SOLAR BATTERY CHARGERS FOR NIMH BATTERIES[1]

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Abstract — This paper proposes new solar battery chargers for NiMH batteries. Used with portable solar panels, existing charge control methods are shown to fail in changing environmental conditions. This article discusses the reasons for the failure and introduces new voltage and temperature based charge control techniques. To increase charge speed, a Maximum Power Point Tracker is also implemented within the micro-controller of the proposed charger.

I. Introduction/Problem Motivation

Recent technological developments in thin-film photovoltaic, such as amorphous silicon [1,2] and hybrid die sensitized/photovoltaic (PV) cells [3], are leading to new generations of consumer portable solar arrays. These new arrays are lightweight, durable, and flexible and have been reported to achieve power efficiencies of up to 10% [1]. Already, commercial-off-the-shelf arrays exist that have panels embedded in fabric that can be folded to dimensions of less than 12" x 12", yet are able to produce up to 50 Watts of power [1] at 12V. These new products make solar power available to hikers, campers, soldiers-on-the-move, etc., since the arrays can now be easily carried in backpacks. Thus, the marketplace for portable solar power is beginning to significantly broaden beyond its conventional (original) boating and recreational vehicle (RV) market.

Older solar battery chargers (for RV's and boats) were primarily developed to recharge gel cell and lead acid batteries. However, since the emergence of these flexible and foldable solar arrays, there has become a need to develop solar battery chargers for more portable batteries, such as NiMH and/or Li-ion batteries that can be carried by hikers. However, charging these types of batteries with solar power leads to new research challenges that have yet to be discussed in the literature, such as: Is it possible to fast charge batteries with solar arrays in unknown outdoor environmental conditions? How should ambient temperature swings, changing illumination conditions, and other environmental changes be incorporated into charge control algorithms? Should Maximum Power Point Tracking (MPPT) be used? What are the best battery charger system architectures using these portable solar arrays? etc.

The purpose of this paper is to answer these and other open research challenges for NiMH batteries[2] being charged by the portable solar arrays. We present the following contributions:

First, in Section II of this paper, we show that existing, conventional [4-8] charge control algorithms cannot be used to properly charge NiMH batteries when used with these portable (mid-power) solar arrays. Specifically, changing weather conditions, such as light illumination, temperature, wind, etc., can actually 'trick' conventional charge controllers to believing that the battery is fully charged. Hence, charging would be falsely terminated when existing battery charging IC's [8] are used.

A system architecture for a portable solar battery charger is proposed in Section III. The architecture includes: a dc-dc converter for maximum power point tracking, a bypass switch to directly charge the battery with the solar array, and a micro-controller to regulate the charging process.

Section IV presents new, robust and reliable charge control algorithms that are suitable for charging NiMH batteries with portable solar arrays. These algorithms can easily be adapted into existing battery charger IC's [8]. One algorithm relies on the battery voltage while a second algorithm relies on the derivative of temperature. Unique to both algorithms are that they include specialized reset mechanisms to eliminate false charge termination due to changing illumination conditions, ambient temperature swings or other environmental changes. Either of these two algorithms can be used separately, but they may also be combined to improve the system robustness.

A prototype charger has been designed, built and experimentally tested. Field experiments verify that the charger is: 1) robust and reliable for solar battery charging NiMH batteries, 2) compact, and 3) that the addition of MPPT [9-10] inside the charger could maximize output power capabilities of the solar array while charging batteries with wide range of terminal voltages, e.g. 24V, 12V, 9V, etc.

[1] This work is supported by a grant from the Collaborative Technology Alliance/ Army Research Laboratory. USPTO provisional patent application 60/643,030 applied for.

[2] We consider only (the common) 'dumb' batteries that are not SMBus compliant. Solar charging SMBus compliant batteries is actually simpler since the battery informs the charger of its State of Charge (SOC).

II. Open Challenges and Research Needs

Different algorithms exist to detect when the battery reaches full State Of Charge (SOC). They can be classified into two different categories:

- Algorithms relying on records of the battery history and characteristics [11].
- Algorithms requiring no prior knowledge of the battery characteristics, such as the dV/dt or temperature based algorithms [4-7].

The first type of algorithms are suitable when the charge controller is monitoring the same battery all the time or when the battery is "smart", that is, when a circuit recording capacity, state of charge and other internal characteristics is embedded inside the battery pack and capable of exchanging data with the charge control circuit.

We focus our research on the second type of algorithm, as there is a need for a charger capable of charging a different batteries each time. In addition, the overwhelming majority of general purpose batteries available (for campers as well as soldiers) are not of the "smart" type.

NiMH batteries are normally fast-charged by regulating the input power source to behave like a constant current source. Then, the constant charging current is applied to the battery until it is desired to terminate charging. Often, a trickle or top-off charge is added after the fast-charge in order to balance the charge between the battery cells. Fig. 1 illustrates how "fast-charge" termination time is typically determined.

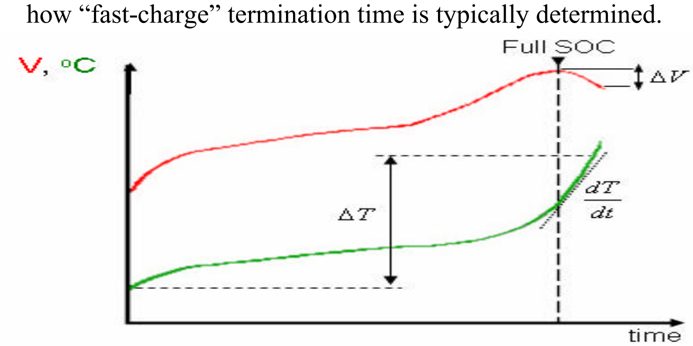

Figure 1: NiMH voltage and temperature profile for constant current charging shows multiple methods available for detecting full State Of Charge (SOC).

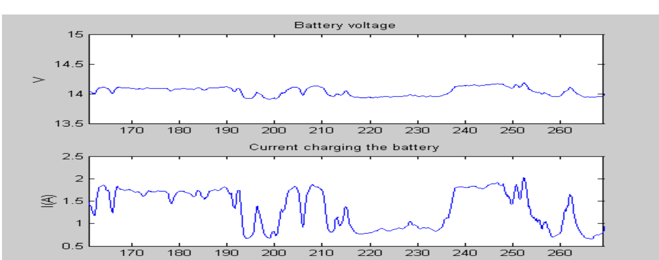

Figure 2: Voltage of the NiMH battery charged with a solar array. Drops in the voltage, due to drops in the solar array current, are falsely detected as overcharge by classical charging algorithms.

A. Existing Voltage Detection Methods Fail When Charging NiMH Batteries with Portable Solar Arrays

Common approaches to determining when NiMH batteries (charged by constant current source) are fully charged rely on measuring battery terminal voltage [4]. Occasionally, the charge process is terminated when the battery's voltage reaches a certain value. However, this is extremely unreliable and does not work when the battery is charged by different current levels or when it is placed in different ambient temperatures. Hence, it is not suitable for discussion here.

A second approach (see Fig.1), which is more prevalent, is to stop the fast-charging process when battery terminal voltage begins to drop, i.e. dV/dt < -K, where K is a positive fixed threshold value set by the user. However, once again, implicit in this approach is that the charging current remains constant during the charging process.

Figure 2 present outdoor experimental data that helps explain why negative dV/dt detection cannot be directly used to determine end-of-charge time when the power source is a solar array. In Fig. 2, a solar array is directly connected to a 12V NiMH battery. Notice that when clouds pass across the sun, the solar array's charging current decreases. This lowers the battery terminal voltage, due to the battery's internal resistance/impedance. Due to the battery's internal capacitance, the voltage continues to drop slowly until the charging process balances and the voltage starts to rise again. These drops are not negligible and are usually higher than the voltage drops due to overcharge. Moreover, they arise from weather changes and are, therefore, unpredictable. So, a charger using conventional voltage detection algorithms will falsely detect overcharge and stop the charge too early. Another approach, proposed in [5,7] is more accurate but subject to the same limitations when facing changing weather.

B. Temperature Detection Methods Fail Also

As Fig. 1 illustrates, when the battery approaches full SOC, its cells start to heat up and temperatures rise sharply. Thus, another approach to determine full SOC is to place a thermistor close to the cells. This enables detection of charge termination when dT/dt is above a threshold value.

Two temperature detection methods are mainly used:

- When the change in battery temperature over the entire charge process (defined as ΔT) reaches a certain threshold, charge is stopped. This method is not very accurate and works only if the ambient temperature is kept constant throughout the charging process.
- Charge is halted when the slope of the temperature curve rises above a threshold value.

The last method is considered more accurate than voltage based detection because the detection usually happens at full SOC. As Fig. 1 shows, voltage methods need to let the cell overcharge for a certain time until a drop is detected (except for the method proposed in [5]).

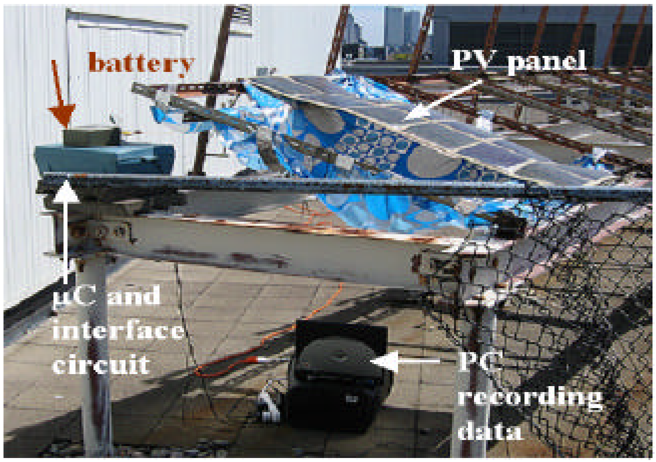

Figure 3: Experimental set-up on rooftop. The 12 V NiMH battery is charged by a solar array and is connected to a prototype battery charger with microcontroller (The size of the box is not at all related to the size of the circuit).

Unfortunately, as with voltage based detection, some challenges exist when the battery is exposed to changing weather conditions [6]:

The magnitude of dT/dt at overcharge depends heavily on ambient temperature. Since the solar arrays are used in all seasons (winter… summer), ambient temperature is unknown.

Ambient temperature swings can occur during the day due to the sunlight, and change in air and ground temperature. These changes cause increases and decreases in battery temperature.

The rise in temperature due to overcharging is dependent on the average charging currents (although temperature is less affected by a quick, sudden disturbance in the charging current. Therefore, the threshold on dT/dt required for accurate detection changes with the average charging current.

Since existing charge control algorithms and IC's are developed for constant ambient room temperature and constant preset charging current, they are not reliable when ambient temperatures vary, as in the case here.

III. Proposed Battery Charger System Architecture

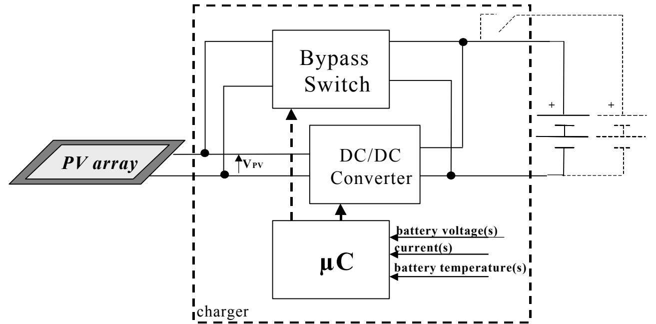

Figure 4: Proposed system architecture for the battery charger. The DC/DC converter for MPPT uses an up/down topology to increase the flexibility of the solar panel over the widest possible range of battery voltage. Depending on the configuration chosen, the battery may be comprised of different legs. Additional corresponding measurement circuits and switches for redirection of energy are then added.

Fig. 4 illustrates the proposed battery charger system architecture, which is composed of three important functional blocks – the DC/DC converter, a bypass switch and the micro-controller (μC). Additionally, the charger contains a current sense resistor to measure the charging current and a thermistor to measure ambient temperature.

The proposed architecture is valid for general solar arrays having arbitrary open circuit output voltage and arbitrary output power, provided that they are both below a maximum level. Likewise, the terminal battery voltage is arbitrary, provided it is within the specification of the DC/DC converter. Essentially, the micro-controller is able to identify the characteristics of both the array and the battery. It then adapts the best charging algorithm according to these characteristics.

Up/Down Converter – The DC/DC converter connects the solar array with the battery and provides battery charging current only when the bypass switch is off. Specifically, the converter has two primary functions

Maximum Power Point Tracking – For each illumination condition, solar arrays produce optimum power at a specific output voltage. Since the output voltage of the up/down converter is fixed to be equal to the battery terminal voltage, adjustment of duty ratio will change the converter's input voltage, which is the solar array voltage V_{PV}. Thus, the duty ratio, D, of the converter is controlled so that the solar array output voltage is operating at its maximum power point. The optimum V_{PV} for the array may occur either above or below the battery voltage. We use a modified perturbed and observe approach [9,10].

Trickle or Top-off charge – By adjusting the duty ratio, D, of the converter, the solar array's output voltage can be made close to its open circuit voltage. At this voltage, the array will produce low output power, thus making the charging current small. Hence, the converter is able to create top-off or trickle charging currents.

Bypass Switch – Portable solar arrays are manufactured to produce optimum power near a pre-specified output voltage. For example, a typical solar array for this application might have maximum power near 12V [1-3]. When it is connected directly to a 12V battery, there is no need for additional MPPT circuitry. Having a DC/DC converter in-between the array and the battery will only add additional power losses. On the other hand, if the array is optimized to charge 12V batteries and it is connected to a 24V or 9V battery, charging current would be low. Thus, a bypass switch is added to the battery charger. When the bypass switch is activated, all charging current is taken directly from the solar array, and the DC/DC converter is not utilized (off). The micro-controller determines whether charging current is taken through the converter or through the bypass switch, depending on how close the battery voltage is to the solar panel's voltage when it operates at Maximum Power Point.

Micro-Controller (µC) – The micro-controller has four primary functions: First, it collects the measurement data: battery voltage, battery charging current and battery temperature. It then controls the charge of the battery. Third, it determines whether to connect the battery to the array through a bypass switch or through the up/down converter, depending on which produces higher charging current. Finally, it controls the DC/DC converter for MPPT or trickle/top-off charging.

IV. New Charge Controller Algorithms

A. New Voltage based algorithm

As we have seen, in Section II, the issue with voltage based detection is that it gets easily fooled by changing current. The main cause of these changes is due to clouds or shade on the solar panel. These changes create large voltage drops accompanied by slow voltage decrease. The two effects combined are hard to predict. However, they can be detected by the sudden drop in current or battery voltage so that end of charge detection will be inhibited.

The voltage detection algorithm is presented in Fig. 5. The idea is to keep track of the current and reset the algorithm whenever the current departs from an acceptable limit. This ensures that any voltage drop due to a change in the current does not falsely trigger the end of charge. This leads to the condition that if the maximum and minimum of the current (Imax, Imin on Fig.5, recorded over a sliding window of around 5 minutes) departs from the average value above or below a certain level, the algorithm should reset. Overcharge can only be detected after the current returns to a constant value (over a period of time) again.

However, due to the battery's internal capacitance, the voltage will continue to drop long after the current has stabilized. To avoid false detection due to this phenomenon, the algorithm requires a positive dV/dt to rearm after it has reset. Therefore, the end of charge is based on both ΔV and on the shape of the overall voltage curve when approaching overcharge, which is characteristic of the NiMH battery.

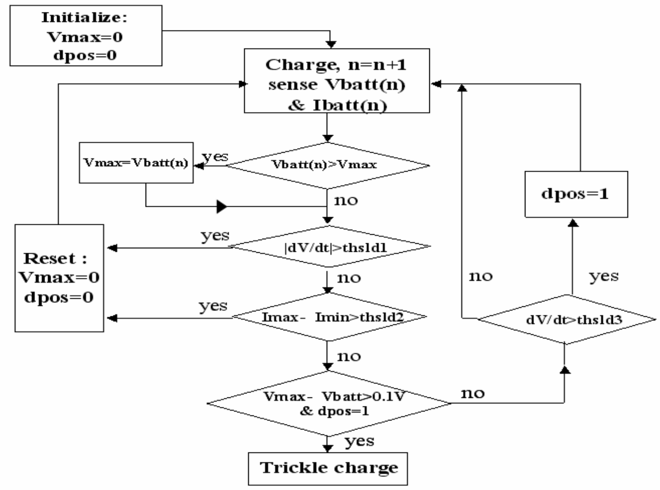

Figure 5: New dV/dt algorithm proposed to overcome the false detection issue. Large drops of voltage or current reset the algorithm. "dpos=1" means that a positive dV/dt has been detected. When dpos=1 and the voltage drops to a threshold below its maximum, the algorithm stops fast-charging. Imax and Imin are the max and min current of a 5 to 10 minutes sliding window.

When charging with constant current, this algorithm performs the same as the conventional algorithm with (maybe) a higher requirement in the ΔV required to halt charging for robustness purpose (ΔVthsld=0.1V for a 12V battery or 10mV per cell). This ΔVthsld can be modified based on the ambient temperature measurement and charging current.

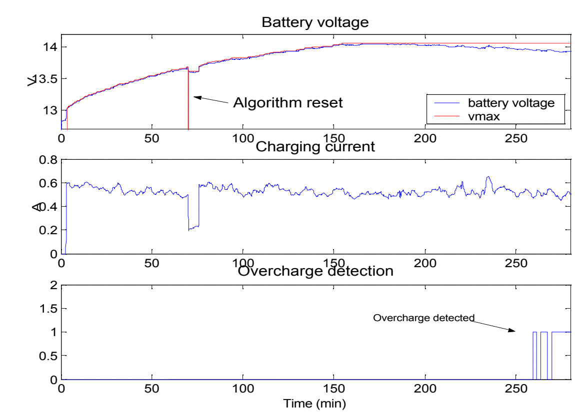

Figure 6: Demonstration of the algorithm's ability to handle disturbances in the current. At t=65min, the drop in the current (due to shade) is detected and the algorithm did not get fooled. At t=260min, overcharge is detected.

Fig. 6 presents typical experimental results that verify the accuracy and robustness of the proposed charging algorithm.

As the figure shows, charge termination was properly determined, despite the fact that there were changing illumination conditions causing different charging currents. It is important to note that conventional, known voltage detection charge algorithms fail to properly charge the battery (because they falsely terminate the charge at around t=65 min in this case). The experiment is based on charging a 12V NiMH battery using a 30W commercial solar panel. The experiment was operated on a rooftop, as shown in Fig. 3.

This algorithm, however, has some limitations:

- If the algorithm resets repeatedly, there are chances that it will miss the voltage detection;
- Thresholds must be carefully chosen, otherwise false detection might still occur.

B. New Differential Temperature Algorithm

To improve the robustness of the charge control algorithm in changing environments, we propose to use differential measurement of temperature. This involves separating the batteries into two (or more) groups.

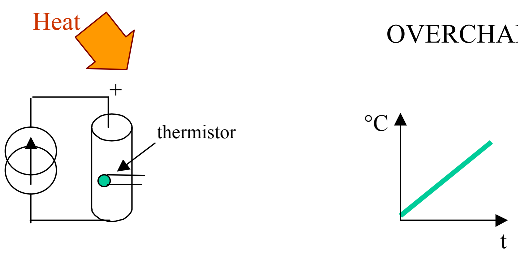

Figure 7-a: The algorithm has no way of telling whether the rise in temperature is due to the external source of heat or overcharge.

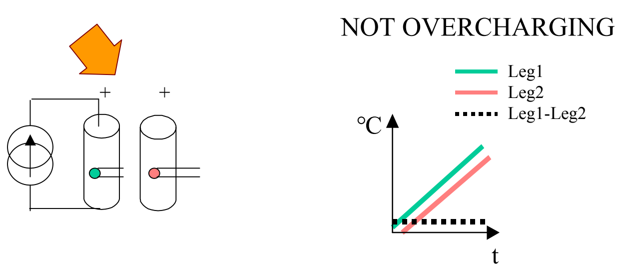

Figure 7-b: A second leg that is certified not overcharging (here it is open circuited) can restore the information by comparison. In this illustration, the rise is due to external heating. Leg1 has not reached full SOC yet.

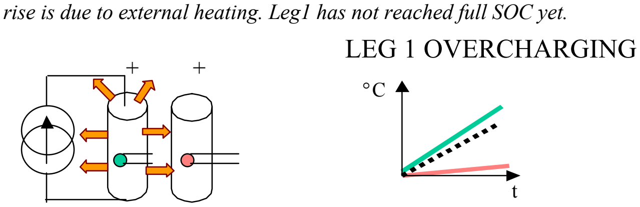

Figure 7-c: Here the battery in Leg1 reached full SOC and starts to generate a lot of heat. Its surface temperature rises much faster than its neighbor Leg2) and overcharge is detected.

The method, illustrated in principle in Figure 7, relies on the fact that changes in ambient conditions affect both legs the same. Thus, the difference in temperature between the two legs stays close to zero unless one leg reaches full SOC. When that happens, both temperature difference and the derivative of temperature difference rise sharply. This way full SOC can be detected in one leg. Of course, this assumes that the two legs are not reaching full SOC or overcharging at the same time. This can be ensured if one leg is open-circuited.

We use two legs to perform differential measurement rather than an ambient temperature thermistor. This is because the temperature measured by the ambient temperature thermistor tends to have a lower correlation with the cells temperature because their thermal time constants are different. This is illustrated in Figure 8.

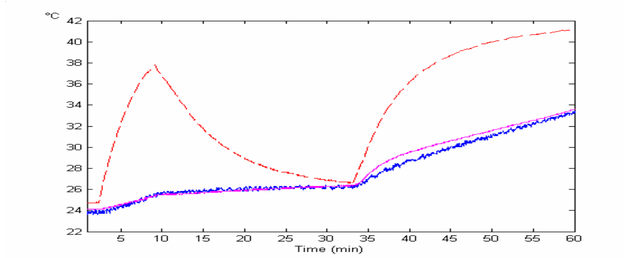

Figure 8: Ambient temperature measurement can lose its utility when the thermistor measuring ambient temperature is placed near a body that has a thermal time constant different from thermal time constant of the cells. The thermistor measuring ambient temperature (dashed line) that is placed in the charger free space reacts very quickly to irradiation by a source of heat while the temperature inside the battery pack (solid lines, one for each leg) takes more time to react. So, differential measurement with the external thermistor loses its direct simplicity.

Charge balance should be kept as much as possible between the two legs. Large unbalance results in reduced operational time and may even damage to the battery (because of the over- discharging of some batteries that might result when the batteries are used in series) if the user removes the batteries from the charger before every cells reached full SOC (something that can be expected).

The algorithm proposed is shown in Fig 9. The cells are separated into two groups and charged either in parallel or through an independent charging circuit. When a high increase in temperature is detected in one of the groups (Leg 1 for example), the algorithm switches to "potential overcharge mode" : The leg (Leg1) is kept charging while the other is stopped. The algorithm will run in this mode for a certain set time. During this time, if a strong differential in the cells temperature arises (high $d(T_1-T_2)/dt$ and/or high (T1-T2), then the algorithm will detect overcharge (of Leg 1 in our example). If no overcharge has been detected after a certain time, the algorithm will switch back to charging both legs. The unbalance that has occurred during this time can be absorbed by either current monitoring (where the proportion of current flowing in one leg vs. the other leg is controlled) or naturally, by having the legs in parallel.

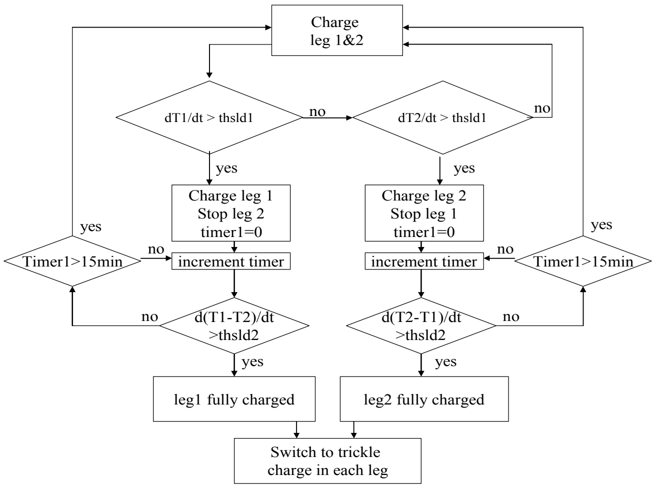

Figure 9: Proposed charge control algorithm. Each leg is first monitored. When high rise in temperature is detected in one leg, the charge is stopped momentarily in the other leg which becomes a "reference" leg. If a strong and fast rising differential appears (d(T1-T2)/dt>thsld), overcharge is detected in one leg. Often, balance can be assumed so the second leg can be assumed to be fully charged as well

Thresholds are dependant on the average charging current (calculated over a sliding window of five minutes) and are stored in a look-up table.

V. More Experimental Results

The charge control experiments were performed using a sealed 2x12V (two 12V legs) NiMH battery consisting of 20 cells (10 in series, 2 in parallel) and built-in thermistors for each leg. The solar panel is a 30W solar panel available to the public and is typical for this application.

A charger implementing the algorithm of Fig.9 was built. The algorithm is programmed in a micro-controller and senses the cells' temperature through two thermistors. Some results are shown in Fig 10. We have chosen to put the legs in parallel when both are charging. The battery is heated by a strong halogen lamp (for 20 minutes) to simulate harsh external conditions. As explained in Fig. 10, the algorithm enters the "potential overcharge mode" on Leg2 but does not identify any overcharge and resumes charging. At that time, it can be seen that the legs naturally rebalance themselves. Leg1 gets all the current and progressively shares it again with Leg2. Both legs reach full SOC at the same time. At that moment, high temperature increase puts the algorithm again in "potential overcharge mode", stopping momentarily the charge in Leg2. This time, overcharge will be detected on Leg1 and then on Leg2.

Different options exist when full SOC has been detected in one leg:

- The legs can be assumed to be balanced. In this case, the other leg can be considered to be also fully charged. The system switches to trickle charge in both legs.
- If the legs cannot be assumed to be balanced after finishing charging one leg, the algorithm has to finish charging the other leg before displaying full charge. In this case, the threshold values for overcharge detection are modified because of the high differential already created by the other leg (the one that has been detected as fully charged).

In the experiment shown in Fig 10, when one leg has been detected as fully charged, the other one is assumed to be fully charged or very close to full charge as well and the charging process ends (this is supported by our observations).

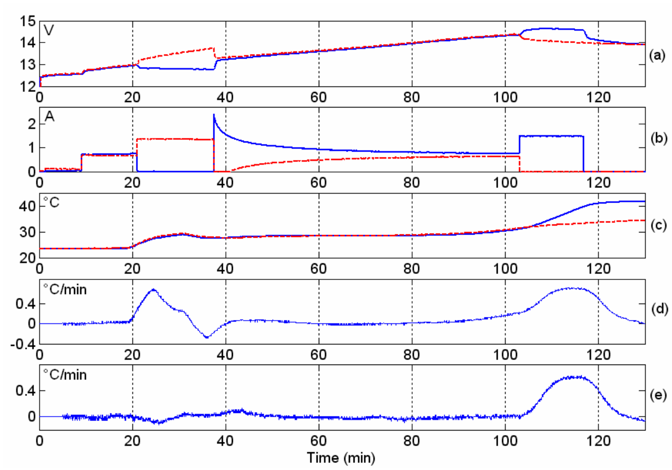

Figure 10: (a) voltage of the two legs, (b) charging current in each leg, (c) temperature of each leg, (d) derivative of temperature at Leg1(calculated over a sliding window of 5min), (e) derivative of the difference of the temperatures.
The charging process starts at t=10min.
- At t=20min, a strong heat source (a halogen lamp) is aimed at the battery. (d) shows the derivative of temperature of Leg1 (only Leg1 shown for more clarity).
- At t=22 min, this value reaches a threshold, the algorithm stops the charge in Leg1, but keeps it in Leg2 (All the current is redirected to Leg2). As can be seen in (e), the derivative of the difference in temperatures between the two legs stays at very low levels during that time (t=22 to 37 min).
- At t=34 min, the source was turned off explaining the drop in the temperature of both legs.
- At t=37min, 15 minutes after, the algorithm deduces that the elevation of temperature was caused by external conditions and resumes charging both legs. During that time no charge was lost since current kept flowing in the battery at the same rate. A rebalance process is then occurring where the Leg1 (which was cut-off) gets all the current from the source in addition to some current from Leg2.
- At t=105min a high rise in temperature is detected again, this time, stopping the charge in Leg2. This rise is due to full SOC being reached on both legs.
With one leg cut off and another leg charging near full SOC, a strong differential arises in the temperatures as seen in (c). This results in a large derivative of the temperature difference.
The algorithm detected full SOC at t=118min..
Note how detection based on simple measurement would have failed in this case, as (d) shows, the rate of elevation at t=25min (external heating) is comparable to that of t=118min (one leg overcharging).

Maximum Power Point Tracking (MPPT)

MPPT is realized using a Perturb&Observe algorithm [9,10]. Classical Perturb & Observe algorithms measure the output current and voltage of the solar panel to calculate the output power. The variable controlled is the voltage of the solar panel (input voltage of the DC/DC converter) through the duty cycle of the DC/DC converter.

In our design, the power delivered to the battery is proportional to the amount of charging current. Therefore, by making sure that maximum current is delivered to the battery, we make sure that maximum power is delivered as well. This is only true when the battery is not connected to any load.

Also, care needs to be taken when using this simplification: The value tracked is the power at the output of the DC/DC converter rather than the power at the output of the PV array (the way it is usually done). Local maxima could arise due to the varying efficiency of the converter at different points. This is the maximum efficiency point of the DC/DC converter is not the same as the maximum power point of the solar panel. However, we did not experience any local maxima due to the DC/DC converter (SEPIC topology) in our system.

Battery voltage.	Direct connection between solar panel and battery.	Current when the proposed battery charger is used.
2.4V	280 mA	430mA
4.8V	660 mA	720 mA
12V	310 mA	310 mA
24V	0 mA	160 mA

Table 1: Current transferred to the various batteries with and without the proposed battery charger. (Experiment involving 4.8V, 12V and 24V were done at same light intensity. The one with the 2.4V was done in lower light intensity).

Improvement in the charging rate with MPPT is presented in Table 1 for a variety of batteries. The experiments were performed at low light intensity using halogen lamp and a fan to cool down the solar panel. Notice that MPPT increases charging current for a broad range of battery voltage except for the 12V battery. The PV module is built to have optimized output power around 12V. Therefore, the controller uses the bypass switch instead of the DC-DC converter when connected to 12V batteries, thus eliminating the losses in the DC-DC converter.

VI. Conclusion

In this article we have shown that existing NiMH charge control algorithms fail in changing environmental conditions (changing weather, changing current). This paper proposes two new charge controller algorithms to overcome this problem. The new algorithms are more robust to variations in current and temperature. By adding a Maximum Power Point Tracker (MPPT) within the controller, higher charging current can often be achieved. This quickens charging time and adds flexibility to the overall system because it becomes able to efficiently charge batteries with wide terminal voltage.

[1] www.globalsolar.com

[2] www.uni-solar.com

[3] www.konarka.com

[4] G. Danese, F. Leporati, R. Lombardi, M. Nucita, G. Pedrazzini and G. Ricotti, "An instrument for the characterization of voltage and temperature profile in NiCd and NiMH batteries", *Proceedings of the 23rd Euromicro Conference,* 1997, pp. 178 - 183.

[5] M. Gonzalez, M.A. Perez, J.C. Campo and F.J. Ferrero, "Accurate detection algorithm of battery full-capacity under fast-charge", *Proceedings of Instrumentation and Measurement Technology Conference,* 1998, vol 2 , pp. 755 – 759.

[6] C.B. Falcon, "Temperature termination and the thermal characteristics of NiCd and NiMH batteries", *WESCON/94. 'Idea/Microelectronics'. Conference Record,* 1994, pp. 309 – 315.

[7] M. Gonzalez, F.J Ferrero, J.C. Anton and M.A. Perez ,"Considerations to improve the practical design of universal and full-effective NiCd/NiMH battery fast-chargers" *Applied Power Electronics Conference and Exposition, 1999,* vol.1, pp. 167 – 173.

[8] F. Lima, J.N. Ramalho, D. Tavares, J.Duarte, C. Albuquerque,T. Marques,A. Geraldes, A.P Casimiro,G. Renkema, J. Been and W. Groeneveld, "A novel universal battery charger for NiCd, NiMH, Li-ion and Li-polymer", *Conference on European Solid-State Circuits,* 2003, pp. 209 – 212.

[9] E. Koutroulis, K. Kalaitzakis and N.C. Voulgaris, "Development of a microcontroller-based, photovoltaic maximum power point tracking control system", *IEEE Transactions on Power Electronics,* 2001, vol 16 , Issue: 1 , pp. 46 – 54.

[10] C.R. Sullivan and M.J. Powers, "A high-efficiency maximum power point tracker for photovoltaic arrays in a solar-powered race vehicle" *IEEE Power Electronics Specialists Conference,* 1993, pp. 574 – 580.

[11] O. Barbarisi, R. Canaletti, L. Glielmo, M. Gosso and F. Vasca, "State of charge estimator for NiMH batteries"; *Proceedings of the 41st IEEE Conference on Decision and Control*, 2002 , vol.2, pp. 1739 – 1744.