Demand Response Inverter for Distributed Generation Energy Management

Darren Hammell (Princeton Power Systems, Inc.) — Princeton, New Jersey, USA —
dhammell@princetonpower.com

Summary
Princeton Power Systems is developing a grid-tied Demand Response Inverter (DRI) to combine commercial-scale distributed generators, particularly photovoltaic arrays, with energy storage and communications, to improve integration of distributed generation with the electric grid. The inverter lowers the cost of produced energy (levelized cost of energy or LCOE) through higher efficiency, higher reliability, and lower capital cost. The inverter incorporates advances in nanocrystalline inductor core materials for greater power density and improved efficiency. In addition, it allows the simultaneous connection of multiple energy sources and load options to provide value-added ancillary services to both the utility and the end user, particularly energy storage integration. The DRI is intended primarily for commercial applications, such as buildings and agricultural, in the power range of 100 – 500 kW. The development program is partially funded under the US Department of Energy's Solar Energy Grid Integration Systems (SEGIS) program.

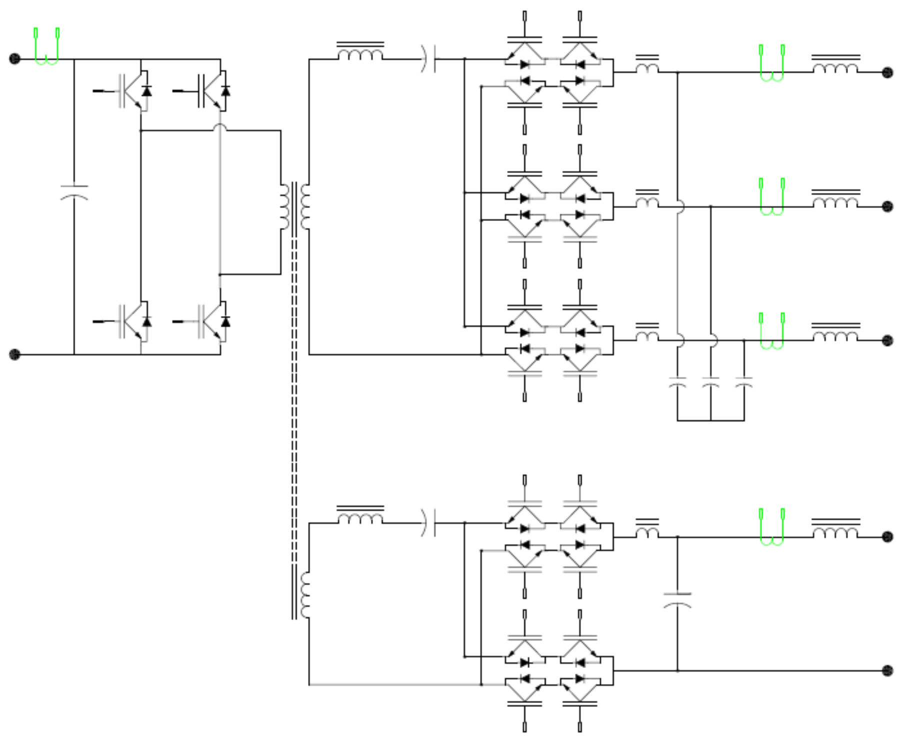

Figure 1. Circuit Schematic the Demand Response Inverter (DRI) for Distributed Generation Energy Management, shown with an energy storage input module (lower right), Grid Connection port (upper right), and PV Array Port (upper left). Not shown is an optional AC Load Port that can control a generator or dedicated AC motor at variable voltage and frequency.

Background of the US DOE's SEGIS Program
The Solar Energy Grid Integration Systems (SEGIS) program is an approximately 3-year, three phase effort that emphasizes the development of advanced inverters, controllers, and other balance-of-system components for photovoltaic (PV) distributed power applications "behind the meter". SEGIS' objective is to develop new commercial hardware that will increase the value of PV systems and increase the power quality and reliability as larger numbers of PV systems are incorporated into utility systems.

The SEGIS program is a part of the broader Solar America Initiative (SAI), which has the objective of bringing the Levelized Cost of Energy (LCOE) of grid-interactive PV systems to parity with the electric grid by 2015. Thus, a related objective of SEGIS is to show direct contributions to LCOE reduction through technology development that help to meet these goals. To this end, hardware that results in system LCOE of $.05-$.10/kWh is high priority.

Contributors to Levelized Cost of Energy (LCOE) Reduction

The main contributors to LCOE are efficiency, initial capital costs, and lifetime maintenance costs. Addressing these specific areas is therefore the most direct way to lower the LCOE of a PV system. The DRI technology and design attempts to address these areas in the following ways:

- Magnetics based on nanocrystalline core material and high frequency operation along with low-voltage silicon contribute to high operating efficiencies, with a projected California Energy Commission (CEC) weighted efficiency of 98.0%;
- High-frequency operation and advanced materials, along with simplicity of design, leads to a reduction in parts count and reduction in size and thus metalwork and other materials, and reduces initial capital cost. The projected weight of the 100 kilowatt system is 500 lbs;
- Verified highly reliable components and design, 15 year service life with ~400k hours Mean Time Between Failures (MTBF).

<u>High Efficiency</u>

In electrical circuits at high power level (100 kW+) operating at high switching frequencies of 5 kHz or greater, the power throughput in the internal inductors is a critical design feature. The inductors must withstand rapid swings in voltage, high current throughput, and must maintain high efficiency in order to both reduce heat management requirements and contribute to high system efficiency. Nanocrystalline core material has been shown to be advantageous, and Princeton Power Systems has developed prototypes for 100 kW systems that shown 99.8% efficiency and have been optimized for rejecting heat from the core and windings.

Figure 2. 750 kW 50 kHz transformer based on a nanocrystalline core with litz-wire windings, in a test bay at Princeton Power's facility.

The DRI uses off-the-shelf Integrated Gate Bipolar Transistor (IGBT) semiconductor switches at low voltage levels in order to maximize operating efficiency for the voltage and current levels required by typical PV and energy storage technologies in the 100 – 500 kW power levels.

<u>Low Initial Capital Cost</u>

The simplicity of design and reduction of parts for the DRI significantly reduces the initial cost of the inverter. When fully configured, the inverter includes four (4) power ports that allow the integration of a PV array, electrical energy storage, grid-tied power import and export, and dedicated AC load including microgrids, variable speed motors, or other loads, with a single inverter box. The integration of all these systems into one unit reduces the hardware cost, as well as the integration and setup time for the system.

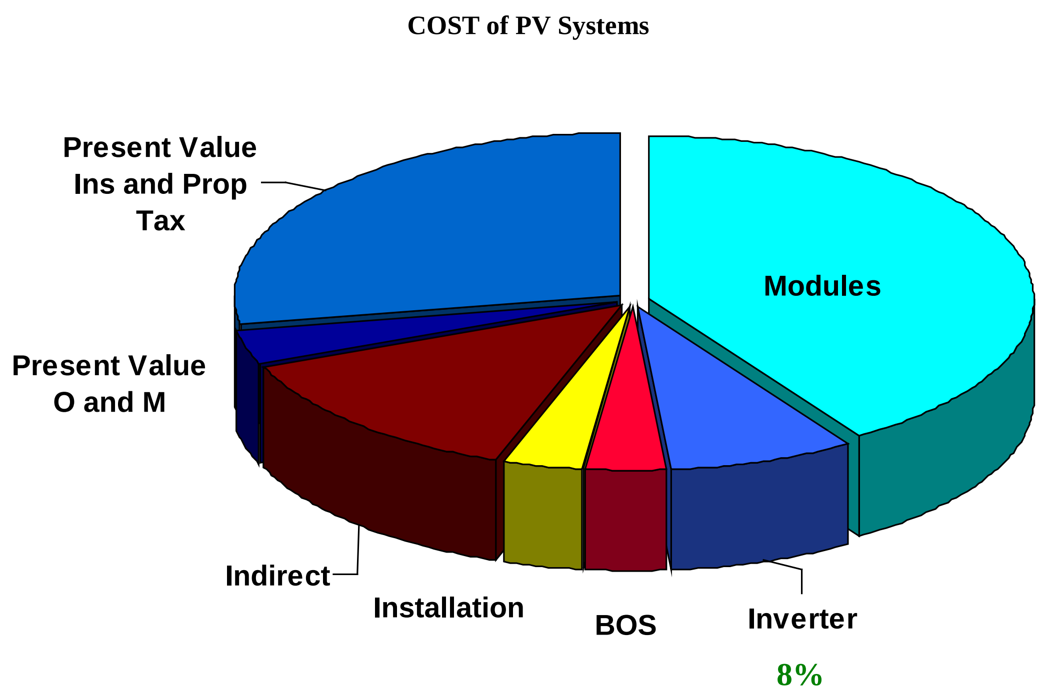

Figure 3. Initial capital cost of a solar system by component as of mid 2007. Today, the price of the Modules has dropped by about 30-40% and the Inverter is a higher percentage of the overall system cost. When energy storage is included, the power electronics become a still larger part of the initial investment.

The DRI design incorporates advanced materials that lead to a significant reduction in the size and weight of the system, which yields reductions in metalwork and raw materials. This in turn contributes to a lower capital cost. Options can be eliminated at the factory to reduce the price further.

<u>High Reliability</u>
The DRI is designed for a 20-year operating lifetime with minimal maintenance and failure rates. Rigorous analysis of all components in the system using a database of historical failure rates of those components in military power electronics applications is being used throughout the design and development program. Highly Accelerated Lifetime Testing (HALT) will be employed in the testing phase to determine design flaws and weak components. Best practices are used for derating of critical components including capacitors and semiconductors.

The LCOE of PV systems using the DRI is lowered based on higher operating efficiencies, lower initial cost, and longer operating lifetime.

Beyond LCOE
Traditional inverters and PV systems have focused on LCOE as the figure of merit. The US Department of Energy has published a software model to help calculate LCOE and evaluate new technologies on a baseline scale to assess their affect on LCOE, with a goal to achieve grid-parity by 2015.

However, ancillary services provided to both the utility and the end user are not currently captured under this model, and understanding the benefit of the DRI and particularly incorporating energy storage into installations requires going beyond the standard LCOE model. The DRI is intended to provide a means for both lowering LCOE in typical

PV applications, but also to allow the integration of energy storage and control methods to increase the value of the PV system beyond the LCOE measurement.

The DRI offers the following value-added benefits:

Flexibility

The DRI can integrate with many types of electrical energy storage, and can be programmed to optimize the charge, discharge, and maintenance profiles for various technologies. The DRI allows multiple installation scenarios for microgrids, off-grid applications, critical load control, demand response and reduction, and various other potential usage scenarios. Since all of the power ports are integrated into one central controller, programming and installation are simplified. The DRI is intended to allow the system designer and installer the flexibility to design systems using new concepts and new technologies that, including those that are note readily available today.

Communications and Monitoring

The DRI provides real-time monitoring and reporting capabilities, with all energy sources and loads integrated into one user interface. It can also provide remote programmability of certain functions to allow grid operators or others to dynamically adjust operating parameters based on system changes or other variables. It is intended to integrate with various communication and monitoring systems to provide a “front end” to smart grid systems.

Value-add to Grid-Operator (ancillary services)

The DRI provides all of the basic safety and power quality features, conforming to UL 1741 and IEEE 1547, that are generally required for exporting power behind the customer’s meter. In addition, it can provide the grid-operator with unprecedented levels of control and programmability, in order to integrate with existing and future scenarios.

The DRI can provide Variable Ampere Reactive (VAR) support, dynamically adjustable by the grid operator, in order to reduce transmission and distribution congestion and increase the efficiency of the grid system. Basic VAR compensation can be provided without energy storage, and a greater level of control is possible with small amounts of included energy storage.

Dynamic peak-shaving, upon a dispatch signal from the utility, provides the capability to lower standby-reserve requirements in systems that include renewable energy generators. The DRI can be programmed to follow the building load where the system is located in order to provide a predictable load curve, for example. If intermittencies occur from loss of generation on the PV array, the DRI can automatically supplement power output using the energy storage or by reducing an AC load power draw, thus providing support to the grid during an event.

Value-add to End User

At the most basic level, the DRI performs the functions of a typical grid-tied inverter, conditioning power generated by the solar array or other generator and exporting it to the grid. However, it can also provide several other functions for the end-user of a distributed generation installation, or the building owner hosting the solar array for example:

AC Load Port – In addition to the grid connection, the DRI contains an AC port that can be connected to a dedicated AC load or a variety of loads. If connected to a motor load, such as a water pump, it can operate the motor at variable voltage and frequency, in order to actively control the power draw of the load. This can be useful both for minimizing power draw, or for responding to utility requests for demand reduction, or responding to time-of-day pricing changes. Many scenarios can be imagined where the end user can benefit from additional revenue streams and energy savings by having the capability to respond to pricing signals or direct commands via load reduction.

Backup Power – With incorporated energy storage, the DRI can provide several hours of backup power for critical loads. Even without energy storage, the DRI can provide backup power directly from a PV array to variable motor or pumping loads when power is available from the array. The DRI can also run in “microgrid” mode, supplying one or more loads directly from the distributed generator, energy storage, or both. This can be done in situations when grid power is out, or even if it is advantageous to reduce utility load for any reason.

The DRI can also be programmed to provide “time-shifting” of solar or other energy, to maximize the price this clean electricity is sold to the grid, where utility rate structures allow.

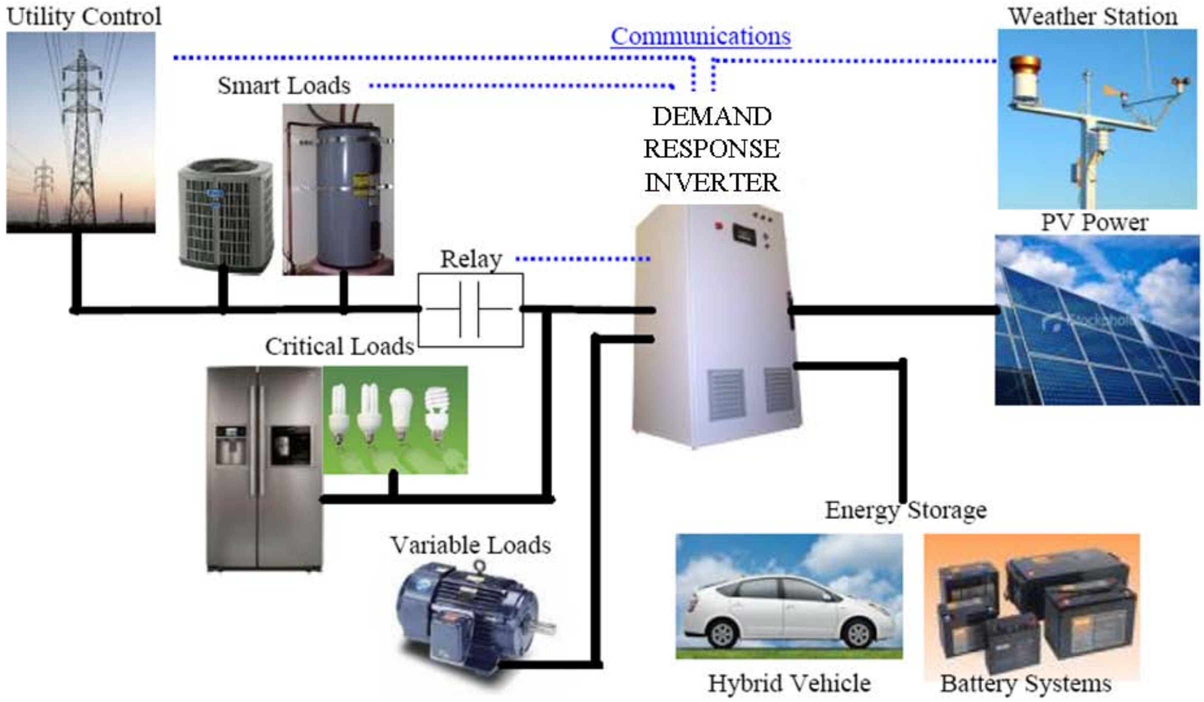

Figure 4. The DRI acts as the "front end" for the smart grid in commercial applications, providing the capability to integrate distributed generation with energy storage and variable load control.

Demand Response Inverter Technology
The Demand Response Inverter was conceived as a way to lower the cost of energy from solar arrays, while providing design flexibility and functionality beyond that currently available with standard inverters. In particular, it allows the easy integration of electrical energy storage with distributed energy generation, particularly solar arrays, and allows several advanced installation and system design scenarios to be developed at much lower cost and with greater simplicity than possible with existing equipment.

Many of the additional benefits of the DRI do not currently fall under the standard definition of the cost of energy from a solar array, but they can be monetized and will provide incentives for both utilities and consumers to adopt greater percentages of renewable energy generation. With the recent drop in solar module prices, it is now possible to install systems using the DRI technology and energy storage for roughly the same cost as a PV system without storage would have cost in mid-2007. Prototype DRI's will be under test in Q4 2009, and beta test sites will be identified and installed in mid 2010.