CAL POLY SUSTAINABLE POWER FOR ELECTRICAL RESOURCES (SuPER) PROJECT

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ABSTRACT

The Cal Poly Sustainable Power for Electrical Resources (SuPER) project is developing a low-cost, sustainable source of electrical power for a family unit for the 2 billion people with no electricity. After two years, the initial prototype system uses a solar photovoltaic source with battery storage, provides a standard DC output voltage, is digitally controlled, and is documented as an open source product. A complete Matlab/Simulink simulation model is validated with measurements from the prototype. The SuPER system design goals are for a 20 year life cycle with a mean time between failure (MTBF) of 25 years, a mean time to repair (MTTR) of 1 hour after receiving parts at the site, and a cost to manufacture of $500. All the work is being done at Cal Poly using undergraduate student senior projects and graduate student master theses, and field testing will be done at the Cal Poly Organic Farm.

1. INTRODUCTION

The Cal Poly Sustainable Power for Electrical Resources (SuPER) project begins its third year of development of a low-cost, sustainable source of electrical power for the 2 billion people who do not have access. The overall goal of the Cal Poly SuPER system is to provide electrical power for a family unit over a 20 year life cycle for a total cost of $500. The initial prototype system uses a solar photovoltaic source with battery storage, provides a standard DC output voltage, is digitally controlled, and is documented as an open source product. A complete Matlab/Simulink simulation model has been developed, and validated with measurements from the prototype SuPER system. The technology is based upon existing PV and battery technology, but the final development will extrapolate existing technical performance into the future using a Moore's Law model. The SuPER system design goals are for a 20 year life cycle with a mean time between failure (MTBF) of 25 years, a mean time to repair (MTTR) of 1 hour after receiving parts at the site, and a cost to manufacture of $500, which are reasonable design goals for the future. The results of this technology development are being made available using the open source software General Public License model. Two graduate students (Tyler Sheffield and Eran Tal) have completed their master’s thesis, eleven undergraduate students have completed their senior projects, and three independent study students have participated on the Cal Poly SuPER project. In Spring 2006 a team of four business students completed their senior projects with a marketing study for the Cal Poly SuPER system.

The long-term goals of the Cal Poly SuPER project are to produce energy at or below the cost of retail energy, conventionally produced, and in a sustainable manner, which are identical to the Solar America Initiative (SAI) goals. The primary goals of the SAI are to reduce the levelized cost of energy (LCOE) to below 10¢ per kWh while scaling up manufacturing capacity to supply 5-10 GW of domestic PV installations by 2015. The current Cal Poly SuPER system has an estimated cost of approximately $1500 and provides electrical power of about 0.7 kWh/day yielding a LCOE = 29 ¢/kWh. There is reasonable expectation to reduce cost at the end of an additional year of development to approximately $1000 for a LCOE = 20 ¢/kWh. These reductions can be accomplished with further improvements in PV efficiency and anticipated reductions in PV module and battery cost. It is further estimated that within three years, or by the year 2010, the SuPER system will achieve the goal of an LCOE = 10 ¢/kWh.
three years will follow three stages of further development of the system and its associated simulation model: year one - completion of the prototype system and initiation of the development of the first generation system, year two - field testing of the first generation system and initiation of the design of the second generation system, and year three - field testing of the second generation system, and completion of the open source documentation of the design. All the work is being done at Cal Poly using undergraduate student senior projects and graduate student master theses, and field testing will be done at the Cal Poly Organic Farm.

The background and rationale for the Cal Poly SuPER project is presented in section 2. Then summaries are given of the development of the prototype system in section 3 and of the simulation model in section 4. Section 5 presents some applications of the validated simulation model. Section 6 discusses the relationship between the original goals of the SuPER project and the goals of the new SAI program. Finally, in the conclusions plans for the future are presented.

2. BACKGROUND: RATIONALE FOR PROJECT

The National Academy of Engineering compiled a list of the top engineering achievements for the 20th century, and the top achievement was electrification [1]. It is not appreciated that of the six billion people on the planet, only two billion have access to reliable electrical power, an estimated two billion people have unreliable access to a grid or battery supply, and one-third of humanity (two billion people) do not have any access. In fact, in 2001 federal legislation was passed to provide electricity to an estimated 18,000 occupied structures on the Navajo Nation [2].

Reviewing these facts, the Cal Poly SuPER project was initiated to develop technology that would provide sustainable electrical power to people in underdeveloped countries. The belief is that the project could provide "leapfrog" technology, such as the introduction of cell phones did to provide telephone service to those who didn't have access. A review of any global insolation map will show that the majority of the poorest people, those with incomes under $2 per day, live within 30 degrees of the equator, the area with the highest annual solar insolation. Hence, solar power is the obvious power source for electrical power. When this fact is combined with the goal of a mean-time-to-failure (MTBF) of 25 years, then the use of solar photovoltaic becomes the best candidate.

It was instructive to review the history at the end of the 19th and beginning of the 20th century of the development of our current electrical power system of generation, transmission and distribution. This period was the era of the "battle of the systems", when the DC system of Edison was in competition with the AC system of Tesla and Westinghouse [3,4,5]. Electrical lighting was the primary load for the power at this time, just as lighting is the resource that the poorest people struggle to obtain. At the time that this technological battle was going on, there was no power electronics and no digital computers; the electrical power technology was mainly electromechanical machines and magnetic circuits (transformers). Today the results of that battle may have been different, and DC power could have won over AC power. Today, the principle household loads from electrical power can be supplied with DC power, including: electrical appliances and machinery (water pumps) using permanent magnet motors, lighting using LEDs, consumer electronics (TV, computers, internet connections, etc.) all use DC power, and battery charging for devices such as cell phones and hand tools. Solar photovoltaic technology is mature [ref], but it is poised to grow in efficiency and to provide lower costs. So the challenge for the Cal Poly SuPER project was to provide a robust design for the system that would adapt to improving technology. The concept is to recognize the applicability of a Moore’s Law to the technologies associated with PV modules and battery/energy storage. Thus the plan is to design a robust, digitally-controlled system that anticipates the improvement of technology in the near term.

In summary, the goals/requirements for the development are: design lifecycle of 20 years, total cost less than $500 for 1 square meter PV module including battery replacements, mean time between failures (MTBF) of 25 years, mean time to repair (MTTR) of 1 hour, power depends on PV efficiency and battery/energy storage capacity, and consideration of load utilization. The final system would provide household electrical power as the only electrical power source for a family, capability to increase the power resource over time with improving PV and energy storage technology, and costs less than $3 per month for all electrical power needs. The system would provide the technology for a decentralized, sustainable development of electrical power in the economically poorest countries. Thus the Cal Poly SuPER system technology would have...
the potential to raise the standard of living of the poorest people to be on par with rest of world.

3. **SuPER PROTOTYPE DEVELOPMENT**

The Cal Poly SuPER project began in Summer of 2005 with the publication of its White Paper [7]. During the Fall 2005, the only activity was a flurry of proposals seeking support, over six foundation and one NSF proposals were submitted with no awards. In the Winter of 2006, the project started using support of indirect cost funds from previous awards. The project lab was established, and the first senior project completed an initial simulation model of the proposed system using Matlab and Simulink. That Spring, four business students completed a business/marketing study for their senior project. In the Summer 2006, the initial Phase 0 prototype system was completed through the work of three senior project students led by graduate student Eran Tal, who obtained his masters thesis. In Fall 2006, a pyranometer for the measurement of local insolati

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The SuPER prototype system with all its loads is shown in Figure 2. The prototype system block diagram is shown in Figure 3. The prototype system is referred to as the Phase 0 system, and the simulation model is based upon the Phase 1 design shown in Figure 3. The only difference between Phase 0 and Phase 1 is the dc-dc converter and its closed-loop control; the Phase 0 is using an Outback MX 60 for the both the dc-dc converter and the battery charging control. The power flow for the SuPER system is shown in Figure 4. The SuPER system includes the DC loads as shown. The status system is shown in Figure 5; the sensor inputs and control outputs use a National Instrument NiDAQ 6009 USB interface to a laptop computer running linux. There are 14 input variables (voltages, currents, temperatures, and insolation) and 7 outputs (MOSFET switches, and the pulse-width modulation signal to control the dc-dc converter). The laptop determines a pulse width modulation control signal for the dc-dc converter using a maximum power point tracking algorithm for the PV array and the mode of the battery state of charge. A total of seven printed circuit boards (PCB) were designed to handle the sensor, control and switch electronics. Figure 7 shows the complete status and control interface diagram.
4. SuPER SIMULATION MODEL

A simple simulation model of the system using Matlab/Simulink was the first result of the project [7], and was completed in Winter 2006. After the completion of the Phase 0 prototype system in Summer 2006, the development of a complete simulation model of the system adding the SimPowerSystems package was initiated and was completed in Spring 2007 [7]. The model uses SimPowerSystems to model the dc-dc converter, the loads and the loss model for the system. C-MEX S-functions (using C code rather than .m files) are used to model the PV array, control, switches, battery, and loads (cooler, laptop, and dc motor). Figure 7 shows the simplified block diagram of the model.

Several separate simulations were used to develop the system model: dc-dc converter with both PSpice and Matlab/Simulink, dc motor with ultracapacitor, cooler, laptop, PWM duty cycle control, and LED load. Measurements from the prototype system were then used to validate the simulation model. Pyranometer data for local insolation was measured and used to test and validate the following models: dc motor, battery state of charge (SOC) estimation, cooler operation, laptop battery characteristics, and LED load operational scenarios. On the basis of these, and other detailed, tests the SuPER simulation model was validated to be accurate enough to be used for the analysis of the SuPER system performance. An example of the results of the validation process is the dc-dc motor load comparison presented in Figure 8.
5. APPLICATIONS OF SIMULATION MODEL

The validated simulation model is being used to provide SuPER system analysis of operation with different PV insolation and load scenarios. Three examples are given here. Figure 9 presents a scenario that shows nighttime LED light operation for numbers of lights and its impact resulting on the SOC. Figure 10 shows the impact on SOC for one hour operation of the one-quarter horsepower dc motor for various times; it shows that the time of operation relative to the solar insolation is critical for maintaining SOC. Figure 11 shows a two day scenario with four loads as an example of extended system simulation capability.

Therefore, the SuPER system with its loads can be treated as a complete power generation and distribution system with power/load scheduling. Some preliminary conclusions for system operation are that a critical system variable to control is the battery SOC. The battery provides a peak power source during insolation and is the primary source when there is no insolation. For example, a peak power demand of at least 230 W can be met without overall degradation to the SOC with the aid of the battery/ultracapacitor storage even though the PV array supplies only a maximum of 150 W. Load demand is important to control SOC, and the system with its switching capability allows the design of a power dispatching function for the loads. Load factor is important to system operation, and average power and peak power along with battery SOC are control variables. Based upon the measurements to date, the prototype system is able to provide at least 700 W hr / day of sustainable electrical energy.

In 2006 the Solar America Initiative (SAI) was introduced by President Bush in his State of the Union Address. The goals of the SAI are: “The goals of the SAI are to reduce the levelized cost of energy (LCOE) to below 10 ¢/kWh while scaling up manufacturing capacity to supply 5-10 GW of domestic PV installations by 2015.” [DOE FOA] While the goal of the Cal Poly SuPER project is to develop sustainable technology for households without access to electricity, the technology also can help achieve the SAI goals. The current SuPER prototype estimated system cost of approximately $1500 with an average daily power of 0.700 kWh yields a LCOE of 29 ¢/kWhr. It is expected that the next phase design of the system will have an average daily power of 1 kWhr with load dispatching and replacement of the laptop with a FPGA softcore processor – this will yield a LCOE of about 20 ¢/kWhr. With research and improvements, the LCOE could reach a value below 10 ¢/kWhr by 2010. Figure 12 presents an estimate of the impact the Cal Poly SuPER project technology could have towards meeting the SAI goals if these estimates are achieved. The SAI goals can be met with a 1 kWh/day standalone PV system with DC output with a 20 year life cycle cost of $730.50 yielding the goals of LCOE = 10 ¢/kWh for residential needs and of 10 GW domestic supply with the purchase of 10M household units at a total cost of $7.3B. A reasonable estimate of the impact of the SuPER technology for appropriate households in the "sun belt" is the replacement of about 4 GW out of the goal of 10 GW, as shown in Figure 12.
7. CONCLUSIONS

The Cal Poly SuPER project is a "low tech, small science" endeavor. It has a clear definition of achievable goals with defined metrics to measure progress: sustainable source of electrical power for a household with a 20 year lifecycle cost of $500, MTBF of 25 years and a MTTR of one hour. The project has a strong team of faculty and students with industrial support. The resources of Cal Poly are available to assist the development through senior projects and master thesis. The project fits into Cal Poly's mission of education and its commitment as a signatory of the Talloires Declaration. The project is based upon a systems approach using digital/computer control, a simulation model implemented with Matlab/Simulink, and the consideration of loads, load factor and power utilization. The SuPER system advocates the use of DC power distribution based upon the efficiency inherent in power electronic circuits, a new market for household appliances, and LED lighting. A development laboratory for the SuPER project is entering its third year, and planning for the field testing of the SuPER system at the Cal Poly Organic Farm is being completed. A strong faculty team from the College of Engineering; College of Agriculture, Food and Environmental Sciences; and Orfalea College of Business; and from industry has been identified and is committed to its success.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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