Developing Affordable Smart Thermostats

The state of California has decided to resolve it's peak-power problem with the help of programmable, communicating thermostats (PCTs).

by William Burke and David Auslander

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This is a recent wireless programmable communicating thermostat (PCT) demo prototype. The thermostat actually receives a demand response message by radio data system (RDS), a standard for sending small amounts of digital information using conventional FM radio signals.

On the hottest days of the year, when air conditioners are working hardest, sometimes California cannot make, or buy, enough electricity to satisfy its tremendous appetite. On these special days, Californians must find ways to save electricity or risk losing power from brownouts or rolling blackouts. They must go around the house turning off lights, computers, air conditioners, and whatever else they can live without. People in a few locales around the world periodically face similar choices, but as world populations and economies grow, it is likely that these types of extreme measure will become more widespread.

In California, the problem usually occurs on very hot summer days during the workweek. Since the majority of businesses operate from around 8 am to 5 pm, they draw most of their power during these times. During the hottest part of the day, from around 2 pm to 5 pm, the load on residential and commercial air conditioners peaks. At normally hot temperatures, plenty of power exists to handle all of the consumption, but the extra AC load on very hot days, or when power supply and distribution equipment failures occur, can push the system too hard. During these times, people are asked to cut back on energy use or risk temporary loss of power. Sometimes these cutbacks, especially among the elderly living alone in big cities, can prove fatal.

The state of California has decided to resolve this problem. In addition to building more power plants, 2009 Title 24 regulations will require that programmable communicating thermostats (PCTs) be installed in all newly constructed homes. In most instances, the PCT acts exactly like a normal programmable thermostat (see "Saving Energy Star Thermostats"). It turns the heating and cooling on and off to maintain the desired temperature, and it changes the setpoint temperature based on homeowner preferences. In fact, it will look and operate almost exactly like a normal digital thermostat. The big difference lies in the special hardware and software used to communicate with the utility distribution company (UDC). The communication will allow the UDC to ask the thermostat to reduce energy consumption by, for instance, increasing the cooling setpoint by a few degrees.

In January 2006, a small team at the University of California at Berkeley gathered to develop a proof of concept for a low-cost PCT. The California Energy Commission funded the project and gave us about four months to develop a prototype, which they would then demonstrate to industry stakeholders. During that time, we specified hardware and wrote software for the PCT prototype. Many people felt that PCTs would cost a fortune, and would therefore be of no use to most people, but the results of our work showed that PCTs could be inexpensively produced and managed, and now manufactures have agreed to produce and sell them for around $100.

To the Drawing Board

The PCT fits into a broad class of technology that enables what is called load side management, or demand response (DR). Both of these terms refer to adjustment of the load on the power system. Currently, the electrical grid adjusts the amount of power supplied. If the demand increases, then the operators ensure that the grid supplies more power. They do very little to adjust the load, despite some DR programs in the industrial and commercial sectors. As the average daily loads get closer and closer to maximum power production capability, operators increasingly look toward DR to help balance the system.

Power system engineers have experimented with DR for a few decades now, and consequently the idea of controlling some aspect of a home's electricity consumption is not a new concept. While PCT experimentation is relatively new, UDCs have had similar small programs for a while. The problem is that no one has ever tested such a system on a scale nearly as large as the whole state of California. So how do you make sure that the PCTs do not cause more harm (like blackouts) than good? How can you understand and predict the results of using the PCT?

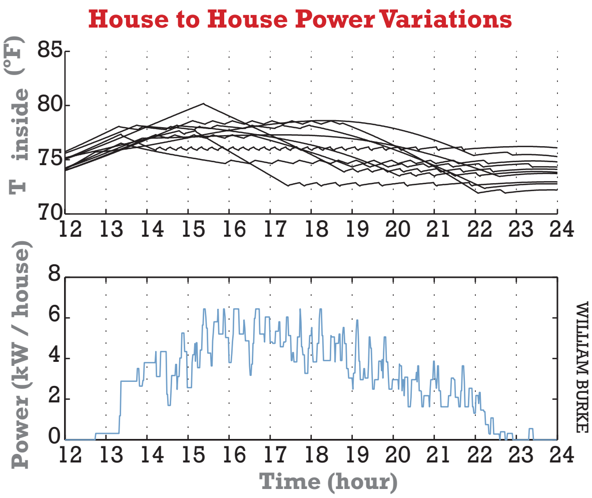

Figure 1. The temperature variations of the different houses are caused by each house having different thermal properties and a different thermostat setpoint. The bottom chart shows the resulting power consumed by these houses.

These are the questions that we are examining.

For a number of reasons, it is not feasible to install a large network of PCTs simply for testing. Most importantly, it might not be safe to test the system on a multitude of actual houses for fear of causing the serious problems we are hoping to cure—blackouts and brownouts. Furthermore, the testing would be very expensive. First, we would have to make and install the PCTs in hundreds of homes. Moreover, we will be testing different software for controlling the PCTs, and it would be prohibitively expensive to upgrade the software in the hundreds of deployed units. Finally, the testing would take too long, since we might have to wait an entire year in order to get the right conditions for the test.

To solve these problems, we created a computer-based simulation of the system, in accelerated time. We based this simulation on software that models an individual house. Each simulated house has walls, windows, air conditioning, and heat, and we can modify all of the parameters of each of these simulated components. Most importantly, each house has a PCT. To improve the accuracy of the house simulations, we compared our relatively simple simulation with a much more complicated one derived from Energy-10. Using the complicated simulation as a reference, we tuned our house parameters for improved accuracy.

Using the individual house-PCT simulation, we created a whole neighborhood of houses. To simulate the variations in the real world, each house is completely different—different walls, AC, thermostat setpoints, setpoint schedules, and so on. To obtain the total power consumption of our digital neighborhood, we added together the power consumed in each house. Finally, we created a virtual communication center that can send and receive messages with the PCT.

The simulation has two huge advantages over real-world testing—quick results and high resolution measurements—that afford us great flexibility. A simulation of 100 houses for 24 hours takes about 15 minutes to complete on two-year-old computer hardware. Also, we can measure the power consumption at the subsecond resolution, and instrumenting actual houses with similar power-measuring devices would be very costly. The high resolution is important because fast power spikes can wreak havoc with the distribution and generation system.

For example let's look at a simple simulation of 10 houses for a period of 12 hours beginning at noon (see

Saving Energy Star Thermostats

Rumors of the demise of the Energy Star-certified thermostat have been greatly exaggerated! (Apologies to Mark Twain and Energy Star for possible misuse of a quotation.)

Home Energy reported in an earlier issue that, since it was difficult to show that definite energy savings could be attributed to the use of Energy Star-certified programmable thermostats, EPA was going to phase out the certification of thermostats and instead focus on creating an educational label that teaches people how use thermostats to save energy and still be comfortable in their homes (see "Surprising Turnabout at Energy Star" and "Energy Star Changed Approach to Programmable Thermostats," *HE* Mar/Apr '07, pp. 2, 10). There is consensus in the thermostat and energy efficiency industries that the best, most sophisticated, and easiest-to-use thermostat is worthless in the hands of someone who doesn't care to use it to save energy. The converse is also true. The simplest thermostat is quite effective when set by someone who is highly motivated to save energy.

After hearing from utility energy efficiency program managers, thermostat manufacturers, and others who believe that the Energy Star certification, along with education, is still an important tool in their toolboxes, EPA held a stakeholders meeting last October to present an alternative to letting the Energy Star designation for programmable thermostats die a natural death—a death that had been scheduled for December 2009. "We want to create a specification for Energy Star programmable thermostats that better differentiates them from the non-Energy Star kind," says Christopher Kent, who is in charge of specification development for the thermostats at EPA. "Also, we want to make the thermostats more user-friendly and [give them] a more consistent user interface." EPA has asked the industry to forward a proposal for revising the current specification that meets these goals. And EPA has asked its manufacturer partners to commit to EPA's campaign to educate consumers on saving energy using programmable thermostats.

In order for a new specification to take effect before the current specification ends, it must be finalized by March 2008. The new specification would then come into effect in December 2009. The old Energy Star programmable thermostat specification is almost dead. Long live the new one!

—Jim Gunshinan

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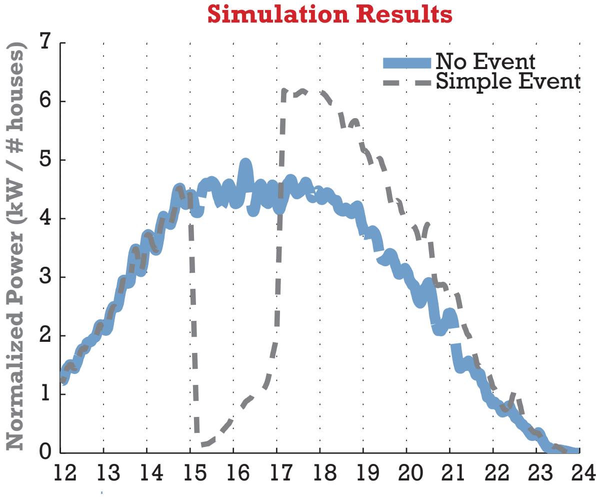

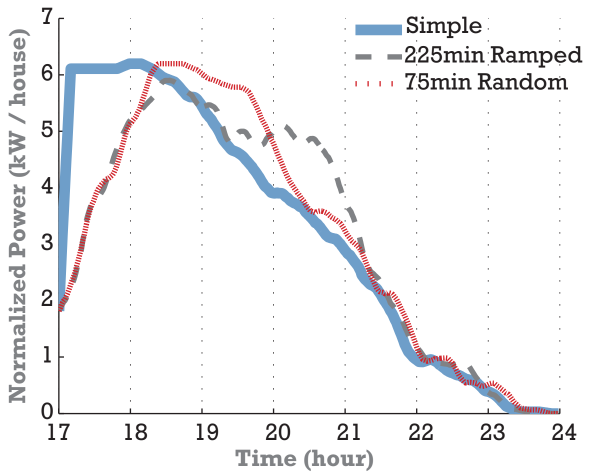

(top) Figure 2. The figure shows the average power for a population of 100 houses with and without a 4°F setback from 3pm–5pm. *(bottom)* Figure 3. This figure shows the post-DR event recovery period for similar events with different exit strategies—no exit strategy, ramped exit profile, and random end times.

Figure 1). In the top chart, we see the temperature variations of the different houses caused by each house having different thermal properties and a different thermostat setpoint. The bottom chart shows the resulting power consumed by these houses. Most simulations use 100 houses to better simulate large house populations, but Figure 1 is instructive because with only 10 houses we can easily see the variations in each house.

To be clear, we are not trying to exactly replicate the response of a single neighborhood. Rather, this simulation aims to represent the response of a general load group. Regardless, simulations are generally difficult to verify, and our simulation is no exception. To improve our accuracy we still need to compare our simulations to actual AC load data.

Getting the Bugs Out

With the simulation nearing completion, we began the most interesting part—seeing what happens when the group of PCT homes responds to messages. Our first experiments tested the effect of raising the setpoint different amounts for different lengths of time. The popular choice for setpoint changes is 4°F (see Figure 2). Look at the results. Does it look like we improved anything? The big peak at around 5 pm is called the rebound peak. Here it occurs when the setpoints in all of the houses simultaneously decrease by 4°F at the end of the event. The decrease causes every AC to come on at nearly the exact same time, resulting in the big peak. This clearly illustrates the potential problems with implementing this type of system. If it occurs at the wrong time, a large rebound peak could easily cause blackouts.

Logically, we next examined rebound mitigation strategies. We want to smooth the peak so that it does not occur so abruptly, and we want to reduce the size of the peak.

Randomizing the end time of the event is the most talked-about mitigation strategy. This strategy works by having everyone's PCT return to the normal setpoint at different, randomly chosen times spread out over a predetermined period. So your neighbor's thermostat might return to normal at 5:21 pm and yours might not return to normal until 6:42 pm. Randomization of the timing is rather easy to implement, but our example perfectly illustrates one of the main problems with this strategy—equity. In the example, you would be uncomfortable for one hour and 21 minutes longer than your neighbor.

In order to solve the equity problem, we next tested an algorithm that slowly brought the thermostat back to the normal setpoint over a period of time—a ramp. The ramped-exit strategy is equitable because everyone's PCT does the same thing, returning to normal at the same time. Clearly this is not the only equitable strategy, but you have to start somewhere.

Using time is not an appropriate way of comparing ramped-exit and random end time strategies. For example: At the end of a 120-minute random end, the last house is still 4°F above the desired setpoint, but at the end of a ramped exit, all of the houses are cooled to their desired setpoints. In order to better compare these two strategies, we calculated the total energy consumed during the whole day. Since the experiments used the exact same houses on the exact same day, the energy consumption prior to the beginning of the exit strategy is exactly the same. After that, the consumptions are very different. In a comparison between a 225-minute ramped exit and a 75-minute random end time event, the total energy consumption in both tests resulted in approximately the same 34 kWh average per house (see Figure 3). More telling, the ramped exit has a lower peak power than the random end time by 0.26 kW per house.

The main point of the work we have done to date was to demonstrate that systemic control of PCT networks needs further examination, and that we have a tool with which to analyze it. Our simulation can safely and effectively test many different scenarios without subjecting homeowners or the power grid to unwanted stress.

Future Work

The UDCs don't want to worry about huge power spikes. They want to set the system to a predetermined load and forget about it. To this end, we are focused on controlling the power to a desired value, and we have a number of ways to accomplish this goal.

Since we wrote the entire simulation, all it takes is a little programming to try just about anything, short of controlling the weather. Currently, PCTs respond only to commands that adjust the setpoint directly. They make adjustments to the current setpoint (as shown in our data), or change the setpoint to a certain value. But many other possibilities exist. For instance, the PCT could respond to commands specifying a maximum AC duty cycle (how often it turns on and off). Alternatively, the thermostat could receive a price signal and then adjust the temperature in an intelligent way based on the homeowner's cost-versus-comfort preferences. Regardless of the message type and response, accurate tracking of a desired power profile requires that an appropriate message be sent at the correct time.

We are working hard to ensure that California's transition to smart thermostats goes smoothly. Our simulation should allow us to deduce precisely what is needed to make the system perform as desired. If we do our jobs, then the future for brownouts and blackouts looks bleak. PCTs are poised to obliterate them and ensure that the lights stay on in California, and the rest of the world, regardless of how hot it gets.

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