FAST BATTERY-TO-BATTERY CHARGE

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Summary

This paper reports on investigations of the feasibility of the fast recharge of an electric vehicle battery from a stationary battery. A model for battery discharge simulation is presented. A real-time simulation of a battery with this model in combination with a real battery is used to simulate various ways of battery-to-battery charge. The validity of the simulation is tested by comparison with real battery-to-battery charge experiments. The advantages and disadvantages of different methods are discussed. Independent of battery-to-battery charge, the thermal limitations of fast battery charge, and charging at constant, resistance-free-voltage as the best method of fast battery recharge, are discussed.**

Why battery-to-battery charge

The use of electric vehicles to solve transportation needs is often limited by the length of time required to recharge electric vehicle batteries. Between six and ten hours are required for the total recharge of a small electric passenger car from the 230 V circuit usually available in the home since a fast battery recharge from the utility grid requires an expensive, special electric unit. Fast battery charge is desirable for all types of electric vehicles that only have relatively short stops and whose required daily range is beyond that provided by the capacity of the battery. The resulting facilities, if implemented on a large scale, may also produce high peak utility loads for brief periods of time.

One possible solution to these problems is to use a stationary battery pack, which has previously been recharged at a low rate, as the source of electric energy. The stationary pack provides load leveling and reduction in line pollution, such as harmonics, since the stationary pack charger will operate at low power. The mobile pack can be directly connected to the

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stationary pack during recharge. The presence of a stationary battery pack would make local energy storage from alternative energy sources such as wind turbines and photovoltaics possible and perhaps more attractive in cost.

An expected disadvantage of fast battery-to-battery recharge, besides the costs of purchase and installation of the additional battery and associated equipment, is the smaller energy efficiency as compared with direct recharge due to the additional transmission of energy. Since the losses of the fast recharge depend greatly on the recharge current, the state of charge of both batteries, and the recharge time, the effect that different fast battery-to-battery recharge methods have on efficiency and power requirements had to be determined.

Due to the properties of lead/acid batteries, and most other types of batteries, the method of fast recharge by applying high *constant* currents cannot be used to recharge a battery completely. Since the poor efficiency of battery recharging with high currents is mainly caused by the high losses which occur while charging a nearly-fully-charged battery, investigations to determine whether battery-to-battery charge can provide a full recharge of the vehicular battery were necessary.

The project focused on lead/acid batteries, because they are still the only type of batteries used in practice for electric vehicles.

Methodology of the experiments

Battery-to-battery charge is possible in many different ways: the two batteries can vary in nominal voltage and/or nominal capacity, and the booster voltage necessary to drive current from one battery into the other at a sufficiently high rate can be provided by either the increased voltage of the stationary battery or by any other kind of d.c. voltage source.

One approach using different battery voltages is described in a recent Japanese paper [1], while a suggestion for a variable d.c. source, suitable for recharge of the stationary battery as well as for boosting during the battery-to-battery charge, has already been patented in Germany [2].

It was desired to test several of these methods, including parameter variations. Since batteries are only available with integer multiples of the single cell voltage, testing several possible stationary vehicular battery voltage ratios with real batteries would require a large number of cells. In addition to the cost of the batteries themselves, the high power involved in testing large batteries is expensive and should be avoided.

On the other hand, a total simulation of battery-to-battery recharge is not practicable since, as yet, no accurate model describing the behavior of lead/acid batteries during the charging process exists. In order to avoid a time consuming development of such a model, a compromise between measurement and simulation was chosen.

A real battery was charged from a simulated battery with the help of a simulated booster voltage source. A Model by Runge [3] for lead/acid batteries during discharge was simplified for the purpose of this project. The model parameters for the batteries in use were determined. With a satisfactory model for the batteries being discharged, parameter variations, such as changes in nominal voltage and simulations of various booster voltage sources, were possible while only charging a 6 V battery from a computer controlled battery charger.

Thermal limitations of fast battery charge

Fast battery charge requires high battery currents which unavoidably cause losses and thus an increase in battery temperature. Since, for high currents, the internal resistance is approximately independent of the current, this resistive heat production is proportional to the square of the current. In addition, the chemical reaction associated with the energy storage in lead/acid batteries is exothermic during charge. This causes additional heat production proportional to the current. The resistive heat is the dominant contributor to the temperature rise in the battery at the high currents needed for fast charge. Thus the integral

$$\int_{T-\Delta T}^{T} i^2 \, \mathrm{d}T \qquad (1)$$

is proportional to the short term rise in temperature during the time, ΔT, at the location of heat generation. If ΔT is larger than the time needed to dissipate the heat to the environment, the heat produced before $T-\Delta T$ no longer affects the local temperature. From the battery data (1000 A permitted for 15 s or 500 A for 7.5 min) one can assume that one minute is large enough for the value of ΔT. Furthermore, it follows that for thermal security of the batteries against local overheating the inequality

$$\int_{T-1\,\mathrm{min}}^{T} i^2 \, \mathrm{d}T \leqslant 15 \times 10^6 \ \mathrm{A}^2\,\mathrm{s} \qquad (2)$$

must hold at all times when the current is larger than 500 A. From the foregoing discussion it follows that the battery can handle all currents smaller than 500 A as long as the average battery temperature, measurable as the acid temperature, does not exceed the specified temperature limit of 52 °C.

The above equations are only valid as long as the battery is not fully charged since the internal resistance of a fully charged battery for charging currents is much higher than the resistance at a lower state of charge. In a fully charged battery, therefore, a given charging current produces much more heat than it would with the same battery partially charged.

Mathematical model of the lead/acid battery during discharge

The usable charge of a battery depends on the discharge current which is drawn from the battery. Figure 1 shows a typical dependence of the usable charge on the constant discharge current for a battery with a 190 A h capacity at a 5 h rate. The reduction in usable charge at higher currents is due to a limited rate of ion diffusion to the reacting surfaces of the electrodes. About 60 A h can be used without the need of additional ions.

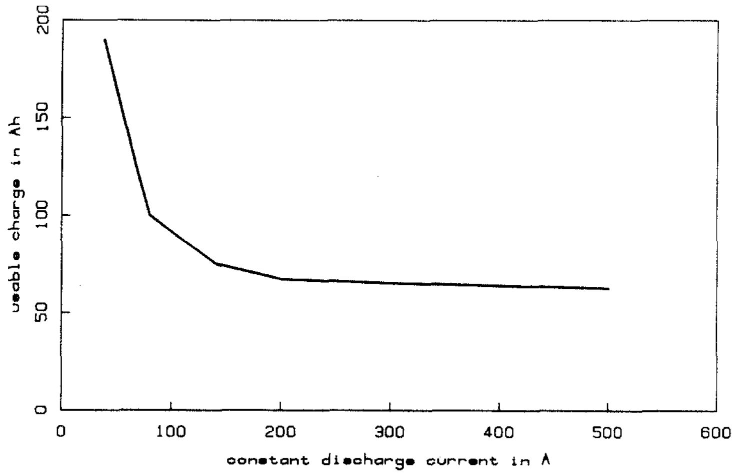

Fig. 1. Usable charge *vs.* constant discharge current for VARTA P-125X batteries.

The mathematical model used to describe the battery terminal voltage during discharge is:

$$u(t) = u_0 + \frac{1}{c}\, q(t) + r\, i(t) + a\, q(t)\, i(t) + u_{D0}\left(1 - \exp\frac{-i(t)}{i_{D0}}\right) \qquad (3)$$

with u = terminal voltage, i = battery current, negative at discharge, q = state of charge $\int i\, dt$, $q = 0$ for fully charged battery. Values of the parameters for a specific battery are given in Table 1.

TABLE 1

Battery parameters for VARTA P-125X

Parameter	Value
u_0	2.13 V/cell
c	2 570 000 Farad·cell
r	0.8 mΩ/cell
a	-2×10^{-6} Ω/A h cell
u_{D0}	−0.075 V/cell
i_{D0}	−50 A

This model includes a zero-load voltage $u_0 + (1/c)q$ (which decreases with decreasing state of charge q), an inner ohmic resistance $r + a\,q$ (which increases with decreasing state of charge), and a nonlinear voltage drop due to polarization at the electrical double layer on the electrode surface. The model reflects the behaviour of the battery quite well as long as

(i) the state of charge is well within the range of the usable charge, as shown in Fig. 1, and

(ii) changes to or from currents with absolute values smaller than $|i_{D0}|$ are slower than 40 A min^{-1} (by including one additional term in the model one can avoid this restriction; see ref. 4).

Figure 2 shows graphically the functional dependence of the terminal voltage on state of charge and current. The performance of the model during a "staircase" current discharge (0 A to 200 A and back in steps of 20 A) is shown in Fig. 3.

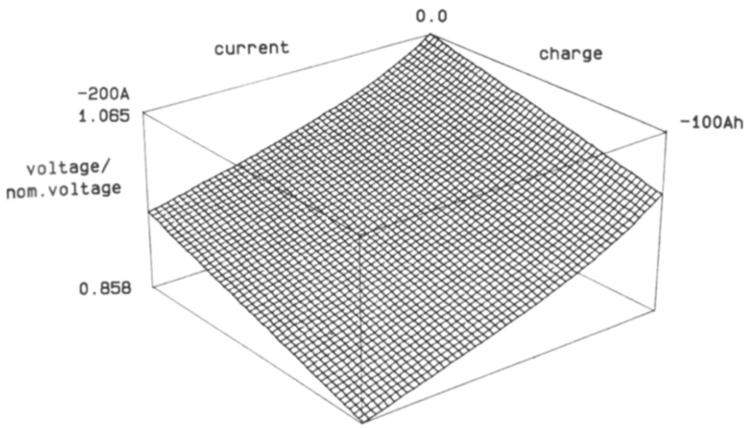

Fig. 2. Battery voltage simulation during discharge showing dependence on current and state of charge.

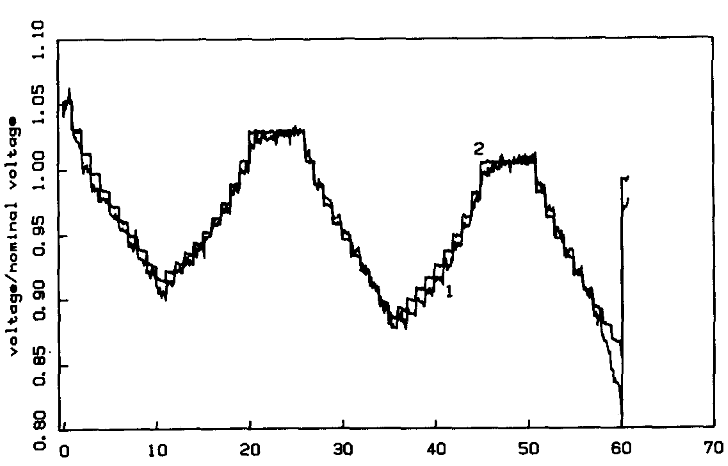

Fig. 3. Model performance: 1, measurement; 2, simulation.

Battery-to-battery charge: simulation *versus* reality

Figure 4 shows a schematic of battery-to-battery charge: a stationary battery (to be discharged) with voltage u_D is connected to the vehicular battery (to be charged) with voltage u_C. A rectifier may be used as a third voltage source, u_R, which would increase and/or control the current during the recharge. The line resistance r_L, includes the resistance of the cables, contacts, and switching elements, as well as the internal resistance of the rectifier.

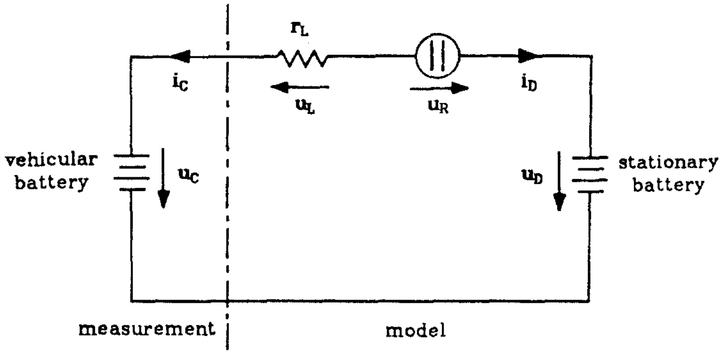

Fig. 4. Schematic of battery-to-battery charge.

In order to perform parameter variation of battery-to-battery charge, the stationary battery, rectifier, and resistance were simulated in real time, and the current into the vehicular battery was controlled at all times to fulfill the Kirchhoff laws for the schematic in Fig. 4. Figure 5 shows how this control was implemented: a Propel charge/discharge unit can drive a current of 200 A (charge) to −700 A (discharge) through a battery with a nominal voltage up to 60 V. The facility included three measurement channels. The battery current was measured on the first channel via a coaxial shunt while the terminal voltage of one 6 V battery was measured on the second channel. By means of a semiconductor temperature sensor, the temperature of the electrolyte above the plates in the middle cell of one battery was measured on the third channel. The current and the voltage signals were isolated from the battery potential by an isolation amplifier. All three channels were connected to the input of a 12-bit A/D converter in a PDP 11/03 computer.

Under the control of a program in the Tektronix 4051 and timed by a clock in the PDP 11/03, the three channels could be read up to once per second, and the current signal was integrated to obtain the charge removed from or supplied to the battery. The data were stored in a magnetic tape and simultaneously displayed graphically for continuous monitoring. The stored data were later transmitted to a PDP 11/70 computer for data processing and plotting. A reference value for the current through the batteries could be calculated and sent to the Propel unit via the D/A converter in the PDP 11/03 computer.

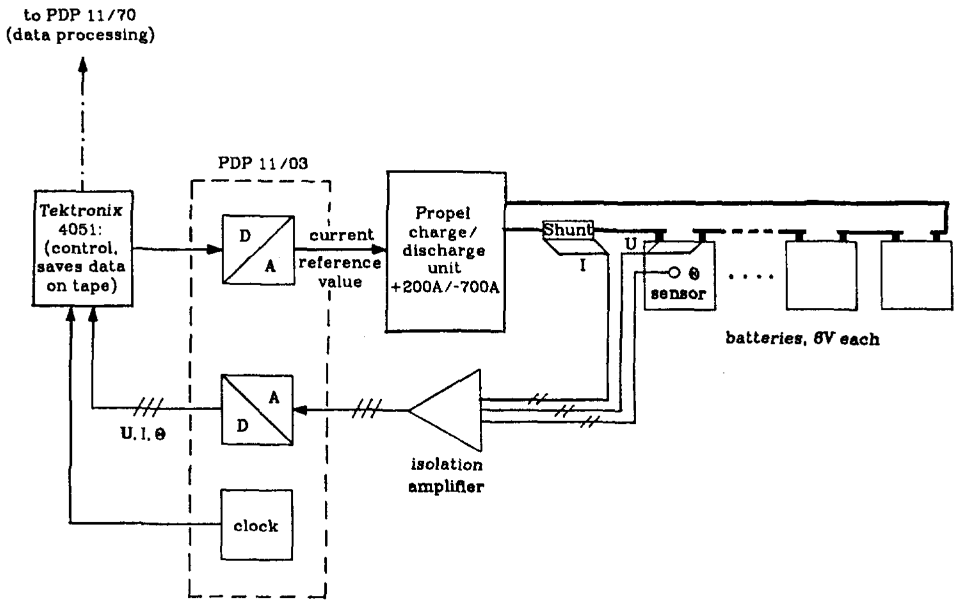

Fig. 5. Schematic of the experimental facility.

To test the simulation, real battery-to-battery charges were performed and compared with simulated battery-to-battery charges. One example without a third voltage source ($u_R = 0$), but with the stationary battery having a 25% higher nominal voltage, is shown in Figs. 6 and 7. The vehicular battery was discharged to −60 A h (which is 60% of the usable charge of the battery for EV application) before the beginning of battery-to-battery

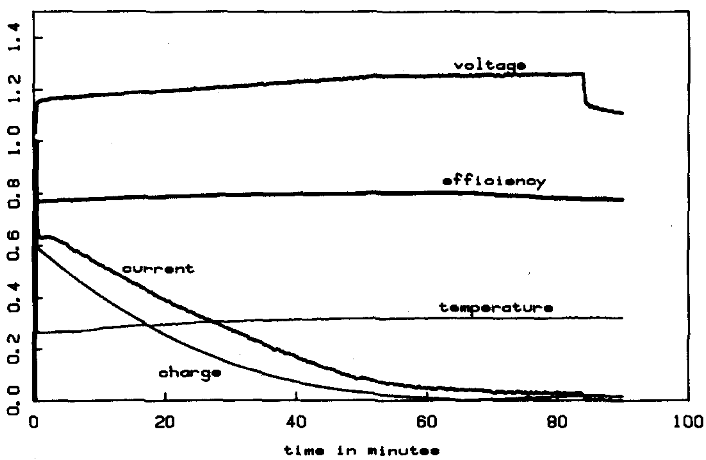

Fig. 6. Measured battery-to-battery charge (voltage ratio 1.25; initial charge of stationary battery 0 A h, or vehicular battery −60 A h). Units of vertical scale: multiply by: 6 V for voltage; 200 A for current; 100 A h for charge (absolute value); 100 °C for temperature; 100% for efficiency.

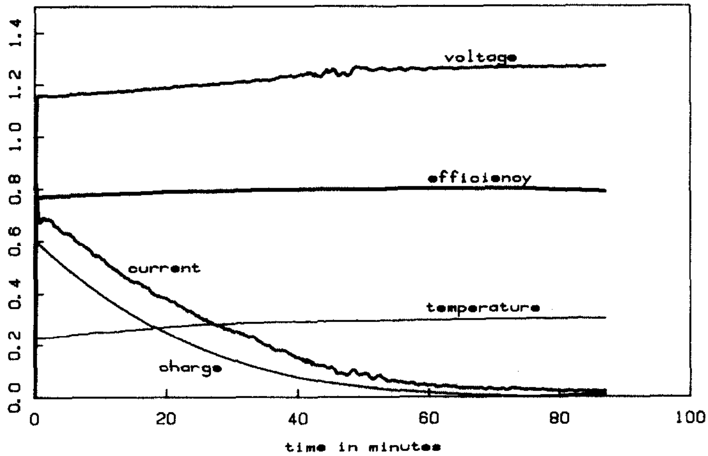

Fig. 7. Simulated battery-to-battery charge (same parameters and scales as in Fig. 6).

recharge. Comparison of the two figures shows very good agreement between simulation and reality. Only the initial current in the simulation is slightly higher since the battery model in eqn. (4) does not include the voltage drop observed at the beginning of discharges of lead/acid batteries. Furthermore, this simulation shows some instabilities in current and voltage close to the end of charge but these have been avoided by improved control during later battery-to-battery charge simulations.

Battery-to-battery charge without a third voltage source

Since during battery-to-battery charge the current is driven by the batteries themselves according to their characteristics (which are similar at charge and at discharge), this type of recharge is probably the most desirable electrochemically. A stationary battery with the same nominal capacity as the vehicular battery is capable of delivering the charge needed for a complete recharge since the current decreases automatically. Figure 8 shows the performance of such a battery-to-battery charge. State of charge and voltage shown refer to the vehicular battery. The vehicular battery had been discharged to −60 A h before recharge. The ratio of nominal voltages between stationary and vehicular battery was 1.25. The higher voltage of the stationary battery delivered an almost exponentially decreasing current through the receiving battery. At the beginning a current peak of 240 A was observed. As in all other experiments this short transient decayed completely within 15 s. After 39 min 55 A h were recharged. A variation in the initial state of charge to −100 A h at this voltage ratio increased the time to reach a state of charge of −5 A h to 80 min. The temperature rise during recharge was less than 10 °C for this voltage ratio. A higher battery temperature permitted a slightly faster recharge. The final voltage of the vehicular battery at this

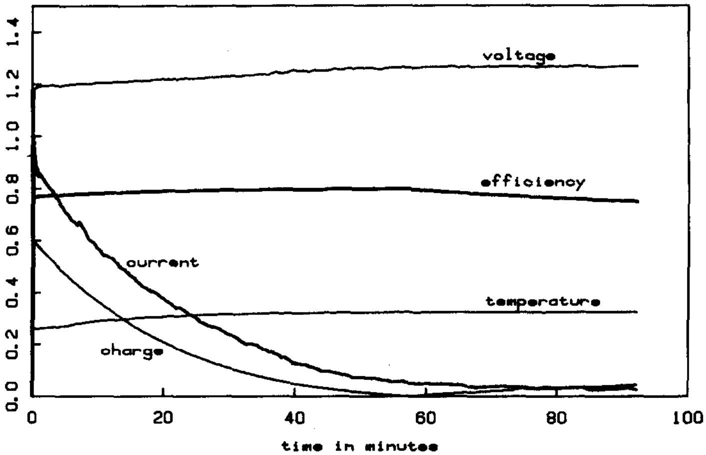

Fig. 8. Simulated battery-to-battery charge (voltage ratio 1.25; initial charge of stationary battery 0 A h, of vehicular battery —60 A h). Units of vertical scale: multiply by 96 V for voltage; 200 A for current; 100 A h for charge (absolute value); 100 °C for temperature; 100% for efficiency.

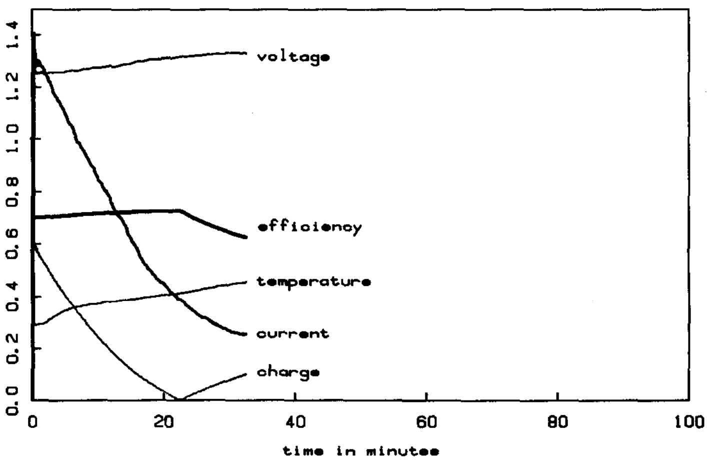

Fig. 9. Simulated battery-to-battery charge (as in Fig 8, but voltage ratio 1.375).

voltage ratio was always close to 2.53 V/cell. The efficiency of battery-to-battery charge was predominantly determined by the inverse of the voltage ratio, in this case little less than 80%.

The influence of a higher voltage ratio of 1.375 is shown in Fig. 9. The recharge time reduced to 18 min since the initial current increased. Also the final current, which only produces losses, increased, and thus the temperature rose significantly at the end of charge and would not reach an equilibrium at an acceptable temperature if the current were not shut off. The efficiency was below 73%.

Generally, the final voltage of the vehicular battery approached the nominal voltage of the stationary battery. Voltage ratios larger than 1.30

caused thermal-run-away and the speed of recharge cannot be increased beyond the value at this voltage ratio without active current control at the end of charge. In addition, efficiency considerations dictate a more leveled current pattern.

Battery-to-battery charge with a controllable third voltage

If the additional voltage is assumed to be variable, the current flow between both batteries can be controlled in a way which yields a compromise between optimal fast charging of the vehicular battery (this is considered the main goal), easy discharging of the stationary battery, and good utilization of the nominal values of the rectifier.

In this case, methods of rapid charging of lead/acid batteries must be considered. Gross [5] did a survey of such methods and the restrictions posed on these by the batteries and concluded that the method which was easiest on the batteries, while being simple to implement, is charging at constant resistance-free voltage, described by Kordesch [6]. In this method the charging current is periodically interrupted for a short time to enable the battery voltage to be measured without any resistive voltage drops. There is no time for any voltage transients caused by concentration recovery. Thus the measured voltage is the actual potential difference at the double layer which is responsible for the undesired production of gas at the electrodes. For this reason control of the resistance-free voltage also controls the gassing.

The performance of a battery charged with a constant resistance-free-voltage of 2.40 V/cell is shown in Fig. 10. With the current limited to 300 A the battery was charged at maximum current until 2.40 V/cell was reached

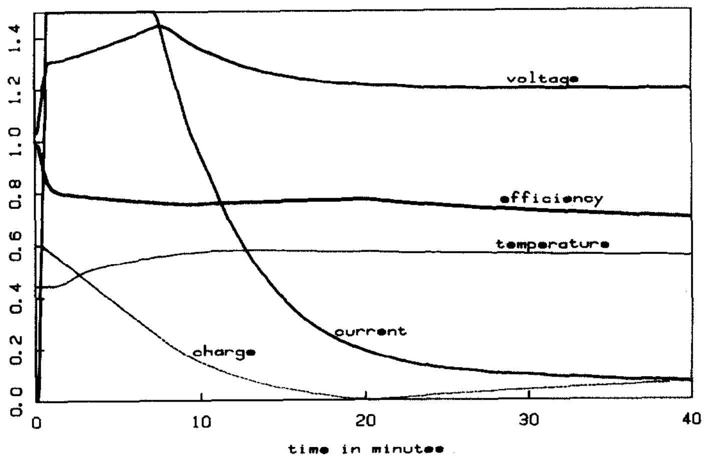

Fig. 10. Charge at constant resistance-free-voltage of 2.4 V/cell. Units of vertical scale: multiply by 2 V for voltage per cell; 200 A for current; 100 A h for charge (absolute value); 100 °C for temperature; 100% for efficiency.

at a state of charge of about −25 A h. The current then decreased rapidly. After 15 min 55 A h had been recharged and the maximum temperature rise observed was 18 °C.

If this charging method is used in battery-to-battery charge, the voltages shown in Figs. 11 and 12 are needed. In Fig. 11 both batteries have the same voltage, thus requiring an additional voltage source of 65% of their nominal value. If the stationary battery has a voltage 20% higher than that of the vehicle battery (Fig. 12), the additional voltage source only needs to supply 45% and almost no additional voltage is needed at the end of recharge. The power taken from the utility grid during such a battery-to-battery charge is shown in Fig. 13. P_{RSV} is the power in the case of a voltage ratio of 1; P'_{RSV} is the power in the case of a voltage of 1.2. For comparison the power

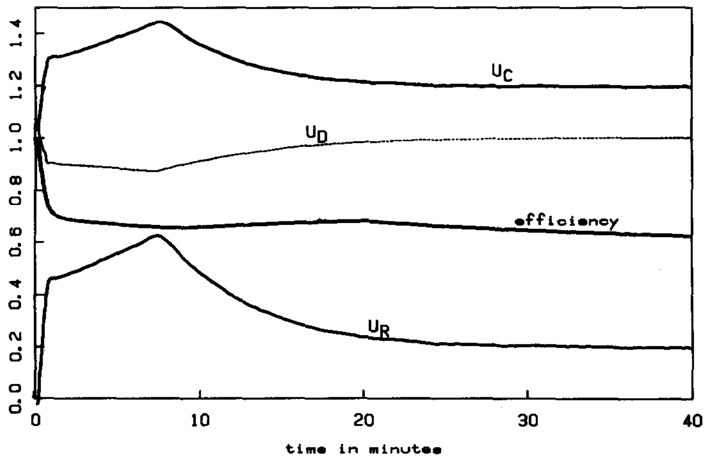

Fig. 11. Battery-to-battery charge: voltages and efficiency (charge at constant resistance-free-voltage of 2.4 V/cell; voltage ratio 1).

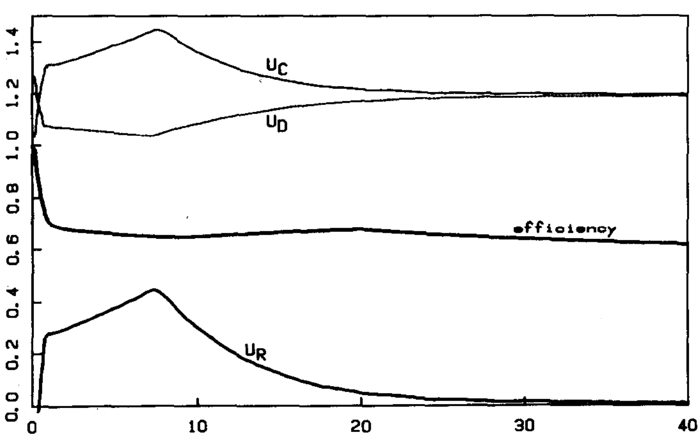

Fig. 12. Battery-to-battery charge: voltages and efficiency (charge at constant resistance-free-voltage of 2.4 V/cell; voltage ratio 1.188).

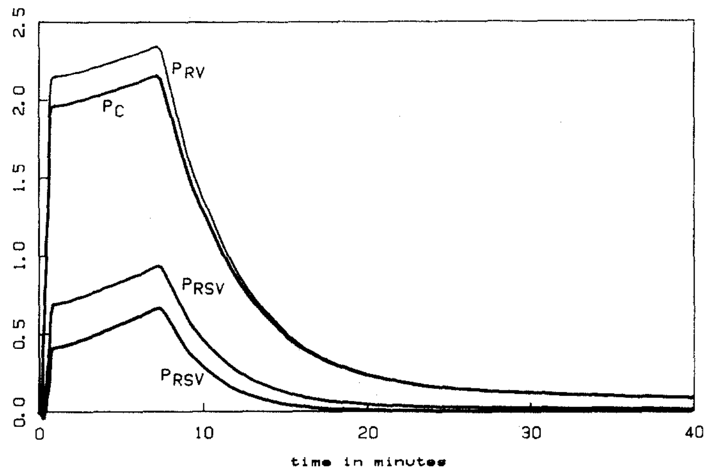

Fig. 13. Power consumption from utility grid during fast battery-to-battery charge compared with direct fast charge (P_{RV}) (charge at constant resistance-free-voltage of 2.4 V/cell; voltage ratio 1 [P_{RSV}] and 1.2 [P'_{RSV}]). Multiply by 400 W for power per cell.

at the battery being charged, P_C, and the power taken from the utility grid during a fast direct line charge, P_{RV}, is shown. It follows from Fig. 13 that battery-to-battery charge can reduce the power taken from the utility grid to less than 30% compared with fast direct line charge. The cost for this reduced peak power, however, is a need for 25% more energy due to the losses during battery-to-battery charge. To insure that the battery being discharged can provide the charge for a completely discharged battery at this high rate, it is necessary that the stationary battery has a 20% higher nominal capacity (see Fig. 1).

Conclusion

Fast battery-to-battery charge is capable of recharging a vehicular battery to about 80% of the operational capacity within 20 min or less. The optimal configuration would be a stationary battery of 20% higher nominal voltage and 20% higher nominal capacity than the vehicular battery, combined with a controllable charger capable of delivering a current of three times the operational capacity per hour at a voltage of 50% of the nominal battery voltage. To make a full and safe recharge possible, control to constant resistance-free-voltage at the end of charge is suggested. The fast battery-to-battery charge needs 25 - 30% more energy than direct fast charge while reducing the peak power demand from the utility grid to a third or a quarter of the value at direct line charge. It is essential that the battery temperature during fast battery charge is monitored continuously.

List of symbols

u	Terminal voltage
i	Battery current, negative during discharge
q	State of charge, $\int i\,dt$; $q = 0$ for fully charged battery, $q < 0$ for discharged battery, $q > 0$ for overcharged battery.
u_0	Zero-load voltage in fully charged state
c	Parameter describing dependence of zero-load voltage on state of charge (Nernst–Faraday capacitance)
r	Internal resistance in fully charged state
a	Parameter describing dependence of internal resistance on state of charge
u_{D0} i_{D0}	Two parameters describing the double-layer polarization
t	Time
u_C	Voltage of battery to be charged
u_D	Voltage of battery to be discharged
u_R	Voltage of third voltage source (rectifier)
i_C	Current of battery to be charged, negative during discharge
i_D	Current of battery to be discharged, negative during discharge
r_L	Total resistance of circuit connecting the two batteries
P_C	Power supplied to battery being charged
P_{RV}	Power taken from utility grid during fast direct charge
P_{RSV}	Power taken from the utility grid during battery-to-battery charge with voltage ratio of 1
P'_{RSV}	Power taken from the utility grid during battery-to-battery charge with voltage ratio of 1.2.

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