IV.C.1 DC-AC Inverter with Reactive-Power-Management Functionality

John N. Mandalakas (Primary Contact) and David J. Shero
Mesta Electronics Inc.
11020 Parker Drive
North Huntingdon, PA 15642
Phone: (412) 754-3000; Fax: (412) 754-3016
E-mail: john@mesta.com

DOE Project Manager: Donald Collins
Phone: (304) 285-4156
E-mail: Donald.Collins@netl.doe.gov

Objectives

- Determine the operating specifications for the DC-AC inverter.
- Determine optimum power designs to meet the system specifications derived during the first objective.
- Determine the control components and algorithms needed to optimize the performance of the power hardware, maximizing performance and minimizing power losses and other undesirable byproducts.

Accomplishments

- Compiled and analyzed utility grid interconnection specifications.
- Identified and quantified utility grid conditions that would influence the design of the DC-AC inverter. Also prioritized inverter functions with respect to perceived value to the utility.
- An optimum design approach for the multi-function DC-AC inverter was developed.
- Designed and tested a low leakage isolation transformer to be incorporated as part of the 25 kW/kVA energy converter prototype.
- Designed, built, and successfully tested a 25 kW/kVA prototype DC-AC inverter/energy converter which demonstrates the feasibility of a multi-function system capable of providing real power, reactive power, harmonic cancellation and three-phase line balancing to the utility grid.

Introduction

Presently, many electrical power distribution circuits have areas that are supplied with substandard power. Sections of the electrical distribution system are often heavily loaded to the point that voltage regulation and reliability deteriorate. These problems can be reduced, but not substantially eliminated, by increasing the size of components in the distribution circuit. An alternative to increasing the size of the distribution circuits is to add distributed generation throughout the system. Distributed generation units with the capability of injecting real and reactive power into heavily loaded sections of the distribution system can correct this problem. Highly reliable (99.9% minimum availability), cost-effective (less than $100/kW in quantity) energy converters that convert DC power from a generating source such as a fuel cell, along with providing reactive power, are needed for such distributed generation units.

The energy converter is a key element in distributed power generation and correcting problems with existing electrical distribution systems caused by heavy loading along the system. Its high performance, high efficiency, high reliability, and low cost will be very attractive to utilities, alternative energy sources (fuel cells, solar arrays, windmills, etc.) and other businesses that benefit from adding distributed power generation and power correction. Such benefits include improving the quality of power, thus decreasing financial losses caused by poor power quality; and decreasing power transmission losses and costs, without resorting to much more expensive upgrades to distribution components (transmission wires, transformers, sub-stations, etc.). The energy converter's concept and modular design will also allow future higher power systems to be developed that could be applicable for the proposed Department of Energey (DOE) 100+ MW FutureGen power plants.

Approach

Working with a utility consultant, Mesta has worked towards developing an accurate set of specifications for the energy converter. This set of specifications will be used to guide the design process. The first part of the design is to identify major components that will make up the energy converter. At the heart of the energy converter is a DC to AC converter, commonly referred to as an inverter. The inverter converts DC power originally generated by the fuel cell into 3-phase AC power that is synchronous with the voltage on the electrical distribution circuit. The inverter can pull power from the distribution circuit by producing a voltage slightly lower than the distribution circuit voltage. This power is stored in the capacitance across the DC side of the inverter. If the voltage produced by the inverter is slightly out of phase with the distribution circuit voltage, reactive power is transferred between the energy converter and distribution circuit. The converter can generate either a leading or lagging reactive power, as needed by the system. In a similar manner, the converter can also produce harmonic currents that "cancel" harmonic currents flowing in the distribution circuit.

During Phase I, Mesta uses portions of several Mesta existing product designs to produce a conceptual design for an energy converter. The transformer that interfaces the energy converter with the distribution circuit is also characterized. The control components and algorithms need to be optimized and the performance of the power hardware is studied. Mesta tests portions of the new conceptual design in a lab environment using actual hardware during Phase I of the project.

Results

During Phase I of the project, a 25 kW/kVA prototype energy converter was developed and tested. This prototype added a DC-DC converter, 480 VDC bank of batteries, and a 3-phase transformer to a 480 VAC, 50 amp (43 kVA) inverter. The inverter and most of the controls were part of a 50 amp standard product DPM (power factor correction equipment incorporating active harmonic filtering, linear power factor correction, and line current balancing) manufactured by Mesta Electronics. The DPM's hardware and software controls were altered to incorporate the additional function of power generation simulated by the bank of batteries. A block diagram of the prototype is shown in Figure 1.

Figure 2 shows the energy converter connected to 480 VAC 3-phase power from the utility. The three utility power lines are powering a simulated load. The simulated load draws current that has a representative amount of harmonics, has inductance to represent a lagging linear power factor, and is unbalanced so that different amounts of current are drawn by the load from each phase. The energy converter is controlled to inject currents into the three power lines to effectively cancel these problems caused by the load. The net result is that balanced, sine wave current is provided by the utility. This results in the utility supplying only "in phase" 60 Hz currents. The magnitudes of these currents are less than what the load draws because the power factor that the utility sees is very close to 1.00, whereas the power factor of the load is less than 0.90. The net benefit is that the distribution network supplying the power for this test network has lower losses (due to the need for less current and due to the absence of harmonics in the supplied current). Also, with the elimination of harmonic currents, the voltage waveform distortion seen by this load, and by other equipment fed by this distribution network, is minimized and the voltage regulation is improved.

In addition to these "reactive" current corrections, the DC source allows "simulated generated power" similar to that generated by a fuel cell, etc. to be injected into the distribution network at the same time that these current corrections are occurring. The energy converter converts the DC power to AC power that is then injected into the network. The AC power from the DC source is almost perfectly sinusoidal and in-phase with the voltage. The powerful control capabilities of the energy converter allow this power injection to occur simultaneously with the "reactive" current corrections. Since the real power derived from the DC source and reactive corrections are out of phase with each other, the total current needed is much less than the amount required if two separate systems performed these tasks.

Figure 3 shows data collected with the energy converter performing reactive power correction only. The first line of Figure 3 shows the line-to-line voltages of the three AC line phases and the rms current from the energy converter (DPM_AMPS) for all three phases. The second line shows the line currents from the utility (LINE_AMPS) and currents drawn by the load (LOAD_ AMPS). The third line shows the harmonic current distortion as a percentage of total rms current for the line (LINE_THD%) and the load (LOAD_THD%). The fourth line shows the actual total rms current of the harmonics for the line and load. The fifth line shows the kilowatts, kilovars, and power factor of the line and load. The sixth line shows the frequency of the line and the regulated DC voltage of the energy converter (nominally

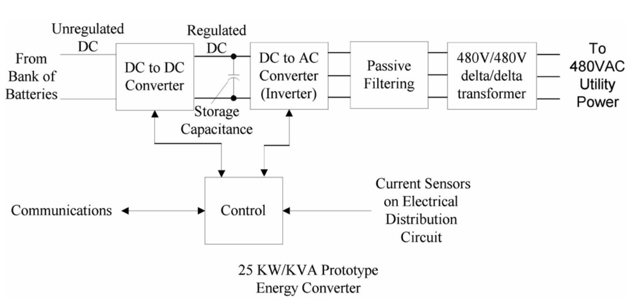

FIGURE 1. 25 kW/kKVA Prototype Energy Converter

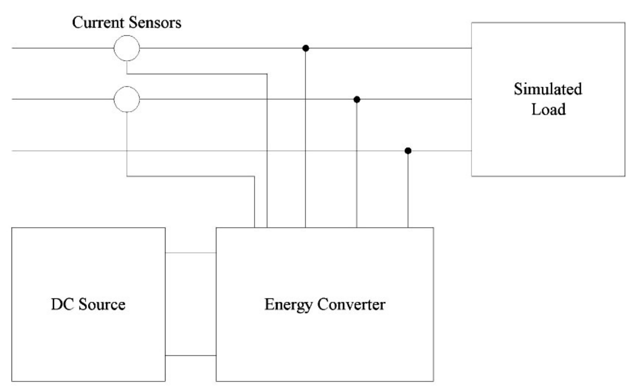

FIGURE 2. Energy Converter Power Test Setup

```
                    *** MESTA DPM STATUS (04/02/07, 15:52:55) ***

LINE_VOLT AB/BC/CA= 489.3/495.2/490.8   DPM_AMPS  A/ B/ C =  25.6/ 17.0/ 19.8
LINE_AMPS A/ B/ C =  44.7/ 44.1/ 43.7   LOAD_AMPS A/ B/ C =  50.5/ 40.1/ 52.4
LINE_THDR% A/B/ C =   2.1/  1.9/  2.9   LOAD_THDR% A/B/ C =  32.1/ 32.6/ 32.3
LINE_AMPS HARMONIC=   0.9/  0.8/  1.3   LOAD_AMPS HARMONIC=  16.3/ 13.1/ 17.0
LINE_PWR KW/KVA/PF=  37.6/ 37.6/0.999   LOAD_PWR KW/KVA/PF=  36.8/ 40.6/0.904
LINE_FREQUENCY(HZ)=        59.98        DC_VOLT(LO+HI=SUM)= 408.7+410.9=819.7
MODE = ON - INV(S) 1        ENABLED     STATUS = FULLY OPERATIONAL
TEMP PCB/HS1A/HS1B=  25.9/ 26.9/ 27.6   BATTERY V/I/KW    = 501.6/  0.0/  0.0
WREQ/WACT/BATTCHRG=     0/   0/  50%
```

FIGURE 3. Full Reactive Current Correction with No Real Power Component

```
                    *** MESTA DPM STATUS (04/02/07, 15:59:00) ***

LINE_VOLT AB/BC/CA= 490.9/496.8/492.3   DPM_AMPS  A/ B/ C =  28.8/ 16.9/ 27.2
LINE_AMPS A/ B/ C =  31.3/ 30.8/ 30.3   LOAD_AMPS A/ B/ C =  50.3/ 40.5/ 52.7
LINE_THDR% A/B/ C =   2.7/  3.0/  4.3   LOAD_THDR% A/B/ C =  32.3/ 32.5/ 32.3
LINE_AMPS HARMONIC=   0.9/  0.9/  1.3   LOAD_AMPS HARMONIC=  16.2/ 13.2/ 17.0
LINE_PWR KW/KVA/PF=  26.3/ 26.3/0.999   LOAD_PWR KW/KVA/PF=  36.8/ 40.9/0.901
LINE_FREQUENCY(HZ)=        59.99        DC_VOLT(LO+HI=SUM)= 407.6+410.9=818.6
MODE = ON - INV(S) 1        ENABLED     STATUS = FULLY OPERATIONAL
TEMP PCB/HS1A/HS1B=  26.8/ 33.3/ 38.2   BATTERY V/I/KW    = 447.9/ 25.9/ 11.6
WREQ/WACT/BATTCHRG=    50/  50/   8%
```

FIGURE 4. Full Reactive Current Correction with 11.6 kW of Power Generation

820 volts). The last half of the eighth line shows the battery DC source's voltage (volts), current (amps), and power (kilowatts); where positive current and power indicate that the battery is supplying power and negative values indicate the batteries are being charged by the energy converter. As can be seen in Figure 3, the load currents are unbalanced (50, 40, and 52 amps), the load currents contain substantial harmonics (about 32% each), and the load has a power factor of only about 0.9. On the other hand, the line currents are balanced at about 44 amps each, there is very little harmonic current coming from the utility (only 2-3% of the total current), and the power factor seen by the utility is at 0.999 out of a possible 1.000. The energy converter is making a fairly obnoxious load look like an ideal balanced, purely resistive load to the utility distribution system.

Figure 4 shows data taken under the same conditions as Figure 3 except the DC/DC converter is activated so that 11.6 kW of power is generated to the AC line. The result is that the line amps supplied by the utility drop from about 44 to about 31. Although 11.6 kW would require almost 14 amps of rms current on each phase to be generated by a separate inverter, the energy converter is only outputting slightly higher current on each phase (28.8, 16.9, and 27.2 vs. 25.6, 17.0, and 19.8) than it did when only reactive correction was being performed in the previous case. This illustrates how doing reactive correction and real power generation with the same equipment can be done much more efficiently than using separate pieces of equipment.

In addition to the above referenced work on a prototype energy converter, efforts were coordinated with Mesta's utility consultant, Southern California Edison, to compile detailed information regarding utility grid interconnection specifications, grid operating characteristics, and utility disturbances that would influence the design of the DC-AC inverter/energy converter. Certain portions of the information influenced the design of the prototype energy converter that was tested. A substantial portion of this information will also be utilized during Phase II of the project when a larger scale production quality system is developed for utility grid application.

Conclusions and Future Directions

The data indicates a very successful demonstration of the energy converter's capabilities, albeit at a reduced power level. However, the system is very scalable and can be scaled up to larger systems that would have a much more profound effect on actual power distribution systems. Future work will be dedicated to further analyzing utility grid specifications and moving forward to develop and test a production quality energy converter capable of 600 kW/kVA total of reactive current correction and/or real power generation from a DC source. This size module will be capable of being paralleled to produce higher total power capabilities.

Special Recognitions & Awards/Patents Issued

1. U.S. patent application is in process.