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THERMAL MANAGEMENT OF BATTERY PACK IN ELECTRIC VEHICLES

S. Murugesan* & P. R. Manigandan**
* PG Student, SSM College of Engineering, Komarapalayam, Tamilnadu
** Professor, Department of Mechanical Engineering, SSM College of Engineering, Komarapalayam, Tamilnadu

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Abstract:

In electric vehicle, battery is the main source of energy for tractive power. It is technically known as "Rechargeable Electrical Energy Storage System (REESS). The durability and efficiency of the REESS is mainly based on its charging rate, discharging rate, Depth of Discharge (DOD) and operating temperature. For a given REESS the charging rate, Discharging rate at conditional temperature and DOD are the main characteristics which are constant. The operating temperature of the REESS can be effectively controlled by optimized design of ventilation systems and enhanced energy efficient electric components. During charging and discharging, REESS temperature rises due to its internal resistance. Rapid charging and discharging of REESS leads to rise in its temperature beyond its safe operating limit. The maximum efficiency coupled with design intended life of REESS shall be attained when it is operated at the temperature of 100C to 45°C. The cell (which is the individual building block of REESS) temperature across the battery pack has to be maintained uniformly. Uneven cell temperatures cause improper charging and discharging and reduction in its capacity and life. The following issues are currently,

- ✓ One particular cell temperature reaches to its cut back temperature, during high speed drive.
- ✓ The overall battery pack temperature reaches its cut back temperature, after undergoing cyclic charge and discharge (drive) of the vehicle.

This project is intended to

- ✓ Identify the heat source / root cause for heat source
- ✓ Assess/Calculate the heat generation rate
- ✓ Design the optimum size of conducting buses and ventilation system (mass flow rate of the coolant across the REESS).
- ✓ Validate the design by conducting set of field tests

1. Introduction:

In today's world of competition and rising fuel prices the automotive industry is struggling hard to survive. Lot of efforts are taken to make their products reliable, efficient, and robust and defect free at the lowest possible cost. This make the automotive product more competitive and the one which meets all the criteria wins the market. Research & development teams are constantly under pressure for providing the value engineering solutions by innovating and implementing new ideas.

2.1 Battery:

A battery is an electrochemical cell (or enclosed and protected material) that can be charged electrically to provide a static potential for power or released electrical charge when needed. A battery cell consists of five major components:

- ✓ Electrodes—anode and cathode
- ✓ Separators
- ✓ Terminals
- ✓ Electrolyte and
- ✓ A case or enclosure.

Battery cells are grouped together into a single mechanical and electrical unit called a battery module. These modules are electrically connected to form a battery pack, which powers the electronic drive systems. There are two terminals per battery, one negative and one positive. The electrolyte can be a liquid, gel, or solid material. Traditional batteries, such as lead-acid (Pb-acid), nickel-cadmium (NiCd), and others have used a liquid electrolyte. This electrolyte may either be acidic or alkaline, depending on the type of battery. In many of the advanced batteries under development today for EV applications, the electrolyte is a gel, paste, or resin. Examples of these battery types are advanced sealed Pb-acid, NiMH, and Lithium (Li)-ion batteries. Lithium-polymer batteries, presently under development, have a solid electrolyte. In the most basic terms, a battery is an electrochemical cell in which an electric potential (voltage) is generated at the battery terminals by a difference in potential between the positive and negative electrodes. When an electrical load such as a motor is connected to the battery terminals, an electric circuit is completed, and current is passed through the motor, generating the torque. Outside the battery, current flows from the positive terminal, through the motor, and returns to the negative terminal. As the process continues, the battery delivers its stored energy from a charged to a discharged state. If the electrical load is replaced by an external power source that reverses the flow of the current through the battery, the battery can be charged. This process is used to reform the electrodes to their original chemical state, or full charge.

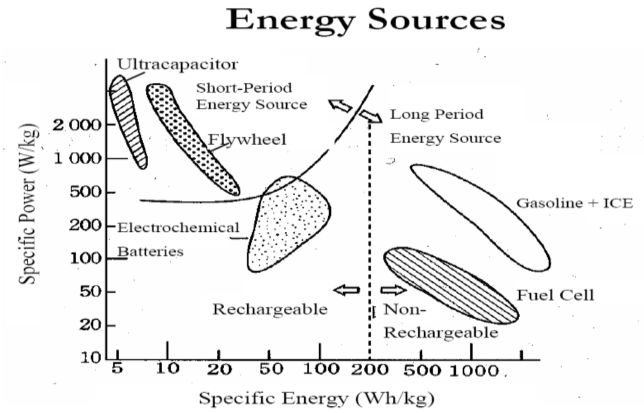


Figure 2.1: Specific Power Vs Specific Energy

2.2 Lead acid Batteries – Salient Characteristics:

2.2.1 Types of Lead Acid Batteries:

2.2.2 Lead Calcium:

- ✓ Electrodes modified by the addition of Calcium
- ✓ Improved battery life by resistance to corrosion, overcharging, gassing, water usage.
- ✓ Larger electrolyte reserve area above the plates.
- ✓ Higher Cold Cranking Amp ratings.
- ✓ Little maintenance.

2.2.3 Lead Antimony:

- ✓ Electrodes modified by the addition of Antimony
- ✓ Lesser internal heat and water loss
- ✓ Improved mechanical strength of electrodes -important for EV
- ✓ Longer service life.
- ✓ Lower cost.

2.2.4 Valve Regulated Lead Acid (VRLA) Batteries:

- ✓ Also called Sealed Lead Acid (SLA) batteries.
- ✓ Designed to prevent electrolyte loss through evaporation
- ✓ VRLA have pressure valves that open only under extreme conditions
- ✓ AGM Absorbed Glass Mat Battery
- ✓ Also known as Absorptive Glass Micro-Fibre
- ✓ Absorbs the free electrolyte acting like a sponge.
- ✓ Promoter combination of the hydrogen and oxygen given off during the charging process.
- ✓ Gel Cell

2.2.5 Advantages:

- ✓ Mature technology –wide availability
- ✓ Low cost.
- ✓ Tolerant to overcharge and abuse.
- ✓ High current capability.
- ✓ Many suppliers –choice of models
- ✓ Amenable to recycling

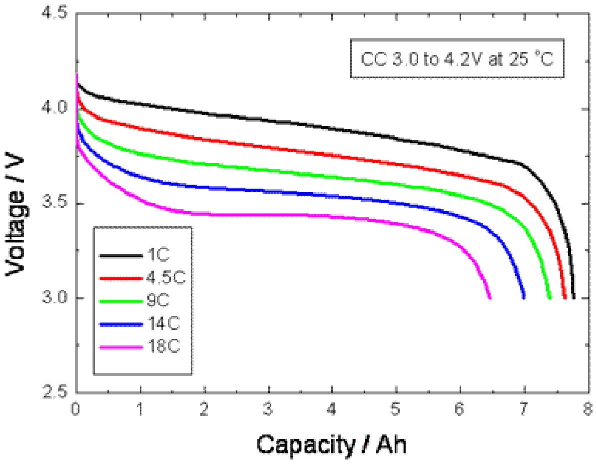
2.2.6 Disadvantages:

- ✓ Bulky and heavy –low energy density
- ✓ Low charge efficiency (~70%)
- ✓ Cycle life low : ~ 500 –600 cycles in EV applications
- ✓ Long charging time
- ✓ Capacity dependence discharge rate

2.3 The Li-ion Battery:

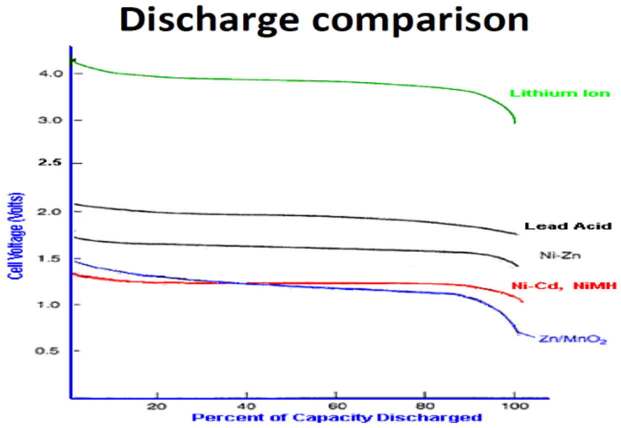
A lithium-ion battery (sometimes Li-ion battery or LIB) is a family of rechargeable battery types in which Lithium ions move from the negative electrode to the positive electrode during discharge, and back when charging. Chemistry, performance, cost, and safety characteristics vary across LIB types. Unlike lithium primary batteries (which are disposable), lithium ion cells use a compound as the electrode material instead of metallic lithium.

2.3.1 Lithium Battery Characteristics:



Graph 2.1: Lithium Battery Voltage Vs Capacity

Li-ion batteries are the third type most likely to be commercialized for EV applications. Because lithium is the metal with the highest negative potential and lowest atomic weight, batteries using lithium have the greatest potential for attaining the technological breakthrough that will provide EVs with the greatest performance characteristics in terms of acceleration and range. Unfortunately, lithium metal, on its own, is highly reactive with air and with most liquid electrolytes.



Graph 2.2: Lithium Battery Voltage Vs Capacity discharge

2.3.2 Life Cycle Vs Temperature:

To avoid the problems associated with metal lithium, lithium intercalated graphitic carbons (LixC) are used and show good potential for high performance, while maintaining cell safety. During a Li-ion battery's discharge, lithium ions (Li+) are released from the anode and travel through an organic electrolyte toward the cathode. Organic electrolytes (i.e., nonaqueous) are stable against the reduction by lithium. Oxidation at the cathode is required as lithium reacts chemically with the water of aqueous electrolytes.

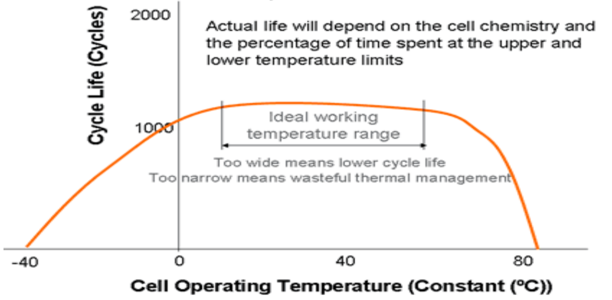


Figure 2.2: Lithium Battery Life Cycle Vs Temperature

When the lithium ions reach the cathode, they are quickly incorporated into the cathode material. This process is easily reversible. Because of the quick reversibility of the lithium ions, lithium-ion batteries can charge and discharge faster than Pb-acid and NiMH batteries. In addition, Li-ion batteries produce the same amount of energy as NiMH cells, but they are typically 40% smaller and weigh half as much. This allows for twice as many batteries to be used in an EV, thus doubling the amount of energy storage and increasing the vehicle's range.

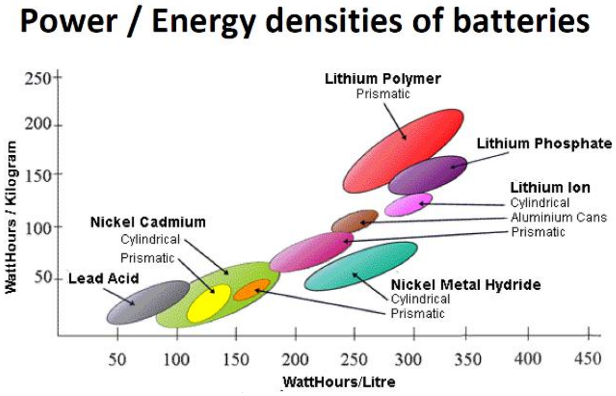


Figure 2.3: Lithium Battery Whr/kg Vs Whr/lit

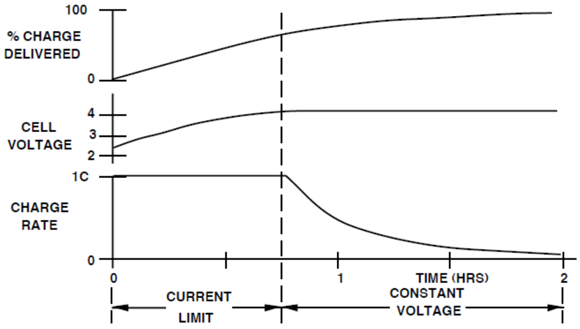
There are various types of materials under evaluation for use in Liion batteries. Generally, the anode materials being examined are various forms of carbon, particularly graphite and hydrogen-containing carbon materials. Three types of oxides of transition are being evaluated for the cathode: cobalt, nickel, and manganese. Initial battery developments are utilizing cobalt oxide, which is technically preferred to either nickel or manganese oxides. However, cobalt oxide is the costliest of the three, with nickel substantially less expensive and manganese being the least expensive.

2.3.3 Li-Ion Charging Information:

A Li-Ion battery is unique, as it is charged from a fixed voltage source that is current lim-ited (this is usually referred to as constant voltage charging).

2.3.4 Constant Voltage Charging:

A constant voltage (C-V) charger sources current into the battery in an attempt to force the battery voltage up to a pre-set value (usually referred to as the set-point voltage or set voltage). Once this voltage is reached, the charger will source only enough current to hold the voltage of the battery at this constant voltage (hence, the reason it is called constant voltage charging). At present, the major Li-Ion cell manufacturer recommends 4.200 +/- 50 mV as the ideal set point voltage, and 1c (a charging current rate equal to the A-hr rating of the cell) as the maximum charging current that can be used. The accuracy on the set point voltage is critical: if this voltage is too high, the number of charge cycles the battery can complete is reduced (shortened battery life). If the volt- age is too low, the cell will not be fully charged. A typical charge profile for a Li-Ion cell using 1c constant voltage charging is shown in Figure.



Graph 2.3: Typical C-V Charge Profile

2.3.5 The Constant Voltage Charging Cycle is Divided Into Two Separate Segments:

The current limit (sometimes called constant current) phase of charging is where the maximum charging current is flowing into the battery, because the battery voltage is below the set point. The charger senses this and sources maximum current to try to force the battery voltage up. During the current limit phase, the charger must limit the current to the maximum allowed by the manufacturer (shown as 1c here) to prevent damaging the batteries. About 65% of the total charge is delivered to the battery during the current limit phase of charging. Assuming a 1c charging current, it follows that this portion of the charge cycle will take a maximum time of about 40 minutes. The constant voltage portion of the charge cycle begins when the battery voltage sensed by the charger reaches 4.20V. At this point, the charger reduces the charging current as required to hold the sensed voltage constant at 4.2V, resulting in a current waveform that is shaped like an exponential decay. The constantly decreasing charge current during the constant-voltage phase is the reason that the Li-Ion charge time is nearly two hours, even though a 1c (maximum) charging current is used (this means that delivering the final 35% of the charge takes about twice as long as the first 65%). To understand why this is true, it must be remembered that every real cell contains an internal ESR (Equivalent Series Resistance), and the voltage that the charger senses across the battery is influenced by the ESR (see Figure 6). The voltage measured at the terminals of the battery is the sum of the voltage drop across the ESR and the cell voltage. The battery is not fully charged until the cell volt- age is 4.2V with only a minute current flowing into it (which means the drop across the internal ESR is negligible, and the actual cell voltage is 4.2V). During the 1c current limit charge phase, the battery reaches 4.2V with only about 65% of charge capacity delivered, due to the voltage drop across the ESR. The charger must then reduce the charging current to prevent exceeding the 4.2V limit, which results in the decreasing current as shown in Figure.

2.3.6 Lithium Polymer Batteries:

This type has technologically evolved from lithium ion batteries. The primary difference is that the lithium-salt electrolyte is not held in an organic solvent but in a solid polymer composite such as polyethylene oxide or polyacrylonitrile. The advantages of Li-ion polymer over the lithium-ion design include potentially lower cost of manufacture, adaptability to a wide variety of packaging shapes, and ruggedness.

2.4 Efficiency Comparison:

2.4.1 Electric Vehicle Efficiency:

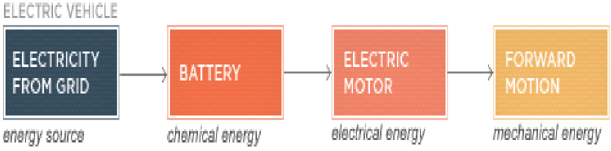


Figure 2.4: Electric Vehicle Energy Diagram

In an electric vehicle, chemical energy is stored in a battery. Lithium-ion batteries are used in Tesla vehicles because of high energy density. Converting the chemical energy to free electrons (electrical energy) can be greater than 90% efficient – some energy is lost to heat in cells and other battery pack components such as current conductors and fuses. The remaining components of the Tesla powertrain – the drive inverter and motor – are also extremely efficient. Overall, drive efficiency of the Tesla Roadster is 88% - almost three times more efficient than an internal combustion powered vehicle.

2.4.2 Internal Combustion Vehicle Efficiency:

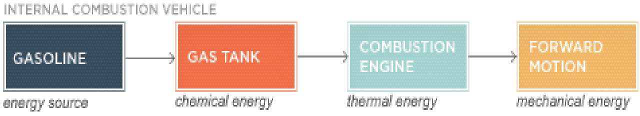
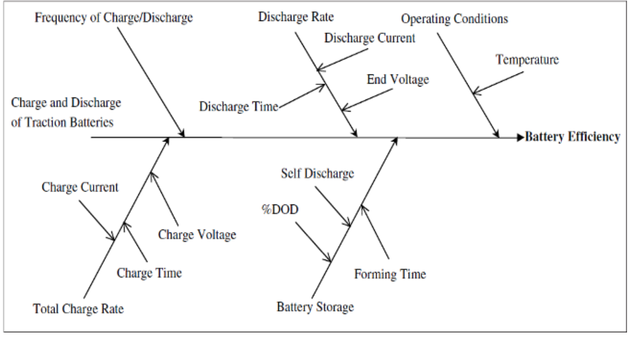


Figure 2.5: Internal Combustion Vehicle Energy Diagram

Chemical energy is stored as gasoline in a conventional car. The internal combustion engine uses combustion to convert the chemical energy into thermal energy. Pistons convert the thermal energy to the mechanical work that turns the wheels. The conversion process is, at best, 35% efficient. The majority of the energy stored in the gasoline is lost as heat

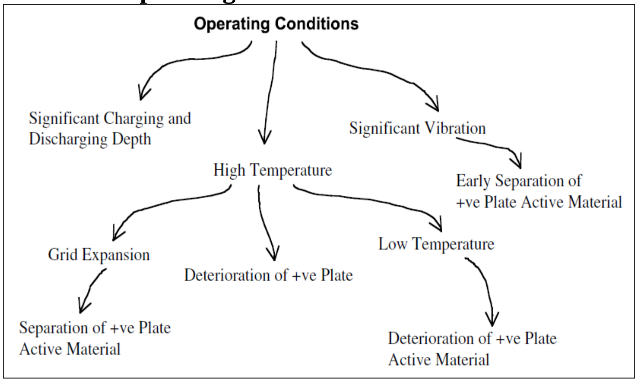
2.5 Factors Affecting the Battery Efficiency:



2.5.1 Regenerative Braking:

Another key aspect of EVs is that they can recapture kinetic energy and store it as electrical energy through a process called regenerative braking. As discussed earlier, electric current is drawn from the battery system and applied, under the management of the electronic control module, to the motor. Inside the motor, this current is passed through a magnetic field, which results in a torque that is used to turn the vehicle's wheels. This process can be reversed during braking of the vehicle. Effectively, the electronic control module converts the motor to a generator. The momentum stored in the moving vehicle is used to pass the conductors in the motor through a magnetic field, which creates a current that is then directed by the electronic control module back to the battery system where it is stored for future use. Regenerative braking systems can increase the driving range of EVs by 10 to 15%.

2.5.2 Battery Failure Modes due to Operating Conditions:



2.5.2.1 Effects of Excessive Heat on Battery Cycle Life:

Depending upon the type of the battery, excessive heat generated during the charging and discharging process has a detrimental effect on the formation of the battery. In the case of VRLA batteries, the deterioration leads to the separator and electrolyte breakdown resulting in the gassing of the electrolyte. During the gassing process, the vents let the electrolyte evaporate and the cell dries out. This effect is accelerated at higher operating temperatures. Applying a general rule of thumb under high charge rates, the life of a traction battery is reduced by half for every increase in the cell temperature. Thus the temperature-time integral affects battery life with the worst case being subject to high temperatures for an extended period of time. The effects of excessive battery charging, as illustrated in Figure, lead to void formations, significant gassing of the electrolyte, and electrode overheating, which in turn leads to oxidation of the cathode. Similar to detrimental factors associated with excessive battery charging, inadequate battery charging leads to sulfation (sulfate formation) at the electrodes, which in turn leads to reduction in battery charge capacity as illustrated in Figure 2–5. The reduction in the charge capacity in turn leads to gassing of the electrolyte. This is due to the inability of conversion of the charge into useful energy at the electrode.

2.5.2.2 Effects of Some Factors on Lithium-Ion Battery Charging Time:

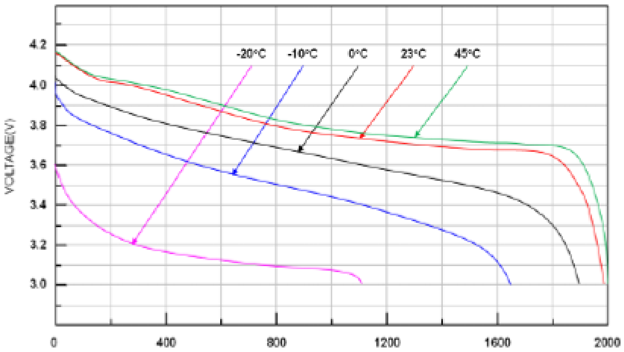
2.5.2.3 Factor 1- Temperature of Battery:

2.5.2.4 Low Temperature Change:

Good charging performance at cooler temperatures. Allow fast-charging in a temperature bandwidth of (5 to 45) °C, i.e. (41 to 113) °F. For (0 to 5) °C, charging is possible, but charge current should be reduced and no charging is permitted at freezing temperatures. Lithium-ion batteries cannot be charged below 0°C (32°F). At lower temperatures, the internal resistance of the battery may increase, resulting in slower charging and thus longer charging times. At below freezing temperatures, charging of lithium-ion cells are indeed possible (according to research papers), but only at very low currents. According to research papers, the allowable charge rate at –30°C (–22°F) is 0.02C. At this low current, the charge time would stretch to over 50 hours, a time that is deemed impractical. There are, however, specialty Li-ions that can charge down to –10°C (14°F) at a reduced rate.

2.5.2.3 High Temperature Change:

Lithium-ion performs well at elevated temperatures but prolonged exposure to heat reduces longevity. High temperatures during charging may lead to battery degradation and charging at temperatures above 45 °C will degrade battery performance. Some lithium-based packs are momentarily heated to high temperatures. For example, surgical tools that are sterilized at 137°C (280°F) for up to 20 minutes as part of autoclaving.



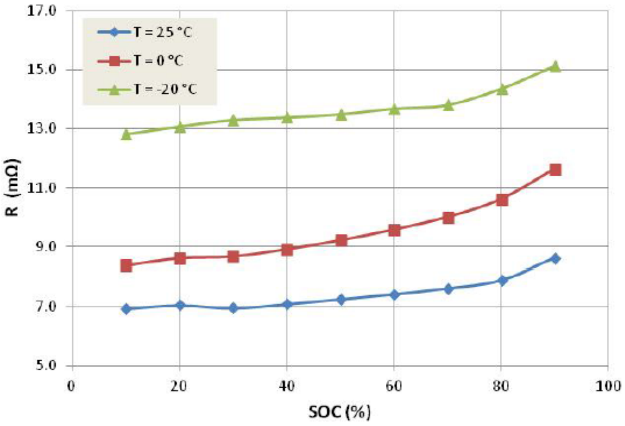
Graph 2.4: Effect of temperature on the Li-ion battery capacity and Voltage

2.5.2.3 Energy and Power Effect:

Battery power and energy are lower due to poor ion transport in cold temperature

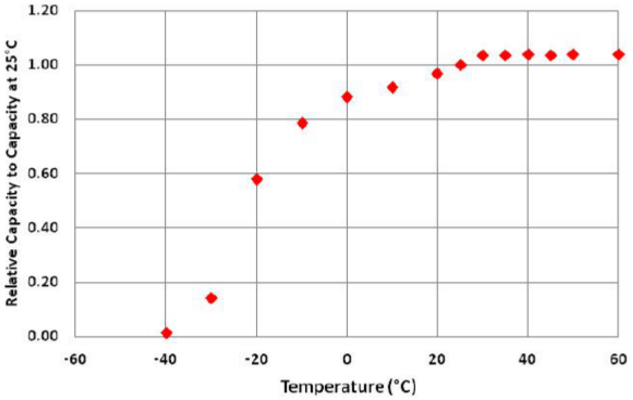
2.5.2.3 Effect of Temperature on Resistance:

The temperature resistance of battery is proportional to state of charge



Graph 2.5: Battery Resistance Vs Temperature

2.5.2.3 Effect of Temperature on Relative Capacity:



Graph 2.6: Battery Relative Capacity Vs Temperature

2.6 Thermal Runaway:

When a traction battery is operating on float or overcharge in a fully recombinant mode, the net chemical reaction is minimum. Virtually all the energy (V * I) results in heat generation. During the design of the system, the heat generated during the charge-discharge process should be dissipated without raising the battery temperature. In case the temperature of the battery pack rises during the charge-discharge process, more current will be required to maintain the float voltage. The additional current results in the production of excessive oxygen, which in turn generates more heat. The heat is produced as a result of the reconversion of water at the negative plate of the battery. The net result is that the battery undergoes a meltdown due to thermal runaway. The possibility of a thermal runaway can be minimized by the use of battery pack ventilation using forced cooling. The ventilation maintains the battery temperature between and around cells. In addition, the charger output (voltage and current) is regulated by using a temperature compensated charge.

2.7 Thermal Performance Test:

This test characterizes the effects of ambient temperature variation on the battery pack performance. The characteristics of the battery that are affected are in most cases, technology related. Thus the number and the types of charge and discharge cycles to be performed cannot be generalized for all battery types. The results of this test provide useful data to determine the need for battery thermal management or the allowable temperature range for a battery that may incorporate thermal management at a later stage

2.8 Thermal Management of the Electric Vehicle Battery:

The battery life and performance both are strongly affected by the operating temperature and the uniformity of the battery pack temperature. On the other hand, these temperatures can be modified by the battery thermal management system. The thermal evaluation of the battery reveals that: Discharging the battery using a driving profile results in a significantly greater temperature rise than that found in a C/3 three-hour constant discharge. The battery thermal management system should account for the upper battery module to lower battery module pressure drop. The battery temperature rise, per unit energy discharge, is significantly greater than that of the flooded electrolyte battery. This is due to the lower heat capacity and greater heat generation. There is a poor heat dissipation of the starved-electrolyte battery. There is a large temperature difference between the electrodes and the battery cell due to the existence of air gaps between the electrode stack and the cell casing. Temperature increases are very sensitive to high-rate discharge, deep discharge, and excess overcharging. External cooling is less effective in the thermal management of the battery pack. A major battery deficiency that inhibits a more rapid development of EVs is low specific energy. In the VRLA battery, this deficiency is at least partially attributable to the low utilization of the active material in batteries designed for deep discharging and long cycle life. The utilization of the positive active material is in order of 30%. It is found that the factors that affect the battery utilization fall into three categories:

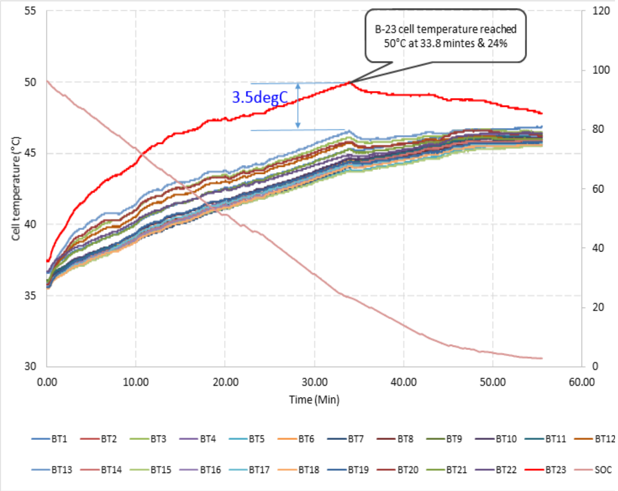
- ✓ Application Conditions (e.g., discharge rate and operating temperature)
- ✓ Battery design parameters (e.g., plate thickness, electrode porosity, electrolyte quantity, and comparison)
- ✓ Intrinsic properties of the active material (e.g., active material composition, morphology, surface area, and crystallographic modification)

The use of thinner plates and increased porosity increases utilization but simultaneously reduces cycle life. Slight improvements in the utilization can be obtained by stirring the electrolyte and/or increasing the operating temperature.

3. Problem Identified:

The cell temperature across the battery pack to be maintained uniformly. The uneven cell temperature cause improper charging and discharging and reduction its capacity and life. The following issues are currently,

- ✓ One particular cell temperature reaches to its cut back temperature during high speed drive.
- ✓ The overall battery pack temperature reaches its cut back temperature during course of charge and drive the vehicle.



Graph 3.1: Battery Temperature Vs Time

3.1 Importance of the Problem:

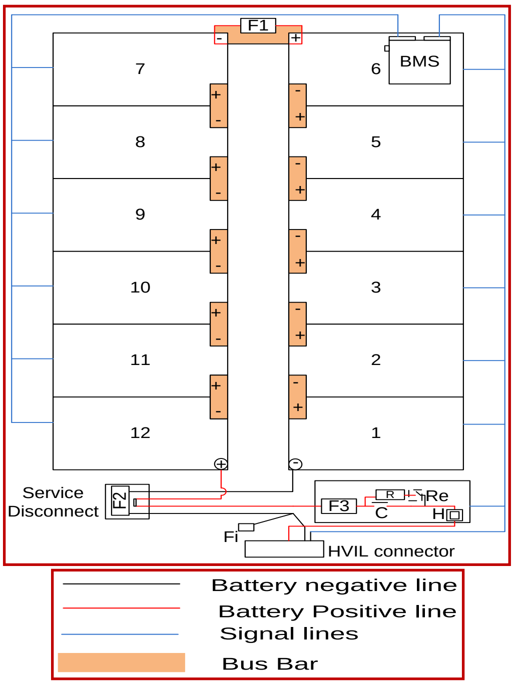


Figure 3.1: Circuit diagram of Battery Pack

In the electric vehicle battery is the main component. The life and efficiency of the battery is mainly based on its charging rate, discharging rate, Depth of Discharge (DOD) and operating temperature. For the given battery the churching rate, Discharging rate and DOD are the characteristics of battery and cannot be changed. The operating temperature of the battery can be effectively controlled by proper design of ventilation and electric component. During charging and discharging the battery is getting heated up due to its internal resistance. Rapid charging and discharging of battery cases to rese its temperature beyond operating limit. The life and efficiency of the battery is maximum when it is operated at the temperature of 10 to 45°C. The battery life and performance both are strongly affected by the operating temperature and the uniformity of the battery pack temperature. On the other hand, these temperatures can be modified by the battery thermal management system. Lithium-ion performs well at elevated temperatures but prolonged exposure to heat reduces longevity. High temperatures during charging may lead to battery degradation and charging at temperatures above 45 °C will degrade battery performance

3.2 The Following are the Probable Root Cause for One Particular Cell Temperature Increase:

- ✓ Tubular lug after crimping creates air gap, leading to temperature rise
- ✓ Lug surface area of contact to be increased from existing 24mm to 30mm
- ✓ Improved Surface finish
- ✓ Current carrying capacity of lug and cross section area
- ✓ Improper Polishing of the lug surface
- ✓ Tightening Torque
- ✓ Resistivity of the lug
- ✓ Resistivity of busbar
- ✓ Tubular lug used at the battery HV cable instead of solid busbar

3.3 Battery Characteristics:

The batteries used have the following characteristics: 12V Deep cycle GEL 200Ah

3.3.1 Nominal Discharge Current (C):

- ✓ The nominal discharge current is calculated with a discharge duration of 1 hour.
- ✓ The nominal discharge current for the chosen batteries is:
- ✓ The nominal discharge current is used in the calculations.

3.3.2 Maximum Discharge Current:

The maximum discharge current of these batteries is 160A. This value is provided by the manufacturer.

3.3.3 Capacity:

The nominal capacity of the batteries is 200Ah. This is determined with a discharge duration of 10 hours. The capacity is reduced when the batteries are discharged in a shorter period. How much can be found in table 1 of the data sheet. When the batteries are discharged in 15 minutes, the capacity will be reduced to:

200Ah * 49% □ 98Ah

Table 3.1: Current carrying capacity of lug and cross section area

Parameter	Values	Units
Max Current (during 1C discharge)	200	A
Rated Current	200.00	A
Total wire length	100	mm
No of copper strips	1	No.
Bus bar dimension A	3.5	mm
Bus bar dimension B	24	mm
wire size	84	sq. mm
Resistivity of copper at 25Deg.C	0.0000177	Ohm mm
Resistance of wire at 25Deg.C	2.1071E-05	Ohms
Resistance variation with temperature	0.00393	Ohm/degC
Operating temperature	80	degC
Resistance of wire at operating temperature	2.5626E-05	Ohms
copper losses	1.02504071	Watts

3.4 Root Cause Analysis:

Discharge the pack at 260Amps, continuously monitor the all the cell temperatures in as it is condition. This test is for replicating the particular battery temperature rise. Discharge the pack at 260Amps, continuously monitor the all the cell temperatures by replacing the new lug. As the new lug surface area of contact is higher than the surface area of old lug, we expect the temperature rise will be much lesser than the earlier case.

3.5 Implementation and Verification:

After chancing the lug size from 24mm to 30mm, the surface area of contact between battery terminal and lug has been increased. The temperature rice of the battery cell has been decreased by 5.0°C.

4. Conclusion:

- ✓ With 24mm width Contact Area- 300 sq mm, With 30mm width Contact Area- 455 sq mm
- ✓ With the new lug of 30mm width is reducing the temperature rise considerably,
- ✓ The Lug of 30mm width as compared to 24 mm width to be confirmed with supplier for availability.

5. Work for Future Scope:

For overall temperature rise issue first needs to identify the heat source / root cause for heat generation, Calculate the heat generation rate, Design the optimal electric component and ventilation system and to validate the project outcome by conducting field test.

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