ALTERNATIVE CONFIGURATIONS FOR BATTERIES OF CONTINUOUS ELECTRICITY SUPPLY SYSTEMS

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INTRODUCTION

When rechargeable storage batteries are used in electric systems, the requirements for power to be delivered to the connected loads in discharge and/or the availability of power for charging typically do not have values that allow maximization of life of the batteries and maximization of the performance of the systems of which the batteries are the electricity storage component. To correct for this, a novel approach to increase the probability that continuous electricity supply systems with batteries will perform optimally has been developed.[1] This new approach has been dubbed an "Alternative Configuration" and is designed for use in hybrid power supplies with two or more strings of batteries and one or more electricity sources, such as an electric utility, an engine-generator set, or a solar photovoltaic array, together with power conversion equipment such as DC-AC inverters and/or rectifiers. Several different alternative configurations have been conceived, but all of these include additional circuitry such as electromechanical or solid-state switches between the battery strings and the DC buss of the power conversion system(s), together with software and hardware to allow the direction and magnitude of the current flowing in each of the strings to be controlled.

There are several types of electricity systems designed to provide a continuous supply of electricity that have batteries, or continuous power systems to which batteries could be beneficially added, for which alternative configurations may be applicable. These include but are not limited to:

a. Remote hybrid renewable electricity systems with combinations of renewable sources such as photovoltaic (PV) arrays and/or wind generators, together with engine/generators, where the batteries provide storage for periods when the renewable resource is inadequate to supply the load.
b. Remote electric systems powered with engine/generators in which the batteries could be used for load following in order to reduce fuel consumption and engine maintenance.
c. Grid connected continuous electricity supply systems with batteries, for example for combination peak shaving and standby power service, where the batteries must be continuously available.
d. Battery electricity storage systems used for electric utility load following or area (frequency) regulation, in which the batteries might be either required to accept a charge or to deliver energy through discharge at any time and in any order.

In all these types of systems, the batteries are not currently managed in such a way that the battery performance and life can be maximized while still operating the system in an optimal fashion. For example, in a solar hybrid system, batteries cannot be fully charged, nor can they be equalized, without using the engine/generator in such a way that both fuel and maintenance costs are significantly increased.

The project that led to the conceptualization of alternative configurations (or AltConfigs for short) was one of number under the Renewable Generation and Storage (RGS) portion of the Energy Storage Systems (ESS) Program of the Department of Energy. The ESS Program is performed for DOE by Sandia National Laboratories. It is for a remote (i.e., not grid-connected) hybrid solar PV system with an engine/generator and batteries, that an AltConfigs unit was first developed and demonstrated. Thus, in this paper, it is for this type of continuous power system that our approach for improving battery life and system performance will be discussed (next section) and for which some experimental results will be described in the third section. In the DISCUSSION section below, the benefits of using an AltConfigs unit in a hybrid solar system will be argued and the applicability of AltConfigs to other types of continuous power systems will be outlined.

ALTERNATIVE CONFIGURATION DESIGN CONCEPTS

A schematic of a typical hybrid solar system of a type to which AltConfigs might be applicable consists of a number of components, shown in Figure 1, as follows:

- Battery energy storage system, often comprising several parallel strings with multiple cells in series.
- Solar PV array with a DC-to-DC converter (Maximum Power Tracker) to ensure a match between the PV array voltage and the battery buss voltage.
- Engine/Generator, producing in general AC, often fueled with propane in remote installations.
- A Power Conversion Unit (PCU) to convert DC to AC for powering the loads, or to convert AC from the Engine/Generator to DC to charge the batteries.

The PCU in general includes the controls that tell the generator when to turn on and off, and other such functions.

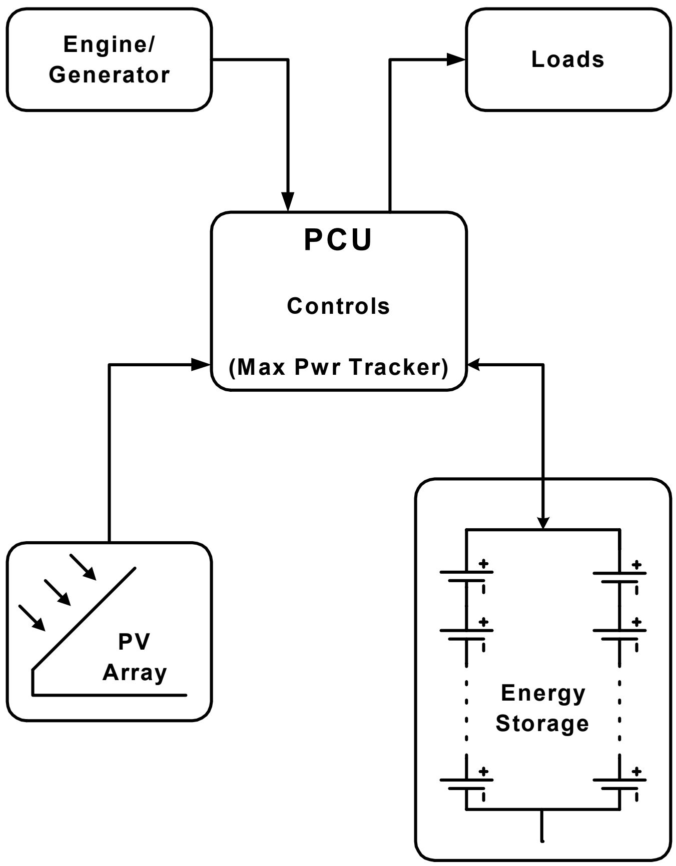

Figure 1: Typical Hybrid Solar System of type in which AltConfigs might be used

The batteries in hybrid solar systems of the type shown generally in Figure 1 are often not managed as well as they might be because such management would entail running the generator for extended periods of time at low efficiency. For example, when the generator has been called for and the batteries are getting close to being fully charged so the charging current begins to taper, the generator is running at lower than optimal power. Taper periods for accomplishing a finish charge can be quite lengthy, so the impact on generator maintenance and fuel consumption can be significant. Moreover, if the taper charge (what we term finish charge) is taking place during a period of time when the sun is shining brightly, then electricity from the PV array cannot be used because the generator is providing more than enough power to accomplish the finish charge. These problems are compounded for batteries such as flooded lead-acid that occasionally require an equalization charge that can take many hours if the batteries have not been adequately finish charged on a regular basis.

In addition to these and similar problems that occur in charge, there is also an issue with the discharge when using a traditionally-designed hybrid solar control strategy. This is because the rate of discharge is variable, and often very slow, so the "under-voltage" control that is traditionally used can lead to a serious overdischarge of the batteries.

These and other problems with managing the charge and discharge of batteries in hybrid solar systems (as well as in other systems with batteries that are designed to provide a continuous supply of electricity) can be solved with the use of one of the alternative configurations that we have developed. An AltConfigs unit consists of several parts:

- Added circuitry between each string of battery and the DC terminals of AC-DC-AC converter.
- Hardware and software to control currents to/from the strings though the additional circuitry.
- String current control on the basis of measured parameters and battery characteristics.

According to the alternative configuration approach, the currents in the strings are controlled in such a way as to ensure that electricity can be continuously supplied to any loads connected to the system, while still ensuring that the batteries are being charged and discharged in such a way as to maximize system performance and battery life.

One of the AltConfigs concepts we have developed is illustrated in Figure 2. This shows that switches and current shunts have been added to each of the strings of a multi-string battery, and that string currents, module voltages and temperatures are measured and recorded by the AltConfigs controls.

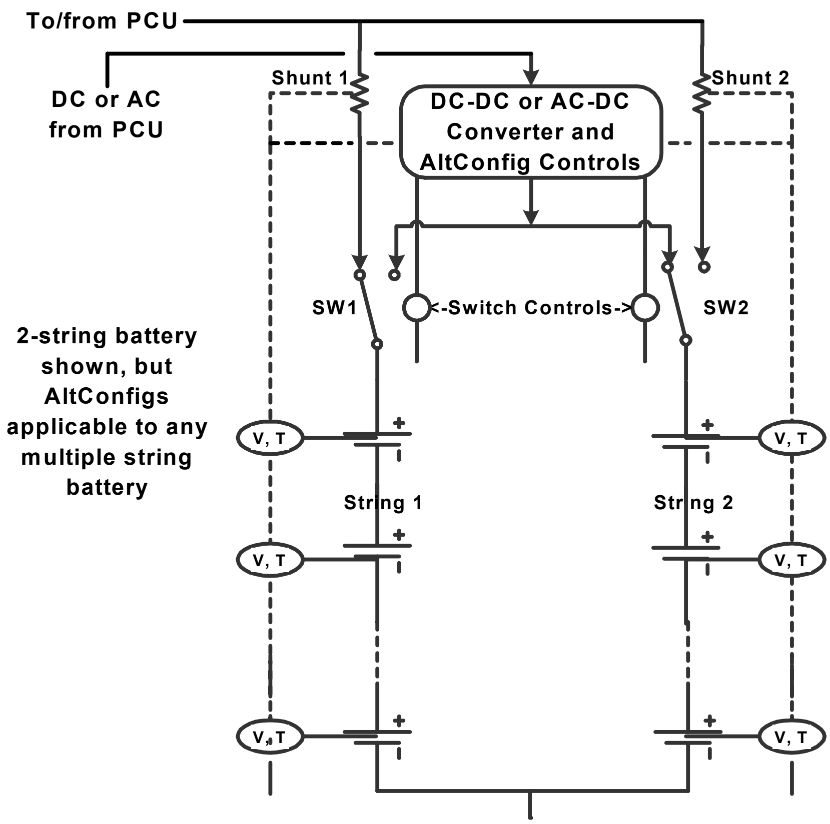

Figure 2: Schematic of AltConfigs Unit with Hybrid Solar System

The AltConfigs unit shown in Figure 2 is operated according to the measured parameters and the known characteristics of the battery modules as follows. For the sake of simplicity, and because it is the way in which such systems inevitably get initialized, we will start this description with the batteries in discharge, i.e., the switches SW1 and SW2 set so that both strings are connected directly to the PCU. This is also the state of the switches for regular (bulk) charging. The batteries can continue to provide the electricity for the loads until end of discharge is reached. The end of discharge is signaled with this particular AltConfigs unit by means of ampere-hour counting. The current flowing in each string is measured and summed over time to give the ampere-hour count; this count is zeroed each time a charge is initiated. When the amp-hour count exceeds a preset limit, corresponding generally to about 50% of the C/8 capacity for a hybrid solar system, then a charge is started by turning on the engine/generator. Charging is continued with the generator until the AltConfigs software deems the strings to have completed a bulk charge, i.e., that the current is about to begin to taper. A proprietary algorithm is used to determine that the bulk charge has been satisfactorily completed. Both strings are discharged or charged at more-or-less equal rates, as discussed further in the EXPERIMENTAL section below.

At the end of the bulk charge period when the generator is turned off, one or the other of the switches (whichever was not actuated in the preceding cycle) is set into its other position, so that one string (String A in Figure 2) continues to be connected to the PCU and is therefore available for discharge, while the other string (String B in Figure 2) is connected to the AltConfigs Finish Charger. Thus, one string of a 2-string battery gets finish charged every other cycle of operation. (In a multi-string battery, strings get finish charged in recurring sequence during repeated cycles of operation.) The "discharge one string, finish charge the other string" operation continues until the AltConfigs software determines (again with a proprietary algorithm) that the finish charge is complete. At this point, the appropriate switch (SW2 in Figure 2) is set back to the position that allows both strings to be discharged, and discharge continues until the amp-hour counter indicates that a charge is again required.

The AltConfigs unit shown in Figure 2 can also be used for module equalization without using the engine/generator, by allowing a finish charge to continue until the required amount of equalization has been accomplished. However, we postulate that if frequent and adequate finish charging is performed, then far less equalization should be necessary than with current practice.

Before we proceeded to develop any AltConfigs hardware and software, a series of modeling calculations were performed that showed that there could be a significant reduction in generator run time for a hybrid system with a generator but no solar PV array, even if the AltConfigs unit were to be used to effect finish charging only. The amount by which the generator run time would be reduced depended on the exact inputs to the model, but for several situations was approximately one third. This should lead to a significant reduction in the maintenance needed for engine/generators in actual solar hybrid systems.

Although the model appeared to be a fairly accurate predictor of the electrical performance of batteries in an alternative configuration system, we decided to present here results with an actual solar hybrid system rather than relying on modeling results, this being the subject of the next section.

EXPERIMENTAL: DEMONSTRATION OF AN ALTERNATIVE CONFIGURATION UNIT

One of the alternative configurations that we have developed has been demonstrated with a hybrid solar system at the Arizona Public Service (APS) Solar Test and Research (STAR) field test facility in Tempe, Arizona. An overall view of the system used for the AltConfigs demonstration is shown in Figure 3.

The hybrid solar system that was used for the AltConfigs demonstration is quite similar in layout to those used with remote telecommunication relaying facilities, although it is in fact designed for powering remote residences. The system has been under test with an AltConfigs breadboard unit since July, 2001. After some initial shakedown testing, the AltConfigs unit at STAR has been shown to perform as expected and has proved to be very reliable. In fact, it is said to be one of the more reliable pieces of equipment at the STAR site.

The Remote Residential Electric System (RRES) test facility that has been used for the AltConfigs demonstration at the STAR Facility consists of the following components:

- Solar PV array that can deliver up to about 2kW on a bright winter day.
- Trace PV Charge Controller, a DC-DC converter to match the voltage from the PV array to that of the main DC buss.
- Propane-fueled engine powering a 115V AC generator, having a 10kW peak power capability but used at a maximum of 4kW in the residential electric system test.

- Four-string, 48V flooded lead-acid battery, with Trojan T105 golf cart modules (6V, 225Ah units) when the demonstration was initiated and currently with US Battery modules of similar characteristics.
- Trace Power Conversion System, a 4kW AC-DC-AC converter that allows control of the flow of electricity among the engine/generator, the battery and the load.

Figure 3: Remote Residential Electric Test System used for Demonstration of Alternative Configuration Unit

The AltConfigs unit under test with the RRES consists of semi-conductor switches and current shunts in an arrangement similar to that shown in Figure 2 except that the demonstration battery has four strings rather than two, a PC104 "embedded" computer with a Compact Flash memory "hard drive" and an 8-channel A/D card, and the AltConfig controls to dispatch the switches on instructions from the software running on the PC104 computer. For this first demonstration of the capabilities of an AltConfigs units, only string voltages, not module voltages or temperatures, have been measured and recorded. Until early March 2002, the AltConfigs unit under test was a breadboard system, but a packaged pre-prototype has now been installed and will be used for further tests at STAR. The AltConfigs system, and the entire test, is run in a fully automated mode, with no personnel present except when data are downloaded from the Compact Flash card. The data are analyzed off-line. The finish charger for this system consisted of a commercial 48V, 20A commercial (115V) charger powered from the Trace inverter, so that electricity for finish charging any one string comes from the other strings.

The electric system as described above is tested with a set of loads in a separate shed, the load shack, that is connected to the electric system according to conventional practices for rural households. The loads available are a refrigerator drawing approximately 300W when running, 700W of incandescent and fluorescent lights on a timer, a swamp cooler requiring about 500W on the "High" setting at which it is always used, and, in a recent addition, a water pump simulator, on a timer system, requiring about 500W.

A sampling of the results that have been obtained in the testing of the AltConfigs unit with the RRES test facility are shown in Figures 4 and 5. In Figure 4, string voltages (left hand {LH}axis) and string currents (right hand {RH} axis) are plotted as function of time (horizontal axis, 24-hour clock) for August 11, 2001, when the loads had been set to be quite heavy. Starting at midnight, it can seen in Figure 4 that the engine/generator was running, it having been started the night before, and that the charge continued until about 3AM. At this time, the switch for String C was set so that a finish charge could occur in this string, while the other three strings were being discharged to the loads and to power the finish charger. The finish charge of String C continued until about 4AM, when the switch for

String C was set so that this string could be used, like the others, for discharge to power the loads. Note that much higher currents were delivered from String C immediately after it had been connected with the others for discharge. This results, of course, from the fact that String C had been more fully charged than the others. Note also, however, that, as predicted by the model described in the preceding section, the currents from the four strings tended towards the same value a few hours after the finish charge had been completed. The discharge of all four strings continued throughout the day on August 11. In fact, during the hours of sunlight, it can be seen that the PV array provided more electricity, at least for part of the time, than was required by the loads, so that the batteries in fact got recharged to a small extent during the day. At about 9PM, the AltConfigs software determined that the strings had been discharged to the preset number of amp-hours, so a new charge was initiated. Examination of the results for the next day showed that String D was finish charged after the charge that started at 9PM on August 11.

It should be noted that the set of tests for which results are shown on just one day of August 2001 represented a time when the highest temperatures of the year are experienced in Tempe. In fact, during the period around August 11, for which test results are shown in Figure 4, daytime temperatures were 110 F or more, and several monsoon storms passed through the area. The temperature in the RRES shed was measured at 120 F at one point during the tests. Despite these extremes, the AltConfig breadboard operated extremely well.

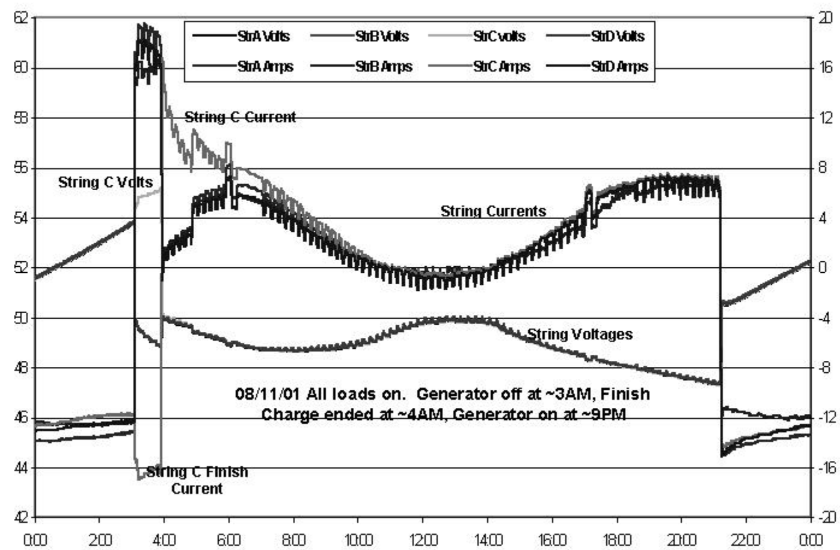

Figure 4: String voltages (LH axis) and currents (RH axis) versus time (horizontal axis, 24 hour clock) for typical day of testing of Remote Residential Electric Test System with AltConfigs unit with heavy loads

In Figure 5, string voltages (LH axis) and string currents (RH axis) recorded with the AltConfigs unit on 10/4/01 are shown. On this date, and in the days immediately preceding it, the loads had been turned off in order to test the capabilities of the AltConfigs hardware and software in this circumstance. With nothing except housekeeping loads until the lights were turned on about 6:30AM on 10/4/01, the batteries became fully charged from the PV array during the hours of sunlight. Referring to Figure 5, it can be seen that that the AltConfigs software first detected a bulk charge completion (from the PV not the generator) just after 10AM, and at that point the String C switch was set so that this string could be finish charged. In the sequence of tests, as was determined from examining data on the days preceding 10/4, String C was the next in order to be finished. This Finish Charge of String C continued until just after 3PM, at which point the String C switch was configured for discharge. At this time, all the strings were connected with their respective switches so that they could be charged or discharged, depending on input power and load requirement. However, the AltConfigs software determined that a bulk charge had, on average for all four strings, again been completed, so the switch for String D was now set so that this string could be finish charged. This Finish Charge continued until about 10:30PM, with much of the electricity for the Finish Charge of String D, and that for the loads that were now turned on, coming from the other three strings. This can be seen by examining the plot from about 4:30PM until the end of the Finish Charge of String D, during which period the voltage of the other three strings is declining, corresponding to a significant level of discharge.

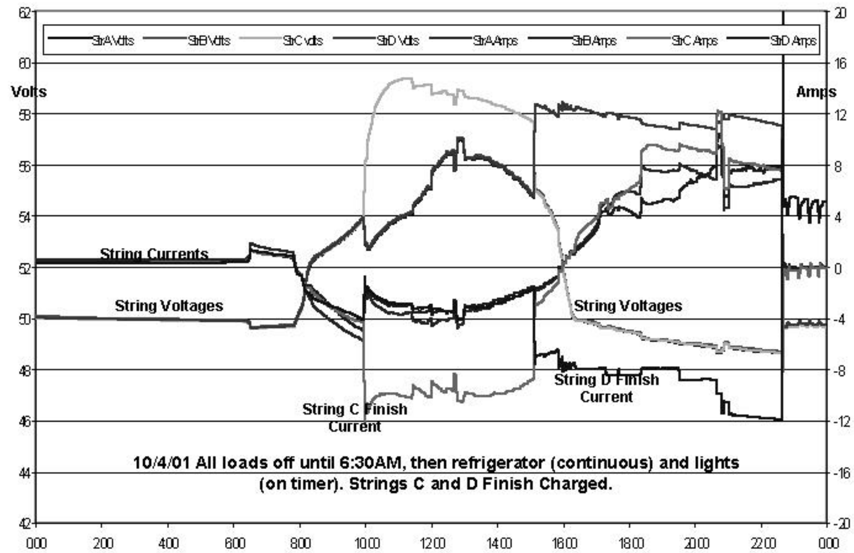

Figure 5: String voltages (LH axis) and currents (RH axis) versus time (horizontal axis, 24 hour clock) for typical day of testing of Remote Residential Electric Test System with AltConfigs unit with light loads

DISCUSSION

On the basis of analyses of data for each day of operation of the AltConfig unit with a Remote Residential Electric System at STAR, samples of which data were shown above, it appears that we have been able to demonstrate that our concept for improving the way in which the batteries of continuous power systems are managed is working very well. In current practice in such applications, finish charging of the lead-acid batteries that are used requires operating the generator inefficiently and at inappropriate times. Data has been presented indicating how the alternative configuration under test in Arizona will probably reduce the generator run time and thus increase the reliability of the electricity supply from the solar hybrid system. A significant reduction in generator maintenance cost might be expected as a result. Additionally, we have anecdotal evidence that the performance of the Trojan lead-acid batteries used for the first eight months of the test improved during this period when charge and discharge were being managed by our AltConfig demonstrator. These Trojan batteries were first installed in the test shed more than three years ago and had been abused by repeated overcharge and overdischarge in the period since they were installed.

The advantages of our alternative configuration approach when used with hybrid solar systems can be summarized as follows:

- Requirements for battery finishing charge or equalization “de-coupled” from engine/generator operations.
- Electricity from the PV array can be used for and while finish charging or equalizing.
- AltConfigs units can easily be made “smart” in relation to expected loads and anticipated solar inputs.
- Generator-starts can be performed on the basis of the performance of the weakest modules, rather than having to rely on average performance, so that overdischarge can be avoided.
- Finish charging can be easily controlled (limited) on the basis of measured module voltages and temperatures.
- There are opportunities to maximize battery and system life, performance, and to minimize life-cycle-cost.

Since the AltConfigs testing so far has indicated that there is a good chance that such units can be highly reliable, we believe that the benefits can greatly outweigh any disadvantages. We think that the cost of an AltConfigs unit could be as low as a few hundreds of dollars, or a relatively small amount compared to the cost of the other equipment in a solar hybrid system.

Beyond hybrid solar systems, we think that the alternative configuration technology could find applicability in other continuous power systems. As one example, batteries are be considered for use in load following in both grid-connected and remote applications. In such installations, an AltConfigs unit could be used to ensure that the charge and discharge of the individual strings of the batteries therein are properly, and most effectively, managed. Such systems would operate in a quite similar way to the hybrid solar system with an AltConfigs unit that has been described above.

Finally, it should be noted that the alternative configuration approach is applicable to battery technologies other that lead-acid. For example, zinc/bromine batteries and some types of nickel/cadmium batteries require complete or deep discharges on a regular basis in order to maintain their capacity to specification. An AltConfigs unit can be used to accomplish these complete discharges whilst still ensuring that part of the battery system is available to provide electricity to loads connected to it on a continuous basis. We are currently exploring ways in which this characteristic of the alternative configuration technology might be exploited.

ACKNOWLEDGEMENTS

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REFERENCE

1) U.S. Patent # 6,353,304, March 5, 2002