AC Coupling
in Utility-Interactive and Stand-Alone Applications

Compiled by Joe Schwartz

While ac-coupling system architecture has been in development for about two decades and has been maturing in recent years, in some ways ac coupling is still the Wild West of renewable energy applications. The majority of the solar industry understands the design and installation of grid-direct inverter systems well. In ac-coupled applications, these grid-direct systems are integrated with battery-based inverter systems. The effective design and deployment of these combined systems quickly becomes complicated on several fronts.

First, ac coupling can be utilized in both utility-interactive and off-grid projects. These two system types have both fundamental and subtle differences in design requirements and operation when ac coupling is employed. Second, the majority of system designers and installers do not have much, if any, experience with battery-based systems, and even fewer have experience with ac-coupled systems. This results in a steep learning curve for many. Third, and perhaps most important, while fully integrated equipment platforms are available, many ac-coupled systems currently utilize equipment from different manufacturers. This mix of equipment adds complexity to ac-coupled system designs and presents challenges related to the amount of experience a given inverter manufacturer has with the use of its products in ac-coupled systems and the level of support it is able or willing to provide. For example, several grid-direct string inverter manufacturers, and most microinverter manufacturers, do not offer a warranty or provide support for their products if they are installed in ac-coupled systems.

An Introduction to AC Coupling

SMA Solar Technology began developing ac-coupling system platforms using its inverter products in the 1990s. I was first introduced to the concept while editing an article, "AC Mini-Grids," for the October/November 2005 issue of *Home Power* magazine authored by Dana Brandt. The article reported on one of the first commercially deployed ac-coupled systems, which formed a microgrid in a remote village in Uganda. In the years that followed, SMA continued to develop and refine its products and integrated approach to ac coupling. In addition, inverter manufacturers Magnum Energy and Schneider

AC-Coupled System Integration Overview

Manufacturer	Model	Recommended ratio of ac PV inverter power to battery-based inverter power	Battery-based inverter has frequency-shift control functionality to regulate ac PV inverters	Diversion load recommended	Battery-based inverter pass-through rating (Aac)
Magnum Energy	MS-PAE models	0.9:1	yes	yes	2x 30
OutBack Power	GS8048 and FX models	0.75:1	no	yes	60
Schneider Electric	XW models	1:1	yes	no	25
SMA America	Sunny Island models	2:1	yes	no[1]	56

[1] Diversion load recommended for Windy Boy inverter systems

Table 1 This table provides a high-level integration overview for battery-based inverter/charger models that are commonly used in ac-coupled systems.

Courtesy Western Sun Systems

Electric modified some of their battery-based inverter models for more seamless integration with ac-coupled systems by adding frequency-shift functionality to regulate battery charging. Currently, SMA and Schneider Electric manufacture both grid-direct and battery-based inverters that can be utilized to develop a complete ac-coupled system using equipment from a single manufacturer.

On a basic level, ac-coupled systems differ from their more conventional dc-coupled counterparts in one primary way—power generated by renewable resources, including PV arrays and wind or hydro turbines, is processed by grid-direct string inverters connected to the ac-output bus of a battery-based inverter system. Such systems can also integrate ac backup generators, with limitations in some cases, into the generation mix. In ac-coupled systems, grid-direct inverters essentially replace dc-charge controllers and frequently PV source-circuit combiner boxes as well. The absence of the dc-charge control in the system requires different and often combined approaches to battery-charge regulation. In ac-coupled systems, battery regulation is accomplished using several methods, including frequency-phase shift, blackout relays, and diversion controllers and loads that regulate the ac output of the grid-direct inverters. These approaches can range from seamless phase-shift approaches that modulate PV array generation based on ac-load demand and battery state of charge, to potentially complex networks of diversion loads driven by multiple voltage-sense relays.

This article compiles information from several sources to present an industry-wide perspective on equipment selection and best practices for ac-coupling system design and installation in stand-alone and utility-interactive systems. Four manufacturers of battery-based inverter/chargers provide technical insights related to the use of their products in ac-coupled system architectures. We also reached out to industry colleagues to share their direct experiences—both positive and negative—with deploying ac-coupled systems in the field. This issue of *SolarPro* also includes a comprehensive grid-direct inverter product specifications table (see pp. 50–62) that identifies which string inverter manufacturers offer a warranty on and support their products in ac-coupled applications.

Magnum Energy Battery-Based Inverters

By Gary Baxter and Brian Faley, Magnum Energy

Magnum Energy designs and manufactures battery-based inverters for use in stand-alone applications and grid-connected systems that require battery storage to provide uninterrupted power during utility-grid failures. In both applications, Magnum Energy permits and supports ac-coupled system designs that synchronize the ac output of utility-interactive string inverters from various manufacturers with its battery-based inverter/chargers. We have made specific software upgrades to some of our inverter models to better support ac-coupled systems, and we have additional related products in development.

Recommending the addition of a battery-based inverter system to your clients with grid-direct string inverter systems can be a profitable up-sell. Even when customers have been clearly informed that their grid-direct PV system will not produce power during utility outages, they may have an after-the-fact realization that they do want a backup system after they experience frequent or extended utility-grid failures.

With the addition of a battery bank, a critical-loads subpanel and a diversion control and load, Magnum battery-based inverter/chargers can be ac-coupled with existing grid-direct inverter systems. The dc side of the existing string inverter system does not need to be rewired. The ac input and output circuits of Magnum MS-PAE inverter/chargers can be connected in parallel with a home's ac wiring without damage to the inverter. These models can operate as a stand-alone inverter/charger in Standby mode, which allows battery charging from the grid with ac transfer to connected loads. Magnum MS-PAE inverters are listed to UL 1741 as stand-alone inverters, not as utility-interactive inverters. These products are not designed to export power to the utility grid. Therefore, the ac output of the inverter should not be connected directly to the utility power-distribution circuits. These inverters can operate in parallel with the ac-wiring circuits only when the utility power is connected to the ac input of the inverter and the inverter is operating in Standby mode.

SYSTEM OPERATION

When working with ac-coupled systems, it is beneficial to understand how a battery-based inverter operates before and during a power outage. During normal operation (see Figure 1), the utility grid provides the ac voltage and frequency reference required for the synchronization and operation of the string inverter. When the Magnum battery-based inverter/charger operates in Standby mode, the inverter utilizes the utility grid and the ac output of the string inverter to maintain the battery bank's state of charge and passes power through to the circuits in the critical-loads subpanel. In such a system, the Magnum inverter/charger is connected as a backup inverter and supplies inverted ac power from the battery to the critical loads only when the grid is down. The grid-direct string inverters are connected on the load side of the Magnum inverter, in parallel with the reference grid power when available or with the inverter power during a grid failure.

During a utility-power interruption (see Figure 2), both the battery-based inverter/charger and the utility-interactive inverter automatically disconnect from the grid. Once this occurs, the battery-based inverter begins inverting and initially uses energy stored in the battery to power the critical loads connected to the ac subpanel. Because the ac output of the battery-based inverter is connected to the same circuit as the utility-interactive string inverter, the string inverter synchronizes with the battery-based inverter's ac-output voltage and frequency. After a required 5-minute disconnect, the string inverter reconnects and starts processing the power from the PV array, charging the battery and supplying power to the critical loads.

With the string inverter synchronized to the output waveform of the Magnum inverter/charger, the string inverter processes all the energy the PV array generates. When the grid is present, household loads normally consume this energy, with any excess exported to the utility grid. During a power outage, however, noncritical loads terminated in the main service panel are not connected to the system, and the utility grid is no longer present. As a result, any excess power that the loads connected to the system's subpanel CONTINUED ON PAGE 78

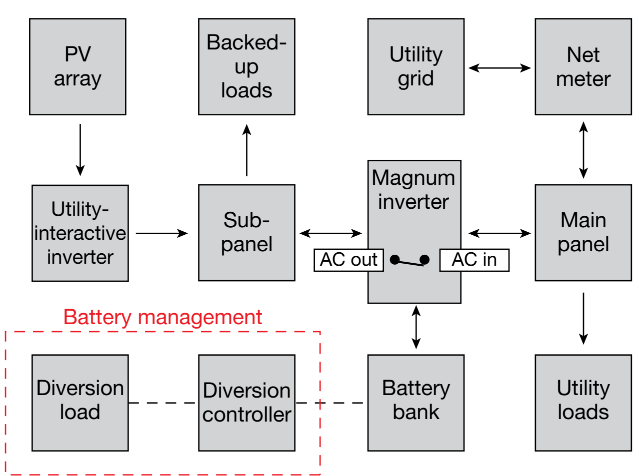
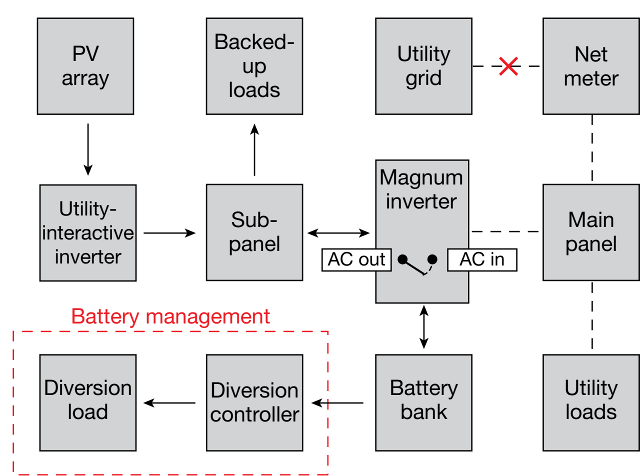


Figure 1 This block diagram shows the major components of a grid-connected ac-coupled system using a Magnum Energy inverter under normal operation with the grid present.



Courtesy Magnum Energy (2)

Figure 2 During a utility failure, the Magnum inverter opens the parallel connection between its ac input and output and provides backup power to the critical loads. In this mode, the grid-direct inverter is ac coupled to the battery-based inverter's ac output. Battery charging is regulated using both frequency-phase shift and a diversion controller and load.

do not consume is pushed back through the ac output of the battery-based inverter and into the battery bank.

Since this is not the normal path for incoming current, the battery-based inverter/charger cannot regulate the current or control the battery voltage. This brings up two important points. First, the Magnum battery-based inverter must be rated to handle the full power output of the PV array. The maximum ac-output power of the PV/string inverter system must be no greater than 90% of the continuous power rating of the Magnum inverter system. Second, the system must include a means to regulate the battery voltage to prevent an overcharge condition. You can best accomplish this with a two-step regulation approach that combines frequency shift with diversion control.

STRING INVERTER REGULATION

Some Magnum battery-based inverters include a feature that allows the ac-output frequency to shift when the battery voltage rises to a predetermined level. Magnum's MS-PAE Series inverter/chargers (revision 4.1 and higher) include an AC-Coupled Support mode. When activated, this causes the inverter-output frequency to shift to 60.6 Hz. This mode is enabled using an optional Magnum remote that allows the *battery type* setting to be set to *custom*. It activates when the battery voltage increases by 2 V (for 24 Vdc nominal inverters) or 4 V (for 48 Vdc nominal inverters) above the *absorb voltage* setting. The frequency returns to 60.0 Hz when the battery voltage falls 2 V or 4 V below the *absorb voltage* setting for 24 Vdc and 48 Vdc nominal inverters, respectively. This frequency shift protects the battery against overcharging by dropping the ac-coupled grid-direct inverter off-line. Activating the AC-Coupled Support mode is one method of regulating ac-coupled string inverters. However, this battery-protection approach does not enable three-stage battery charging. We therefore recommend that frequency shift be viewed as a secondary approach to a primary diversion-based battery-management system that provides more advanced battery-charging functionality.

In most systems, dc or ac diversion loads should be added in parallel with the battery to reduce the on/off cycling of the grid-direct string inverter that frequency shift would otherwise control. Relying solely on the frequency-shift method is rather crude because it is essentially a bang-bang controller—off or on—and once the frequency-shift happens, the string inverter attempts to reconnect every 5 minutes. While this approach is technically sufficient to prevent battery overcharging, is it optimal to have the battery voltage repeatedly swinging around by several volts? A more sophisticated option is to employ a diversion-based battery-management system. These regulation systems can utilize a dc diversion controller with dc resistive loads and/or ac resistive loads driven by dc-controlled relays. In a dc or ac diversion system, three-stage battery charging is maintained and the surplus energy from the string inverters can be put to work rather than just taking the PV system off-line.

To better support ac-coupled systems, Magnum is developing the AC Diversion Controller, which is optimized for use with Magnum MS-PAE Series inverter/chargers. This controller maximizes the use of on-site–generated PV power by diverting excess energy to ac loads such as domestic water-heater tanks. It includes complete three-stage battery charging functionality and also supports inverter frequency shift as a fail-safe protection against battery overcharging. The AC Diversion Controller communicates with Magnum MS-PAE Series inverter/chargers and automatically diverts excess current into specified diversion loads. When a diversion load such as an electric water heater reaches its regulation setpoint, excess current is diverted to a resistor bank. Alpha versions of the system are currently operating very well with SMA and Solectria Renewables string inverters, and additional testing is under way. Magnum Energy has started the listing process for the AC Diversion Controller system with ETL. The product is currently scheduled for release in Q4 2012.

OutBack Power Technologies Battery-Based Inverters

By Phil Undercuffler, OutBack Power Technologies

For many PV system designers, a watershed moment comes when they realize that they can connect a grid-direct inverter to the output of a battery-based inverter. The flexibility and scalability of these ac-coupled system architectures provide benefits over dc-coupled systems in some cases. In the retrofit market, ac coupling may be a good solution when customers with existing grid-direct systems suddenly realize that their substantial investment in solar power is unusable during a power outage. Off-grid projects with large daytime ac loads and sites with multiple buildings or significant array-to-battery distances may also be good candidates for an ac-coupled design approach. However, today's higher voltage dc-charge controllers have offset some of the commonly perceived advantages of ac coupling. In many applications, dc coupling can provide more reliable and stable operation than can ac coupling and ultimately makes more sense.

OutBack Power Technologies designs and manufactures a full range of products, including stand-alone and utility-interactive battery-based inverter/chargers that can be utilized in both dc- and ac-coupled systems, and high-efficiency MPPT dc-charge controllers. While ac coupling seems like a simple concept, ac-coupled systems have nearly endless ramifications, implications and subtleties. The following insights and guidelines, based on my experience CONTINUED ON PAGE 80

supporting the integration of OutBack products in ac-coupled systems, will assist you in the development of optimized and reliable ac-coupled installations and help you make informed and accurate choices when deciding between ac-coupled and dc-coupled system designs.

SYSTEM DESIGN AND OPERATION

Grid-direct inverters are *current-source* inverters. They convert power generated by a PV array from dc to ac, but rely upon an external ac source to operate because they cannot create an independent ac-voltage waveform. In contrast, multi-mode battery-based inverter/chargers are *voltage-source* inverters. In Stand-Alone mode, they generate an ac voltage and frequency supply independent of any external ac power source. Some models can also operate in a Utility-Interactive mode that exports excess PV array generation to the utility in a similar fashion to grid-direct inverter systems.

Battery-based voltage-source inverters can provide a stable ac voltage and frequency reference that allows grid-direct current-source inverters to operate when the grid is not present. In this operational mode, ac PV generation from the string inverters is synchronized with the battery-based inverter output via a critical-loads subpanel and is consumed first by local loads, including battery charging. If loads exceed PV production, the system meets the deficit with energy pulled from the batteries.

In most ac-coupled systems, the battery-based inverter must reliably process the entire output of the connected ac PV generation from the string inverters under all conditions. My experience indicates that the battery-based inverter must be sized to more than 125% of the power rating of the connected ac-coupled array. Multiple OutBack Radian inverters can be stacked in parallel at 120/240 Vac. Our standard FX and VFX inverter models can be CONTINUED ON PAGE 82

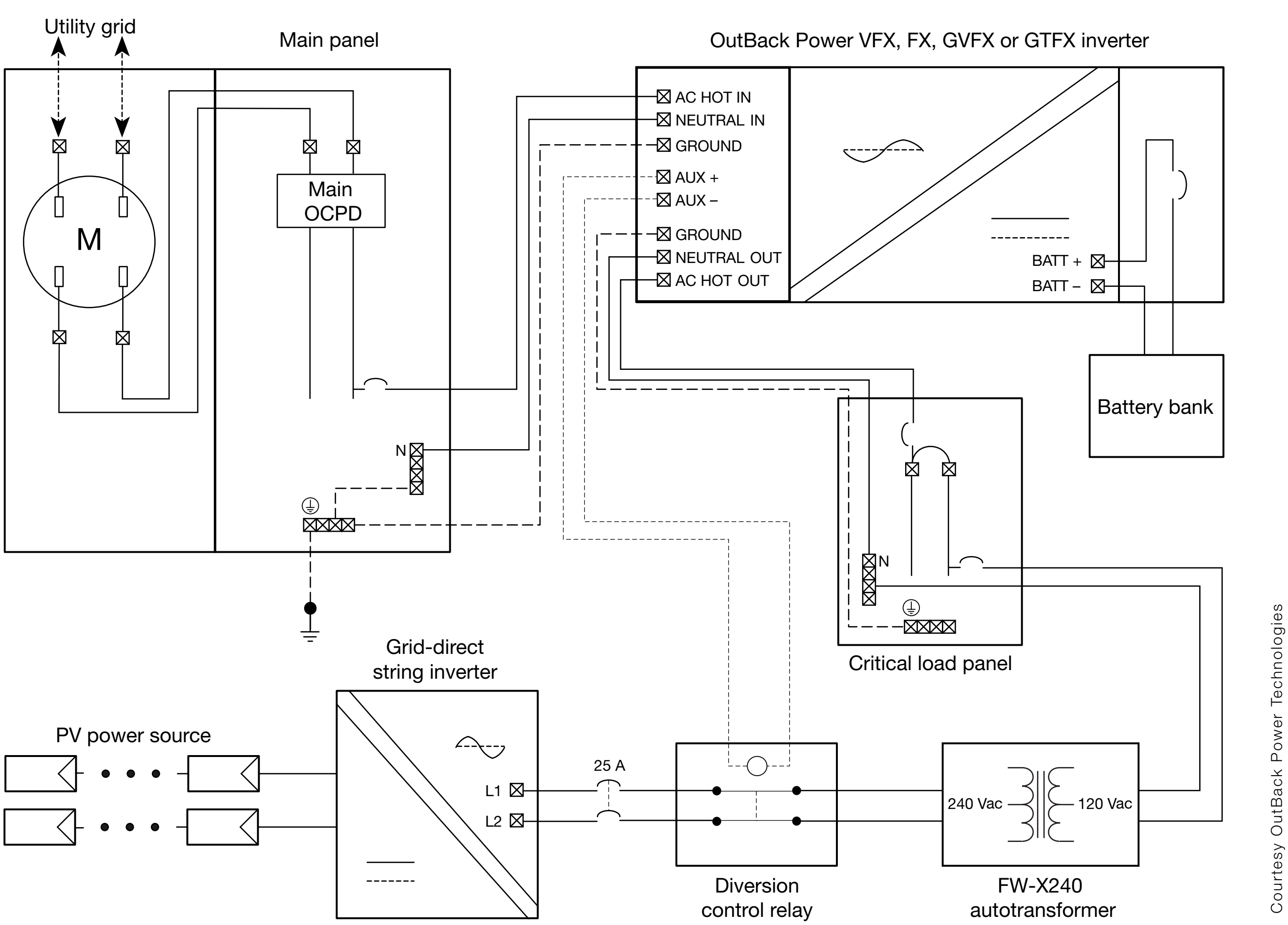


Figure 3 OutBack Power Technologies manufacturers the Radian inverter/charger, which features 120/240 Vac split-phase output. In ac-coupled systems that utilize a single OutBack FX series inverter/charger with a 120 Vac single-phase output, an autotransformer can be used to integrate 240 Vac grid-direct inverters with the system.

stacked in both series and parallel configurations to increase capacity as well. If a single FX inverter is ac-coupled with a 240 Vac grid-direct inverter, an OutBack autotransformer can be used to step down the grid-direct inverter's output voltage to 120 Vac (see Figure 3 , p. 80). If multiple OutBack inverters are stacked to increase capacity in ac-coupled systems, the Power Save function must be defeated by setting the *master-power save* level to 1 on the master inverter and the *slave-power save* levels to 1 on all slave inverters. In addition, there should be at least 100 Ah of battery capacity at 48 Vdc nominal per 1 kW of array power to ensure that the battery capacity is sufficient to absorb the PV output without excessive heating, which can damage batteries or shorten their service life.

One aspect of ac-coupled systems you should consider is that the battery-based inverter must be able to provide a stable ac supply to meet the default IEEE regulatory limits of the grid-direct inverter. Battery-based inverters used in ac-coupled systems must have good voltage regulation and must be sized to support the largest expected motor-starting surge without allowing voltage to sag or spike. Any instability in the ac supply due to poor regulation during power surges caused by local loads or excessive voltage drop in the ac wiring results in unstable operation and reduced PV output due to the grid-direct inverter dropping off-line. In addition, integrators have learned—sometimes the hard way—that some grid-direct inverters are more sensitive to changes CONTINUED ON PAGE 84

Microinverters and AC Coupling

Microinverters, and more recently ac modules, have redefined the industry's notion of modularity over the past few years. The modular and expandable platform ac coupling provides makes it seem like a natural fit with the growing number of microinverters and ac modules entering the market. However, these products are almost entirely absent from the ac-coupled application landscape. *SolarPro* editors asked several microinverter and ac module manufacturers, as well as two companies that have microinverter products scheduled for release in 2012, about the use of their products in ac-coupled systems. While the responses were not always definitive, they do serve to clarify the manufacturers' positions.

Enphase Energy is the leading microinverter manufacturer in the US and is currently expanding its presence in the European market. As such, questions from integrators who are interested in developing microinverter-based ac-coupled solutions often revolve around using Enphase products. While Enphase does informally permit the use of its microinverters in ac-coupled systems, it has not devoted internal resources to testing or developing support services for its products in ac-coupled applications. Considering the comparable sizes of the grid-direct and ac-coupled markets, Enphase understandably has a deep focus on other priorities. As a result, while this is not explicitly stated, its warranty terms currently exclude the use of its products in ac-coupled systems.

Enecsys, a European microinverter manufacturer with listed and CEC-eligible products for North America, has a similar position to Enphase. The company does not have any immediate concerns about using its products in ac-coupled systems that operate within normal grid specifications, but its warranty coverage does not currently include this use.

Exeltech recently released one of the first fully integrated ac modules in the US market. The company does not have any warranty restrictions regarding the use of its AC Module product in ac-coupled systems, provided that those systems meet several conditions. Its position could change in the future if Exeltech finds that the ac-coupled system topology is detrimental to its product. General prerequisites it currently notes include the following: A means must exist to disconnect the system from the utility in the event of grid failure, allowing the battery-based inverter to continue providing power to selected loads; the battery-based inverter must be designed to work with grid-direct inverters in a manner that is not detrimental to either device; and the battery-based inverter must employ a universal, nondestructive method such as momentary frequency shift to disconnect the ac modules when the batteries are fully charged and power production exceeds the requirements of the system's critical loads.

Both Power-One and SMA America have microinverter launches scheduled for 2012. Power-One's AURORA Micro 250 and 300 products (250 W and 300 W, respectively) are in final evaluation and beta-site implementation. The expected production ship date of these products is July 2012. At this point, Power-One's microinverters have not been tested with battery-based inverters in ac-coupled applications. SMA has scheduled its Sunny Boy 240 (240 W) microinverter for release in early fall. Deploying the Sunny Boy 240 in ac-coupled systems will not void the warranty. The product is designed to be compatible with SMA's Sunny Island system with special considerations, but the details of these are not yet available.

Integrators would undoubtedly welcome microinverters with full warranties and support for use in ac-coupled systems. However, the reality is that the potential market for these products in ac-coupled systems pales in comparison to the size of the grid-direct market that microinverter and ac-module manufacturers are focused on. While only a few of these manufacturers have devoted resources toward the testing and support of their products in ac-coupled systems, it is likely that additional manufacturers will follow suit as ac-coupled systems become more common. ●

in ac supply than others and that several string inverter manufacturers do not support the use of their equipment in ac-coupled applications.

Another complicating factor is the integration of motor-driven ac generators with ac-coupled systems. For backup-generator–based system charging, the battery-based inverter must shift its frequency to synchronize with the new ac input source when the generator is running. Once connected, the generator becomes the new ac voltage and frequency supply for the system, including the ac-coupled string inverter. The initial inverter/generator synchronization often results in the grid-direct inverter disconnecting from the system. Few motor-driven generators can provide sufficient voltage and frequency regulation to meet the IEEE regulatory requirements for grid-direct inverters to ensure stable operation. More important, generator electronics can be damaged if they are subjected to back-fed current from the string inverters. Therefore, ac-coupled systems are often designed to prevent input from ac-coupled string inverters and generators at the same time. If this is the case, the generator must be sized to not only charge the batteries, but also power all ac loads to make up for the PV generation that is lost because the string inverters are off-line. Frequently, this scenario ends up requiring a larger generator than would be necessary if the PV array was simply dc coupled.

CONTROLLING EXCESS GENERATION

Determining the best approach for regulating excess PV generation is a primary challenge when designing an ac-coupled system for stand-alone or utility-interactive applications. This is further complicated when systems utilize equipment from different manufacturers. In dc-coupled systems, traditional methods of controlling PV power involve some variation of pulse-width modulation (PWM) to regulate the output of the PV array and optimize battery charging. However, PWM regulation approaches do not apply to ac-output regulation for a grid-direct inverter. Therefore, the typical methods available for regulating the energy balance in ac-coupled systems are to either knock the grid-direct inverter off-line using a blackout relay or frequency-phase shift, or absorb excess generation using diversion loads.

The ideal regulation strategy for a specific application varies based on the amount of time the system is expected to operate in Off-Grid mode. In grid-tied, ac-coupled systems, the string inverter spends most of its time in Grid-Direct mode, where it is synchronized to the grid's voltage and frequency reference. Assuming a relatively stable utility supply, the string inverters are ac coupled with the battery-based inverter's output during infrequent, short-term outages only. In this case, it is acceptable to rely on a simple control method such as blackout relays or the frequency-shift functionality provided by some battery-based inverters to drop the string inverters off-line. If the system is off-grid or the utility-power source to the site is unstable, a more sophisticated regulation approach is recommended.

Knocking the PV generation off-line using frequency shift is perhaps the easiest, least expensive way to control excess generation. However, when the system is operating within IEEE regulatory limits, this approach is an all-or-nothing solution. Once the frequency exceeds a window of 59.3 Hz to 60.5 Hz, the grid-direct inverter disconnects and ceases to export power. In addition, once the inverter is dropped off-line, it remains off-line for 5 minutes, and the battery must be able to support the full ac load for the duration of the string inverter's waiting period. This is often referred to as the *5-minute sledgehammer*. Using a blackout relay to drop the string inverter off-line results in a similar system operation.

If an ac-coupled system includes multiple string inverters, a more sophisticated approach is to utilize multiple staged voltage-controlled relays to regulate each inverter's output. This method provides more granular regulation by shedding PV generation in smaller increments. In this configuration, as the batteries approach full charge, a portion of the PV array can be knocked off-line, leaving the remainder operating to support the ac load.

Compared to frequency-shift or relay-based regulation approaches, using diversion loads to control excess generation provides more stable and reliable operation, as well as more sophisticated battery-charging functionality. A diversion controller regulates in seconds or milliseconds and provides much finer resolution than a 5-minute array/string inverter disconnect. PWM diversion controllers shunt excess power to a dc load and provide a tapered, temperature-compensated charge to the battery. Depending on the size of the array, one possible limitation is that large dc-diversion loads may not be common or readily available. However, ac-diversion loads such as space heaters and water heaters are inexpensive and commonly available, and can put excess PV generation to good use. When using dc- or ac-diversion loads, remember that they must always remain available and should be sized to absorb the maximum PV generation expected. To protect against battery overcharging, you should build some redundancy into diversion-load systems.

All OutBack FX and VFX inverter models include a 12 Vdc programmable auxiliary output with adjustable standard algorithms that can drive an external relay or contactor to control excess generation. OutBack's Radian inverter includes a 12 Vdc auxiliary output as well as a 10 A 250 Vac/30 Vdc dry-contact relay that can independently control diversion loads or supplemental relays. One counterintuitive aspect of the OutBack inverter auxiliary programming is that the DC Divert function is preferred when systems are ac coupled.

NEED FOR STANDARDIZATION

A general lack of standardization is an issue throughout various segments of the PV industry, including CONTINUED ON PAGE 86

ac-coupled applications. Successful ac coupling requires a delicate balance between energy production, battery charging and total load demand, and, ideally, communicating that balance across multiple brands of equipment. Ultimately, industry stakeholders need to develop a universal, interoperable method for ac coupling by adopting a standardized control structure to ramp up PV production as required.

One way to achieve this standardization is to use the structure codified in the newly adopted German standard VDE-AR-N 4105, which lays out a method of frequency-dependent active power control. Designed for stabilizing the European utility grid during periods of excessive renewable generation, it outlines a structure whereby PV inverters decrease output at a defined rate as the grid's frequency rises, ramp up production upon return to normal and soften the transition upon reconnect. Battery-based inverters could use this method to control the output of any number of VDE-AR-N 4105–compliant grid-direct inverters as required, providing designers with freedom of choice when selecting components for ac-coupled systems.

Schneider Electric Battery-Based and Grid-Direct Inverters

By James Goodnight, Schneider Electric

As interest in and deployment of ac-coupled PV systems has grown, Schneider Electric has directed product development and support resources toward these applications. Currently, many ac-coupled systems utilize equipment from multiple inverter manufacturers. This mix of products can create issues with system design, installation and operation and lead to warranty issues in some cases. Schneider Electric is one of two companies that designs and manufactures both utility-interactive grid-direct inverters and battery-based inverter/chargers for the North American solar market. Schneider Electric's solar inverters now feature the Conext product range name, followed by letter designations for the various models. The Conext TX is our newest generation of residential grid-direct inverters and replaces the GT inverter models. The Conext TX integrates with the Conext XW battery-based inverter/charger to create an ac-coupled system.

CONEXT INVERTER OPERATION

In residential or light commercial utility-interactive ac-coupled PV systems, all energy sources and loads are connected directly to the ac bus. This system design topology has benefits over dc-coupled systems in some applications. CONTINUED ON PAGE 88

In ac-coupled systems, the dc infrastructure is kept to a minimum by enabling higher voltage PV arrays (up to 600 Vdc). Higher voltage arrays minimize system material costs because smaller, lower-cost conductors, conduits and BOS components can be specified. These components are also more easily handled and installed in the field, which drives down installation labor cost.

Array-to-grid efficiency is improved in ac-coupled battery-based systems as well. In a utility-interactive ac-coupled system with battery backup, the array is connected directly to the utility grid through a grid-direct inverter. In a dc-coupled utility-interactive battery-based system, the array output is connected to the battery bank through a charge controller, which is then connected to the grid through an inverter/charger. The ac-coupled design approach increases system efficiency by removing a conversion step when the utility grid is present.

Grid-present operation. On Schneider Electric's Conext XW battery-based inverter/chargers, each of the two ac inputs is equipped with an input relay that closes only when the ac source is qualified and is within the parameters of the customer-adjustable voltage and frequency ranges. Closing the input relay connects the ac source directly to the inverter's ac-output terminals. In this Pass-Through mode, the XW essentially behaves like any other load as it charges the battery bank using its multi-stage algorithm. This charging feature helps deliver good battery performance and operational life. In ac-coupled systems, if the grid ac voltage and frequency are within limits per UL 1741 and CSA C22.2 No. 107.1, Schneider Electric's Conext TX grid-direct inverters synchronize with the utility-power reference and process power from the PV array. Local loads consume the energy from the PV array, including the XW charger as it charges the battery bank, and any excess is exported directly to the grid.

No-grid–present operation. The battery-based Conext XW inverter/charger continuously monitors the utility-input voltage and frequency. If the voltage or frequency moves outside the acceptable ranges—for example, during a power surge or outage—the XW opens its input relay, disconnecting all the inverters from the grid. As soon as the relay opens, the XW transfers from Charge mode to Invert mode to provide power to the critical loads terminated in the ac subpanel using energy stored in the battery. The grid-direct Conext TX inverter may detect the temporary loss of ac during this transfer and go off-line until it detects a stable ac output from the XW for a minimum of 5 minutes.

During utility failures, the XW serves as a voltage source for the grid-direct TX inverter, providing tightly controlled voltage and frequency on its ac output. The TX inverter qualifies and synchronizes with the ac-voltage reference provided by the XW just as it would if the utility grid was present. The XW's anti-islanding feature prevents the export of power from its AC1 connection during a utility outage, and the XW and the TX inverter continue to power backup loads. Any excess power from the TX inverter charges the battery bank in a Bulk Only mode.

SYSTEM REGULATION

When the Conext XW inverter/charger is in Invert mode, electrical current flows through it in either direction. If the Conext TX inverter is providing more power to the ac bus than the loads can consume, current flows back through the XW to charge the battery bank. Unlike in Charge mode, in Invert mode the XW does not regulate charging when power is flowing from its ac output to the battery. During brief grid failures, this is not a problem if the battery is sufficiently discharged. However, if the battery is fully charged and there is not enough load on the ac system, and if the TX inverter continues feeding power to the ac bus, the battery voltage could potentially rise until an overvoltage fault condition (*high batt cut out* setting) is reached. This causes the XW and the entire system to shut down, including the ac loads terminated at the subpanel, and could result in damage to the battery if *high batt cut out* is not set appropriately for the installed battery type.

To avoid this mishap, the Conext XW inverter/charger features integrated frequency-phase–shift protection for ac-coupled applications. This strategy varies the line frequency according to a predetermined pattern to prevent the grid-direct Conext TX inverter from overcharging the battery. The XW executes a pattern-generator algorithm that varies the line frequency in a linear manner to avoid overload. The frequency-generation function of the XW changes the ac-coupled grid frequency with a linear rate of change of 0.4 Hz/s. When the charge-bulk voltage is exceeded, the frequency decreases in a linear progression until the TX inverter drops off-line. While the XW and TX inverters are in AC-Coupling mode, the XW changes the frequency only when the *charge-bulk voltage* setting is exceeded. You can adjust this setting in the custom battery menu.

Once the battery voltage reaches its *charge-bulk voltage,* the Conext XW shifts its output frequency, causing the TX to disconnect and begin its 5-minute anti-islanding waiting period. No separate control wiring is required. During this period, the ac loads are powered from batteries via the XW only. When the 5-minute waiting period is complete, the TX reconnects to the XW's ac output and provides power for ac loads and recharging the battery. If the battery is fully charged and the ac critical loads are insufficient to absorb the PV array's ac output, the TX on-off cycle continues until the grid is restored and the system returns to normal operation.

EQUIPMENT, DESIGN, INSTALLATION AND OPERATION

Schneider Electric's Conext XW inverter/chargers and TX inverters have been developed to CONTINUED ON PAGE 90

provide a fully integrated ac-coupled system. However, in some applications, ac-coupled systems can be more complex than their dc-coupled counterparts, and integrators tend to have less experience with ac-coupled systems. Here I address specific equipment specifications and use of Conext inverters in ac-coupled systems, as well as general design details that you should consider related to ac-coupled system architectures.

Grid-direct inverter compatibility. Schneider Electric has developed and tested the integration of its Conext XW and TX products in ac-coupled systems. Although this architecture may work with UL 1741/CSA 107.1-01–compliant inverters from other manufacturers, Schneider Electric has not tested these products in ac-coupled systems, so support for systems that integrate other vendors' products with Conext inverters may be limited.

Stand-alone, off-grid systems. To maximize battery performance and life, the Conext XW– and TX–based ac-coupling architecture is intended for utility-interactive systems connected to a dependable utility grid. Schneider Electric does not recommend or support its ac-coupled system architecture for use in stand-alone, off-grid applications.

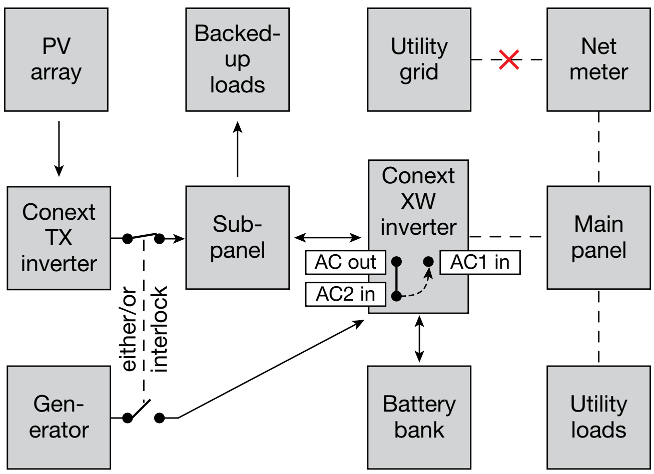
Power ratings for single Conext XW installations. The battery-based XW inverter power rating should match or exceed the grid-direct TX inverter power rating. Accordingly, the XW 6048 (6.0 kW/48 Vdc) is compatible with a single TX 5.0 (5.0 kW) or TX 3.8 (3.8 kW) inverter, or with one or two TX 2.8 inverters (2.8 kW each, 5.6 kW total). The XW 4548 (4.5 kW/48 Vdc) and XW 4024 (4.0 kW/24 Vdc) are compatible with a single TX 3.8 or TX 2.8 inverter.

Power ratings for parallel Conext XW installations. In applications that utilize multiple XW inverter/chargers configured in parallel, the total TX inverter power rating should not exceed the power rating of a single XW inverter deployed in the system. For example, while two TX 2.8 inverters can be connected to a single XW 6048, a stacked pair of XW 6048s would also be limited to two TX 2.8 inverters.

Conext XW firmware. To prevent battery damage in ac-coupled applications, XW inverter/chargers should be updated to the latest firmware that includes the ac-coupling feature. At present, XW-specific firmware (version 1.07) is available for each North American XW model and can be downloaded at schneider-electric.com/conextxw.

Conext XW ac qualification period. The XW and TX products are fully compliant with UL and CSA anti-islanding standards. However, for ac-coupled applications, the XW inverter/charger's *ac-qualification* CONTINUED ON PAGE 92

Figure 4 When a backup ac generator is included in an ac-coupled system that uses Schneider Electric's Conext TX grid-direct and XW battery-based inverters, the manufacturers recommends the installation of an "either-or" interlock switch to prevent the unintended back-feeding of current from the TX inverter to the generator.



Courtesy Schneider Electric

period default setting of 10 seconds must be adjusted to 300 seconds.

Backup generators. Schneider Electric's ac-coupled system has not been tested with a generator providing the ac reference for TX inverters. If the system includes a backup generator, I recommend installing an "either-or" interlock switch to prevent unintended back-feeding of current from the TX inverter to the generator (see Figure 4).

System metering. In ac-coupled applications, the power metering on the Conext XW may not work reliably when the inverter/charger is in Voltage-Source Invert mode and power is flowing back into the batteries.

Terminating ac circuits. The designated Conext XW and TX ac outputs are typically connected in the critical-loads subpanel. Each TX inverter requires its own ac breaker in the subpanel, which is connected to the output of the XW inverter/charger. Although there is space to add breakers for the TX inverters directly into the XW power distribution panel, it is more straightforward to install the TX inverter breakers in the ac subpanel.

Critical load and battery-bank sizing. Critical loads that are terminated in the ac subpanel should be selected based on the customer's essential safety and lifestyle requirements during utility failures. It is not practical to back up all of a home's loads. The battery bank should be sized to power the critical loads for a specific time period and to avoid completely discharging the battery bank during utility outages. An occasional 50%–60% maximum discharge may be appropriate. When specifying battery bank Ah capacity for ac-coupled systems, the designer should consider potential excess current that the TX inverter produces while it is powering the critical loads in relation to the battery manufacturer's charge-current recommendations.

Alternatives to ac coupling. If array-to-battery distance is the primary design driver for an ac-coupled system, you should weigh the potential cost and operational benefits of utilizing a dc-coupled system architecture with a higher voltage dc-charge controller. Schneider Electric manufactures charge controllers rated at 150 Vdc (XW-MPPT60-150) and 600 Vdc (XW-MPPT80-600).

SMA Battery-Based and Grid-Direct Inverters

By Greg Smith, SMA America

In both utility-interactive and stand-alone systems, ac coupling offers a scalable system platform based on grid-quality alternating current. Due to its modular design, suitable applications for ac coupling range from small off-grid or grid-tied residential systems to large stand-alone microgrids developed for village electrification projects. AC-coupled systems are more scalable than dc-coupled systems and can seamlessly integrate diverse charging sources, including PV arrays, wind and hydro turbines, and ac backup generators. In addition, ac-coupled systems can be more easily expanded than dc-coupled systems as ac load and generation capacity is added.

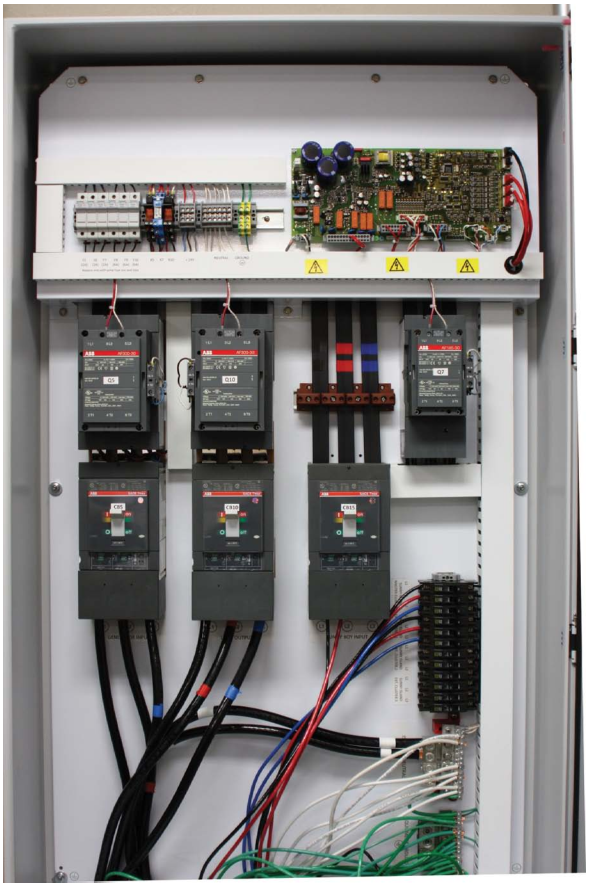
The components that make up an ac-coupled system are themselves another benefit of ac coupling. BOS components for an ac-coupled system are considerably less expensive and more readily available than dc-powered alternatives and simplify everything from system design to ongoing maintenance. AC coupling offers increased planning flexibility, since long distances between the power supply, batteries and loads do not pose the same limitations that they do in high-current dc systems. In ac-coupled microgrids, the connection of additional ac-power sources and loads is possible at almost any point in the system, allowing for subsequent expansion even years after the initial installation.

SMA is no stranger to ac coupling. In fact, it researched the feasibility of this approach to battery-based systems throughout the 1990s with the Institut für Solare Energieversorgungstechnik with funding from the German Ministry of Finance and Technology. By 2005 it had commercialized ac-coupling technology with the development of a fully integrated system platform that utilized grid-direct and battery-based inverters and controls. Today, SMA continues to expand its offerings for ac-coupled systems with the launch of new products like its Multicluster Box off-grid ac distribution solution. CONTINUED ON PAGE 94

INTEGRATED EQUIPMENT

One of the strengths of SMA's offerings for ac-coupled applications lies in the highly integrated nature of the products. SMA Sunny Island battery-based inverters and Sunny Boy and Windy Boy grid-direct inverters can be used in conjunction with one another and with backup generators to form a highly integrated stand-alone ac power grid.

Sunny Island inverters. SMA's ac-coupled solution is driven by the bidirectional Sunny Island inverter/charger, which is equipped with sophisticated ac grid-management functions and highly developed battery management that includes full system monitoring. The Sunny Island continuously tracks the batteries' state of charge, and as system manager makes ongoing decisions based on those states. For example, during operational periods where the batteries are discharged and there is little solar generation, the Sunny Island can remotely and automatically start a backup generator, or even switch off consumer loads using a built-in load-shedding relay parameter. The Sunny Island also determines the optimum strategy for charging the batteries, and in doing so increases their service life.



Courtesy SMA America

Multicluster Box SMA recently released a US version of its Multicluster Box (MCB). The MCB connects up to four 3-phase three-inverter clusters for battery-based system capacities up to 110 kWac. Backup generators can also be integrated with the system via the MCB product.

To complement the existing Sunny Island 5 kW 5048-US inverter/charger, SMA will soon add two new models to its battery-based inverter family: the 4.5 kW 4548-US and the 6 kW 6048-US. SMA Sunny Island inverters feature peak dc-to-ac conversion efficiencies of above 95% and offer high-surge capabilities for starting and supporting large inductive loads such as motors and water pumps. For example, the Sunny Island 5048-US model can provide 6.5 kW output for 30 minutes, 8.4 kW for 1 minute and 12 kW for 30 seconds at 25°C. US Sunny Island inverter models have single-phase 120 Vac output. Multiple-inverter systems can be configured for single, split-phase or 3-phase Vac.

Sunny Boy inverters. SMA manufactures a wide range of grid-direct string inverters that can be used in ac-coupled applications. With rated power outputs of 700 W to 10 kW, these inverters can be fully integrated with and controlled by SMA Sunny Island inverters in ac-coupled systems. In addition, SMA manufactures Windy Boy grid-direct inverters that process power from wind turbines; these can also be integrated with an ac-coupled system platform.

Multicluster Box. For large ac-coupled stand-alone systems, SMA manufactures the SMA Multicluster Box (MCB), an off-grid ac-distribution hub that combines and manages a variety of ac-generation sources in large-scale Sunny Island multicluster systems. While a Sunny Island inverter cluster can be used in grid-tied battery-backup applications, the MCB was developed for stand-alone 3-phase 208 Vac systems only. A preconfigured ac-distribution board in the MCB allows you to easily connect all the ac components in the stand-alone grid, including batteries, ac generator and renewable energy sources, loads and Sunny Island inverters.

Smartformer. SMA will soon be releasing the recently UL-listed Smartformer, a 120/240 Vac autoformer designed for systems that utilize a single Sunny Island inverter in conjunction with a single Sunny Boy inverter. The autoformer provides step-up and step-down options to supply loads with 120 Vac and 240 Vac and allows coupling of a Sunny Boy inverter with a single Sunny Island inverter.

THE MULTICLUSTER PLATFORM

Developed for off-grid village electrification projects, SMA's multicluster system platform (see Figure 5, p. 96) integrates Sunny Island inverters in groups of three, referred to as *clusters.* The inverters in each cluster share a dedicated battery bank and are configured for 3-phase ac output. Two, three or four 3-phase clusters, each consisting of three Sunny Island inverter/chargers, can be connected in parallel via the MCB for system inverter capacities of up to 110 kWac. Additional clusters can be connected to the MCB's distribution board at any time, enabling expansion of renewable energy generation capacity. Limiting factors of the multicluster system CONTINUED ON PAGE 96

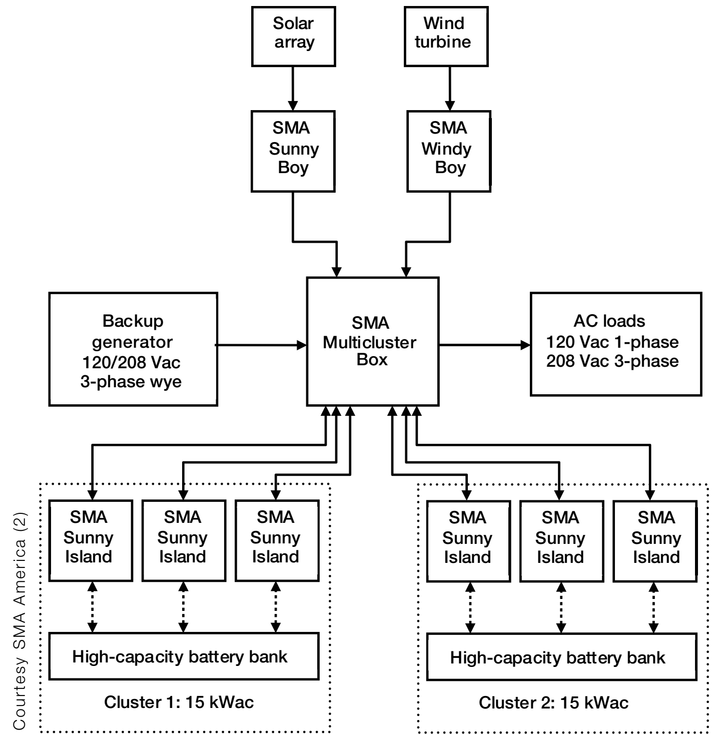


Figure 5 SMA's Sunny Island multicluster system is designed to integrate diverse ac-coupled renewable generation sources and backup generators with multiple clusters of three Sunny Island battery-based inverters. SMA's new Multicluster Box serves as an ac network distribution hub for the system.

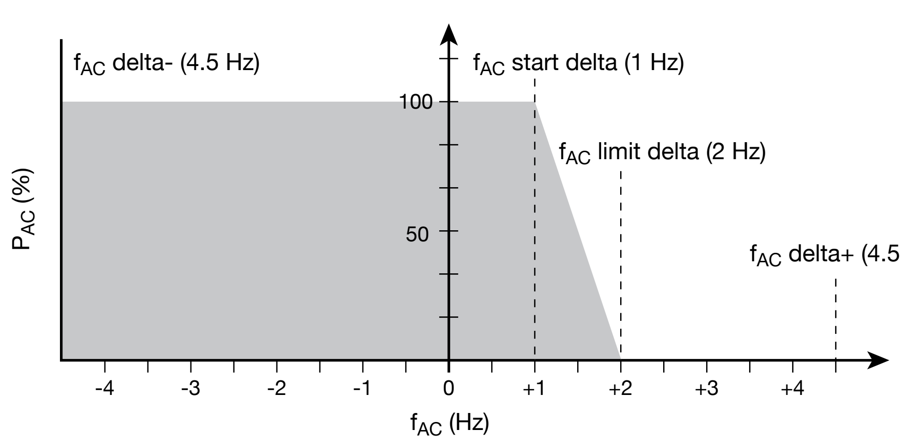
are the number of inverter connections possible on each MCB ac-distribution board and the ampacity of their switching devices. With the exception of the master cluster, maintenance or replacement of individual inverters can take place during system operation—the only operational difference during system maintenance is that the total output of the system is correspondingly lower.

In ac-coupled multicluster systems, SMA Sunny Boy inverters communicate with Sunny Island battery-based inverters via a shielded RS485 communication cable. When the batteries are completely charged and the ac-load demand is low, the Sunny Island uses frequency-shift power control to gently throttle down the power output of the grid-direct SMA inverters. These frequency shifts prevent battery overcharging and are independent of any other communication functions between the inverters. Unlike the operation of ac-coupled solutions from other manufacturers that use frequency shift to completely drop ac-coupled grid-direct inverters off-line, SMA's fully integrated approach allows the ac-coupled string inverters to remain online during frequency shift while operating at lower power levels (see Figure 6).

Most ac-coupled systems that utilize SMA's battery-based and grid-direct inverter products do not require any additional components such as relays and remote disconnects to manage power production when ac production exceeds the on-site load. In addition, if the battery reaches a preset low state-of-charge threshold, a load-shedding contactor can be programmed to open to prevent an over-discharge of the battery, which could cause the individual cluster to disconnect from the system. With a portion of the loads off-line, the ac-coupled charging sources continue to charge the battery bank. When a sufficient battery state of charge is achieved, all loads are automatically reconnected to the ac-distribution system.

The MCB includes several heavy-duty contactors. Each generator contactor connects grid-forming generators, such as those used in high-power diesel generating plants. When the generator voltage and frequency parameters are within limits, the Sunny Island synchronizes with the generator voltage and frequency reference and uses both generator power and ac renewable energy sources to either supplement loads or charge the battery banks. If an inverter cluster fails or is switched off, the generator contact automatically closes and the generator is directly connected to the loads. If the generator fails, the system quickly disconnects it and maintains power CONTINUED ON PAGE 98

Figure 6 Three battery-based inverter manufacturers utilize frequency shift in some of their inverter models to regulate the ac output of grid-direct inverters that are ac coupled. Figure 6 illustrates SMA's *Frequency Shift Power Control,* which modulates the power output of the string inverters based on battery state of charge and system load. f_{AC} 0 Hz refers to the base frequency of the microgrid generated by the Sunny Island inverters.



to the loads via the batteries and the available renewable energy sources. This system redundancy ensures that power is still available for the ac loads, even when one component fails.

MULTICLUSTER CASE STUDY

An example of an off-grid, ac-coupled multicluster power supply system is on Scotland's Isle of Eigg. The island is part of the Scottish Inner Hebrides chain and is approximately 12 square miles with a population of 90. Due to high costs, the island has not yet been connected to the mainland's power-distribution grid, which is about 10 miles away. Until 2008, diesel generators supplied the island with electricity and the entire ac-distribution network had to be taken off-line when a generator required maintenance.

Since 2008, the islanders have reaped the benefits of a modern 3-phase electricity grid, 95% of which is supplied by renewable energy sources. This ac-coupled hybrid system integrates hydroelectric, wind and solar generation. Generator operation is limited to times when the combined renewable generation sources do not fully meet the load demand. Although grid-quality power is now available 24 hours a day, electricity costs for the islanders have fallen by more than 60%.

The central element of the stand-alone grid is the SMA MCB-12, which serves as the distribution hub for four Sunny Island clusters. Each cluster is rated at 15 kWac. Three hydro turbines with a total generation capacity of 110 kW, four small wind turbines with a total capacity of 24 kW, and a 32 kW PV plant provide a diverse supply of electricity. Two 64 kW diesel generators serve as backup. Each cluster's battery bank has a storage capacity of 2,242 Ah at 48 Vdc nominal and can meet the island's load for approximately 24 hours.

During normal operation, the master cluster controls the entire grid and ensures that the distribution system's energy balance is maintained at all times. Excess energy from the renewable sources is stored in each inverter cluster's battery bank. When the battery is fully charged, the master cluster reduces the power output of the Sunny Boy and Windy Boy inverters using frequency-shift power control. It also activates remotely controlled diversion loads such as water-heating tanks located in public buildings.

The master cluster starts the diesel generator when the system's battery state of charge falls below 60%. In this case, the diesel generator sets the network's power frequency and the Sunny Island clusters are synchronized to the generator's voltage and frequency reference. The overload CONTINUED ON PAGE 100

capacity of the Sunny Island inverter/chargers makes an important contribution to the system's operation. When large loads are cycled, the load on the generator does not immediately change because the Sunny Islands compensate for load fluctuations. In this application, the Sunny Island system can supply 144 kW of battery power to the grid for 3 seconds. In its role as grid manager, the master cluster weighs the alternatives of operating the diesel generator with the highest possible efficiency while delivering the appropriate charge current to the system's battery banks. As a result, the generator runs less frequently, runs more efficiently under partial loading, and is not subjected to short start-and-stop cycles.

Integrator Perspectives on AC Coupling

On one hand, equipment manufacturers are able to provide valuable technical insights on the use of their products in ac-coupled applications. On the other hand, the diverse nature of these sometimes complex systems makes the lessons integrators have learned equally important in many instances. We surveyed several solar professionals with ac-coupled system design and installation experience who graciously devoted some time to sharing their experiences from the field.

TOMMY JACOBY, PRINCIPAL, JACOBY SOLAR CONSULTING

When compared to dc-coupled PV systems, ac-coupled systems may provide a more efficient means for utilizing array output if the majority of a site's ac loads (including energy exported to the grid in utility-interactive systems) is utilized during peak solar production hours. Assuming that losses from conductors are equal in the two systems, and that the majority of the ac-load consumption corresponds with PV production, ac- and dc-coupled system efficiencies can be compared as shown below. This simplified comparison uses sample inverter and charge controller efficiencies. More accurate comparisons can be developed using equipment-specific efficiency figures. In addition, this example does not include any losses associated with array power passing through or over the battery bank, which would result in a more favorable power output advantage for ac-coupled systems.

AC-coupled PV system. PV production x ac-coupled inverter efficiency = available ac power; 10,000 Wdc x 0.95 = 9,500 Wac

DC-coupled PV system. PV production x charge controller efficiency x battery-based inverter efficiency = available ac power; 10,000 Wdc x 0.95 x 0.95 = 9,025 Wac

When evaluating the cost of ac- versus dc-coupled system designs, account for all materials and installation-labor savings on the dc side of the system. In ac-coupled systems, the grid-direct inverter essentially replaces the dc-charge controller, but ac coupling may also eliminate the need for a source-circuit combiner box if PV source-circuit fusing is included in the ac-coupled grid-direct inverter.

Make sure to compare the power output from the ac-coupled portion of the PV system with the pass-through capability of the battery-based inverter when designing ac-coupled systems. This need applies to both grid-tied and off-grid applications. Additionally, be sure to match the grid-direct inverter voltage requirements with the battery-based inverter voltage output. For example, grid-direct inverters that have 240 Vac output cannot be ac coupled with a single battery-based inverter with 120 Vac output without the addition of a step-up/step-down transformer that lowers overall system efficiency. The SMA Sunny Island system requires an RS485 communication cable between the Sunny Boy and Sunny Island inverters. This enables full communication between the inverters and allows the battery-based Sunny Island inverters to modulate the power output of the string inverters based on ac load requirements and battery state of charge. While the communication cable can connect inverters over a distance of up to 3,937 feet if necessary, it is advantageous to group inverters as close together as possible.

KELLY KEILWITZ, PRINCIPAL, WHIDBEY SUN & WIND

Our most complex ac-coupled system integrates a 21 kW PV array and a XZERES 442 wind turbine with two SMA Sunny Island 5048-US inverters. The system utilizes a transfer-relay contactor to switch the PV output from the grid-connected main panel to the critical load panel powered by the Sunny Islands when the grid goes down. This strategy avoids an ac amperage pass-through bottleneck through the two Sunny Islands during normal system operation when the grid is up.

From my perspective, ac-coupled systems offer the following advantages:

- The efficiency of grid-direct inverters is much higher than the efficiency of a dc-coupled battery-charging system.
- PV array stringing options, combiners, and wiring are simpler and more flexible in ac-coupled systems than in dc-coupled systems.
- The material and labor cost of installing an ac-coupled grid-direct inverter is comparable to the total cost of a charge controller, a dc-integration panel and the associated equipment required for dc-coupled systems.
- Some inverter combinations, such as those used in SMA's Sunny Island system, work in harmony to reduce grid-direct–inverter output without fully disconnecting the grid-direct inverters. This allows for regulated battery charging when the system is in Off-Grid mode and generation exceeds the ac load.
- Renewable energy production metering is simpler in ac-coupled systems because it is CONTINUED ON PAGE 102

not necessary to account for grid and renewable energy generation that is consumed by critical loads or battery charging.

Some disadvantages of ac-coupled systems are also critical to consider:

- When a system is in Off-Grid mode during utility outages, many ac-coupled–inverter combinations require an ac relay controlled by the battery-based inverter's *aux* output to disconnect the grid-direct inverter when generation exceeds the energy consumed by the critical loads. This disconnect relay can cycle repeatedly, resulting in a loss of energy production during the 5-minute resynchronization waiting period every time the grid-direct inverter reconnects to the system.
- The capacity of renewable generation sources is limited by the ac pass-through capacity of the battery-based inverter system. For example, the battery-based inverter capacity may need to be increased to handle the production of a large PV system even if the critical load requirements do not call for it. One work-around is a fairly complex contactor-relay setup that switches the grid-direct inverter output between the main electrical panel and the critical load subpanel.
- While the frequency-shift regulation approach used in SMA's Sunny Island system works well, the installation manual is not as clear or complete as it could be. That said, SMA's documentation, experience, understanding and support for ac-coupled systems is likely better than that of other manufacturers. Expect to develop a close relationship with the inverter tech support people. Good cellphone coverage from the job site is a big advantage.
- If the grid-direct inverter has a possibility of syncing with a backup generator, I instruct the system operator to disconnect the grid-direct inverter before running the generator. The operator can accomplish this with the installation of an either/or interlock switch.

DANA BRANDT, OWNER, ECOTECH ENERGY SYSTEMS

My first experience with ac coupling was in 2003 while I was doing graduate studies in renewable energy in Germany. For my thesis project, I had the opportunity to design and install a hybrid PV-and-generator minigrid system that provided power for a rural boarding school located in Bulyansungwe, Uganda. This project included two 1.7 kW Sunny Boy 1700E inverters and a 3.3 kW Sunny Island 3300, CONTINUED ON PAGE 104

and was one of the first deployments of SMA's ac-coupled Sunny Island system.

One of the key advantages of ac coupling is higher system-production efficiency. Here in Washington state, we have a production incentive that pays an elevated rate per ac kWh produced. With an ac-coupled system, we can take advantage of the high conversion efficiencies of grid-direct string inverters—instead of the lower efficiencies of battery-based inverters. This results in a substantial increase in production incentive payments. The increased efficiency is also a benefit for off-grid systems with a high percentage of daytime loads.

The frequency control used in SMA's Sunny Island system allows the Sunny Island battery-based inverters to incrementally decrease the Sunny Boys' production when the batteries are approaching a full state of charge and ac loads are low. This is a very elegant solution. There is a real advantage to keeping the array generating at partial capacity instead of turning the grid-direct inverters completely off and pulling energy from the batteries. This can, of course, also be accomplished in mix-and-match inverter systems by using a diversion controller and load.

One of the things to watch for in ac-coupled system design is that the battery-based inverters typically cannot pass through to the grid more power than their rated inverting capacity. This means that the battery-based inverter capacity has to be at least as large as your grid-direct string inverter capacity, which can present an unfortunate bottleneck when you have the typical large grid-direct system and only a small requirement for backup power. To solve this scenario, you can use an automatic transfer switch or divide the grid-direct inverter and array capacity between the main panel and the critical loads panel.

MARK DICKSON, LEAD DESIGNER AND INSTALLER, OASIS MONTANA

In 2008, Oasis Montana installed an off-grid ac-coupled system that integrated two Sunny Boy 3000-US inverters with a quad stack of four OutBack VFX3648 battery-based inverters. Because of tall trees around the home, the 5.6 kW pole-mounted PV array was located 685 feet from the inverters and battery. By going with ac coupling, we were able to configure the array at high voltage, which reduced wire costs significantly. The ac-coupled approach did require more components and increased the complexity of the system, however.

In an ac-coupled configuration, ac power produced by the Sunny Boy inverters is back-fed through the *ac-out* terminals of OutBack VFX inverters. When you back-feed the Outback inverters, all the charging parameters are bypassed and the charge you are applying to the batteries is unregulated. In this system, we used a series of relays to switch dump loads on and off, simulating a three-stage charging process.

A Morningstar Relay Driver monitors the battery-bank voltage and controls four different relays. The first three relays control three 1,500 Wac electric heaters. Each relay is set at a slightly higher regulation voltage. A fourth relay is set at 62 Vdc and acts as our fail-safe in case one of the three diversion loads malfunctions. This relay is configured to disconnect the combined 240 Vac output of the two Sunny Boy inverters.

In the past few years, higher voltage dc-charge controllers such as the MidNite Solar Classic and Xantrex XW-MPPT80-600 have come to market. On midrange to long wire runs, consider using a higher voltage charge controller rather than ac coupling. If you decide to go with ac coupling, I would recommend the SMA Sunny Island system because it is fully integrated. Based on our crew's experience, we would not recommend mixing equipment from different manufacturers in residential-scale off-grid ac-coupled systems. We learned this the hard way. Some grid-direct inverter manufacturers do not support or warranty their products in ac-coupled applications.

LARRY BROWN, OWNER, SUN MOUNTAIN

Here in New York, I am seeing an increase in existing customers wanting to add battery backup to their grid-direct systems, as many of them experienced power outages for a week or more after Hurricane Irene last season. When the grid goes down, clients suddenly become aware that their PV system is not functional. During and after an extended power outage, that realization really starts to settle in. Because it doesn't require any rewiring on the dc side, ac coupling is a good approach for retrofitting these systems. However, it has the disadvantage of adding system complexity and therefore cost. In New York, the financial incentives are based on kilowatts of installed solar modules, so there is no additional incentive money for ac-coupled systems.

What currently makes the SMA ac-coupled approach work well is that installers can set up all of the inverters to communicate with each other. However, in a retrofit, if the Sunny Boys and the Sunny Islands are not relatively close to each other (say the Sunny Boys are out in a field with the array and the Sunny Islands are down in the basement), then the communication part of the system can become problematic. The standard approach is running a hardwired communication cable between the inverters. However, it may not be practical or possible to connect them in retrofitted systems. In that case, the Sunny Island inverters still use frequency shift to regulate battery charging, but do not modulate the string inverter's power output as they would with the communication cable in place. Using only frequency shift, the Sunny Boy inverters drop completely off-line and have to go through the 5-minute waiting cycle, which repeats until the combined load in the critical loads subpanel and the battery-charging power requirement is equal to or greater than the output of the Sunny Boy inverters.

We have installed ac-coupled systems only with SMA equipment and have some suggestions for how SMA could improve integration of these systems. The first is CONTINUED ON PAGE 106

to make the Sunny Islands capable of providing 120/240 Vac output so that only one Sunny Island battery-based inverter is necessary. At present, either two Sunny Islands or a step-up/step-down transformer is required. Two ac inputs, one for the grid and one for a generator, would be handy as well. Currently, you need to add a separate automatic or manual transfer switch if you want to include grid and backup-generator charging.

KENT OSTERBERG, SENIOR ENGINEER, BLUE MOUNTAIN SOLAR

One of the more common applications for ac-coupled systems is for homeowners who decide to add battery backup to a grid-tied PV system. In most cases, I suggest to these customers that a generator is a better choice for occasional backup power. Folks in hurricane areas may be able to make a better argument for using batteries to back up grid power. If the PV array is a long distance from the batteries, they should consider ac coupling. However, with higher-voltage charge controllers such as the MidNite Solar Classic 250 and Xantrex XW-MPPT80-600 available, I would consider those alternatives first.

Keep in mind that in utility-interactive systems, the grid-direct string inverter that is set up for ac coupling with a battery-based inverter is not operating in AC-Coupled mode except when grid power is down. So 99% of the time, you will not experience any of the annoyances that come with a specific ac-coupled system. If the system is off-grid, ac-coupled operation is the normal routine and any problems become quite apparent. For an off-grid system where the ac-coupled inverter is normally the primary charging source, an external diversion controller and load should be used in mixed inverter systems. Additionally, making the system fail-safe is important. For example, if the diversion controller is inadvertently turned off or fails, a relay-based approach should be in place to disconnect the ac-coupled inverter.

When considering ac coupling, one important question is how much support the inverter manufacturer is willing or able to provide. At one end of the spectrum, SMA has a fully integrated product line and a training program for its Sunny Island system. Other battery-based inverter manufacturers may offer only a short white paper on using their products in ac-coupled applications, and their technical support staff may have limited experience with these systems.

Benefits and Drawbacks of AC Coupling

Depending on the application and equipment used, ac-coupled systems may offer several advantages over their dc-coupled counterparts. In large stand-alone microgrid systems, such as those found in rural electrification projects in the developing world, ac coupling provides an extremely scalable and modular platform that can integrate multiple charging sources located throughout the system's distribution network. Large stand-alone projects here in the US may also benefit from an ac-coupled rather than a dc-coupled design approach. The inverter/battery cluster platform developed by SMA that is common in these large systems allows segmentation of battery storage into manageable bank sizes that limit the number of series battery strings required to achieve sufficient storage capacity.

In residential systems, ac coupling is one approach that can be used to increase PV system voltages (up to 600 Vdc) to minimize wire costs when PV arrays are located a significant distance from the power-conditioning and -storage equipment. It can be a great solution in the retrofit market when customers want to add battery backup to existing grid-direct systems. Finally, ac-coupled systems can achieve higher dc-to-ac conversion efficiencies, especially when the generation matches periods of high-electricity demand.

In spite of the benefits ac coupling has to offer, it may also have some downsides when compared to more standard dc-coupled system designs. Again, depending on the application and equipment used, system regulation and optimized battery charging can be a challenge, especially when equipment from different manufacturers is installed. The introduction of higher voltage charge controllers has offset one of the perceived advantages of ac coupling when long-distance array-to-battery power transmission is required. In general, ac-coupled systems can be more complex in design and installation, and this is compounded by the fact that the knowledge base in the industry to support inexperienced integrators is still underdeveloped compared to what is available for the more common grid-direct and dc-coupled systems.

In spite of the benefits and drawbacks of ac-coupled system architectures, they are an important and viable approach for integrators to have in their design toolkit. AC coupling can provide solutions for systems that would otherwise have been undevelopable. As interest in ac-coupled systems continues to grow, installers will continue to learn valuable lessons from the field. Correspondingly, manufacturers will continue to develop both products and more-robust support services to aid integrators in the design and installation of this modular and scalable system platform.

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