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# LOAD LEVELED BATTERY SYSTEM CHARACTERISTICS USING SEALED LEAD-ACID BATTERIES

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## ABSTRACT

The characteristics of a load leveled battery system were studied experimentally using a 36 V pack of sealed lead-acid batteries (38 Ah, 12 V modules) as the energy source and a 24 V pack of the same batteries as the pulse power unit. The control strategy for the load leveling was implemented such that the results could be easily interpreted relative to the use of ultracapacitors as the pulse power unit. The system response and test results are in good agreement with previously published SIMPLEV simulations of battery load leveling with pulse power batteries and ultracapacitors in electric vehicles and show the importance of high efficiency control electronics and the expected high charge/discharge efficiency of ultracapacitors to optimize system performance.

## INTRODUCTION

Batteries for electric vehicles must be designed to provide the peak power required by the vehicle during accelerations and to accept high charging power from regenerative braking during rapid vehicle decelerations. These requirements mean that the batteries must have a high maximum power density (W/kg) along with high energy density (Wh/kg), long cycle life, and relatively low cost ($/kWh) if they are to be attractive for use in electric vehicles. The requirement to design for high power density (200-400 W/kg) for most battery types results in compromises in energy density, cycle life, and cost. One approach to decoupling the power requirement from the other requirements is to load level the energy storage battery using a pulse power device that is especially designed for high power in both discharge and charge. In this way, the energy storage battery can be discharged at the average power required by the vehicle and it never experiences the transient power pulses that it must endure if it must meet the instantaneous power excursions of the vehicle driveline. There have been numerous "paper" studies (References 1-3) of load leveled battery operation, but few, if any, experimental studies or vehicle demonstrations of a battery system that consists of an energy battery and a pulse power unit. This paper, which is based on the M.S. Thesis of J.T. Guerin (Reference 4) at UC Davis, is concerned with such an experimental study directed to evaluating in the laboratory a system in which one battery pack is used to load level another with electronics to control the discharge of the energy battery based on the state-of-charge of the pulse power battery.

Ultracapacitors are a near optimum technical alternative for the pulse power unit as they have very high power density (>1000 W/kg) for both charge and discharge at all states-of-charge and very long cycle life (>200,000 cycles). The development of ultracapacitors for vehicle applications is in a relatively early stage (Reference 5,6) and units storing even 50-100 Wh are not readily available and if available, are very expensive. For these reasons, batteries rather than ultracapacitors were used as the pulse power unit in the present study of battery load leveling, but the useable Wh capacity of the pulse power battery was limited to that expected to be available from an ultracapacitor - that is 300-500 Wh in a full-scale vehicle driveline system. The response of the battery-battery and battery-ultracapacitor systems would be expected to be quite similar so the results of the present study of the battery-battery system should be relevant to the operation of future systems consisting of batteries and ultracapacitors. A second special feature of the present study is that the control electronics (a DC/DC converter chopper) is between the energy storage batteries and the load and not between the pulse battery and the load as battery-ultracapacitor systems are usually configured (Reference 7). In order to utilize this configuration, the voltage of the energy storage battery must always be above that of the pulse power unit, because the DC/DC converter can not boost the voltage if the voltage of the energy storage battery falls below that of the pulse power unit. In that case, either the battery or the pulse power unit would be forced to provide the required power to /from the load and the system will return to normal operation when the voltage of the energy battery becomes higher than that of the pulse power unit.

## DYNAMIC STRESS TEST (DST) CYCLE AND AVERAGE POWER DISCHARGE TESTS

The batteries used in this study were 12 V, 38 Ah sealed lead-acid modules from Hawker Energy Products. The module weight was 16 kg. Before the load leveled tests, a 36 V pack of these batteries was characterized to determine a baseline performance with which to compare the load leveled cycle results. Tests of the 36 V pack were performed as follows: (1) a constant current discharge at C/3, (2) DST cycle discharges with the peak power step of 80 W/kg and 120 W/kg, and (3) constant power discharges at 10 W/kg and 15 W/kg, which are the average powers for the two DST cycles. A voltage cut-off of 10.5 V per module was used for the constant current and constant power tests and 8.4 V was used for the DST cycles. Multiple tests were made using each of the discharge profiles and the batteries were charged after each discharge using the six-hour charging algorithm recommended by Hawker (15.4 A to 14.7 V, current taper at 14.7 V to 1 A, 1.9 A to 15.9 V for a total of 5 hours for the first three steps, a final step at 15.9 V for 1 hr). The results of the characterization tests were the following: 37.5 Ah at C/3, 36.5 and 36.3 Ah at 10 W/kg and 15 W/kg, respectively, and 36.1 and 33.2 Ah for the 80 W/kg and 120 W/kg DST cycle tests, respectively. There was relatively little scatter ( less than 1 Ah) in the data from repeat tests. The test results are summarized in Table 1. The effect of load leveling the battery on energy capacity can be seen by comparing the energy density for the DST cycles with the energy density for a constant power discharge at the average power of each of the DST cycles. For the DST cycle with a peak power step of 80 W/kg, the ratio of the energy densities is .99 and for the cycle with a peak power step of 120 W/kg, the ratio is .915. These characterization results indicate that the capacity of the Hawker battery is relatively insensitive to peak power for discharge on transient high power cycles like the DST. Thus on a performance basis, it can be expected that the Hawker battery would not benefit greatly from load leveling. It would, however, be anticipated that the cycle life of a large pack of the Hawker batteries would benefit from load leveling, but that was not the subject of the present study. Other batteries having lower peak power than the Hawker battery, especially those designed for maximum energy density with less attention to peak power density, would be expected to benefit much more from load leveling. The methods for investigating the effect of load leveling on the energy capacity of those batteries would be the same as presented in this paper for the Hawker batteries.

## LOAD LEVELED DISCHARGES

### Test Set-up and Instrumentation

The arrangement of the two sets of batteries and the instrumentation to measure the voltages and currents during the tests are shown in Figure 1. The discharge of the 36 V pack that is to be load leveled is controlled by the use of a DC/DC chopper (Curtis Model 1205-001). The 24 V pulse power unit consists of four 12 V Hawker modules connected in two parallel strings. The energy storage and pulse power units are connected to a Bitrode Battery Cycler, which controls their discharge. The discharge cycles used in these tests were modifications of the DST cycle as shown in Figure 2. The 36 V battery pack was charged at the end of each test using the Bitrode and the same charge algorithm cited previously for the characterization testing. The 24 V pack did not need to be charged as it was maintained at a near constant state-of-charge from the 36 V pack during the discharges. Control of the discharge of the load leveled battery with the DC chopper and data acquisition were implemented using a PC and LabTech software. Voltage and current data were taken at one second intervals and when required, were integrated to monitor the Ah and Wh out of and in to the 36 V and 24 V battery packs.

### Control Strategy

The intent of these tests was to show in the laboratory how a battery pack could be load leveled, that is discharged at near constant power, when the power demand on the battery system (energy battery plus pulse power unit) was highly transient as would be the case in an electric vehicle in stop-and-go city driving. The pulse power unit was to be maintained within a near range of state-of-charge by recharging it from the load leveled battery during periods of low power demand and from regenerative braking energy. As noted earlier in the paper, the battery pulse power unit was managed as if ultracapacitors were serving the pulse power function. A control strategy for the discharge of the system was devised and implemented that met these objectives. In the strategy, the power from the load leveled 36 V battery pack is controlled based on the net Wh that have been taken out of the 24 V pulse power battery pack. The control strategy is shown graphically in Figure 3. This is the same strategy used in the SIMPLEV computer simulations of electric and hybrid vehicles using ultracapacitors that have been discussed since 1990 in References 1-3. To relate the present tests to a full scale electric car battery system, it was assumed that the energy battery in the car weighed 350 kg and that the pulse power unit (ultracapacitors) stored 500 Wh. For this design, the test system is 1/7 scale and 70 Wh should be taken from the pulse power unit if it is to function like the ultracapacitors in the actual electric car. As shown in Figure 4, the power from the load leveled battery in the tests was maintained at the average power of the test cycle except when the pulse power unit is near full charge requiring the power from the load leveled battery to be reduced and near maximum discharge of the pulse power unit when the power from the load leveled battery is increased above the average power of the cycle. In the tests, the average power was changed to reflect the different discharge cycles and the losses in the system as they became known during the course of the tests.

### Test Data and Data Analysis

The initial tests were done using the average power for the DST cycles. These tests indicated the pulse power battery pack was gradually being discharged due to the losses in the system and that the average power from the load leveled battery should be set at 1.1-1.15 times the average power of the test cycle. When this was done, the state-of-charge of the pulse power unit was maintained in a narrow range during the complete discharge of the load leveled battery. As shown in Figure 4, the control strategy was successful in maintaining a near constant power, load leveled discharge of the 36 V battery pack even for the DST with the 120 W/kg peak power step, which would have required a peak power of 5760 W without load leveling. As shown in Figure 5, the power vs. time from the load leveled and pulse power battery packs look almost exactly as predicted by the SIMPLEV simulations of the battery-ultracapacitor systems discussed in References 1-3 using the same control strategy (Figure 3).

The primary objectives of the data analysis were to determine the energy capacity (kWh) of the load leveled battery system, the efficiencies of the overall battery system, the DC/DC chopper, and the pulse power battery pack, and the energy storage requirements (Wh) for the pulse power unit for the various discharge cycles (Figure 2). The energy flow in the load leveled battery system is shown in Figure 6. The various energy capacities and efficiencies are defined in terms of the system diagram. The results of the data analysis are discussed in the following sections:

**System Energy Capacity.** It would be desirable if the load leveled battery system would to deliver significantly more energy (kWh) to the load (vehicle driveline) than the same battery without load leveling. For this to occur, the energy capacity of the energy storage battery pack ( the 36 V pack in this study) would have to be sufficiently greater for a constant power discharge than for the transient DST discharge to overcome the losses in the system. It was noted previously in the paper that for the Hawker batteries, which exhibited only a relatively small gain (5-15%) between constant power and DST discharges, it was not likely that the load leveled battery system would show a net gain in energy capacity to the load. As shown in Table 2, this was indeed the case in the present tests, which showed a net loss of 6.8% and 3.9% for the 80 W/kg and 120 W/kg DST cycles, respectively. A net gain in energy capacity would be expected for either a lower peak power battery or a battery especially designed to maximize energy density at the discharge powers to be utilized in the load leveled battery system.

**System and Component Efficiencies.** There are unavoidable losses in the load leveled battery system as the power from the energy storage battery is controlled by the DC/DC chopper and energy flows into and out of the pulse power unit. The efficiency of the DC chopper was determined by monitoring the energy flow from the 36 V battery and out of the chopper on a second-by-second basis. As shown in Table 3, the efficiency of the chopper varied slightly with discharge cycle, but was on average 90.5%, representing a 10% loss in the electronics.

The overall system efficiency is equal to the ratio of the net energy being delivered to the load (the Bitrode tester) and the sum of the total energy discharged from the load leveled battery (the 36 V battery pack) and that needed to charge the pulse power battery to its initial state-of-charge. The system efficiencies for the various discharge cycles are also given in Table 3. These efficiencies vary from 82% to 85%. The overall system efficiency is the product of the efficiency of the electronics and the efficiency of the pulse power unit. The effective efficiency of the pulse power unit can be calculated as the ratio of the chopper and system efficiencies. As shown in Table 3, the effective efficiency of the pulse power unit (the 24V battery pack) for the various cycles varies from 91% to 94%. The actual efficiency of the pulse power unit is lower than its effective efficiency because only part of the energy discharged from the load leveled battery is stored before being send to the load. Integration of the energy to and from the pulse power unit from the load loaded battery shows that 41-42% of the energy is sent to the pulse power unit. The remainder of the energy is sent directly to the load. The actual efficiency of the pulse power unit is the ratio of the energy out of the pulse power unit to the sum of the energy coming to the unit, including regenerative braking energy, and the energy needed to return the unit to its original state-of-charge. The actual efficiencies vary between 80-85%. It would be expected that the pulse power unit efficiency would be 90-95% using ultracapacitors, which would increase the overall system efficiencies significantly.

**Pulse Power Unit Energy Storage Requirements.** The energy storage requirement (Wh) for the pulse power unit to be able to load level the energy storage battery pack depends on both the control strategy and the test cycle (the driving cycle for the vehicle). In this study, the effect of test cycle was investigated by varying the magnitude, frequency, and timing of the high power pulses in the test cycle (see Figure 2). The average discharge power, including the losses, was adjusted to reflect the test cycle. The maximum total Wh excursion of the pulse power unit was measured for each of the test cycles as the load leveled battery was discharged. The results of the tests are shown in Table 4 for the different cycles. The measured data indicate that the Wh requirement is much smaller than the 70 Wh used in planning the tests implying that less than 500 Wh would be needed in the actual electric vehicle to load level its battery pack. The inferred energy storage requirements for the full-scale vehicle application range from 200-300 Wh based on the test unit being 1/7 scale . The energy requirement can be reduced by altering the control strategy or increasing the average power at which the energy storage battery is discharged.

## SUMMARY AND CONCLUSIONS

A load leveled battery system was set up and tested in the laboratory using a battery pack as the pulse power unit. The tests were performed, however, treating the pulse power batteries as if they were ultracapacitors having a relatively small energy storage capacity ( less than 70 Wh). All the battery packs used in the tests were made up of Hawker Energy Products sealed lead-acid modules (38 Ah, 12 V). The control strategy used was the same as used in previous SIMPLEV vehicle system simulations of electric vehicle drivelines using batteries and ultracapacitors. The test results indicated that the system responded as predicted in the simulations and that the energy storage battery was discharged at nearly constant power even when the system was meeting the DST (120 W/kg) cycle. The overall system efficiency varied from 82-85% with the efficiency of the control electronics being about 90% and the effective efficiency of the pulse power unit being 91-94%. The actual efficiency of the battery pulse power unit was 80-85% for the energy that it processed. The load leveled battery system showed a net loss of capacity (4-6%) compared to the same battery pack without load leveling on the DST cycles. This result was not unexpected as the Hawker batteries showed relatively small (5-15%) differences in capacity for constant power and DST discharges. The study indicated clearly the importance of using high efficiency control electronics and the advantages of ultracapacitors, which are expected to have significantly higher efficiency than batteries as the pulse power unit.

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TABLE 1. SUMMARY OF THE CHARACTERIZATION RESULTS FOR THE 36V BATTERY PACK

| Test Cycle | Ah | kWh | Wh/kg |
|---|---|---|---|
| C/3 | 37.3 | 1.338 | 27.9 |
| 10 W/kg | 36.5 | 1.310 | 27.3 |
| 15 W/kg | 36.3 | 1.293 | 26.9 |
| DST, 80 W/kg | 36.1 | 1.24 | 25.9 |
| DST, 120 W/kg | 33.2 | 1.13 | 23.5 |

Hawker Energy Product Batteries: Sealed Lead-Acid, 12V, 38Ah, 16kg/module

TABLE 2. LOAD LEVELED BATTERY SYSTEM ENERGY CAPACITY RESULTS

| Test Cycle | Energy Capacity Gain due to Load Leveling | Loss Due to the PPU and Control Electronics | Net Efficiency Gain/Loss |
|---|---|---|---|
| DST, 80 W/kg Peak | 7.7% | 14.5% | -6.8% |
| DST, 120 W/kg Peak | 11.9% | 15.8% | -3 .9% |

TABLE 3. SUMMARY OF THE SYSTEM AND COMPONENT EFFICIENCY DATA

| Discharge | Chopper Efficiency (%) | Battery System Efficiency (%) | Effective Pulse Power Unit Efficiency (%) |
|---|---|---|---|
| DST, 80 W/kg Peak | 90.5 | 85.5 | 94.4 |
| Mod. DST #1, 80 W/kg Peak | 88.1 | 81.7 | 92.7 |
| Mod. DST #2, 80 W/kg Peak | 89.9 | 83.1 | 92.4 |
| Mod. DST #4, 80 W/kg Peak | 89.5 | 82.0 | 91.6 |
| DST, 120 W/kg Peak | 92.5 | 84.2 | 91.0 |
| Mod. DST #1, 120 W/kg Peak | 91.4 | 82.9 | 90.7 |
| Mod. DST #2, 120 W/kg Peak | 91.6 | 84.0 | 91.7 |

TABLE 4. PULSE POWER UNIT ENERGY STORAGE REQUIREMENTS FOR THE VARIOUS TEST CYCLES

| Test Cycle | Minimum Whr Range (Calculated) | PPU Whr Range (Measured) | Full Size Whr Range |
|---|---|---|---|
| DST 80W/kg Peak | 21.33 | 29.0 | 211 |
| Modified DST #1 | 20.69 | 32.1 | 234 |
| Modified DST #2 80 W/kg Peak | 20.05 | 27.7 | 202 |
| Modified DST #4 80 W/kg Peak | 22.35 | 29.8 | 217 |
| DST 120 W/kg Peak | 32.00 | 41.8 | 305 |
| Modified DST #1 120 W/kg Peak | 31.04 | 38.3 | 279 |
| Modified | 30.08 | 39.0 | 284 |

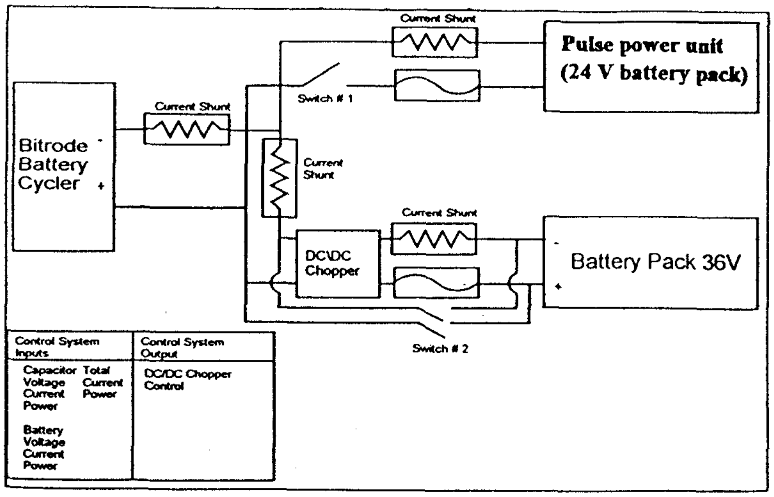


**Figure 1 : Test Set-up and Instrumentation**

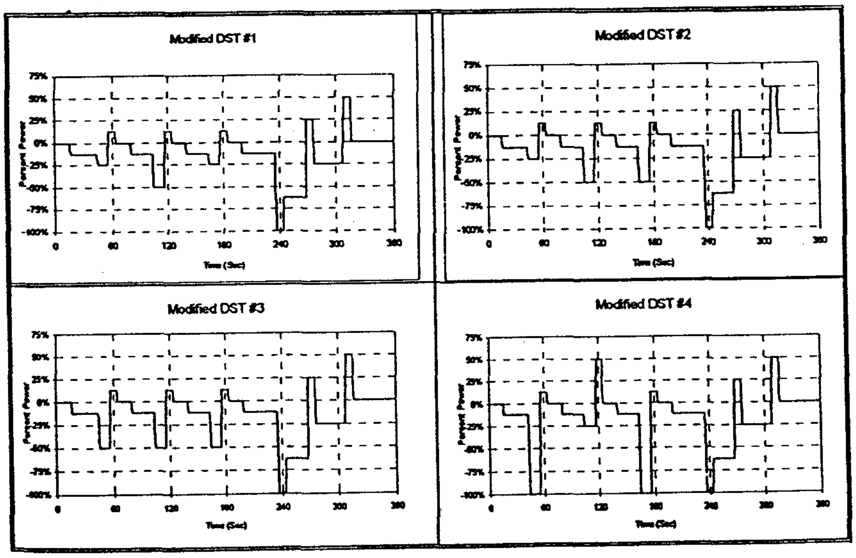


**Figure 2: Modified DST Test Cycles**

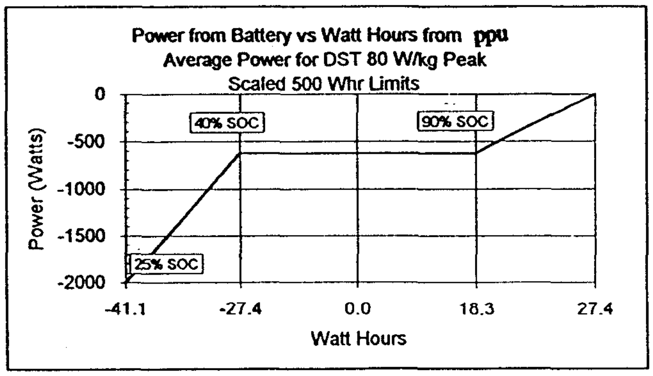


**Figure 3: Control Strategy - Load Leveled Battery Power vs. Pulse Power Unit SOC**

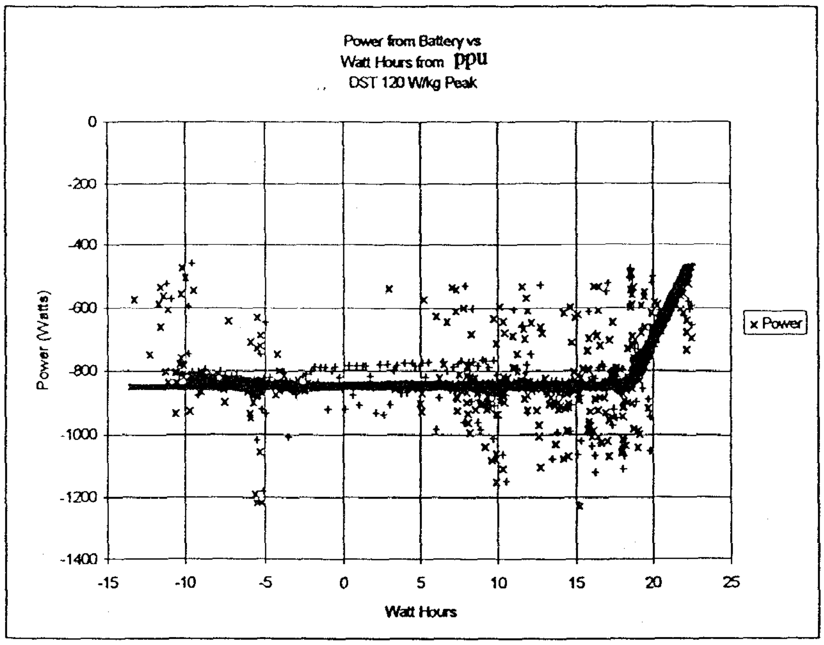


**Figure 4: Load Leveled Battery Power Test Data**

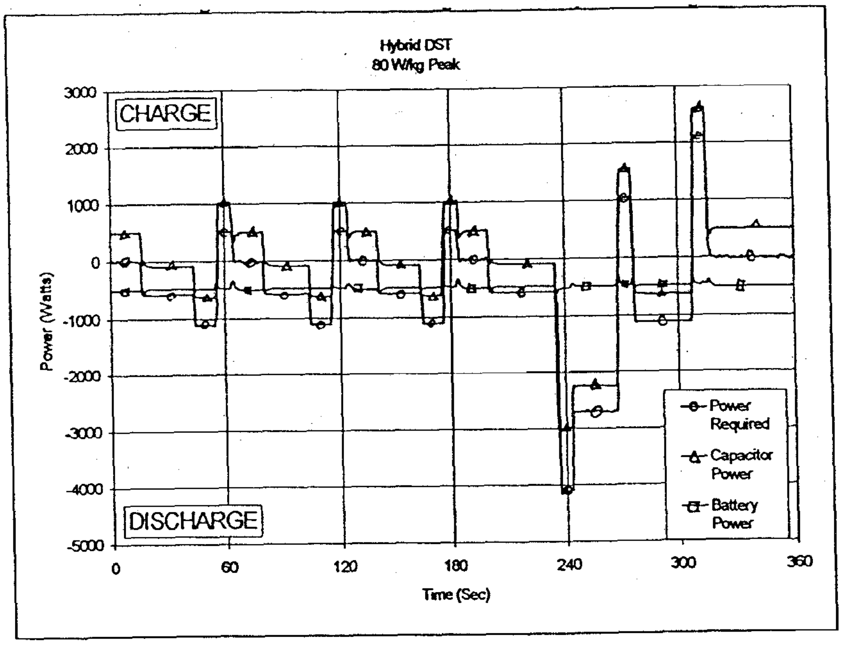


**Figure 5: Power Profiles for the Energy Battery and Pulse Power Unit on the DST Cycle**

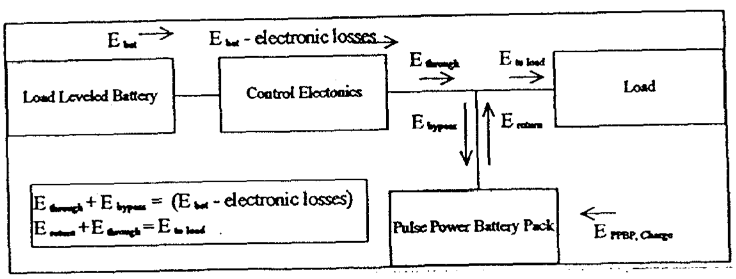


**Figure 6: Schematic of Energy Flow in the Load Leveled Battery System**