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A "ONE-WIRE" BATTERY MONITORING SYSTEM WITH
APPLICATIONS TO ON-BOARD CHARGING
FOR ELECTRIC VEHICLES

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1.0 INTRODUCTION

The use of Lead-Acid batteries with gelled electrolyte in electric vehicles (EVs) promises a significant reduction in EV maintenance. Such batteries, subsequently referred to as "Gel Batteries", are being produced by Johnson Controls under the name of "Gel Cell". Gel Battery technology reduces outgassing of the cells to practically zero and makes it possible to eliminate the maintenance cost associated with watering.

Gel Cell application for traction is problematic because Gel Cells are sensitive to exceeding the gassing voltage ¹ during charging. This is because the characteristic recombination of oxygen at the negative electrode of gel batteries during charging causes considerable differences in cell gassing voltage from one cell to the other when battery cells are connected in series. Therefore, voltage limitation during charging in terms of a battery charge voltage limit is likely to overcharge some cells while others are undercharged.

As a first step to solve the charging problem, a charge method was developed at UAH that allows charging of strings of cells without under or overcharging any of the cells. The method uses the change

¹ The gassing voltage is here defined as the cell voltage at which oxygen production in the cell exceeds oxygen recombination.

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in cell resistance and the corresponding cell voltage rise with the onset of gassing to control the charge current.

Initial laboratory tests of the new charge algorithm for lead-acid batteries with gelled electrolyte on 96V battery packs yielded promising results in terms of high battery efficiency and the ability of the algorithm to facilitate reproducible discharge capacity [R1].

The successful application of the charge algorithm to electric vehicle batteries lead to the next step: an investigation of the cost associated with installation of the necessary hardware to run the algorithm under user conditions and ways to reduce this cost. The complex charge algorithm requires the availability of a fully programmable charger² that is interfaced with a microprocessor controller. The microprocessor is programmed with the charge algorithm and used as a means to translate voltage input signals from the battery modules into a control output signal to the charger that produces the charge current.

Three major costs items are involved in this charge system: (1), the cost of the programmable power supply, (2), the cost of the

²"Fully Programmable" means here that an arbitrary current profile can be programmed.

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microprocessor controller which runs the charge algorithm software, and (3) the cost of monitoring individual module voltages which requires one data acquisition channel per module and an appropriate wiring harness to measure module voltages.

To reduce the cost of microprocessor controlled charging, work was done to investigate the possibility of sharing one charge controller between several vehicles, thus reducing the number of needed controllers. The resulting charge system accommodates the simultaneous charging of several batteries, whereby each battery may be switched on-line at a different time and with a different state-of-charge of the battery. This work was reported in reference [2].

Controller sharing is feasible only under special circumstances where fleet vehicles are operated at common charge stations. Further, even with shared controller charging, each controller needs a substantial amount of electronics, proportional to the number of cell voltages that need to be monitored. This makes the controller expensive. Therefore, a reduction of cost associated with single cell monitoring was the next step in our effort to make the application of our charge algorithm economically feasible.

When the UAH charge algorithm for gelled batteries was developed,

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it was seen that the practical application of this algorithm would depend primarily on the availability of an inexpensive microprocessor-based control system. In particular, the monitoring cost per channel needed to be drastically reduced if the algorithm was to be economically feasible. There was no obvious solution of this problem available and any research into this problem was risky and without certainty of success. EEPL therefore started an in-house program using EEPL funds to investigate various ideas to reduce the electronics for voltage monitoring. This work was begun as a major effort in 1987 and came to a first conclusion in the Spring of 1989 when the first workable prototype was tested. It was decided to patent the procedure and the University of Alabama agreed to transfer patent rights to Dr. Nowak. He subsequently applied for a patent in Spring 1989. In the following months additional testing confirmed the validity of the concept and EEPL proposed to INEL the prototype testing of such a system in an electric automobile.

Meanwhile, a parallel charger development was initiated as an in-house research project, cooperatively with the Aachen University in Germany. A new and highly efficient programmable on-board charger was developed that was ready for testing about the time that the monitoring system was completed. It was, therefore, decided to combine the two systems into a complete charge control system for

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on-board charging. The new charger technology is a 20 kHz switching power supply based on bipolar transistors that is both lightweight and highly efficient, with a power factor of unity.³

This report concerns the description and the test results of the total charge system which consists of three components: (a) the UAH charge algorithm for batteries with gelled electrolyte, (b) a new data acquisition and control system that greatly reduces the amount of electronics needed for single cell voltage monitoring (and therefore cost) as compared to conventional systems, and (c) a lightweight, low volume and highly efficient ($\eta > 90\%$) switching power supply with a unity power factor to deliver the charge power to the vehicle battery.

Section 2 describes the battery charge system hardware and operating system. It also indicates the capabilities of the system and gives test results obtained from charge/discharge cycles with the charge control system using the new "One-Wire" monitoring method, subsequently called "One-Wire". Section 3 is a project summary.

³ Meanwhile a second model working with 40 kHz has been developed.

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2.0 CHARGE SYSTEM HARDWARE

In order to be economical, on-board charge systems of the future need to be efficient, inexpensive, lightweight, small in size and programmable⁴. In addition, the electric utilities will require a minimum distortion on the power line once these chargers appear in great numbers. This means that the power factor needs to be near 1.0. Consequently, the charge current must be in phase with the AC line voltage. The result is a pulse mode charge profile where the charge current is periodic with the AC line frequency. Further, the charger should be programmable to accommodate different battery types and the charge controller requires state-of-charge information on the battery cells to optimize the charge current profile.

The charge system is designed to satisfy these requirements. The power supply is seen in Figures 1 and 2. It is based on power electronic concepts that have been in development at ISEA, Aachen University, Germany for several years.

The microprocessor-based charge controller is seen in Figure 3 with 2 floppy disk drives. It uses the inexpensive Z80B microprocessor and has all interfaces and accessories to run the charger and to

⁴ "Programmable" here means that an arbitrary charge profile can be delivered.

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monitor the battery, on two boards. The wiring harness for monitoring the cell voltages is seen in Figure 4. It is simple to install and inexpensive, consisting of one strand of wire and a voltage pick-up sensor at each module of the battery pack. Section 2.1 compares our charger technology with conventional technology.

2.1 Comparison Between the 20 ISEA kHz Charger and a Conventional Charger.

The ISEA power unit offers substantial advantages over known conventional designs in terms of weight, space requirement, versatility and efficiency. The present prototype unit compares with the most recent EV charger from Lester (Lestronics) as follows:

	20 kHz Charger	Lestronic
Dimensions	11x6x15.5 inch	14x8x18.5 inch
Weight	19 kg	46 kg
Power Output (nominal)	3.5 kW	3.5 kW
DC Current (max)	30 A	30 A
AC voltage	220-240 V	198-256V (60 Hz)
DC voltage (nominal)	96 V	96 V
Efficiency	>90%	not known

From this data it is seen that although the 20 kHz charger is a handmade prototype without optimized design, the Lestronic charger is twice the volume and 2 1/2 times the weight. With a more efficient design, the weight of the 20 kHz charger can be

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substantially reduced.

The charger has a power factor of practically 1.0. As seen in Figure 5, the input current and voltage are synchronized yielding an output DC current which is a square sine function at 60 Hz. This characteristic leaves the power line network undisturbed from harmonic distortion. Because of the sine square current output, the battery is pulse charged at 60 Hz. At 30A average charge current, the charge current peak is 120A with a current profile as indicated in Figure 5.

In contrast, conventional linear series and shunt regulators operate in a continuous conduction mode, dissipating comparatively large amounts of power. SCR chargers show a poor line input current in terms of power factor. All low frequency (60 Hz) chargers need a heavy and large transformer for isolating line and battery potential.

2.2 Comparison of the Charger Control with Conventional Charger Control.

Charger control of the UAH system is divided into two areas. One area is responsible for ensuring that charge current and AC voltage are in phase and for monitoring charge component performance and providing safety functions in case the performance of charger

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components is outside the operating envelope. This control is subsequently called "internal charge control". The other area concerns the monitoring of the batteries and the optimization of the charge current profile according to a predefined charge algorithm.⁵ This control is subsequently called "external charge control". Internal and external charge control are physically separated. The power factor control and safety functions are analog circuits to provide the fast reaction speeds that are necessary in case of emergency. This part of the control electronics is independent of the microprocessor-based charge current control which is also responsible for collecting data on the battery during charging as input for the charge algorithm that transforms this information into a charge current output signal.

Because of the analog nature of the internal control, this part of control cannot be altered without hardware change. The microprocessor-based charge current control (external control) is highly flexible and allows the implementation of different charge strategies for different batteries by just changing the software that runs the controller (changing disks).

⁵ Note, that an algorithm is a set of rules that do not necessarily result in the same charge profile for each cycle. In fact, our algorithm produces different charge profiles in consecutive cycles, indicating that the battery condition is never identical.

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In comparison, conventional charger control for electric automobiles is very limited. Older charger models have only overcurrent and overvoltage protection: newer models include high temperature protection. The programmable Lester charger (Lestronic) allows the user to set the maximum charge current, the battery voltage limit compensated for temperature and a timer to set the trickle charge duration. Recent models for forklifts have a microprocessor for decision-making in case of battery irregularities but use generally the same constant current, constant voltage, constant current charge profile, that has become the industry standard for charging deep cycle lead-acid batteries.

2.3 Comparison Between Conventional Methods of Cell Voltage Monitoring and the One-Wire Method.

Cell/module voltage monitoring is frequently employed for industrial batteries using conventional microprocessor (computer) based monitoring systems. Voltage monitoring has the problem that the negative post of a cell/module within a battery string can have a voltage in excess of 100V with reference to battery ground. Thus, the cell voltage cannot be input directly into the computer system which can usually not tolerate more than 15V. Voltage isolation requires differential voltage isolation amplifiers for each cell/module and therefore a considerable amount of electronics. Common mode isolation between the battery and controller is

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provided by an impedance of 400 k Ω , enough to provide some protection against injury from electric shock. However, care must be taken not to touch high voltage leads and grounds simultaneously. In addition, a substantial amount of wiring is required because each positive battery post must have its own wire to the control system. During cell hook-up, care must be taken that the voltage wire corresponds with the cell identification in the software; otherwise the software will associate the wrong cell number with a measured cell voltage. This makes cell voltage monitoring expensive⁶, cumbersome and also more failure prone because of the many connections needed for the system. The labor required to make and install the wire harness is usually substantial.

Figure 6 compares the amount of the electronics hardware of a 60 cell conventional monitoring system and a 60 cell one-wire monitoring system. The UAH monitoring system harness is a single strand of wire, as indicated in Figure 4 and in subsequent Section 2.5. On this wire are a number of nodes (T-connections, see Figure 7) equal to the number of batteries and each node is randomly connected to the battery positive post by a voltage pick-up sensor. No hook-up errors can be made during installation. The voltage

⁶ 1 ft of 60 conductor flat cable cost between \$ 1.30 and \$ 2.00.

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pick-up sensor is an inexpensive electronic circuit. Installation of this system is fast, simple and inexpensive. There is complete voltage isolation between controller system and battery and virtually no way to get an electric shock by handling the wire harness unless the voltage sensors are defective. Therefore, the harness provides maximum safety for the personnel working around the battery. Voltage isolation from the battery also protects the controller electronics.

2.4 Technology Description of the On-Board Charging System.

This section provides a discussion of the technology that went into the charge system. The system with all components is seen in Figure 8. The figure indicates the three components of the high frequency switching power supply consisting of the input stage, the booster stage and the DC/DC resonant converter. Figure 8 also indicates how the battery is connected via a rectifier bridge to the power supply. The left-hand side of the figure indicates the four block diagrams for the system control. First, there is the power factor control and charger protection electronic (internal) charger control. Then there is the microprocessor-based charge control (external control) that implements the charge algorithm and communicates with the one-wire driver which operates the one-wire cell voltage monitoring harness with the voltage sensors called OWC in the figure and seen below the battery symbols. Both internal

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and external charge control are connected to a power supply, providing 5V, -15 to +15 V and 12V.

2.4.1 Charger

One of the primary objectives of switching power technology is to reduce charge transformer size and weight. A transformer is needed in any charge system to provide isolation between battery and charger for safety reasons. If line voltage is transformed to battery voltage at high AC frequency, the transformer can be much smaller than if the voltage transformation is at 60 Hz line frequency. AC line power is converted to DC before it is input to a transistor switching network that produces high frequency AC. It is then transformed to battery charge voltage AC and rectified at that level. In order to keep currents through the transformer small to minimize conductive losses and to maintain a continuous charge current (see discussion below), the AC line voltage is boosted to between 340V and 600V DC depending on nominal battery voltage. A special circuit arrangement switches the needed power transistors, which convert DC to high frequency AC at precisely the moment when no current flows through the transistors. Therefore, switching is essentially without loss. In addition, the internal controller switches the transistors such that the charge current is in phase with the AC charge voltage, thereby providing a unity power factor. The charger technology is discussed in more detail

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below.

The power at Point 1 in Figure 8 is AC line power with a sinusoidal line voltage. The internal control circuit of the power supply, that is located downstream of the AC input, regulates the incoming AC current such that it is in phase with the AC voltage. After conversion to DC, the charge current value

$$\frac{1}{T} \int_T I_{dc}(t) dt = I_{charge}$$

is set equal to that requested by the external charge controller. The current and the voltage behavior at the various Points in the charger from AC input to DC output are seen in Figure 9.

The input power passes through a rectifier bridge resulting in a pulsed rectified voltage with 340V peak voltage and current as seen in Figure 9.3. The voltage pulses drop below the battery voltage periodically. This would result in periods of zero current flow, extending the charge time. To maintain a steady current into the battery, a device is needed which allows a current to flow at all times. This is accomplished by the booster stage. The boost converter uses the energy storage capability of an inductor to transfer energy from low voltage DC to the higher voltage DC link (see Figure 8) with maximum efficiency such that the current is always flowing and is sinusoidal as is needed to generate a unity

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power factor. Use of a more conventional rectifier-choke arrangement would cause high harmonics on the power line and, therefore, a low power factor.

The booster stage consists of the inductor, L, the transistor, T1, and the diode, D1. The inductor is an energy storage device. The energy is stored in the magnetic field that exists while current passes through the coil when the transistor, T1, is conducting. When the transistor is switched off, the energy in the magnetic field causes the current to keep flowing by reversing the coil voltage. The current flows through the diode, D1, since the voltage across the coil will increase after transistor switch-off until the voltage difference across the diode is high enough to allow the current flow. The on and off switching process of the transistor, T1, occurs 20,000 times per second and the on/off time relationship is such that a sinusoidal current draw is generated that is in phase with the incoming AC voltage. This is seen in Figure 9.4 where the on/off switching time of the transistor T1 is seen to vary with the magnitude of the AC voltage. With this type of arrangement charge current flows into the DC link even if the rectified line voltage is below battery voltage as is seen in Figure 9.3 and 9.6. The effective DC link voltage at any time is at least 340V. Hence the battery voltage is lower than the DC link voltage. A DC/DC converter reduces the link voltage to battery

charge voltage.

Referring to Figure 8 the DC/DC converter works as follows.

One side of the transformer primary is connected to the center of the DC link capacitors (C in Figure 8). The series capacitors (as seen in Figure 8) make the converter a soft switching (zero current switching) resonant converter by forming a resonant circuit with the stray inductance of the transformer. This results in significantly reduced switching losses and radio interference. Consequently, the power supply has high efficiency and low electronic pollution. The other side of the transformer is connected to two transistors T₂ and T₂^{*}. Switching the transistors alternately to higher (+ w.r.t. primary winding) or lower (- w.r.t. winding) voltage, causes the voltage across the primary to alternate. In this context, if the transistor T₂ is switched on (T₂^{*}=off) then half of the DC link voltage is applied to positive terminal of the transformer. This causes a current to flow into the battery. The current will increase at first and then decrease again to zero as seen in Figure 9.8. This is because the capacitor C_{res} in Figure 8 is charged opposite to the transformer voltage by the battery current. Then Transistor T₂ is switched off at zero current through the transistor. This switching at zero current significantly decreases switching losses of the transistors that would be high if the transistor was switched while current is still

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flowing. Also radio interference would be high. The magnetic current of the transformer now charges C2 and discharges C2* in Figure 8, which causes the transformer voltage to reverse. This completes the 1/2 AC cycle seen in Figure 8.9. To start the other half of the cycle transistor T2 is switched on and the operation continues analogously to the first half of the cycle. On the battery side of the transformer a bridge rectifies the output current.

The converter offers the transformer isolation which is needed for safety reasons. The half bridge design has been chosen to reduce the number of power transistors and driver circuits needed for the converter. In addition, the connection of the output transformer to the center of the DC link capacitor suppresses DC current in the transformers primary, making the DC/DC converter more efficient. Figure 9.7 through 9.9 illustrates the effect of the DC/DC converter on current and voltage.

Different battery voltages can be accommodated by the charger by simply changing the transformer. This is done by choosing the right number of windings in the transformers. All other components of the charger do not change with the battery voltage.

2.4.2 Internal Charger Control

Internal charger control provides unity power factor and safety functions for the charger.

Unity power factor is attained by measuring the AC voltage, comparing it to the current output and adjusting the current output continually such that it is in phase with the AC voltage input. This is done by the link PWM to the driver circuit DV of transistor T1 in Figure 8.

The protective functions of the battery charger are listed below:

- 1) overcurrent circuit breaker - Disconnects the charger from the AC lines if a diode or a transistor fails.
- 2) overtemperature protection - If the heatsink temperature exceeds 60°C, a fan is turned on. If temperature increases further the current is automatically reduced to allow safe operation.
- 3) overcurrent protection - Both battery current and line current are limited to safe values.
- 4) low line voltage protection - If line voltage drops below 200V the charger stops operation.
- 5) low battery voltage protection - If battery voltage drops below 77V the charger stops operation.
- 6) DC link overvoltage protection - If DC link voltage exceeds

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620V, which may occur if no battery is connected to the charger or an internal component failure occurred, the charger stops operation.

2.4.3 Charge Current Control

The charge current controller needed for the implementation of the charge algorithm is basically an industrial microprocessor-based data acquisition and control system. In principle, any IBM PC equipped with input/output boards could serve as a charge controller if it were not for the price of such a system, its bulky size and the environmental requirements that are needed to operate a PC. Such a machine is not made for the outdoors or vehicle on-board operation. Therefore using PC's is not a practical approach for a charge controller.

The charge controller used in the UAH system is a high performance, microprocessor-based industrial grade control and data acquisition system with a highly efficient architecture. Its data structure is DOS compatible. This allows the data to be accessed by IBM compatible computers and processed with commercial software such as Lotus 123. Data are collected with a maximum speed of 8,000 measurements per second with 14-bit resolution. The controller is seen in Figure 4. The figure indicates the two boards (CPU and I/O board) each not larger than the base area of a 5 1/4 disk drive.

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The two boards of the controller have two serial ports, a Centronic parallel port, an SCSI bus and a floppy disk controller that can accommodate up to four disk drives. Twenty-four analog input channels with 14-bit accuracy and 8 analog output channels with 12-bit accuracy as well as 16 digital input channels and 64 digital output channel are also provided. However, only three of the analog channels are actually used for control and voltage monitoring.

The charge algorithm that is used by the system for batteries with gelled electrolyte is described in detail elsewhere [References 1, 2, and 3]. Therefore, only a brief description is given here.

The algorithm uses the effect that the onset of gassing in a battery is accompanied by an increase in its internal resistance. This is indicated by a significant increase in voltage of those cells/modules that are beginning to gas. By comparing the maximum and minimum cell (module) voltages in the battery pack, the onset of gassing can be determined by observing when the voltage difference increases strongly. This is taken as a signal that the current acceptance limit of the battery has been reached and the charge current should be reduced slightly below the present current level. The current is then held constant for some time until the current acceptance of the first cell is reached and an increase of

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the voltage spread occurs. This procedure can be used to control charging at the current acceptance limit of the battery. The charge schedule consists, therefore, of a series of constant current charge periods. Whenever the current acceptance of the module with the highest voltage is reached, as is indicated by an increase in the voltage spread, then the current is reduced by a small step, such that all modules are charged at or slightly below maximum charge acceptance.

2.4.4 Cell Voltage Monitoring

The one-wire voltage monitoring system is basically a software analog to digital conversion. The result is similar to the one that would be obtained if at each positive battery post location there was an analog to digital converter sending the cell voltage value through a signal wire to the data acquisition system. There are, of course, several methods to achieve this measurement and local A/D conversion is just one of them. The problem with most of these methods is that the implementation is very expensive requiring a considerable amount of electronics at the voltage sensor location.

The UAH one-wire method that has been demonstrated in this project replaces extensive hardware by extensive software. Once the software is developed, the method is low-cost to apply and,

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therefore, economically feasible. In principle, an electronic signal is sent through the sensor wire which is modulated at each of the low-cost voltage sensors that are located at each positive battery port. The modulated signal is analyzed in the controller microprocessor and the analysis provides battery cell location and corresponding cell voltage.

The method requires a considerable amount of software and fast processing, since 200 data readings are taken for each cell voltage and the analysis has to be done in real time. In addition, the data acquisition of the signals through the one-wire line has to be very precise. The signal transmission is virtually noise free. However, the electronics for the signal converter in the controller is susceptible to noise and must be protected. This, of course, requires a careful design of the hardware. A noise-free environment cannot be counted on, so it is necessary to apply noise filters in terms of software routines to get a clean voltage signal. Problems still remain if electronic noise is severe, such as is the case with corroded battery line connectors or similar disturbances of the cell voltage monitoring hardware. However, under normal circumstances of battery operation, even under the influence of SCR controlled power supplies or high frequency switching, battery voltage monitoring of 96V battery packs was satisfactory.

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The one-wire monitoring system underwent several tests. These tests concerned repeatability of the module voltage measurements, accuracy of the measured voltages against values taken with a commercial 3.5 digital voltmeter (open voltage measurements) and a HP 3497 data acquisition system, susceptibility to electronic noise and the ability of the system to work in conjunction with a switching power supply during charging.

Repeatability tests were done on a six module battery pack at open circuit voltage. Data were taken with the "One-Wire" system for several hours on different days. Data were displayed on the CRT (see Figure 10). A plot-out of data over a 20 minute period is shown in Figure 11. The test results in the figure are typical. It is seen that the data variation is within the acceptable limits (-5 to +5 mV). The indicated voltage variation is probably due to electronic noise and would also be experienced with a conventional data acquisition system.

Accuracy tests were done by comparing one-wire test results with a Fluke 77 Voltmeter. The voltmeter measurement of voltage is based on the averaging of many samples which is the reason that it takes a short time for the reading on the meter to stabilize. Comparing instantaneous one-wire measurements with voltmeter measurements showed a deviation of -12 to +12 mV. If the one-wire measurements

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were subjected to an averaging process simulating the voltmeter, the deviation was reduced to -2 to +2 mV.

To compare the quality of measurements made with the "One-Wire" system with those of a conventional system, the complete charging system was installed in an electric vehicle (EVA Pacer) with a 96V Gel IV battery from JCI and operated using the UAH charging algorithm for batteries with gelled electrolyte. To monitor the functions of the charger as well as the module voltage, a Wyse 30 monitor was used. The monitor displayed certain conditions of the charge components as well as the module voltages along with information on error of the reading (See Figure 10). The system underwent several charge/discharge cycles. For comparison, the battery in the car was also connected with a conventional wire harness to a Hewlett-Packard (HP 3497) data acquisition system. This conventional data acquisition system uses reed relays to control channels. Although relatively slow in comparison with other commercial data acquisition systems, the HP 3497 gives reliable readings of the module voltages. We, therefore, had data from a good conventional system to compare with the "One-Wire" system.

Typical test results are seen in Figure 12a and 12b. Figure 12a indicates voltage measurements of a 16 module battery pack as measured with the Hewlett-Packard system. Figure 12b is a similar

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graph of the simultaneous measurements taken with the one-wire data acquisition system. It is seen that the voltage measurements from the two systems are almost identical. The HP system has additional filtering circuits; therefore, the voltage curves appear to be smoother than for the one-wire system.

Figures 13 and 14 show additional charging data taken at various times during the charging process. These figures indicate that module voltage monitoring with the "One-Wire" system yields accurate data to serve as feedback to the charge controller. A 300 ft signal line was used in one test to determine if the signal could travel through exceptionally long signal lines. It was found that the voltages could still be measured although not reliably.

Also investigated was the influence of the number of modules in the past on the capability of the "One-Wire" system to measure individual module voltages. To this end, a 30 module battery was tested using the one-wire system (Figure 15). The results of this test indicated that the ability of the "One-Wire" system to function was not affected by the number of voltages that were measured. Thirty module voltages of 6V could be measured as well as 60 cell voltages of 2V. However, the reliability of the system was affected by the maximum battery voltage. Above 150V, the last cells of the battery string tended to produce an unreliable

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reading. Initial indications are that a problem exists with the selection of electronic components for the one-wire. This needs to be addressed as "One-Wire" system development continues.

For discharge control under electric vehicle driving conditions, the system in its present configuration is too slow. Major improvements can be expected, however, by using a faster microprocessor (at present a Z80B is in use) and more efficient programming. Because of the sizable amount of numeric data reduction required, a co-processor would speed up voltage monitoring substantially. It is anticipated that the system can be made fast enough for voltage monitoring under dynamic discharge conditions during driving.

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3.0 SUMMARY

A novel on-board charge system which utilizes a "One-Wire" system for voltage monitoring has been discussed and test results obtained using the system have been presented. The system consists of a 20 kHz high frequency charger, an algorithm for charging lead-acid batteries with gelled electrolyte, such that gassing is avoided, the control system to implement this charge algorithm and a one-wire battery monitoring system to provide cell/module voltage information to the battery charge controller. Prototype elements of the system have been tested and the system was installed into an EVA Pacer electric vehicle. Charge tests were performed and data taken with the system installed. All elements of the system functioned properly under user conditions. In particular, the charger demonstrated good efficiency, near unity power factor and full programmability. The charge controller functioned reliably and without flaw. The one-wire monitoring system which permits monitoring of cell/module voltages in a battery pack without an extensive conventional wire harness was proven effective and voltage measurements were taken fast enough for control of charging. It was found that for the purpose of voltage monitoring under driving conditions, the system in its present form is too slow. However, areas of improvement were identified that would speed up the data processing to the point that the one-wire monitoring system would be capable of voltage monitoring during

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dynamic load discharging as it occurs during driving an electric vehicle.

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Figure 1. The Battery Charger.

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Figure 2. The Interior of the Battery Charger.

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Figure 3. External Charge Controller.

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Figure 4. One-Wire Harness.

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Figure 5. DC Current and AC Voltage of the Charger.

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Figure 6. Conventional 60 Cell Monitoring System.
One-Wire 60 Cell Monitoring System.

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Figure 7. Voltage Sensor.

Figure 8. On-Board Charging System.

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Figure 9. Time Functions of Voltage and Current at Various Stations of the Charger. Each number corresponds to a station number in the diagram of Figure 8.

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Figure 10. Screen Display of the On-Board Charging System.

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Figure 11. Long Term Monitoring of 5 Open-Circuit Voltages of a 5 Module Battery with the "One-Wire" System.

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(a) Conventional System

(b) "One-Wire" System

Figure 12. Charge Voltages of 5 Cells.

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Figure 13a

Figure 13b

Figure 13c

Figure 13d

Figure 13. Test Results of Charging a Gel Cell Battery while Monitoring Module Voltages with the "One-Wire" Monitoring System. The voltage spread in Figure 13c is the difference between maximum and minimum module voltage and serves as control voltage for setting the charge current. Figure 13d indicates the pressure development in a selected cell during charging. At the beginning of charge, there is an underpressure and at the end of the constant current phase, there is the maximum cell pressure which levels off because of recombination in the current taper phase.

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Figure 14a

Figure 14b

Figure 14c

Figure 14d

Figure 14. Test Results demonstrating the Effect of Overcharge (Charge time with 30A constant current is too long). Because of gassing, there is a large voltage increase of the module voltages and a corresponding overshoot in the control voltage represented by the voltage spread of Figure 14c. The voltage spread and module voltage overshoot are correlated to the relative cell pressure in Figure 14d which is the absolute cell pressure minus atmospheric pressure.

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Figure 15. 60 Cell Battery Voltage Monitoring System (white objects are voltage sensors). All sensors are on the same strand of wire, (one wire simplifying the harness).

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