Design and Performance of Solar Decathlon 2011 High-Penetration Microgrid

Preprint

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To be presented at the 2012 World Renewable Energy Forum
Denver, Colorado
May 13–17, 2012

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-7A30-54719
April 2012

Contract No. DE-AC36-08GO28308

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Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

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WREF 2012: DESIGN AND PERFORMANCE OF SOLAR DECATHLON 2011 HIGH-PENETRATION MICROGRID

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ABSTRACT

The U.S. Department of Energy Solar Decathlon challenges collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive. The Solar Decathlon 2011 was held in Washington, D.C., from September 23 to October 2, 2011[1]. A high-penetration microgrid was designed, installed, and operated for the Solar Decathlon 2011 to grid-connect 19 highly energy-efficient, solar-powered competition houses to a single utility connection point. The capacity penetration of this microgrid (defined as maximum PV generation divided by maximum system load over a two-week period) was 74% based on 1-minute averaged data.

Temporary, ground-laid conductors and electrical distribution equipment were installed to grid-connect the Solar Decathlon village, which included the houses as well as other electrical loads used by the event organizers. While 16 of the houses were connected to the 60 Hz microgrid, three houses from Belgium, China, and New Zealand were supplied with 50 Hz power. The design of the microgrid, including the connection of the houses powered by 50 Hz and a standby diesel generator, is discussed in this paper.

In addition to the utility-supplied net energy meters at each house, a microgrid monitoring system was installed to measure and record energy consumption and PV energy production at 1-second intervals at each house. Bidirectional electronic voltage regulators were installed for groups of competition houses, which held the service voltage at each house to acceptable levels.

The design and successful performance of this high-penetration microgrid is presented from the house, microgrid operator, and utility perspectives.

1. SOLAR DECATHLON 2011 EVENT

1.1 Event Description

The U.S. Department of Energy Solar Decathlon challenges collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive. The Solar Decathlon 2011 was held in Washington, D.C., from September 23 to October 2, 2011.

Solar Decathlon 2011 consisted of 10 contests. Many of the contests required the consumption of energy for control of indoor temperature and relative humidity, as well as for typical household appliance activities. Contest 10, Energy Balance, enabled teams to earn 100 points if their houses produced as much as or more energy than they consumed over the 9-day competition period.

The Solar Decathlon 2011 was held in the National Park Service's West Potomac Park in Washington, D.C., east of the Franklin Delano Roosevelt Memorial. The weather varied from sunny to rainy during the event.

1.2 Event-Specific Rules

Teams were required to design a house to the 2009 International Residential Code (IRC) of the International Code Council with amendments, the 2009 International Energy Conservation Code, and the 2008 National Electric Code (NEC) of the National Fire Protection Agency (NFPA).

Having a photovoltaic (PV) system was not a competition requirement, but necessary if a team wanted to score points in the Energy Balance contest. The size and orientation of the PV system was determined by each team, and was often based on the location and orientation of each house as well as other architectural factors.

Solar Decathlon 2011 included teams from Belgium, China, and New Zealand, where the standard residential service is 230 V_{ac} at 50 Hz. These teams were provided with 50 Hz power from a dedicated 40 kW voltage/frequency converter for house energy consumption. These teams were required to export all PV production at 60 Hz because the voltage/frequency converters were unable to accept reverse-fed power. Many inverter manufacturers sell both 50 and 60 Hz models, so this was not considered a significant concern for these teams.

New for Solar Decathlon 2011 was an Affordability Contest, for which a professional cost estimator assigned an estimated construction cost to each project. All 100 available points were earned for achieving a target construction cost of $250,000 or less. Reduced points were earned for a construction cost between $250,000 and $600,000, and no points were awarded for a construction cost above $600,000. The Affordability Contest, therefore, required teams to balance PV system costs with their estimated energy production.

1.3 Summary of PV Systems

The total installed capacity of PV systems in the Solar Decathlon 2011 village was 145.2 kW_{dc}. PV system sizes ranged between 10.9 kW_{dc} and 4.03 kW_{dc}. The size and orientation of the PV systems were determined by each team. The tilt of the PV systems ranged from 0 degrees (flat) to 40 degrees, all with an azimuth of approximately 180 degrees (facing true south). The houses were connected to five different microgrid electrical panel boards, labeled A, B, C1, D and E.

TABLE 1: LIST OF PV SYSTEM SIZES

Team	PV System (kW_{dc})	Electrical Panel
Tidewater Virginia (Old Dominion University and Hampton University)	4.03	A
New Zealand (Victoria University of Wellington)	6.30	A
Team Florida (The University of South Florida, Florida State University, the University of Central Florida, and the University of Florida)	5.06	B
Middlebury College	6.75	B
Appalachian State University	8.20	B
Team New Jersey (Rutgers – The State University of New Jersey and New Jersey Institute of Technology)	8.40	B
Purdue University	8.64	B
Parsons The New School for Design and Stevens Institute of Technology	4.16	C1
University of Illinois at Urbana-Champaign	6.69	C1
Team Canada (University of Calgary)	8.70	C1
Team China (Tongji University)	8.80	C1
Florida International University	8.96	C1
The University of Tennessee	10.90	C1
Team Massachusetts (Massachusetts College of Art and Design and University of Massachusetts at Lowell)	6.72	D
Team Belgium (Ghent University)	7.74	D
University of Maryland	9.24	D
Team New York (The City College of New York)	9.52	D
The Southern California Institute of Architecture and California Institute of Technology	7.98	E
The Ohio State University	8.37	E
Total PV Capacity	**145.20**	

2. MICROGRID DESIGN

2.1 Design Constraints

The Solar Decathlon 2011 rules stated that the competition houses would be supplied with fused 150 A, 120/240 V, single-phase, three-wire service. Teams from countries with 50 Hz utility power could choose to receive 150 A, 230 V, single-phase, two-wire service at 50 Hz. Teams were required to complete service/feeder net computed load and neutral load calculations (NEC Article 220). The net computed loads were in the range of 90 A to 120 A. All teams were required to install 2/0 AWG copper conductors, or equivalent, to minimize the voltage drop in the service laterals and to meet the load requirements.

The microgrid had to be easy to install and remove, because there were a limited number of days to set up and take down the temporary system. As overhead power lines and trenching were prohibited by the National Park Service (NPS), all cabling was ground-laid DLO. In addition, because Solar Decathlon organizers, who acted in the role of the electric utility to the teams, and were bound to the NEC in the microgrid design, all cabling and protective devices were designed or selected according to the 2008 NEC. From a house perspective, the microgrid interconnection was similar to a U.S. residential utility interconnection.

2.2 Utility Connection

The local electrical utility company, Pepco, provided a temporary service connection at the 277/480 V level for the event. The service connection came from the secondary side of a 13.8 kV/480 V, 500 kVA transformer that provides power to the Franklin Delano Roosevelt Memorial. Pepco disabled the network protector for this transformer to permit reverse power flow to its secondary network distribution system. Because the transformer supplies power to the Franklin Delano Roosevelt Memorial, which has a significant electrical load for water pumps, little power, if any, was exported further into Pepco's network.

2.3 Electrical Loads

In addition to the estimated loads of the competition houses of approximately 24 kW per house, the event organizers also had electrical loads. The largest loads were typical construction-office trailers with standard heaters and air conditioners. These trailers were supplied with 120/208 V, single-phase power, which is typical for trailer panels. Predicting the electrical loads in advance was difficult, as the weather during the event would be unknown. Also, the trailers were rental equipment so advance electrical load measurements were impractical. The locations of all of the trailers were not known until about a month before the event, so the electrical panel boards were designed and installed with additional circuit breaker positions to meet unknown load requirements. One of the trailers housed the information technology (IT) servers for the local area network and the Internet service. As power availability to the IT trailer was mission critical, a separate standby engine generator with a manual transfer switch was installed to limit any electrical outage to less than 15 minutes. All critical equipment in the IT trailer had at least 15 minutes of uninterruptable power supply runtime. If needed, larger electrical loads, such as space heating or cooling of the main tent during special events, would have been supplied by dedicated diesel engine generators.

2.4 PV Production

The previous Solar Decathlon event, held in 2009, was also grid connected. However, only net energy was recorded (consumption minus production). The PV production for the 2011 event was estimated from the dc ratings of the total installed PV modules. A typical derating factor from dc to ac production used by PVWATTS[2] is 0.77, which includes inverter losses, wiring losses, soiling, and other losses. The typical losses in a Solar Decathlon house would be reduced because the PV modules were constantly being cleaned, very high efficiency inverters were used, and the wiring might have been upsized to reduce wiring losses. For design purposes, a 10 kW_{dc}, or 7.7 kW_{ac}, PV array was assumed for each competition house.

Table 1 lists the actual PV system sizes for each Solar Decathlon 2011competition house. Some of the houses had multiple PV systems with different tilts and azimuths. The aggregate PV system size is shown for each competition house. Also shown in Table 1 is the electrical panel board that powered each competition house.

2.5 Microgrid Design and Layout

Schneider Electric provided fault and load flow studies, a one-line electrical schematic, and layouts of the microgrid and the electrical panel boards. Figure 1 shows a simplified block diagram of the main panel boards, but does not include details about the size of the loads or the number of competition houses for a particular panel board. Figure 2 is a layout of the Solar Decathlon 2011 event with the competition houses and the event organizers' equipment.

For this event, Pepco provided 277/480 V, three-phase power. The voltage was then stepped down to 120/208V, three phase by the organizers. In a more conventional, permanent microgrid, the electric utility might provide medium voltage (4kV-25kV) to transformers serving groups of main panel boards. Because the distribution was low voltage, many of the long power runs were two or three parallel sets of 4/0 DLO copper conductors per phase to reduce voltage losses.

For backup power to the event, Solar Decathlon organizers rented a diesel isochronous generator. The generator output was connected into the main panel C. Organizers selected a key interlock system to prevent connection of the generator when connected to the utility. The key needed to close the generator circuit breaker could only be released from the utility main circuit breaker when the breaker was opened.

Bidirectional electronic voltage regulators from MicroPlanet (model 103037, 120/240 V, 400 A) were selected to provide full four-quadrant voltage regulation of 60 Hz power to the competition houses, which were assembled in groups of two to four. The voltage to all of the competition houses was regulated because over or under voltage to one house resulting in PV inverter or HVAC equipment controls shut down would result in an unfair competition. Trying to determine the scoring impact from a "utility" power quality problem was difficult because many of the contests were interrelated. Solar Decathlon organizers did not experience any detrimental interaction between the PV systems and the voltage regulators.

The main reason for the voltage regulators is the low voltage distribution of the microgrid. The impedance of the network resulted in unacceptably wide variations in voltage. Furthermore, local loading (such as organizer loads) could adversely affect some of the houses and not others.

M.C. Dean, the event's electrical contractor, installed and operated the microgrid. To facilitate installation of the microgrid on the competition site in the allotted amount of time, M.C. Dean prefabricated all of the electrical equipment associated with each panel board into a climate controlled shipping container or on an open-framed skid. All of the cabling was 50-ft lengths of 4/0 copper DLO cabling with waterproof quick connects. Some of the power runs were over 500 ft, resulting in at least 10 50-ft sections connected together for each phase.

In addition to designing the microgrid, Schneider Electric also provided a comprehensive monitoring system for the event. Power Logic PM870 meters were used at all of the panel boards as well as at the competition houses. A PM820 meter was installed at Panel C (the Solar Decathlon 2011 service entrance and utility point of connection). Two PM870 meters were used at each competition house. One meter measured PV production. The second meter measured net energy for 60 Hz houses and consumption for 50 Hz houses. A Schneider Electric ION Enterprise server connected all of the meters through a hardwired local area network (LAN).

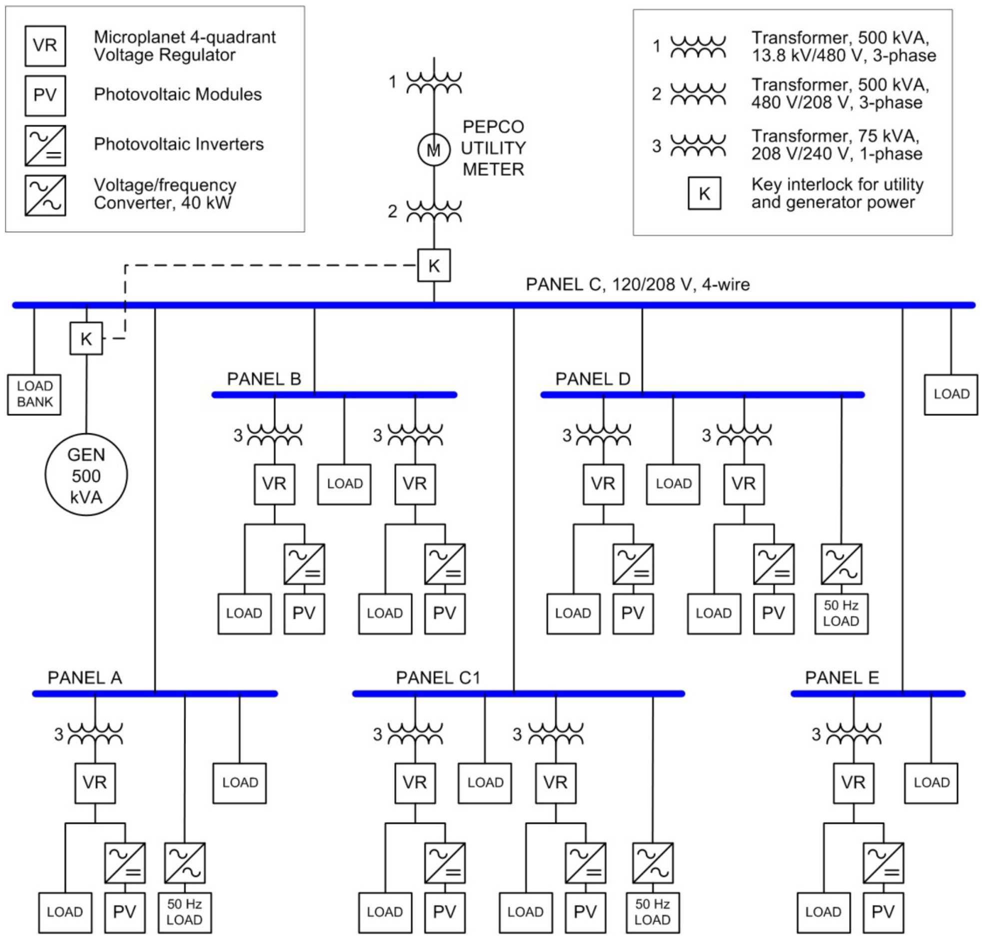

Fig. 1: Solar Decathlon 2011 Simplified Microgrid Electrical Diagram

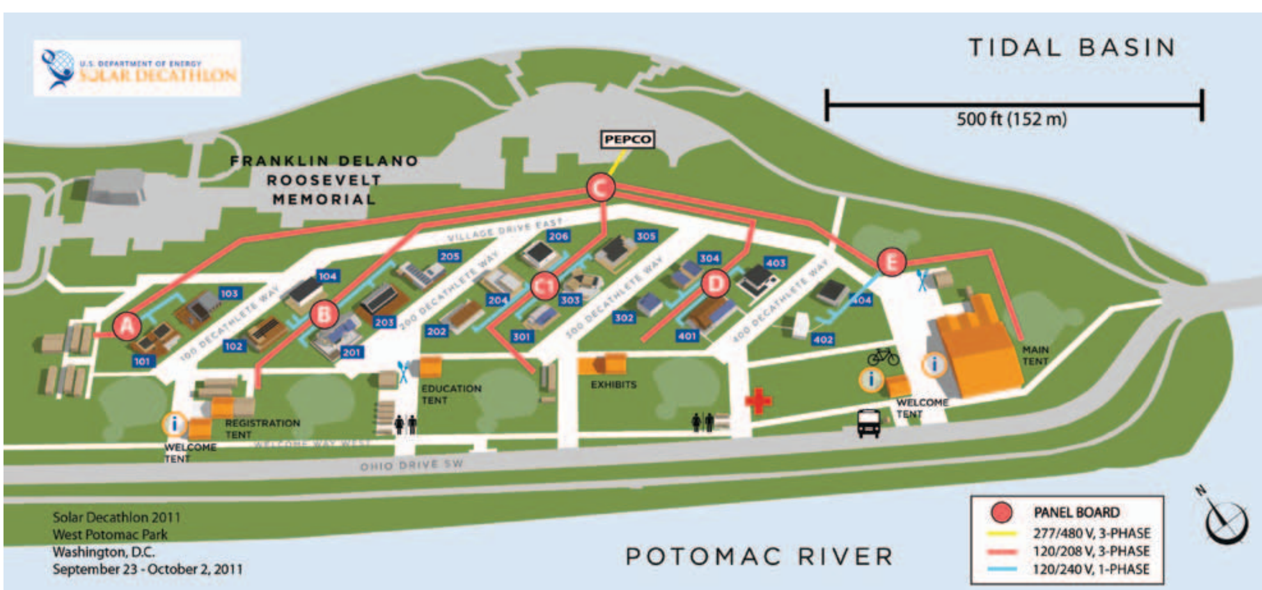

Fig. 2: Solar Decathlon 2011 Microgrid Electrical Layout

3. MICROGRID OPERATION

3.1 Power Quality

Power quality, especially voltage control, was important to keep the competition houses operating so that the teams could compete in contests that required energy. The ION Enterprise server provided real-time and historical data on the microgrid performance. Operation of event organizer electrical loads and other competition houses had no effect on the operation of an individual competition house. The electronic voltage regulators kept the voltage at each competition house at 120/240 V, ± 0.5 V.

3.2 Power

The power flow in both directions was monitored and recorded at the competition houses and the microgrid panel boards. Initially, averaged data were recorded at 1-hour intervals. The impact of the data transfer requirements on the Solar Decathlon LAN was monitored. At different times, the measurement interval of averaged values was reduced to 15 minutes, then 5 minutes and finally 1 minute. When it became obvious that the Solar Decathlon LAN could handle significantly more data traffic, a separate data sampling of voltage, current, power, and frequency was made at the 1-second interval at the competition houses and the main panel boards.

The instantaneous peak load at the utility service entrance was 187 kW on September 25, and the 1-minute averaged peak load was 167 kW. The loads on the three-phase system were unbalanced, resulting in different phase voltages at utilization points. The instantaneous peak export from the Solar Decathlon 2011 service entrance was 87 kW on September 29. On September 28, the 1-minute averaged peak PV production was 124 kW and on September 30, the 1-minute averaged peak export was 58 kW. The capacity penetration of the microgrid (defined as maximum PV generation divided by maximum system load) over a two-week period was 74% based on 1-minute averaged data.

Figure 3 shows the power at the main panel board C. On several days, power was exported back to the utility.

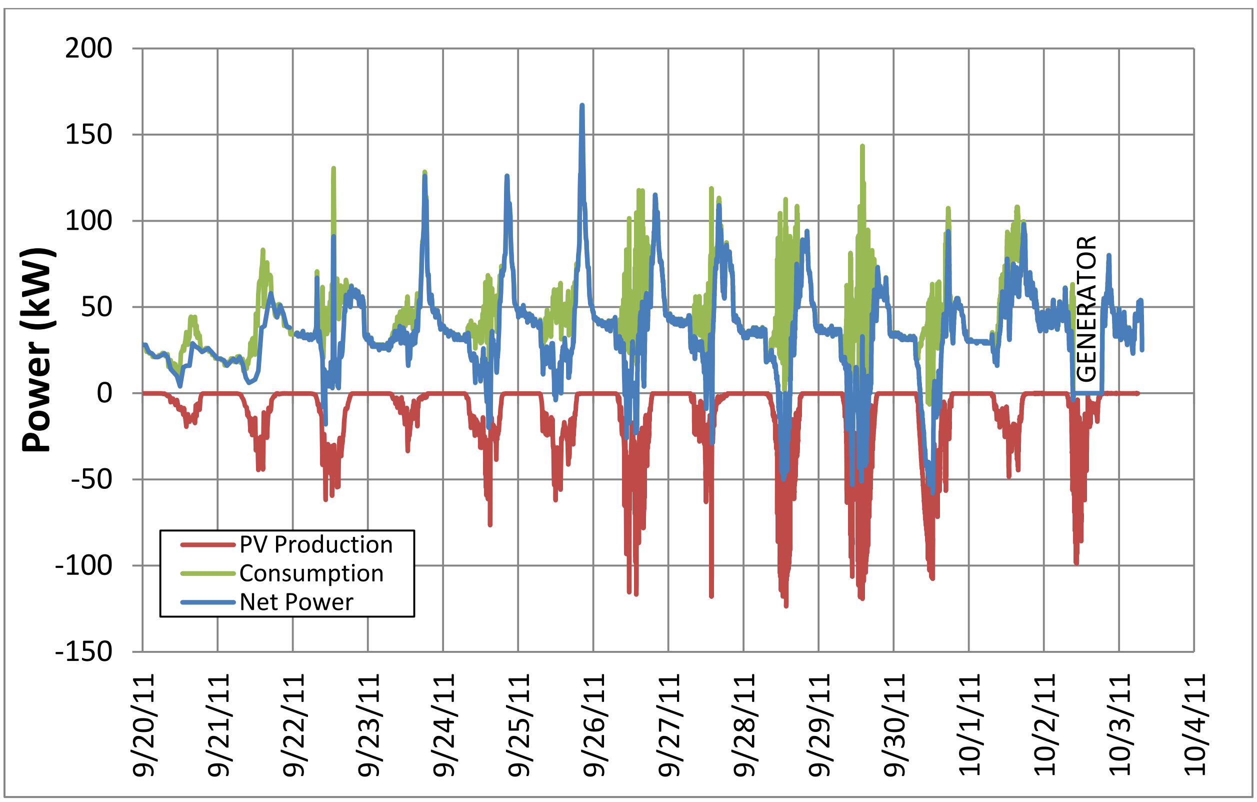

Fig. 3: Solar Decathlon 2011 Total Consumption, PV Production, and Net Power

3.3 Generator Usage

Although reliable electric service was expected from Pepco, a backup generator was installed to help ensure that the Solar Decathlon event could be held without electric utility service. The generator was not needed for any emergency during the 2011 event; however, experience operating the Solar Decathlon event from a generator was desired. So, after the contest period, on the last day of the public exhibit (October 2, 2011), the generator was turned on and allowed to supply power to the Solar Decathlon Village for evaluation purposes.

Prior to connecting the generator, the utility power was disconnected. At 9:32 a.m. on October 2, there was PV production from the competition houses, the office trailer HVAC loads were turned off, and the main electrical load bank was adjusted so that approximately 1 kW of power was being exported to the utility. With the PV generation and loads within the microgrid approximately equal, the utility power was disconnected to observe the voltage decay at the main panel board. Figure 4 shows the voltage decay when the utility power was disconnected. After 20 cycles, the three-phase voltages decayed to zero volts. The PV inverters were required to disconnect within six cycles of voltage loss. Possible reasons for the long decay time include islanding of some PV inverters, phase imbalance, and the impedance and capacitance of the microgrid.

As seen in Figure 3, October 2 was a partly sunny day and there was significant PV production that approached 100 kW at times. Although there were electrical loads at the competition houses and the event organizers' equipment, the resistive load bank was operated at 90 kW most of the time to prevent power feeding back to the generator (which would be detrimental to the generator). As the day was also partly cloudy and there was no automatic demand control (and only manual control on trailer loads), the load bank had to remain on for most of the time while the generator was operating.

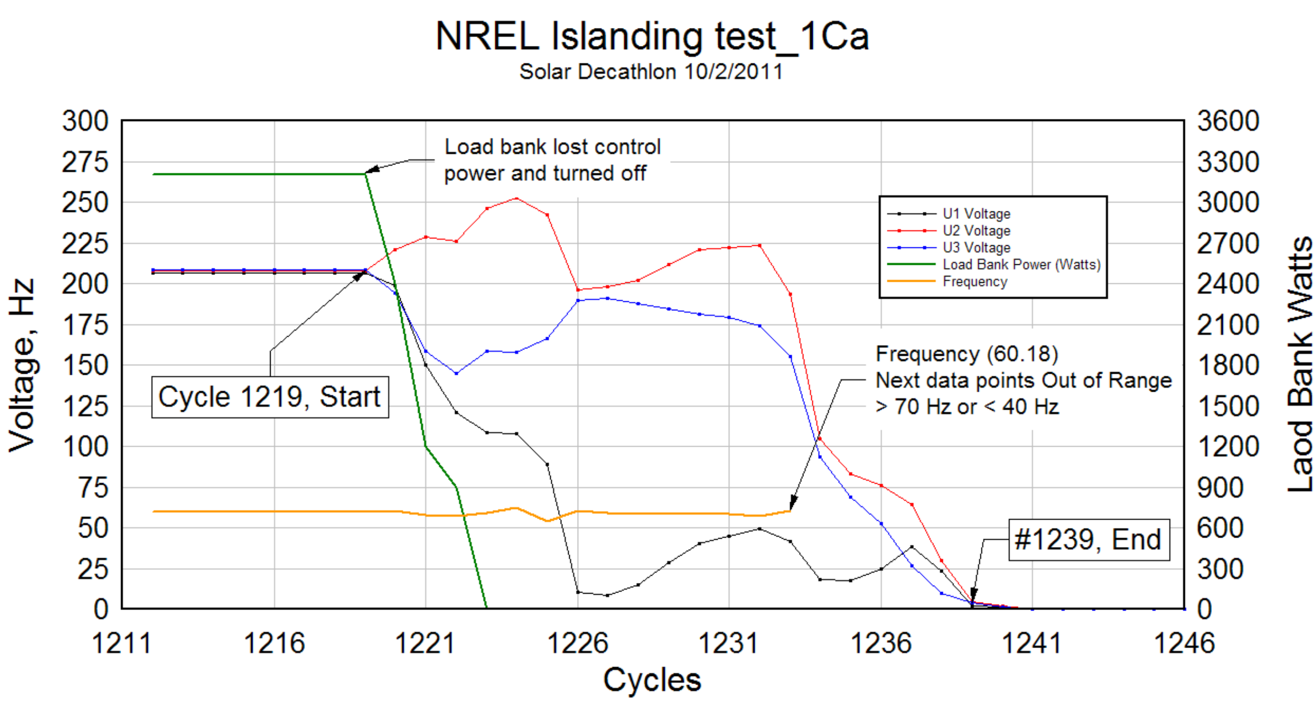

Fig. 4: Voltage and Frequency Decay During Islanding Test With Intentional Loss of Utility Power

4. SUMMARY

The Solar Decathlon 2011 microgrid operated extremely well over the duration of the event, with no power quality or reliability problems. The use of the electronic voltage regulators was key to maintaining voltage control at the competition houses because of the event's unique constraints. The conservative design of the temporary microgrid allowed for last-minute or unknown event organizers' loads to be added. Performance monitoring at multiple points was crucial for assurance that the utility service met expectations and there was minimal disruption to the competition. Preconstruction of the panel board containers and skids, along with excellent electrical project management, resulted in the installation and removal of the temporary microgrid within days. At a future Solar Decathlon event the use of an energy storage system instead of an electrical load bank would be desirable to utilize PV production when operating from an engine generator. While the Solar Decathlon microgrid was unique in many aspects, it demonstrated that it is possible to have a high-penetration of PV systems within a microgrid or subdivision with acceptable performance and power quality for both the utility and the customers.

5. ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

The primary author would like to thank Richard King, the founder and director of the U.S. Department of Energy Solar Decathlon, for his continual project and team support. The authors wish to thank their respective companies and organizations for their generous support of the Solar Decathlon and in particular their support related to designing, installing, and operating a high-performance microgrid.

[1] The U.S. Department of Energy Solar Decathlon 2013 will take place Oct. 3–13, 2013, at Orange County Great Park in Irvine, California. For more information, visit www.solardecathlon.gov.

[2] PVWATTS, a calculator to determine the energy production and cost savings of grid-connected photovoltaic (PV) energy systems, www.nrel.gov/rredc/pvwatts, accessed March 17, 2012.