control schemes and circuit conditions. Semiconductor switches and the manner in which they are applied are usually dictated by their ability to accommodate forward and reverse current and voltage conditions. The scale of the system, where each type of switch is usually found is generally dictated by the required switching frequency, and system voltage and current levels. The following short list is a brief description of the most common types of semiconductor switches. For more details on PE devices, see [12] and [13].

*1) Diode:* The diode is a two terminal PE device that can only conduct current in one direction and block voltage in the reverse direction. The diode is typically used in circuits, where unidirectional current flow is required and reverse voltage levels must be blocked. Diodes exhibit a negative temperature coefficient, which makes them difficult to parallel when higher current levels are required.

*2) Thyristor:* The thyristor family of semiconductor switches includes a host of similar devices with slightly different operational capabilities. They wield the highest power handling capabilities of all the semiconductor devices and are found being applied in circuits handling thousands of amperes at almost any voltage level, including high-voltage transmission levels. In general, thyristors are like a diode with a gate control signal that initiates a change in conduction state if the unit is forward biased. Once gated, the device will continue to operate in that mode until current crosses zero or a reverse voltage is applied across them, or a different gate turn-OFF signal is applied (if applicable). Various configurations and packaging methods are employed to obtain devices that act as gate to turn on (SCRs), gate to turn off (GTOs), and MOS-controlled uni- and bidirectional current flow (MCTs) switches. Their main drawback is that their maximum switching frequencies are orders of magnitude slower than other modern devices.

*3) MOSFET:* The MOSFET is a gate voltage controllable switch. Usually found in low-voltage (<500 V) and low-power systems, MOSFETs are capable of the highest switching frequencies—a feature highly desired when the amounts of magnetic materials in a circuit are being minimized. Unlike thyristors, MOSFETs can quickly start and stop forward conduction even with a constant forward voltage applied. This makes them highly useful in switch-mode power supply applications, where dc is being converted to another magnitude or to ac. By their nature, MOSFETs have large conduction losses at high voltages making them uncompetitive with other types of devices. Also, due to the nature their construction, MOSFETs allow uncontrolled (and inefficient) reverse current to flow when a reverse potential is applied. This feature is due to their "body diode" and is usually accounted for by manufacturers during packaging. MOSFETs have a positive temperature coefficient, making them relatively easy to parallel.

*4) Insulated Gate Bipolar Transistor:* The majority of higher power, PE systems today rely on the insulated gate bipolar transistor (IGBT) as the switching PE device. Like the MOSFET, the IGBT controls power flow in the switch by the gate voltage and can switch at relatively high frequencies. IGBT are available with ratings up to 1700 V and 1200 A and are used on DE systems 10 kW and higher. The available switching frequencies for IGBTs are lower than MOSFETS, but still orders of magnitude faster than thyristors.

### *C. PE Topologies*

In the most general sense, PE circuits imbedded in DE systems fall into one of five categories: 1) ac to dc controlled and uncontrolled rectifiers; 2) dc to ac inverters; 3) dc to dc switch-mode converters; 4) inline solid-state breakers; and 5) ac to ac cycloconverters. Cycloconverters are only used for unique large power applications and their discussion is beyond the scope of this paper. The other four categories can and do occur frequently in DE applications and will be discussed in the following.

*1) AC to DC Rectifier:* Rectifier circuits are generally used to generate a controlled dc voltage from either an uncontrolled ac source (microturbine and small PMG wind turbine) or the utility supply. When converting from a utility supply, a rectifier's application is usually for dc linking of systems or providing dc voltage for specific-load applications, such as battery regulators and variable frequency drive (VFD) inputs.

*2) DC to DC Converter:* Converter circuits are almost always found in circuits that are used for renewable energy to battery charging applications. They take an uncontrolled, unregulated input dc voltage and groom it depending on the specific-load application. They are commonly found in PV battery charging systems. PV converter circuits are usually specialized units designed to extract the maximum power output of the PV array.

*3) DC to AC Inverter:* Inverter circuits generate a regulated ac supply from a dc input. They are commonly found in systems providing stand-alone ac power, utility connected DE systems, and on the motor side of a VFD.

*4) Solid-State Breaker:* As the penetration of DE technologies in power systems increase, the negative effects on protection schemes, coordination, and available fault current become more acute. Solid-state breaker technologies hold the potential to standardize and greatly simplify the installation of grid-connected DE technologies, while also minimizing their negative impacts. Truly in its infancy, the field of solid-state breakers is ripe for breakthrough innovations and could hold the key for real-grid modernization. The concept of solid-state breakers is relatively simple: replace the traditional interrupting medium (vacuum, SF6, air, oil, etc.) in circuit breakers (or switchers) with a semiconductor switch. The speed of even the slowest semiconductor switch is scales of magnitude faster than traditional technologies. Faster switching speeds coupled with advanced sensing and controls can be used to eliminate fault current contributions, thus making impacts of DE on coordination negligible. Further research has been conducted to develop systems that can even further optimize system coordination by having a controllable fault current level [14].

The general topologies described earlier are commonly combined in single use packages. For example, an inverter used on a PV system will obviously contain a dc to ac inverter, but will also usually contain a dc to dc converter to regulate and optimize the inverter input and PV array output. An excellent overview of various topologies used for renewable energy applications can be found in [15].

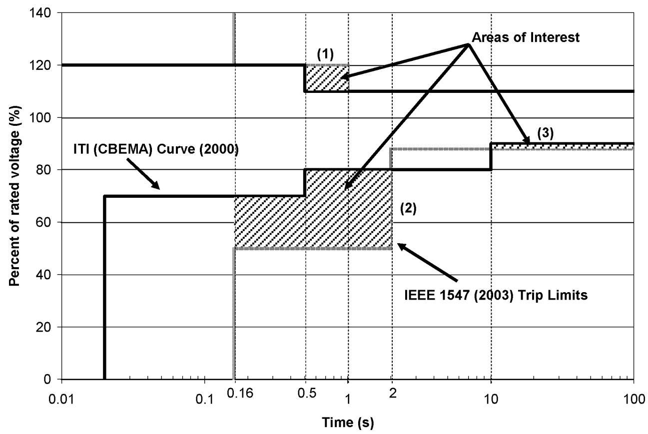


Fig. 2. ITI/CBEMA curve relation to IEEE 1547 trip limits.

## V. Benefits of the PE Interface

### A. Improved Power Quality

By having a PE-based interface for DE systems connected to the electric power system, the power quality of the DE system improves through the ability to both control harmonic content of the output voltage and current and provide fast operation to switch modes between utility connected and stand-alone modes.

*1) Harmonic Control:* The specific design and topology of the PE interface can impact the harmonic content of the electric power system to which it is connected. PE systems can alleviate and even eliminate grid reactive power requirements and at the same time restrain the power factor within a prescribed value. In order to have a continuous controlled active and reactive power as demanded by a variable load and source conditions, the "*p–q* theory" [16] has been currently applied to renewable energy power injection.

In addition to harmonic mitigation, this also can compensate for the reactive power and voltage harmonics, in order to optimize the bus utilization. A universal power quality conditioner (UPQC) consists of the integration of both a series active filter and a shunt active filter. The *p–q* theory is used to obtain the reference compensating current (for the shunt active filter) and reference compensating voltage (for the series active filter) that should be applied to the system to compensate for the undesired power components.

*2) Power for Sensitive Loads:* Sensitive loads are equipment that requires special power source to remain in operating conditions. This includes a variety of information technology (IT) equipment, such as computers, printers, and fax machines. A standard has been developed that details the power requirements for these devices [17]. Fig. 2 shows the Information Technology Industry Council (ITI)/Computers Business Equipment Manufacturers Association (CBEMA) curve in relation to the trip limits from the IEEE Standard 1547 interconnection standard. The IEEE 1547 trip limits are defined, where a DE is required to cease to energize the area electrical power system. This trip will still allow the DE system to serve the load, but it must not energize the grid. This graph shows several areas of interest, where the IEEE Standard 1547 trip limits are outside the normal operation range of the ITI/CBEMA curve. If the DE system were being used for power quality, the switch from grid interconnected to stand-alone mode needs to occur within the ITI/CBEMA curve.

Area 1 is an example, where the IEEE 1547 limits for overvoltage are above the ITI/CBEMA prohibited region. If computer equipment is subjected to such conditions, for example, damage to the equipment may result.

Area 2 and 3 are examples, where the IEEE 1547 limits for undervoltage are below the ITI/CBEMA normal operation region. If a voltage excursion was in this range, the equipment may not be damaged, but it might stop working. To have a seamless transfer, the DE system would need to transfer the connected load from a grid-connected mode to a stand-alone mode within the ITI/CBEMA curve. This may be an issue for non-PE-based interconnection systems. Induction and synchronous generator interconnection systems typically use a circuit breaker at their point of interconnection. Typical circuit breaker trip times range from 20 to 100 ms (1–6 cycles). This means that even if the control system can recognize the condition, the combined time for the control signal and breaker operation may be too slow to keep the equipment operating. However, PE interfaces can have subcycle response times that vary depending on the technology used. This extremely fast response time can allow the DE systems to transfer loads from the utility to the DE source within the ITI/CBEMA curve.

### B. VAR Support and Voltage Regulation

PE interfaces can also allow for control of voltage and reactive power at the generation source [18]. Most inverters for DE systems are self-commutated and can produce an ac voltage of arbitrary amplitude and phase. This allows the DE systems to produce any power at any power factor. The PE interface has a wider operating power factor range than a synchronous generator. This can be an extremely useful attribute if the DE system is allowed to regulate voltage and/or supply reactive power to the system. Currently IEEE Standard 1547 states that the DE system shall not actively regulate the voltage at the point of common coupling (PCC), although a utility could allow this mode of operation. Most DE systems operate at unity power factor. This can be a concern, since if a system is only supplying real power, the power factor at the PCC will go down on a lagging power system. Fig. 3 illustrates this point. The power of the original load is given as $S_1$ at a power factor of $\cos(36.8°) = 0.8$ lagging. If a DE system that provides only real power at unity power factor is added to the system at the PCC, the power factor of the combined power $S_2$ that is seen at the PCC will decrease to $\cos(52.7°) = 0.6$ lagging. Therefore, it would be beneficial to the electric power system if the DE systems could regulate VARs at a local level.

Voltage regulation on radial distribution systems is normally maintained using the load-tap-changing transformers at substations and/or line-voltage regulators or switched capacitors on feeders. If DE systems are allowed to regulate voltage, they can also be used to provide voltage support. This is can be of

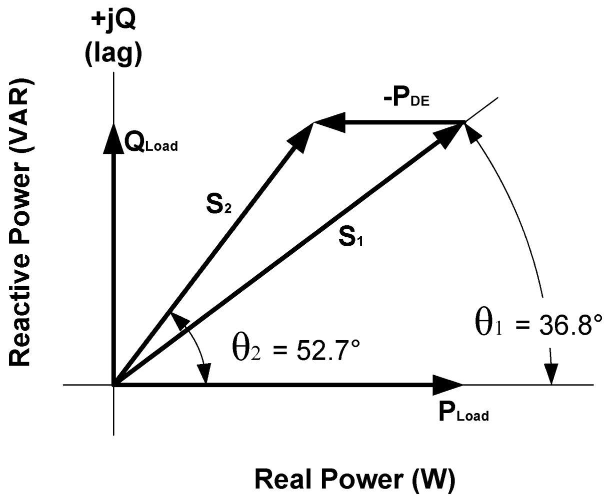


Fig. 3. *P–Q* relationship for unity power DE system.

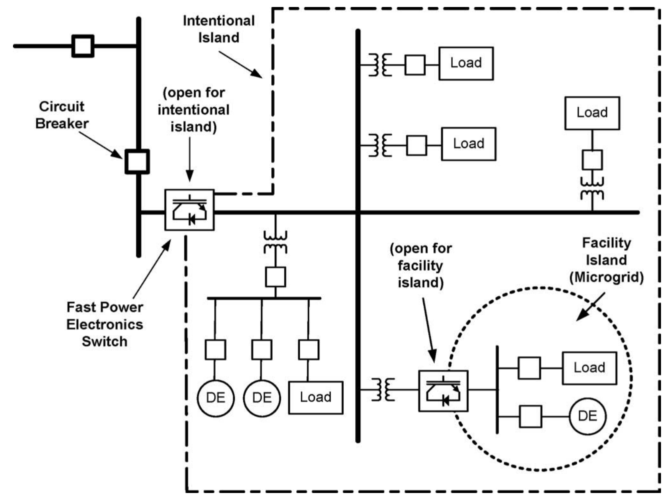


Fig. 4. Intentional island and microgrid example.

benefit to the utility. However, it must be coordinated with existing equipment on the line.

Using appropriate PE systems, the VARs can be controlled continuously from maximum capacitive to maximum inductive at a given network voltage. The basic principle mimics the operation of a rotating synchronous condenser implemented in a static converter. For voltage-controlled systems, the magnitude of the converter output voltages are used to control the VAR flow to or from the ac system. Raising the converter voltage above the system voltages causes leading (capacitive) current and decreasing the converter voltage below the system voltage will result in lagging (inductive) current. Many modern inverters employing current-controlled schemes can also vary VAR import and export levels by varying the phase angle between the current being injected onto the grid and the line voltage.

### *C. Improved DE-Fault Current Coordination*

Adding a DE source to an existing utility system, can add many benefits to the system, such as voltage support, release capacity, and harmonic mitigation. Unfortunately, DE systems can also negatively impact the fault coordination of a system to the point that modifications in existing relay settings and fuse sizing changes may be required. This is because added generation can contribute fault current and reduce the percentage of fault contribution from upstream devises, effectively desensitizing them. This factor is further complicated by grounding methods, transformer connections, and the nature of the utility and generator's system topologies. PE-based DE systems can respond to fault conditions at the subcycle level, and as such, can quickly eliminate DE fault contributions before any impact on existing coordination occurs. Ideally, DE systems would be added to any legacy system and have no effect on fault current, grounding, and overvoltages resulting from faults.

There is tremendous potential for PE interfaces, in mitigating the negative consequences and enhancing the fault characteristics of a system. The potential exists for cutting-edge PE interface systems to orchestrate multiple transformer interconnection topologies with fast, subcycle semiconductor switches in a manner that mitigates almost all negative consequences of DE systems.

### *D. Interoperability With Other DE Sources*

PE interfaces can also be used to integrate hybrid systems. Hybrid power system is a term used when integrating more than one DE technology. Hybrid systems combine capabilities of several DE technologies and can be extremely beneficial when integrating multiple types of DE technologies together. Typically, there is a dc bus within the PE section that could be used to integrate a variety of DE technologies at a common point. Use of a common dc bus can also allow the integration of several inverters into one larger inverter that would be common to several DE technologies. As an example, energy storage is often integrated with PVs or wind systems to provide power when there is no solar or wind resource available.

### *E. Fast Switches for Microgrids or Intentional Islands*

One of the possible applications for DE is in the development of microgrids or intentional islands. Microgrids and intentional islands can be defined in several ways from the perspective of the power system. Microgrids can be defined as aggregation of loads and DE sources to provide power and heat [19]. They have the capability to be isolated from and reconnected to the main electric power system. They are connected to the electric power system through a single PCC with a single-metered customer. There has been a considerable amount of research on microgrids in the past few years in both control [20], [21] and PE interfaces in microgrids [22], [23].

Intentional islands can include parts of the utility distribution system. This may include several PCC and distribution system level equipment. IEEE Standards Coordinating Committee 21 on fuel cells is developing a new standard IEEE P1547.4 Guide for design, operation, and integration of distributed resource island systems with electric power systems [24] that address intentional islands and microgrids. Fig. 4 shows a typical arrangement for an intentional island on the distribution system and a facility microgrid [25].

When DE systems are used in microgrids, they must have the ability to switch between a utility-connected mode and a stand-alone mode. Depending on the power quality requirement of the load, an extremely fast switch would be needed to meet the ITI/CBEMA curve. These requirements were addressed in the power quality section of this paper.

### *F. PE Modularity and Standardization*

Another benefit to PE is their inherent modularity. Currently, designers use an application, specific approach to minimize the size, cost, and complexity of DE system PE. The short-term advantage of this approach is a least-cost option for the specific application. The long-term disadvantage, however, is that the narrow market opportunity for such a device disqualifies it from the cost advantages that larger economies of scale realize. In other words, making a device that is acceptable to more technologies would likely bring down its overall cost because of higher production. Another disadvantage of the application-specific approach is higher lifetime maintenance costs because of less availability of replacement parts and less expertise of maintenance personnel.

There have been a few projects in the past that have tried to create standardized modular PE for interconnection systems for DE. The power electronic building block (PEBB) program [26] sponsored by the Office of Naval Research has focused on the development of modular components that make up the actual inverter or rectifiers. The PEBB concept has been researched and demonstrated by a number of researchers [27]–[29]. Fernandez provided in a modular architecture that can be modified to suit a particular configuration of the three basic PE blocks (dc/dc, dc/ac, and ac/dc) and control electronics for integrating a wind turbine and a combustion engine driven ac generator [30]. The Universal Interconnection Technology (UIT) project [31] sponsored by Department of Energy (DOE)/ National Renewable Energy Laboratory (NREL) examined a higher level of standardization around the actual inverter looking at modularity and scalability to improve volume manufacturing. A study on PE modularity was also conducted by the University of Wisconsin for the California Energy Commission [32]. These projects have shown that standardization of electrical interfaces, connections, and communications will be needed to achieve a truly universal plug-and-play environment for interconnection of DE. Standardization accommodates a variety of multifunctional interconnection systems that can optimize generation, storage, and load, while providing ancillary services that benefit the customer and the utility grid. With standardized cross-DE system capability, near-universal functionality for load management and grid support can be achieved for all DE system resources, including microturbine, fuel cell, reciprocating engine, solar, wind, and energy storage systems. Modularity of PE interfaces can also lead to higher volume manufacturing that can lead to reduced costs for interconnection. Modular inverter packages that can be scaled to various power levels and used across DE platforms will increase the market for the device, in general, and allow designs to be standardized.

## VI. Conclusion

This paper describes the basic types and technological aspects of PE for DE applications. Clear benefits in using PE interfaces to interconnect DE systems were discussed and evaluated. The proper design and use of PE-based systems can be done in a modular approach by targeting the overall system needs. PE interfaces can improve power quality of the customer by improving harmonics and providing extremely fast switching times for sensitive loads. PE can also provide benefits to the connected electric power system by providing reactive power control and voltage regulation at the DE system connection point. A unique property of a PE interface is the ability to reduce or eliminate fault current contributions from DE system, thereby allowing negligible impacts on protection coordination. Finally, PE interfaces provide flexibility in operations with various other DE sources, and can potentially reduce overall interconnection costs through standardization and modularity.

## References


[1] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'haeseleer, "Distributed generation: Definition, benefits and issues," *Energy Policy*, vol. 33, pp. 787–798, 2005.

[2] L. Goldstein, B. Hedman, D. Knowles, S. Freedman, R. Woods, and T. Schweizer, "Gas-fired distributed energy resource technology characterizations," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-620–34783, Nov. 2003.

[3] F. A. Farret and M. G. Simões, *Integration of Alternative Sources of Energy*. New York: Wiley, 2006, ISBN 0-471-71232-9.

[4] *Seventh Edition Fuel Cell Handbook*, EG&G Technical Services, Inc., Albuquerque, NM, DOE/NETL-2004/1206, 2004.

[5] A. Akhil and S. Kraft, "Battery energy storage market feasibility study—Expanded report," Sandia National Laboratories, Albuquerque, NM, SAND97-1275/2, 1997.

[6] I. Gyuk, P. Kulkarni, J. H. Sayer, J. D. Boyes, G. P. Corey, and G. H. Peek, "The United States of storage," *IEEE Power Energy Mag.*, vol. 3, no. 2, pp. 31–39, Mar./Apr. 2005.

[7] D. Linzen, S. Buller, E. Karden, and R. W. De Doncker, "Analysis and evaluation of charge-balancing circuits on performance, reliability, and lifetime of supercapacitor systems," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1135–1141, Sep./Oct. 2005.

[8] C. Abbey and G. Joos, "Supercapacitor energy storage for wind energy applications," *IEEE Trans. Ind. Appl.*, vol. 43, no. 3, pp. 769–776, May/Jun. 2007.

[9] N. R. Friedman, "Distributed energy resources interconnection systems: Technology review and research needs," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/SR-560-32459, 2002.

[10] S. Chapman, *Electric Machinery Fundamentals*, 4th ed. New York: McGraw-Hill, 2005, pp. 267–342.

[11] *IEEE Standard for Interconnecting Distributed Resources to Electric Power Systems*, IEEE Standard 1547-2003, 2003.

[12] N. Mohan, T. Undeland, and W. Robbins, *Power Electronics*, 3rd ed. New York: Wiley, 2003, pp. 16–30.

[13] R. Erickson and D. Maksimovic, *Fundamentals of Power Electronics*, 2nd ed. New York: Wiley, 2001, pp. 74–92.

[14] G. Tang and M. R. Iravani, "Application of a fault current limiter to minimize distributed generation impact on coordinated relay protection," presented at the Int. Conf. Power Syst. Transients, Montreal, Canada, Jun. 19–23, 2005, Paper No. IPST05-158.

[15] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. PortilloGuisado, M. A. M. Prats, J. I. Leon, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002–1016, Jun. 2006.

[16] H. Akagi, Y. Kanazawa, and A. Nabae, "Generalized theory of the instantaneous reactive power in three-phase circuits," in *Proc. Int. Power Electron. Conf. 1983*, Tokyo, Japan, pp. 1375–1386.
[17] Information Technology Industry Council (ITI). (2010). [Online]. Available: http://www.itic.org/archives/iticurv.pdf
[18] P. Barker and R. de Mello, "Determining the impact of distributed generation on power systems: Part 1: Radial distribution systems," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, Jun. 2000, pp. 1645–1656.
[19] R. Lasseter, A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromson, A. S. Meliopoulous, R. Yinger, and J. Eto, "Integration of distributed energy resources—The CERTS microgrid concept," California Energy Commission Consultant Report, P500-03-089 F, Oct. 2003.
[20] A. L. Dimeas and N. D. Hatziargyriou, "Operation of a multiagent system for microgrid control," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1447–1455, Aug. 2005.
[21] F. Katiraei and M. R. Iravani, "Power management strategies for a microgrid with multiple distributed generation units," *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1821–1831, Nov. 2006.
[22] G. Weiss, Q.-C. Zhong, T. C. Green, and J. Liang, "H repetitive control of DC-AC converters in microgrids," *IEEE Trans. Power Electron.*, vol. 19, no. 1, pp. 219–230, Jan. 2004.
[23] G. Hernandez-Gonzalez and R. Iravani, "Current injection for active islanding detection of electronically-interfaced distributed resources," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1698–1705, Jul. 2006.
[24] *IEEE 1547.4 Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*, Draft 1, IEEE P1547.4.
[25] M. Davis and D. Costyk, Guide for design, operation, and integration of distributed resource island systems with electric power systems, Draft 1, Aug. 2005.
[26] T. Ericsen, "Power electronic building blocks—A systematic approach to power electronics," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, Jun. 2000, pp. 1216–1218.
[27] D. Ghizoni, R. Burgos, G. Francis, X. Ma, J. Guo, L. Solero, F. Wang, D. Boroyevich, and D. A. Cartes, "Design and evaluation of a 33-kW PEBB module for distributed power electronics conversion systems," in *Proc. IEEE 36th Power Electron. Spec. Conf.*, 2005, pp. 530–536.
[28] P. K. Steimer, O. Apeldoorn, B. Odegard, S. Bernet, and T. Bruckner, "Very high power PEBB technology," in *Proc. 2005 Eur. Conf. Power Electron. Appl.*, Sep. 11–14, pp. 1–11.
[29] Y. Khersonsky and G. Robinson, "PEBB modules in distributed generation applications," in *Proc. 2003, IEEE Power Eng. Soc. General Meeting*, Jul. 13–17, vol. 3.
[30] H. Fernandez, A. Martinez, V. Guzman, and M. Gimenez, "An experimental and training platform for uninterrupted power in isolated locations: Wind turbine—electric generator—battery bank (TP-WT-UPS)," in *Proc. 2005 Eur. Conf. Power Electron. Appl.*, Sep. 11–14, pp. 5–10.
[31] P. Sheaffer, P. Lemar, E. J. Honton, E. Kime, N. R. Friedman, B. Kroposki, and J. Galdo, "Universal interconnection technology workshop proceedings," National Renewable Energy Laboratory Golden, CO, Rep. BK-560-32865, 2002.
[32] P. Flannery, G. Venkataramanan, and B. Shi, "Integration of distributed technologies—Standard power electronic interfaces," California Energy Commission Consultant Report, P500-2005-119, Apr. 2004.

**Benjamin Kroposki** (S'90–M'92–SM'00) received the B.S. and M.S. degrees in electrical engineering from Virginia Tech, Blacksburg, VA, in 1990 and 1992, respectively. He is currently working toward the Ph.D. degree from the Colorado School of Mines, Golden, CO.

He is also a Senior Engineer at the National Renewable Energy Laboratory, Golden, and a Leader of the Distributed Power Systems Integration Team.

Mr. Kroposki has been engaged as a Chairman for IEEE P1547.4 *Guide for Design, Operation*, and *Integration of Distributed Resource Island Systems with Electric Power Systems.* He is also a Registered Professional Engineer in Colorado.

**Christopher Pink** (S'02–M'03) received the B.S. and M.S. degrees in electrical engineering from the Colorado School of Mines, Golden, CO.

He is currently a Research Engineer at the National Renewable Energy Laboratory, Golden, where he is involved in research for advanced systems to interconnect both renewable and conventional distributed generation systems to the utility grid. He has also been engaged in designing, installing, and commissioning protective relay, controls, and distribution systems.

**Richard DeBlasio** (M'65–SM'83) is currently a Technology Manager at the National Renewable Energy Laboratory/Department of Energy Distributed Energy and Electricity Reliability Program, Golden, CO, where he is also involved at Distribution and Interconnection R&D. From 1974 to 1978, he was with the U.S. Atomic Energy Commission, Washington, D.C., and with Underwriters Laboratories from 1972 to 1974.

Mr. DeBlasio is an IEEE SA Standards Board Member and also a Chair of IEEE SCC 21 on Fuel Cells, Photovoltaics, Distributed Power, and Energy Storage.

**Holly Thomas** (M'01) is currently a Senior Project Manager at National Renewable Energy Laboratory, Golden, CO and a Project Manager for the Technology Partnership Agreement Interconnection, Grid Effects and Tariff Design for Distributed Energy Resources with the California Energy Commission. She is also the Leader of the infrastructure analysis in the Department of Energy Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project. Her research interests include microgrid and other distributed resource applications and systems.

**Marcelo Simões** (M'95–SM'98) received the B.S. and M.S. degrees from the University of São Paulo, São Paulo, Brazil, the Ph.D. degree from the University of Tennessee, Knoxville, TN, in 1985, 1990, and 1995, respectively, and the D.Sc. degree (Livre-Docência) from the University of São Paulo, in 1998.

He is currently with the Colorado School of Mines, Golden, CO. He has also been involved to establish research and education activities in the development of intelligent control for high-power electronics applications in renewable and distributed energy systems. He is also an Associate Editor for *Energy Conversion*.

Dr. Simões is a recipient of a National Science Foundation—Faculty Early Career Development (CAREER) in 2002. He has also engaged as IEEE Power Electronics Society Intersociety Chairman, an Editor for *Intelligent Systems* of IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS, and an Associate Editor for *Power Electronics in Drives* of IEEE TRANSACTIONS ON POWER ELECTRONICS.

**Pankaj K. Sen** (SM'90) received the B.S.E.E. (Hons.) degree from Jadavpur University, Calcutta, India, and the M.Eng. and Ph.D. degrees in electrical engineering from the Technical University of Nova Scotia (Dalhousie University), Halifax, NS, Canada.

He is currently a Professor of Engineering and Site Director of the Power Systems Engineering Research Center, Colorado School of Mines, Golden, CO. He has authored or coauthored more than 80 articles in various archival journals and conference proceedings. His research interests include application problems in electric machines, power systems, renewable energy, and power engineering education.

Dr. Sen is a Registered Professional Engineer in the State of Colorado.