Design, Operation, and Controlled-Island Operation of the U.S. Department of Energy Solar Decathlon 2013 Microgrid

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Technical Report
NREL/TP-7A40-62997
April 2015

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NATIONAL RENEWABLE ENERGY LABORATORY

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Executive Summary

This document reports on the design and operation of a high-capacity and high-penetration-ratio microgrid, which consists of 19 photovoltaic-powered residential houses designed by collegiate teams as part of their participation in the U.S. Department of Energy Solar Decathlon 2013. The microgrid was interconnected with the local utility, and resulting net-power and power-quality events were recorded in high detail (1-minute data sampling or better). Also, a controlled-island operation test was conducted to evaluate the microgrid response to additional events such as increased loads (e.g., from electric vehicles) and bypassing of voltage regulators. This temporary ground-laid microgrid was stable under nominal and island-operation conditions; adverse weather and loads did not lead to power-quality degradation.

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Introduction

The U.S. Department of Energy (DOE) Solar Decathlon challenges collegiate teams to design, build, and operate solar photovoltaic (PV) houses that are cost-effective, energy-efficient, and attractive. Solar Decathlon 2013 was held at the Orange County Great Park (OCGP) in Irvine, California, October 3 – 13, 2013. The competition included ten contests and a public exhibit of the houses. Of the ten contests, five were juried (Architecture, Market Appeal, Engineering, Communications, and Affordability) and five were measured (Comfort Zone, Hot Water, Appliances, Home Entertainment, and Energy Balance). The Energy Balance contest enabled teams to earn 100 points if their houses produced as much as—or more energy—than they consumed over the nine-day competition period.

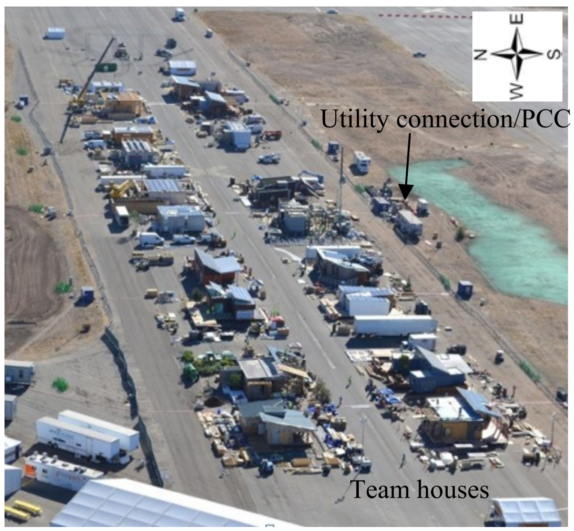

Figure 1. Aerial photo of the Solar Decathlon 2013 village.
Photo by Amy Vaughn, NREL

A high-penetration microgrid was designed, installed, and operated by the Solar Decathlon 2013 organizers to operate 19 PV-powered collegiate houses as well as the supporting infrastructure (see Fig. 1). As a temporary ground-laid installation, this microgrid presented technical challenges such as long low-voltage cable runs—up to 650 ft to some houses. (This arrangement is similar to European low-voltage networks but runs at half the voltage and twice the current.) A low-voltage microgrid with circuit lengths greater than 500 ft – 600 ft needs special consideration for voltage regulation. The parameters that determine voltage regulation requirements for typical systems are maximum and minimum load. The parameters that determine voltage-regulation requirements for a microgrid are maximum load and maximum generation. The Solar Decathlon 2013 village presented both of these scenarios, which complicated the microgrid design process. One or a combination of the following options was needed:

- Massively paralleled conductors
- Voltage regulators
- Higher low-voltage distribution
- Medium voltage distribution.

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Technical tradeoffs and costs needed to be optimized for a particular application. For Solar Decathlon 2013, a combination of the first three options was chosen.

The resulting microgrid had a 100% customer PV penetration ratio (meaning every house had a PV system installed), a 28% capacity penetration ratio (defined as PV generation as a fraction of total capacity of the interconnection), and a 105% load penetration ratio (defined as peak PV generation with respect to peak load). It is important to define all three of these ratios as each describes a unique aspect of power flow for the Solar Decathlon 2013 microgrid.

Seventeen of the houses were supplied with 60-Hz alternating current (AC) power and two of the houses (designed by European universities) were supplied with 50-Hz AC power through frequency converters. In addition to the utility-supplied meters, a comprehensive monitoring system for the event was provided by Schneider Electric to log data for approximately 72 power attributes for each house and for 5 subpanels at 1-min intervals.

After the Solar Decathlon 2013 competition, a controlled-island test was conducted during the final public exhibit day (Day 11 in the following figures) to evaluate the microgrid response in an islanded condition by creating additional load (stress) to the microgrid as well as to determine the effectiveness of voltage regulators.

Microgrid Design

A oneline diagram of the Solar Decathlon 2013 microgrid is shown in Fig. 2. This microgrid was constructed within 4 days. Design priorities were safety for students and the public as well as reliability for the student competition.

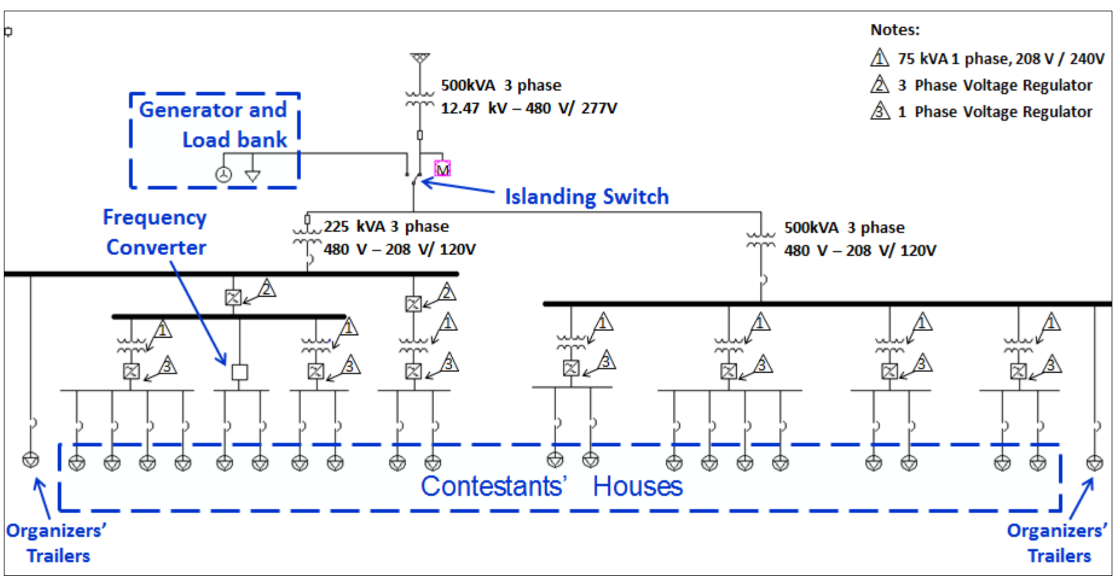

Figure 2. One-line diagram of the Solar Decathlon 2013 microgrid.

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Utility Connection

The local electric utility company, Southern California Edison, provided a 12-kV connection to OCGP and, subsequently, OCGP provided a 277/480-V, 3-phase connection for Solar Decathlon organizers. The organizers stepped-down the voltage to a 120/208 V, 3-phase connection for village distribution, and further transformed the voltage into 120/240 V, 1-phase, for house interconnection. For backup power to the event, a 500-kVA, 480-V diesel isochronous generator was used along with a 100-kW load bank.

The generator output was connected to a manual transfer switch (MTS), which supplied both the north and south parts of the site (teams and organizer loads). The MTS prevented connection of the generator to the utility (open transition). A momentary OFF position was provided at the transfer switch for this purpose. The generator and load bank were only used during the day of controlled-island operation.

PV Production

The total installed nameplate capacity of PV systems in the Solar Decathlon 2013 village was 140 kW_{dc}. PV system sizes varied between 4 kW_{dc} and 10 kW_{dc}, as shown in Table 1. The tilt of the PV systems ranged from 0 degrees (flat) to 40 degrees. The size and orientation of the PV systems were determined by each team and were often based on the location and orientation of each house as well as other architectural factors.

All houses were facing exactly due south (as shown in Fig. 1). This is different from a typical residential neighborhood where the orientation and architectural style of individual houses normally result in some “disorientation” of residential PV arrays. Additionally, because of the compact layout of the Solar Decathlon 2013 village, there was no time delay between PV power generation onset of all houses (i.e., inverters started producing power at exactly the same time). Again, this is different from a typical residential neighborhood where the spatially distributed nature of PV installations leads to smooth PV power generation onset. Such a situation describes an extreme case of 100% customer penetration ratio coupled with 100% coincidence factor of PV generation. A goal of this investigation was to determine if this was an issue with the operation of the microgrid.

Table 1. Participants’ PV Systems Sizes

Team/University	PV System Rating (kW)
Missouri S&T	10.5
AZ State/New Mexico	9.0
North Carolina	9.0
Team Alberta	8.6
West Virginia	8.5
Team Texas	8.1
Team Austria (1st place)	8.0

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Team Capitol DC	7.8
Santa Clara	7.1
Team Ontario	7.0
Stanford	7.0
Kentucky/Indiana	7.0
U of So Cal	6.8
Las Vegas (3rd place)	6.7
Stevens	6.3
Middlebury College	6.0
Norwich	6.0
SCI-Arc/Caltech	5.3
Czech Republic (2nd place)	5.0
Total	140

Electrical Loads

Electrical loads of the village microgrid consisted of residential household loads of each of the collegiate houses as well as additional loads of the event organizers' office trailers. The loads on the 3-phase system were unbalanced, resulting in different phase voltages at utilization points.

The contests required energy consumption to control indoor temperature and relative humidity as well as typical household appliance activities. For these purposes, the majority of loads in the houses were typical, commercially available energy-efficient appliances and loads. However, the time of day these appliances were used was not typical due to the timing of the contests and needing to perform energy-intensive tasks (such as washing and drying a load of laundry) at a time interval prescribed by Solar Decathlon organizers. Such operation is counter-intuitive to performing energy-intensive tasks at times when, for example, electricity tariffs may be lowest, typically later at night. During Solar Decathlon 2013, competition teams were not judged on peak load or other load characteristics. Incorporating some version of load management, load curtailment, or demand-response strategies for teams may be an interesting possibility as one of the contests for future Solar Decathlon competitions.

Data Management System

In addition to designing the microgrid, Schneider Electric provided a comprehensive monitoring system for the event. Two PM870 meters were used at each house. One meter measured PV production. The second meter measured net energy for 60-Hz houses and consumption for 50-Hz houses. The meters recorded values (described below) and sent them through the site's ethernet network to the centralized StruxureWare Power Monitoring server on site. Values were logged to a SQL database to be queried and analyzed at any time. StruxureWare Power Monitoring software is a complete, interoperable, and scalable supervisory interface dedicated to power monitoring.

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As mentioned earlier, 72 power attributes for each house and for 5 subpanels were recorded at 1-min intervals or better. Recorded power attributes included:

- Apparent Energy
- Reactive Energy Into the Load
- Reactive Energy Out of the Load
- Reactive Energy Absolute
- Real Energy Into the Load
- Real Energy Out of the Load
- Real Energy Absolute
- Apparent Power Total
- Real Power Total, Reactive Power Total
- Real Power A, Real Power B
- Reactive Power A, Reactive Power B
- Apparent Power A, Apparent Power B
- Frequency
- Line Voltages, Line Currents
- Line Voltages THD, Line Currents THD
- Power Factor Total, Power Factor A, Power Factor B
- Displacement Power Factor Total
- Displacement Power Factor A, Displacement Power Factor B.

Voltage Regulators

Bidirectional electronic voltage regulators (VRs), supplied by MicroPlanet, provided 4-quadrant voltage regulation of 60-Hz power. The VRs were needed because of an anticipated voltage drop during power import (load greater than PV power) or voltage rise during power export (PV power greater than load). If unregulated, the impedance of the network would have resulted in unacceptably wide variations in voltage. Furthermore, local loading (such as organizer loads) could adversely affect some of the houses and not others, resulting in unequal competition conditions.

Voltage regulators were incorporated into the microgrid as shown in Fig. 2 and they served two purposes. First, 3-phase models were installed on the north backbone to counter voltage drop along the "North-South Backbone Connection." Next, single-phase models were selected to provide full, 4-quadrant voltage regulation of 60-Hz power to the competition houses, which were assembled in groups of two to four, as shown in Fig. 2. Voltage to all houses needed to be regulated because over or under voltage to one house (resulting from PV inverter or HVAC equipment controls shut down) may have resulted in unfair competition conditions for other houses.

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Frequency Converters

Solar Decathlon 2013 included two teams from Europe (Czech Republic and Austria), where the standard residential service is 230 V_{ac} at 50 Hz. These teams were provided with 50-Hz power from a dedicated 30-kVA voltage/frequency converter for house energy consumption. These teams were required to export all PV production at 60 Hz because no 4-quadrant frequency converters were currently available or feasible. Many inverter manufacturers provide both 50- and 60-Hz models so this was not considered a significant concern for these teams, but this presents an interesting academic and engineering challenge. Both 50-Hz power and 60-Hz PV power were monitored at the houses of the European teams.

Microgrid Operation Results

Power Flow

Power flow was monitored and recorded in both directions at the competition houses, distribution panel boards, and microgrid point of common coupling (PCC). During the operating period, the power flows are shown in Fig 3. Peak power imported to the Solar Decathlon 2013 village was 98 kW on Day 3 (black) while peak power exported from the village was 77 kW on Day 8 (green). The shape and amplitude of the power swings are clearly identifiable as a “duck curve” [2]. (Teams’ PV systems did not produce power close to the maximum installed capacity values because the competition was held in October; peak exported power would have been higher if the competition had been held during summertime.) The red curve is gross inverter output for all the houses.

Furthermore, 100% customer penetration ratio coupled with the 100% coincidence factor of PV generation shows that additional abrupt spikes in power consumption can be observed in the mornings, just before PV inverters start producing power, or in the evenings, just as PV inverters shut down. These can be seen as small spikes in net village power, shown in black in Fig. 3. High PV penetration localities are reporting similar trends in power and load flow [3,4]. Therefore, energy use coincidence factor (in time) is important for microgrid planners to consider.

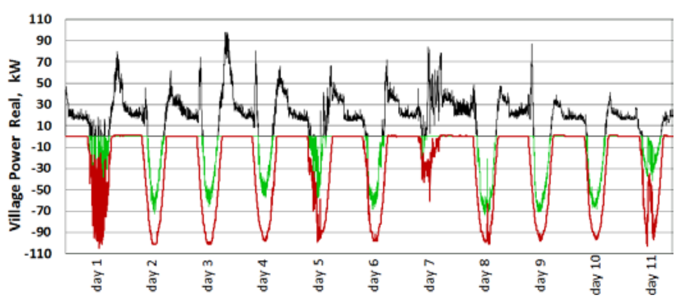

Figure 3. Real power of the Solar Decathlon 2013 village.

Legend: Red – PV power production, green – power exported by the village, black – power imported to the village.

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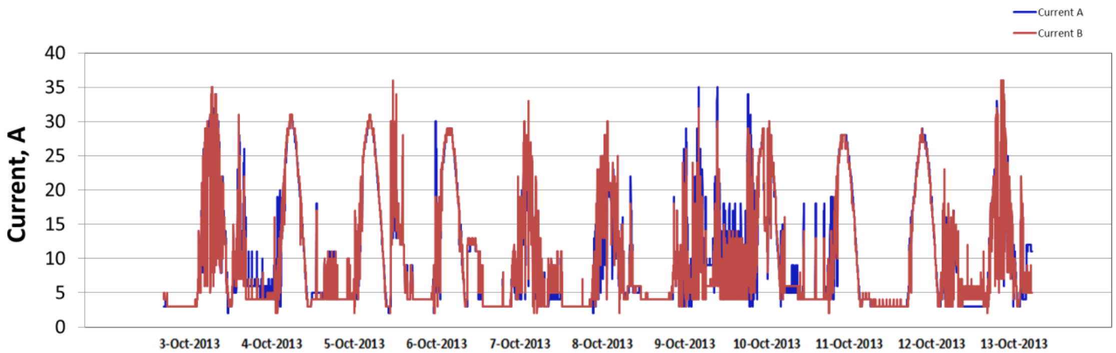

Figure 4. Line currents factor for one of the houses at Solar Decathlon 2013.

Fig.4 shows daily current for all days for one of the houses. These profiles are important to observe as utilities prepare for more and more distributed residential PV systems. Currents produced by residential PV systems may strongly dominate peak current – which may be particularly true for energy efficient housing, where energy consumption may be low.

Both the "duck curve" from Figure 3 and cloud-induced power intermittencies can be characterized by calculating power ramp rates in kW/min. Single-sided power ramp rates (ramp-up or ramp-down) at the PCC for all days of Solar Decathlon village operation are shown in Fig. 5; the inset shows the cumulative density function (CDF) for this distribution. The histogram shows that a majority of the power ramp rates are less than 10 kW/min, and the CDF function shows that 50% of the ramp rates are less than 5 kW/min. These values are typical for high penetration residential PV installations [5]. Power ramps of this order of magnitude can be easily mitigated and smoothed by incorporating co-located residential, community-scale, or utility-scale storage [6,7,8,9]. Several teams used thermal storage in their Solar Decathlon 2013 house designs and this smoothed their load profiles. Incorporating electrical storage (batteries) may be an interesting addition to future Solar Decathlon contests.

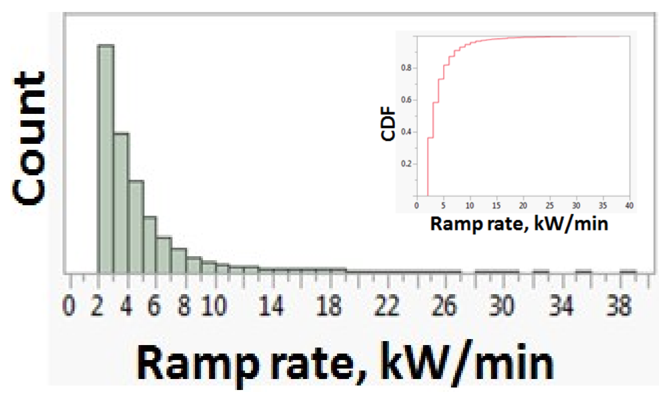

Figure 5. Number of occurrences of real power ramp rates for all days of Solar Decathlon 2013.
Inset: CDF of ramp rates.

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Power Quality

As a temporary distribution network, the Solar Decathlon village was not required to comply with ANSI C84.1 or other stringent power-quality requirements. To guarantee fair competition conditions, Solar Decathlon 2013 organizers agreed to provide collegiate teams with service-level voltages within ±5% of the nominal voltage (Table 2, Range A). For up to two hours each day, the service voltage was allowed to be as high as +8% above, or as low as -10% below, nominal voltage (Table 2, Range B).

Voltage levels and other power-quality attributes were monitored continuously.

Table 2. Typical Team Service Voltages for 120-V Service.

	Service Voltage Range A	Service Voltage Range B
High	126	129.6
Nominal	120	120
Low	114	108

Fig. 6 shows line voltages for all collegiate houses except the two European teams; different colors correspond to different houses. Slight voltage swells were observed daily when inverters were generating. However, all voltages stayed within the Solar Decathlon allowed ranges for all days—even during the last day of the controlled-island test.

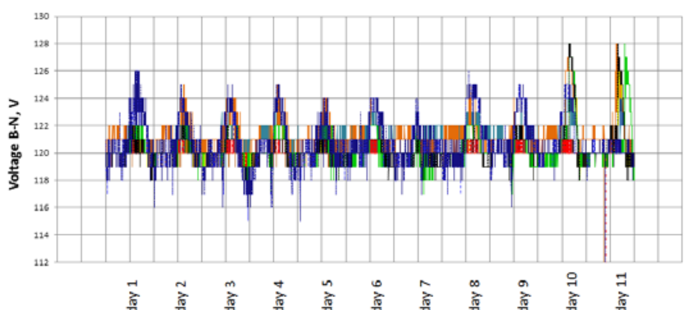

Figure 6. Line voltages for collegiate houses during Solar Decathlon 2013 competition days.

Beyond verifying that utility-service voltages were within acceptable ranges, Solar Decathlon organizers wanted to evaluate all other power-quality features for each of the contestants' houses to see if a collection of all energy efficient and (in some teams' cases) novel loads would produce high-harmonic currents, which, in turn, would create high-harmonic voltage distortion for the whole village. This can be of significant concern for utilities facing clustering of high-end residential housing with high percentages of energy-efficient loads.

Total harmonic distortion (THD) for line voltages is shown in Fig. 8. With harmonic voltage distortion between 3% and 4%, there were no unusual levels of harmonic current generated by the homes during either daytime (when PV inverters were generating) or nighttime (when teams' house loads may have been on), or even during the last day when electric vehicles (EVs) were plugged in.

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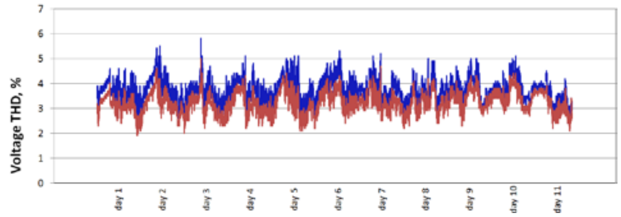

Figure 8. Line voltage THD for one of the houses at Solar Decathlon 2013.

The next section shows that additional heavy load from EVs did not introduce further PF or harmonic-composition problems.

Controlled-Island Operation and Results

The first time a U.S. Department of Energy Solar Decathlon microgrid was operated in islanded mode was during Solar Decathlon 2011, after the competition ended [1].

The Solar Decathlon microgrid was operated in islanded mode again after the competition ended at Solar Decathlon 2013. Goals of the controlled-island test in 2013 were to:

1. Evaluate the microgrid operation in an islanded condition
2. Further evaluate microgrid stability by creating additional loads (stress) to the microgrid
3. Evaluate performance of the VRs operating with high-PV penetration.

In this case, additional loads were provided by plugging in Level-1 and Level-2 EVs at corresponding teams' plug load outlets or dedicated NEMA 14-50 outlets. Six EVs were charged simultaneously throughout the day to observe microgrid stability during the test—with and without EVs. This represented a 31% household EV ownership ratio. Table 3 describes the procedure for the controlled-island operation and the tests conducted.

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Table 3. Controlled-Island Operation Timeline.

Time	Event(s)	Goals or purposes
6:00 a.m. – 6:30 a.m.	All EVs plugged in	Baseline test while still connected to the grid.
7:00 a.m.	Transfer to generator	Islanded operation.
7:00 a.m. – 8:00 a.m.		Observe microgrid for stability; record all data as needed.
8:00 a.m. – 10:30 a.m.	All EVs plugged in	Before PV generation is significant, observe microgrid for voltage and frequency instabilities due to islanded operation with additional loads (EVs). As power export begins, observe microgrid for voltage and frequency instabilities due to interplay between inverters, EV loads, and islanded operation.
10:30 a.m.– 1:30 p.m.	All EVs unplugged	Observe microgrid in islanded mode during intermittent cloud conditions.
1:30 p.m. – 2:00 p.m.	Systematically bypass all VRs	Observe microgrid in islanded mode as VRs are bypassed, one by one.
2:00 p.m. – 6:30 p.m.	All EVs plugged in	While PV generation is significant, observe microgrid in islanded mode with all VRs disabled and with additional EV loads. As PV generation reduces and village returns to power import condition, observe microgrid for any instabilities during this transition (while all VRs are still disabled and EVs are plugged in).
6:30 p.m.	Transfer to grid	End of islanded operation.

Note that during the islanded-operation test, the load bank was operating at 100 kW with the intent of dissipating all the exported energy. This was done to prevent governor instability and overspeed of the generator.

Results of the controlled islanded operation are shown in Figure 8. PV power, line voltage and currents, as well as frequency and voltage THD are shown, and annotated with time steps, as per the schedule in Table 3.

During the first morning test, when all EVs were plugged in during the islanded mode, but prior to the onset of PV generation, no disturbance to the microgrid operation (voltage or frequency) was observed. As PV power generation started ramping up, and the village transitioned from power consumption to power export, still no problems were observed. Throughout the day, EV charging did not introduce additional THD injection. This is even more so important for case of Solar Decathlon village - given that the simulated EV ownership was 31%.

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Several further observations are important to point out:

- Line voltage stays well regulated in islanded mode throughout the PV intermittency period and during the EV loading period—up until the time when the VRs are bypassed. After VR's have been bypassed, a short-term voltage rise was observed, due to power production by inverters. This confirms that VRs are essential to this microgrid design. However, even unregulated, line voltages stayed within ANSI range – both due to internal regulation by inverters, and due to evening reduction of PV power.
- No harmful frequency variations were observed during controlled-island operation.
- No significant changes in THD composition were observed during controlled-island operation or during the main competition event.
- Therefore, by utilizing the right equipment, it is possible to design and operate a stable microgrid for fairly atypical conditions.

Summary

The Solar Decathlon 2013 microgrid was designed with safety and reliability as top priorities. During the competition, the microgrid was stable even during adverse weather conditions as well as during power export conditions. No unexpected power-quality violations were observed during the Solar Decathlon competition or during the controlled-island operation. Fig. 8 shows power, voltage, current, frequency, and THD plots for one of the houses during the controlled-island day.

The Solar Decathlon 2013 village has proven itself to be a useful test bed for collecting a large amount of high-resolution data. The village was a unique combination of 100% PV customer penetration ratio with 100% coincidence rate, 28% capacity penetration ratio, and 105% load penetration ratio—with an additional 31% of EV customer ownership ratio during the controlled-island operation test.

Solar Decathlon organizers did not experience any detrimental interaction between the PV systems and the VRs. The MicroPlanet regulators did an excellent job in all modes of operation. For the island test, the question was not whether they would stabilize the microgrid when on. Rather, would the village grid continue to operate when the VRs were bypassed? The bigger question for readers is whether microgrids need regulators and, if so, under what circumstances?

PV inverters with grid-voltage support modes and frequency droop would be ideal for future microgrid power-quality considerations. Additionally, the use of battery energy storage for peak shaving, frequency regulation, voltage, and reactive power support would be important in the design of a future Solar Decathlon distributed microgrid.

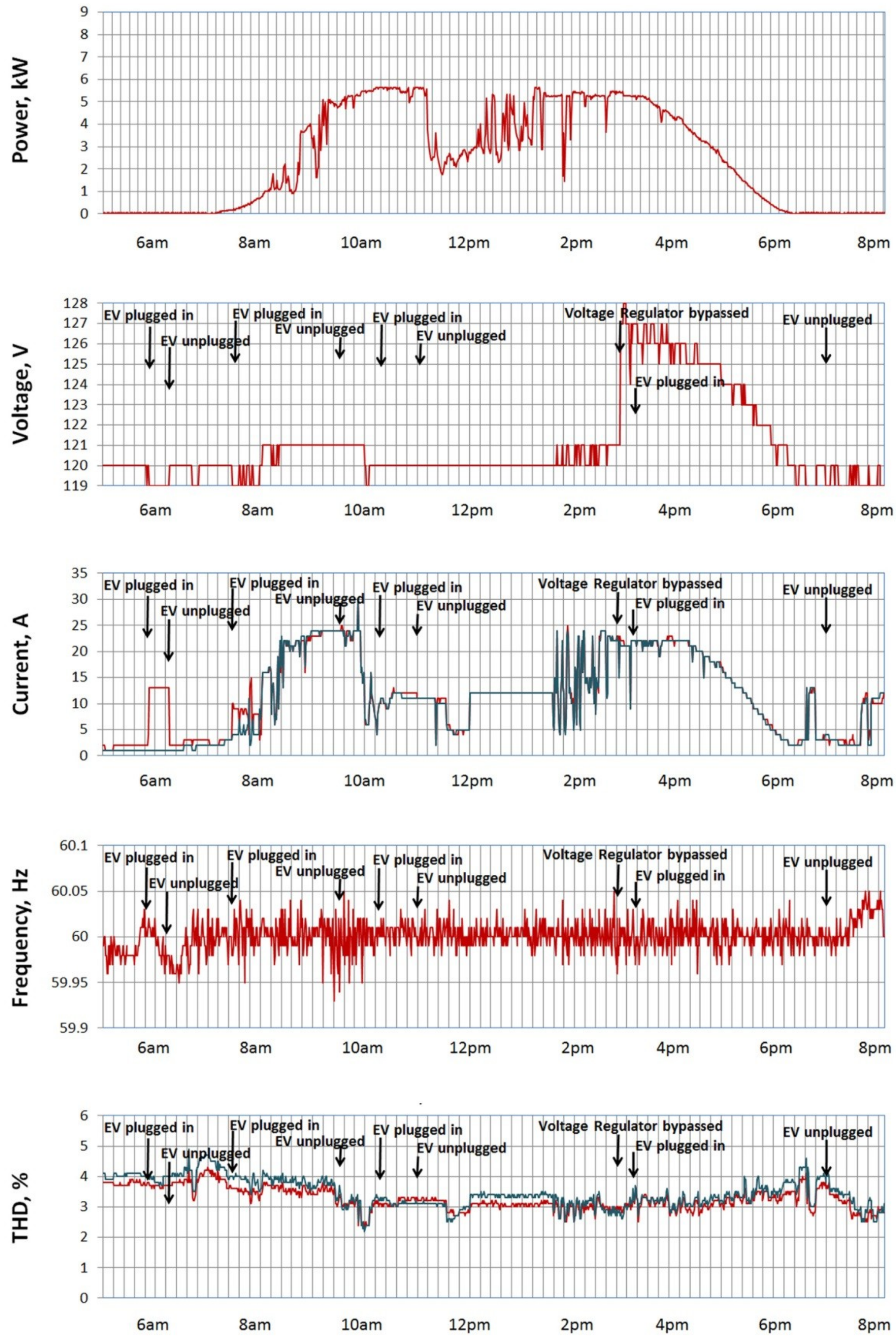

Figure 8. Power, voltage, currents, frequency, and THD plots for one of the Solar Decathlon 2013 houses during the controlled-island day.

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Future Work

The U.S. Department of Energy Solar Decathlon 2015 competition will be held October 8-18, 2015 at OCGP in Irvine, California. Several new challenges will be added to the competition. For example, a new Commuting contest will require each team to use an EV that needs to be charged from the team's house and be driven at least 25 miles each day. This will transform the Solar Decathlon microgrid into 100% PV and 100% EV customer penetration. At the time of this writing, further islanded microgrid operation testing is planned.

For up-to-date information on Solar Decathlon 2015, visit the Solar Decathlon website: http://www.solardecathlon.gov/.

References

[1] Stafford, B.; Coddington, M.; Butt, R.; Solomon, S.; Wiegand, G.; Wagner, V.; Gonzalez, B. (2012). *Design and Performance of Solar Decathlon 2011 High-Penetration Microgrid: Preprint.* 10 pp. NREL Report No. CP-7A30-54719.

[2] http://www.caiso.com/documents/flexibleresourceshelprenewables_fastfacts.pdf.

[3] Mather, B.; Russell, N. "Integrating High Penetrations of PV into Southern California: Year 2 Project Update." *Photovoltaic Specialists Conference (PVSC)* 2012, 38th IEEE, pp. 000737-000741. IEEE, 2012.

[4] Stewart, E.; MacPherson, J.; Vasilic, S.; Nakafuji, D.; and Aukai, T. "Analysis of High-Penetration Levels of Photovoltaics Into the Distribution Grid on Oahu, Hawaii." Contract 303 (2013): 275-3000.

[5] Kleissl, J.; Lave, M.; Jamaly, M.; and Bosch, J. "Aggregate Solar Variability." *Power and Energy Society General Meeting*, 2012 IEEE, pp. 1-3. IEEE, 2012.

[6] Lavrova, O.; Cheng, F.; Abdollahy, S.; Barsun, H.; Mammoli, A.; Dreisigmayer, D.; Willard, S.; Arellano, B.; Van Zeyl, C. (2012). "Analysis of Battery Storage Utilization for Load Shifting and Peak Smoothing on a Distribution Feeder in New Mexico." *IEEE PES Innovative Smart Grid Technologies (ISGT)*, 2012, pp 1-6.

[7] Cheng, F.; Willard, S.; Hawkins, J.; Arellano, B.; Lavrova, O.; Mammoli, A. "Applying Battery Energy Storage To Enhance the Benefits of Photovoltaics." *IEEE Energytech,* 2012 IEEE, pp. 1-5.

[8] 15. Abdollahy, S., Lavrova, O., Heine, N., Mammoli, A., & Poroseva, S. (2013, August). Integrating heterogeneous distributed energy resources to manage intermittent power at low cost. In Technologies for Sustainability (SusTech), 2013 1st IEEE Conference on (pp. 223-229). IEEE.

[9] "Coordinated Collaboration between Heterogeneous Distributed Energy Resources", S Abdollahy, O Lavrova, A Mammoli - Journal of Solar Energy, volume 2014, 2014

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