POLITECNICO DI TORINO

Engineering Faculty

MASTER THESIS IN MECHATRONIC ENGINEERING

Electrification of the hydraulic control system of off-road vehicles

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Acknowledgements

This is source of immense pleasure for me to work with Prof. Andrea Vacca and Prof.Luigi Mazza, for their guidance and support.

Their assistance plays key role to approach this thesis, they were invaluable in the formulating of the research topic.

My deep regards also go to the colleague to the research, who discussed their precious ideas and knowledge with me.

I am extremely grateful to my parents and my family who, though far away, always have accompanied me in this beautiful journey.

Also, to all of those with whom I have had the pleasure to work during my time at Maha Fluid Power Research center.

Abstract

The main objective of this thesis is to electrify the mobile hydraulic application through the Electro-hydraulic actuator implementation (EHA) integrated with two novels-designed electro-hydraulic units (EHU) which consist of fixed displacement pump and variable speed electric motor (PMSM) with higher compactness and it act as the prime mover in high power-level applications such as off-road mobile applications like construction, agriculture machines and mining machines. The valve manifold contains the needed electro-hydraulic parts to manage the cylinder actuation with the help of electro-hydraulic unit (EHU) control. The efficiency of the proposed system is analyzed under steady state and real drive cycle of industrial compact loader. To power those off-road vehicle, high voltage storage devices are required so we perform different evaluations and simulations for the sizing of battery system which power EHA system by enabling energy recuperation during assistive drive cycles and also review the charging technology which made it feasible.

Introduction

There is strong inclination is happening in declining the fuel consumption, gaseous and acoustic emissions for off-road vehicle which has far-ranging environment effect by increasing the air pollution such as emission of different pollutants such as nitrogen oxide, sulfur dioxide and carbon dioxide. Due to this effect , increasingly strict emissions regulations have been accelerated that's where electrification research came into play in off-road application where main purpose is to replace the ICE (Internal combustion engine) of the reference application with electric motor because ICE (Internal combustion engine) depend on burning fossil fuels which is big source of emissions of pollutants which is used in order to produce energy in hydraulic system and apart from the emission it also abstain the loud noise from ICE (internal combustion engine). Electrification implementation rate world wide for off-road vehicle significantly increases from 38% in 2017 to 55% in 2028 which show massive implementation opportunity for electric motor and electric battery [6]. Emission regulations and standards come to force to push the electrification for zero- or reduced-emissions construction equipment. To avoid these pollutants USDOT (The United States Department of Transportation) is implementing certain regulations standards. Transportation sector has surpassed as the largest emitter of a greenhouse gas emissions. In 2019, U.S greenhouse gas emissions totaled 5,222 million metric ton (MMT) of carbon dioxide (CO_2) equivalents in which 33% this emission comes from transportation sector and out of 33% we have 9% coming from off-road vehicles which is further divided into two categories agriculture and construction machines[6]. Electrify transportation has increasingly consider as a key step to reduce transportation related emissions by maximize the environmental benefit. Also implementing proper charging infrastucture for off-road vehicles is one of biggest challenge for Electrefication .

Chapter 2

Electrification of Mobile hydraulics

Growth of Electrification in Off-road vehicles

Due to strict emission regulations by Environmental Protection Agency demand for electrification of off-road vehicles are accelerating so many off-road mobile applications which include agriculture, mining, and construction machines, are being electrified for higher capability, better emission control, and better reliability. Also, electrification provide many benefits by improving overall efficiency and high level of capability for different maneuver operations of these off-high way vehicles. But apart from its advantages it opens out over many challenges like insufficient and confined charging infrastructure and limited storage devices.

In construction sector many manufacturers like Caterpillar, Komatsu Ltd, Liebherr , Takeuchi , Wacker Neuson , Bobcat , Kobelco , Casoli and Vauhkonen are electrifying their construction machines which abstain ecological degradation and keep their sustainability .

In off-road vehicle loader and excavator are used as high duty construction machines so significant amount of work has been done in their development and advancement to their electrification. World largest construction manufacturer Caterpillar Inc developed an electric excavator of 26 ton which is integrated with big 300 kWh battery pack when fully charged can operate for continuously 7 hours [3].

Also, the Japanese Manufacturer Komatsu introduced mini-fully electric excavator integrated with Lithium-Ion battery which last for 2 to 6 hours on full charge and with the advanced features to oversight the power consumption and charging characteristics[4].

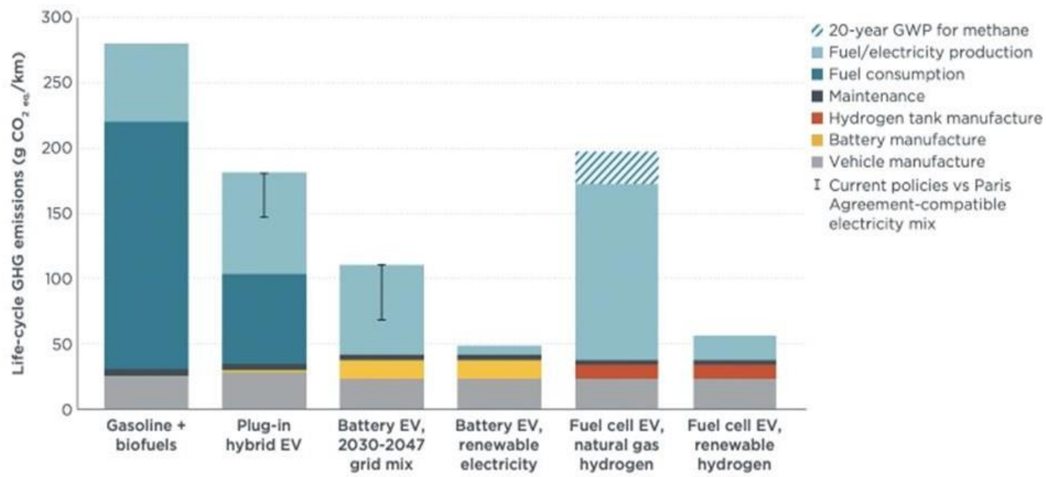
In Vauhkonen, study of electrification of excavator was done in which transition of working JCB Mini excavator to an excavator that operate fully electric. The 14-kW diesel powered engine integrated with its internal components was changed with a 10-kW electrical motor. Four lithium titanate batteries, with a voltage of 96 V having charge capacity of 60 Ah, operate the electric motor [20].

Electrification and Decarbonization

There are mainly three pillars of decarbonization, so we have pathways to reduce Greenhouse Gas Emissions which are energy efficiency, decarbonization electricity and switch direct-use fuel to electric sources. Off-road vehicles based on electric motor convert 80% available energy in the battery into motion while off-road based on combustion engine convert only 20% into motion and rest of energy goes to heat, noise and unburned hydrocarbons[21]. Electrifying the transport sector give us flexibility to change portfolio of energy source.

Co_2 emission from different Electricity Fuel

This is research carried out by ICCT (International Council on Clean Transportation) [4] which contains different life analysis of gasoline ICEVs, PHEVs, BEVs, and FCEVs for GHG emissions. It can be seen in this graph that only BEVs show the capability to reduce GHG emissions according to emissions regulation set by the environmental protection agency. So, from this ICCT graph with gasoline ICEVs, PHEVs decarbonization is not possible. Here there is also one thing more to be noticed, that there is no co2 emission at the tail pipe but there are co2 emission at the power station which depend on the fact how this electricity system generated. Electricity generated from Natural gas emit less CO_2 Emission in comparison with the electricity generated from coal. There is substantial reduction of CO_2 emission from electricity generated from wind, nuclear and solar.



Life-cycle GHG emissions of SUV segment gasoline ICEVs, PHEVs, BEVs, and FCEVs projected to be registered in the United States in 2030. A graph from the ICCT report: A global comparison of the life-cycle greenhouse gas emissions of combustion engine and electric passenger cars

Figure 2.1: Life-cycle GHG emission of different mode of transport

Life cycle CO2 equivalent emissions depend on emission from production and emission from driving vehicle. Many studies shown that conventional car on average emit 7 tons of greenhouse gas emission during production and it's same for BEV's excluding the battery but if we include battery in BEV's during production these 7 tones become double. According to 2019 studies by Swedish IVL Svenska Miljoinstitutet [6] material extraction ,transport and mining of lithium ion emit 60-150 kgCo2/kWh meaning that bigger batteries produces more emissions so finally we can conclude this manufacturing BEV's produce more gas emission than conventional automobile Off course there is no emission of CO_2 to the atmosphere while driving the electric car versus gasoline power automobile but greenhouse gas footprint to manufacture the electric automobile is much higher because a lot of metals and minerals used in manufacturing of battery and mining of these metals and minerals i.e., lithium, cobalt and nickel etc are really impacting the environment so the places where these refining process

carried out loses the environmental standards and CO_2 emission are higher but this can be avoided in the future, especially by implementing the cleaner electricity during the whole manufacturing process studies shown that 30% decrease in grid can make the reduction up to 17% in battery manufacturing process . [5]

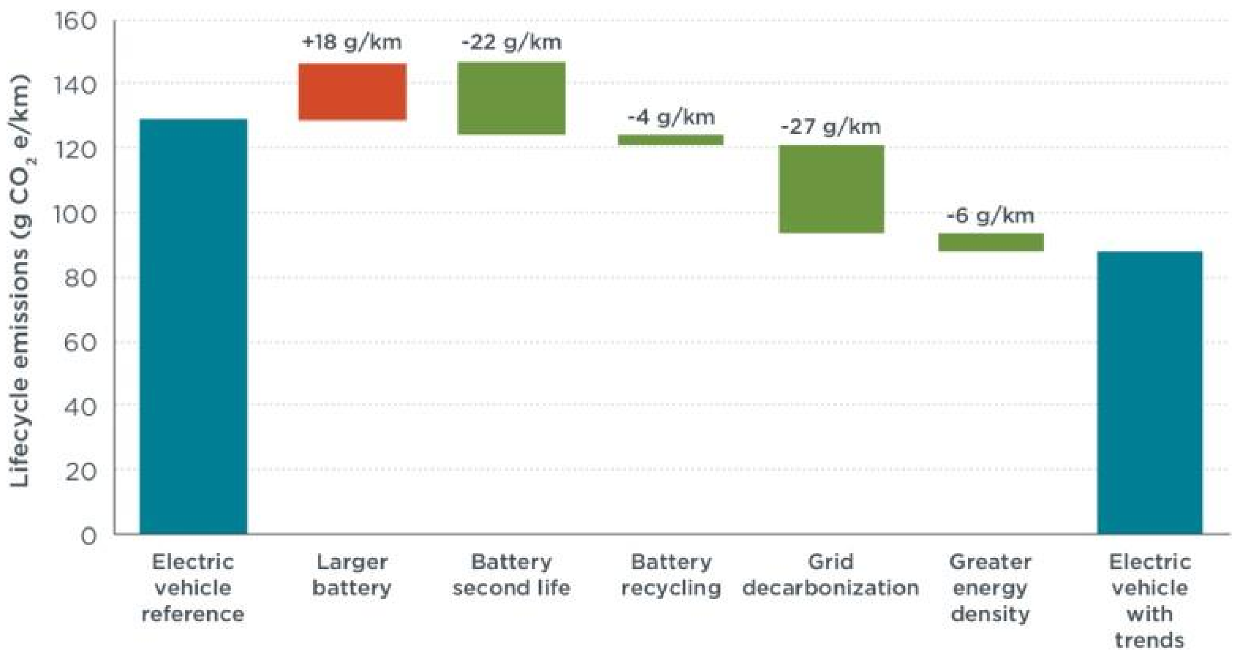


Figure 2.2: Life-cycle GHG emission during battery manufacturing process

Comparison between different mode of transportation

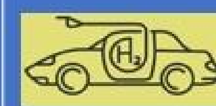
				
1	Energy to travel 100 km	10-25 kWh	6 liters gasoline , 57 kWh	50 kWh
2	Carbon dioxide Emissions	4 kg	14 kg	9 kg
3	Cost Analysis	4-6 $	9$	14 $
4	Refueling or Charging time	Depend on charger	3-5 mints	5 mints
5	Other sources (GHG) emissions	No tailpipe emissions	Methane and nitrous oxide	Water

Figure 2.3: Comparison between different mode of transportation

Here on the top line of this table [3], how much energy is required for different automobile applications.

For 100 km (about 62.14 mi), fully battery driven electric automobile consumes 15-25 kwh, the reason here we have this range 15 to 25 kwh is because energy consumption depends on mass of electric automobile, if it is heavier it took more energy in comparison with the lighter one and conventional petrol car uses 6 liters of gasoline and energy content equate to that is 57 kwh. So, this significant difference between ICE and BEV's because when we burn gasoline inside theICE's most of energy lost straight away as heat, noise as well loses in the engine and transmission. In BEV's 80 % of available energy in battery goes into motion while in ICE only 20%

of useful energy goes into motion. Also, in BEV's electricity system is low carbon which reduces carbon dioxide emission

In the second line, we can estimate what Co_2 emission are for different automobile applications. Due to strict emission regulation much electricity comes from low carbon sources nuclear, wind, solar and gas instead of coal or oil which emit higher amount of Co_2 emissions. So, for electric automobiles it emits around 4 kg. If we investigate ice-based automobiles, 1 liter of gasoline emits 2.3 kg of Co_2 so 6 liters emit around 14 kg. In the case of Hydrogen power automobile application, it is around 9kg.

This is drawback having BEV's that to charge the electric vehicle to have this energy of 15-25 kwh may take few minutes to several hours depending on the charger.

BEV's does have compact elements which is more simplified when it comes to maintenance and, it's more cost effective as it is cheaper in terms of energy per kilometer in comparison with conventional automobile powered by ICE (Internal combustion engine). BEV's doesn't have vibration and un-necessary noise which make it more comfortable. Apart from the following benefit, the most significant benefit of Battery driven electric vehicle is the efficiency, studies shown that BEV's has highest efficiency if it powered by renewable source like solar wind or nuclear instead of natural gas or oil. Also, there are some restricted areas where there are strict emission regulations area where ICE based automobiles aren't allowed, BEV's does have accessibility in the low emission zone. Below there is cost saving comparison between different automobile fed by different fuel type [7] .

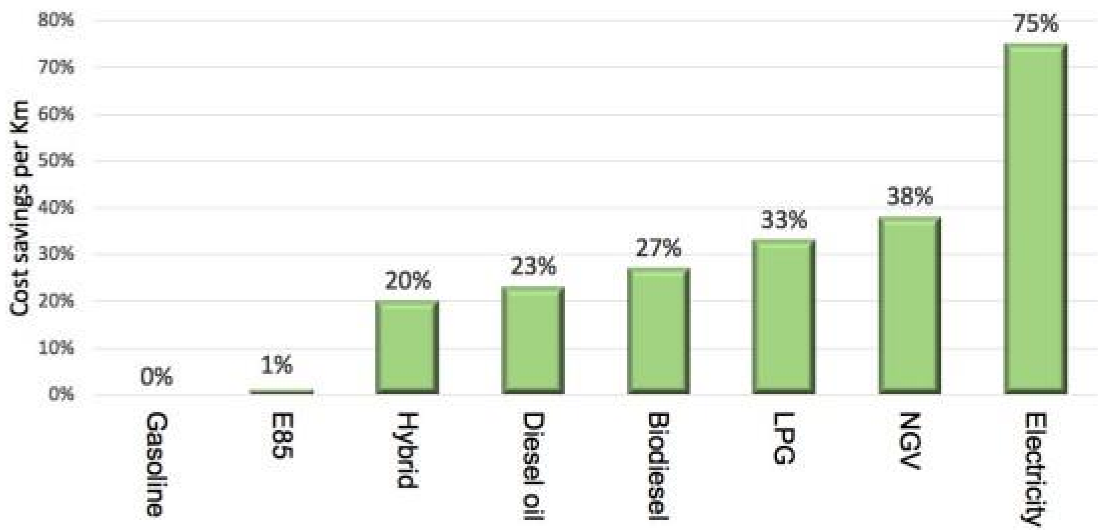


Figure 2.4: Cost saving comparison between different fuel type

Key Challenges:

There are many challenges for full integration of the charging infrastructure apart form that also the cost is a big problem. All those additional components related to electrification are too expensive. If we can hit the cost target which will develop together with manufacturer, battery manufacturer then we come up with several modelling scenario. Usually, majority of the cost in the whole electric system is in the battery which should be drawing down because manufacturing of battery is very complex and there is little of economies of scale. How do we solve this issue, by dealing with energy density? If we are producing the same battery for same cost but we put material which store double the amount of energy cost will divided by half. We have large variety of battery proposal nowadays at our disposal. Manufacturing of battery typically divided into three main sector including electrode processing, cell assembly and formation to get better performance over a long period of time. Usually in electrode manufacturing solvent choice is NMP (N-Methyl pyrrolidone) used as a solvent in manufacturing. Small battery contains relatively small amount of material which does not need big distillation process but when we compare high voltage batteries inside electric vehicle, distillation facility became big with high cost. As metal surface don't like water so on aluminum foil it's difficult to have water-based slurry to wet the surface, this is because surface energy (mN/m) of treated aluminum foil is much lower than the surface tension of water, that's why water form droplets and de-wet from surface so in order to have better adherence on electrode which determines longevity of material used in manufacturing. so slurry is little better but it's surface energy (mN/m) is little less than surface tension of water so in order to meet those values we need plasma treatment surface it allows to clean the surface , anything float around the air settle on it and also oxide the surface so by doing that we can meet the requirement by increasing or decreasing the surface tension of slurry because of this plasma treatment method we can make the surface wet between cathode and treated Aluminum foil and contact angle get zero meaning we have perfect wetting .

Improving the Cost structure:

By improving the wettability improve cost structure by up to 15 % of the full body battery cost which mean 10k$ big heavy battery can reduce its electrode coating cost by up to 1500$ with high performance and high energy density. Elimination of toxic organic solvent also extend cycle life and reduces the processing cost for electrode and eliminate expensive, toxic NMP (N-Methyl pyrrolidone). If we don't perform such changes in the system, we end up with low performance battery, very low energy density, quick fading mechanism, with low-rate capability and expensive. Other the hand if we do those changes it will improve the battery performance with high-rate capability.

To make it quite cheaper, we should keep in mind that electric ranges should be satisfactory so with lithium-ion intercalation chemistry by introducing new class of cathode material it can be possible. In these intercalation chemistries we put lithium ion into crystal without many changes which make it more efficient. If it charges it at high voltage 4.8 Volt the capacity get tremendous high

Role of Power electronic in electrification:

In the next few decades many countries phase out the fossil-based automobile application and of course it tends to be seen this pledge has been already realized so here what is role of power electronic in this technology.

Conventional fossil fuel-based automobile has ICE which burn fuel that causes engine to rotate which is connected to transmission system and gear system which is connected to axle which allow the wheel to rotate. But in electric automobile fuel tank and ICE are no longer used so no burning of fuel but the gear and transmission system are still existed. Fuel tank is replaced by battery and has capacity to move the electric automobile. Battery in fossil-based automobile application does have low voltage system which only used to start some basic auxiliary function inside the automobile, but it's not used in moving the automobile.

On the other side, combustion engine is replaced by power converter and motor and motor is coupled to the transmission system through gears. There might be some difference between mechanical system of fossil fuel-based automobile and Electric automobile application. Batteries used in automobile are lithium-ion batteries which are high voltage energy storage devices. Electric motor can be induction motors or synchronous motors.

Role of Power converter

Role of power converter to control the flow of power from battery to motor or from motor to battery. This power converter is built out of static devices such as Insulated Gate Bipolar transistor (IGTBs) or Metal–oxide–semiconductor field-effect transistor (MOSFET) which are constantly improving the capacity these devices have with respect to its size that they occupy. So, the battery produces a dc voltage which is the input to the converter also it can be integrated with super capacitor which improve the transient performance means that energy should not be drawn all from the battery pack only but from other energy storages like ultra-capacitor. This is because battery usually does not provide instant energy to the load, in order to receive faster response supercapacitor can be used because they have high charging and discharging cycles and it prevents the battery from intense decrease in battery SOC which can impact the battery longevity so by using them in series and parallel combination with batteries it can guarantee desired energy and power density. The big challenge is for Power converter need to produce a voltage and supply a current such that this torque is produced. When the motor needs to accelerate, the power converter must generate a positive torque only then it accelerates. When the motor needs to decelerate, the power converter must generate a negative (braking) torque. In braking, motor is supply power back to the battery pack, it's regenerating braking meaning power is feeding back to battery pack from motor. In fossil fuel-based automobile application we don't have any regeneration duty cycle, so in fossil fuel-based automobile when we are braking, we are dissipating mechanical energy as friction. So, power electronic engineer is controlling the power converter in a such a way that electric automobile can behave exactly the same way as fossil fuel-based

Chapter no 3

Electro-hydraulic Architecture system (EHA)

Electro-Hydraulic Actuator:

For centuries Fluid Power system serve in variety of application for a transmission of power because of high power density and compactness but hydraulic actuation system does not have remarkably high efficiency.

Ongoing trend has significantly shown interest toward electrification of heavy-duty vehicles.

In construction and agriculture industries a centralized hydraulics approach is used in all the off-road hydraulics applications which introduced throttling losses linked with control valves which in result decrease the efficiency. To improve efficiency, a decentralized hydraulics approach will be preferred which enhanced productivity, decreased energy consumption, and able to produce robust behavior in hydraulic actuation systems.

To get rid of throttling losses which are associated with control valves there are two approaches which will be preferred. These are displacement-controlled systems integrated with fixed speed combustion engines and variable displacement pumps or Electro-hydraulic actuators (EHA) architecture [1][2].

Displacement-controlled systems integrated with fixed speed combustion engines and variable displacement pumps is an expensive approach which is mostly used for hydraulic actuation systems depend on ICE, but Electro-hydraulic actuators (EHA) architecture are hydraulic actuation systems which depend on electric motor as a primary mover.

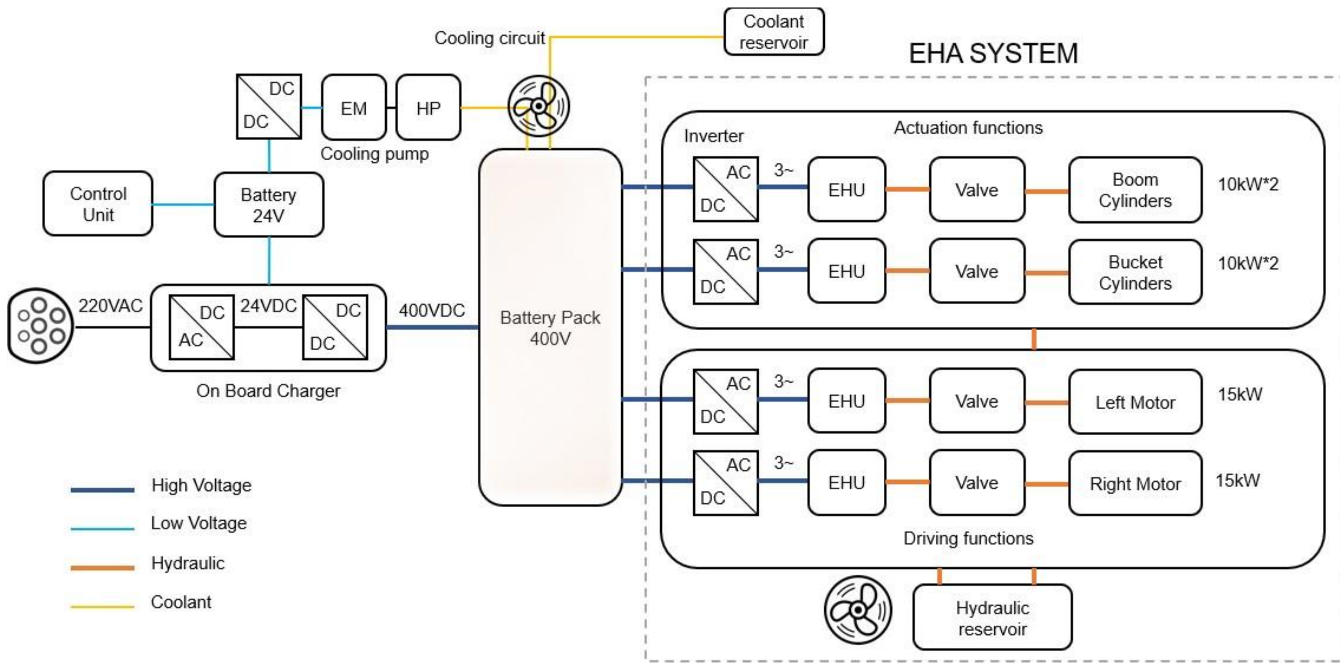


Figure 3.1: Overall schematic of electrified skid steer

This schematic implies full electrification of Electro hydraulic Actuation which is integrated with four EHU (Electro-hydraulic unit).

This EHA (Electro hydraulic Actuation) contain Full fluid power system with a recognizable layout for the components including actuator, valve manifold and power drive, at this stage our compact loader is partially electrified and we are using only 2 EHU (Electro-hydraulic unit) to drive the actuators with peak power of 15 and 30 kW. In both EHU (Electro-hydraulic unit) Hydraulic machine is coupled with PMSM. The EHU (Electro-hydraulic unit) also integrates an air-cooling system for the electric motor. First unit is air cooled using fans mounted on rotor of electric machine and 2nd EHU (Electro-hydraulic unit) is liquid cooled. Both are compact and power dense.

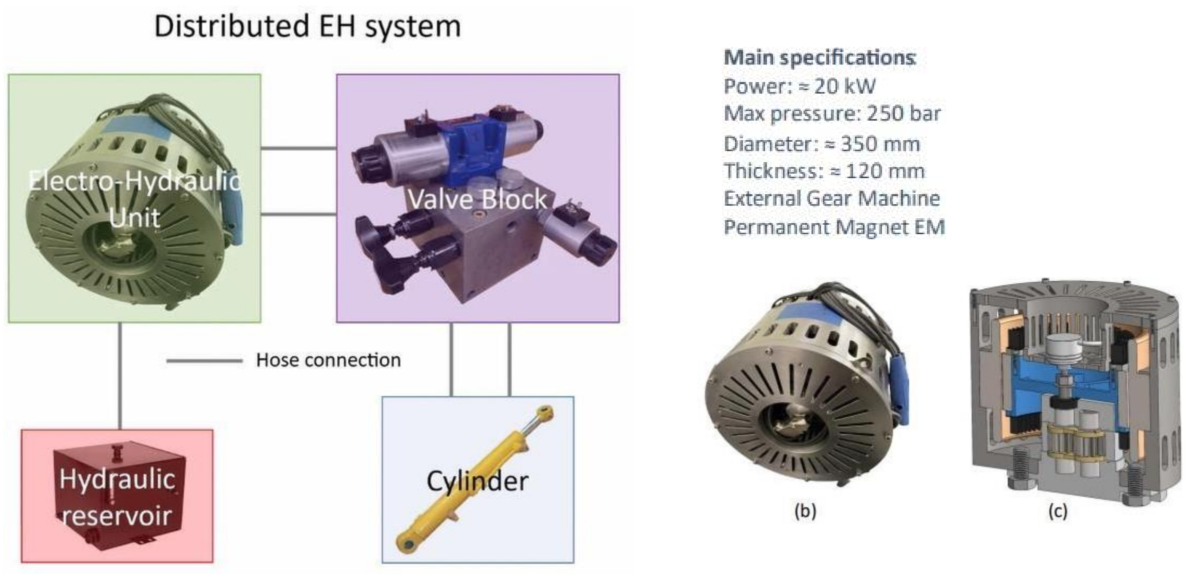


Figure 3.2: Distributed Electro-Hydraulic system and EHU

The is distributed EH system and basic idea here is to connect hydraulic hoses to each electro hydraulics power unit with the hydraulic tank of reference vehicle and valve manifold and hydraulic cylinder to implement EHA system by keeping the original configuration [9].

This implementation of EHA system used to electrify the mobile hydraulics application. So, in this schematic Electro-hydraulic system is used to full electrification of mobile hydraulic. So, the key element here is Electro hydraulic power unit

Types of electro-hydraulic unit (EHU)

When we classify the type of electro-hydraulic unit (EHU) which consists of VM-FP (Variable-speed electric motor and fixed-displacement hydraulic pump) and CM-VP (Constant-speed electric motor and variable-displacement hydraulic pump). In terms of better efficiency and cost-effective VM-FP (Variable-speed electric motor and fixed-displacement hydraulic pump) approach will be preferred [9]. But if we compare VM-FP (Variable-speed electric motor and fixed-displacement hydraulic pump) with CM-VP (Constant-speed electric motor and variable-displacement hydraulic pump) studies show it is more convenient in term of energy efficiency and minimizing energy consumption [10].

Study of thesis is to focus on Electro-hydraulic actuator architecture for electrification of off-road which is integrated with two electro-hydraulic units (EHU) composed of a VM-FP (Variable-speed electric motor and fixed-displacement hydraulic pump) in a single unit having distinctive attributes of high-power density and firmly dense [10]. Implementation of EHA (Electro-hydraulic actuator) architecture takes place in a way that real framework of the reference machine does not alter meaning that configuration of hydraulic components remains same.

To validate the high yielding performance of Electro-hydraulic actuator (EHA) architecture test rig is developed at Maha Fluid power Research center [11].

Technology demonstration

For technology demonstration reference machine is skid-steer loader Case TV 380 with the following speciation shown in table and only two functions (boom, bucket) considered for the technology demonstration and for baseline measurements of hydraulic power consumption.

Machine Main Specification	
Engine Type	Diesel, Turbo – Direct Injection,4 cylinders
Max power	90 hp [67 kW]
Fuel Capacity	25.5 gal [96.5 L]
Max Standard flow	24.2 gpm [91.5 L/min]
Machine Weight	10,207 lb [4630 Kg]
Engine speed	1150-2500 rpm

Hydraulic circuit configuration

Here we define hydraulic configuration in which open circuit or closed circuit is define which can be implemented by the method we use the pump. In a closed circuit, actuator is connected to the pump by both directions, where high-pressure port can switch but not pre-defined. In an open circuit, pump work on one side with high pressure and connected to a low-pressure reservoir on the other direction.

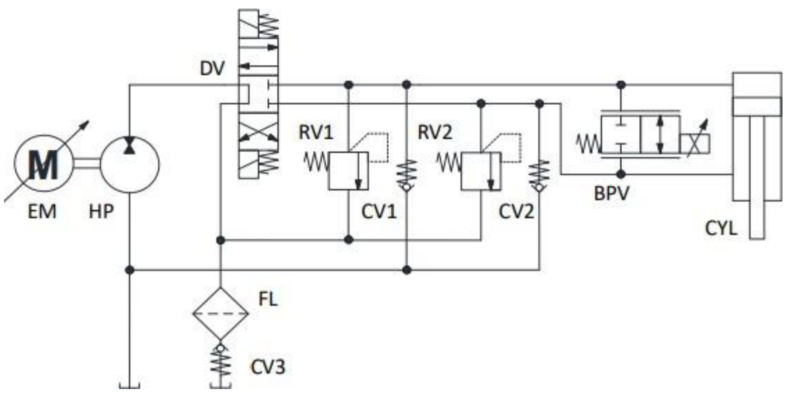


Figure 3.3: Open circuit configuration

HP operates only in two quadrants, but a 4/3 directional valve (DV) guarantees the 4-quadrant functionality of the actuator, which is a single-rod double-acting cylinder (CYL). Two relief valves (RV1, RV2) on both side of cylinder to avoid the damage due to over pressurization. Two check valves (CV1, CV2) address the cavitation issues, which may appear when high flow is needed from a reservoir during assistive operation. A filter (FL) in combination with a check valve (CV3) is present for maintenance. CV3 blocks the connection between tank and DV in assistive phases.

Functionality of proposed system

The proposed layout below is open circuit in which we have 2 quadrant hydraulic machine containing 4/3 directional control valve for switching function, check valves to avoid cavitation issues and bypass valve parallel to cylinder, this will help the system to achieve the low actuation speed operation, minimize the throttle losses for better efficiency and also help in fast assistive retraction [11].

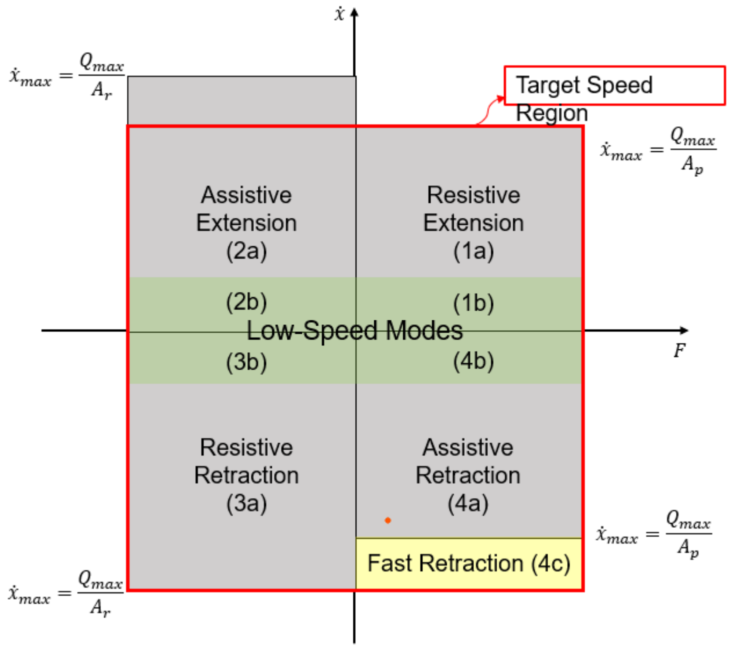


Figure 3.4: Working modes algorithm

Here all the working mode can be defined in 4 quadrants in term of actuation velocity and applied load[11].

System can work in assistive mode or resistive mode depending upon on the direction of actuation velocity and applied load.

In each quadrant, further sub modes are defined. Under the normal mode 1.1 and 4.1 EHA

is pump controlled system and actuation velocity only dependent on commanded pump speed so by pass valve (BPV) is always closed in normal mode in that case we have high efficiency and low throttling loses and we can regenerate the energy during assistive phases duty cycle[11].

In low-speed mode bypass valve is used to control the actuation velocity of the cylinder and in resistive phases 1.2 and 3.2 hp is set to min speed. Also, low speed assistive phases 2.2 and 4.2 the speed of hp is set to zero and only opening of bypass determine the velocity of actuation. So, in low speed we can't regenerate the energy.

In fast actuation mode avoid oversizing the EHU with the bypass valve, HP is set to maximum speed (*nmax*) to regenerate as much energy as possible, and BPV is opened to recycle the rest of the flow from CYL, thus enables operation with higher speeds than HP alone would allow

HP operates only in two quadrants, but a 4/3 directional valve (DV) guarantees the 4-quadrant functionality of the actuator, which is a single-rod double-acting cylinder (CYL). Two relief valves (RV1, RV2) on both side of cylinder to avoid the damage due to over pressurization. Two check valves (CV1, CV2) address the cavitation issues, which may appear when high flow is needed from a reservoir during assistive operation. A filter (FL) in combination with a check valve (CV3) is present for maintenance. CV3 blocks the connection between tank and DV in assistive phases.

Power electronic setup in EHA

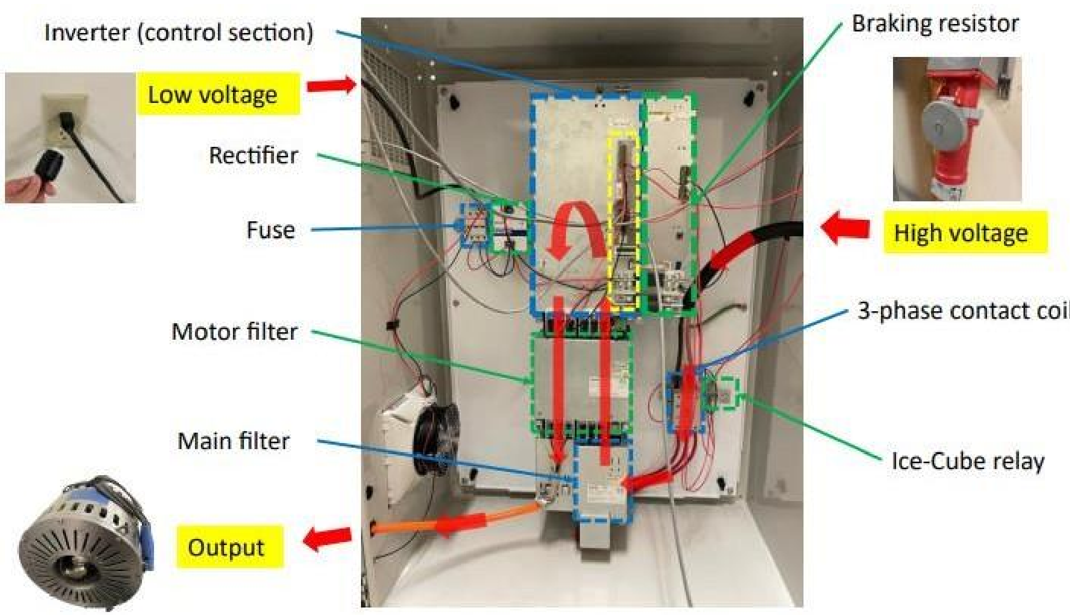


Figure 3.5: Power electronic setup

At this moment both EHU (Electro-hydraulic unit) is powered by an external electric supply. Two stationary inverters are installed which provide power to low voltage control section and three phase high voltage to PMSM (Permanent Magnet Synchronous Machine) as storage device for energy recuperation still need to implemented so with the help of main and motor filter voltage should be regulated for PMSM (Permanent Magnet Synchronous Machine) function properly to perform the actuation.

Here in this schematic one input with voltage 120 VAC is rectified to 24VDC for low voltage section and second input with three-phase high voltage (440VAC) to actuate the PMSM (Permanent Magnet Synchronous Machine). Inverter is integrated with control section manage the input voltage for the functioning the electric motor. The relays and contactor coils guarantee the safety concerns while operating high voltage section. These filters avoid the noise from the input power and the mains filter used for the mains power from the grid to the inverter, and the motor filter is for the power flow from inverter to the electric machine. As we don't have energy storage devices so we need braking resistor used to dissipate the energy from overload. High voltage battery system is used in reference machine to regenerate energy during assistive loading condition.

Control system of proposed layout

The control section of proposed layout has local IOs to communicate with the Compact RIO controller integrated with analog and digital I/O. With the help of Joystick speed command of EHU is given and safety concerns ensured with the help of E-stop button with digital ports [9].

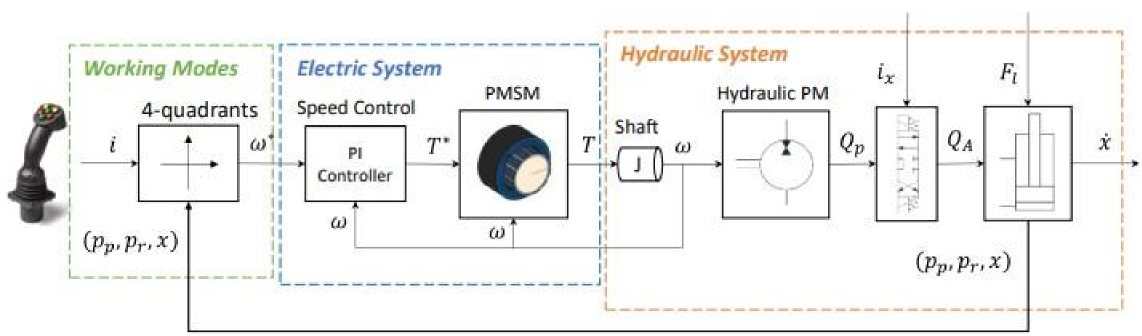


Figure 3.6: Control algorithm of Electro-hydraulic system

The working mode is implemented by measuring actuation displacement and pressure then speed command is given to EHU (Electro-hydraulic Actuator). Afterward PI controller change the desired speed to torque. Therefore, EHU deliver flow to the hydraulic system and actuate the cylinder function (Boom & Bucket). Digital signal sends to the DV (directional valve) upon different working mode for switching function.

Chapter no 4

Charging schematic of li-ion cell

Charging is very important factor to be consider because it directly impacts the battery capacity and its life span. There are different charge methods which are characterized by voltage time and effectiveness but we require balancing speed and capacity at which we charge our battery so when we charge at any charging rate it should be keep in mind that the gassing voltage or cutoff voltage should not be crossed.

Li-ion with the traditional cathode materials of cobalt, nickel, manganese and aluminum typically charge to 4.20V/cell.

Manufacturer of lithium is very strict on correct setting of lithium-ion cell that is why lithium ion doesn't accept any overcharging so it can take only what it absorbs.

Lithium-ion charger is voltage limiter device and we have full control on it so that's we should respect the required threshold while setting the voltage using charge controller.

Constant current (CC) and constant voltage (CV) Method

The most important charging method is constant current and constant voltage.

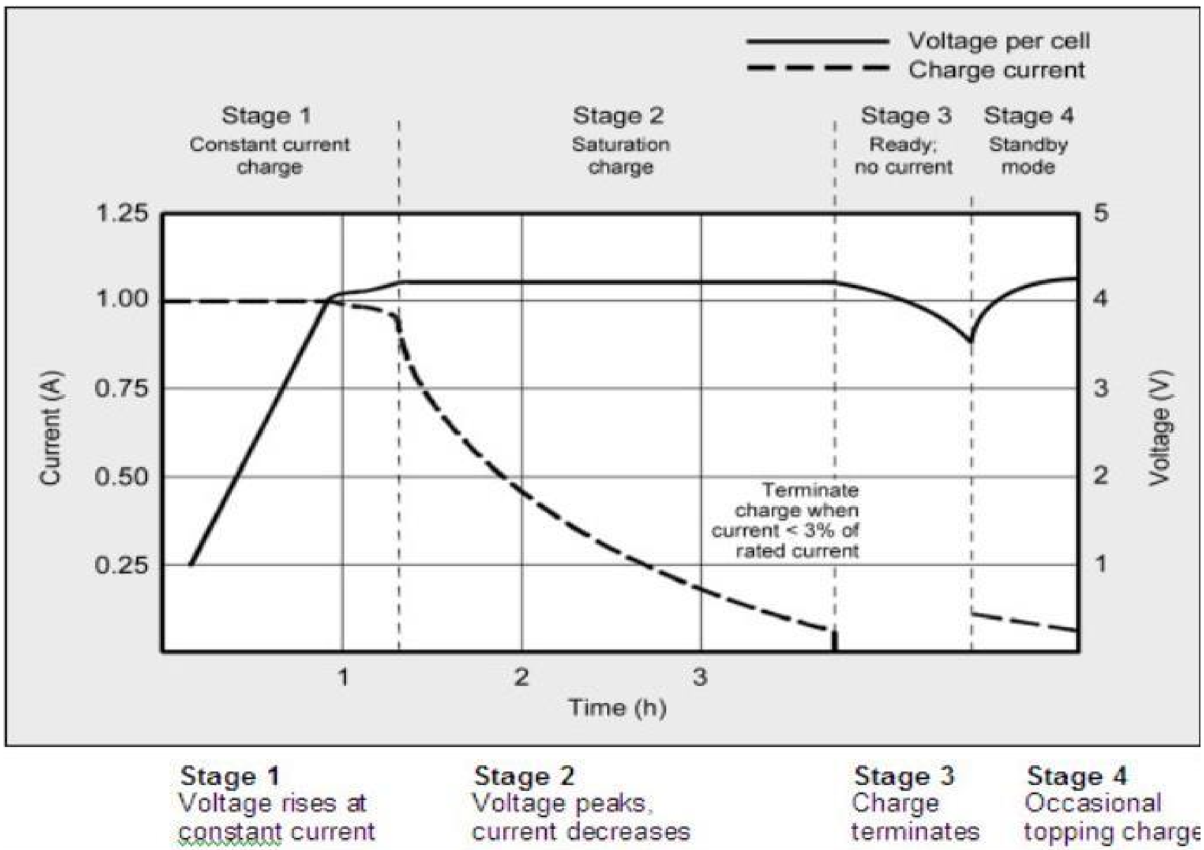


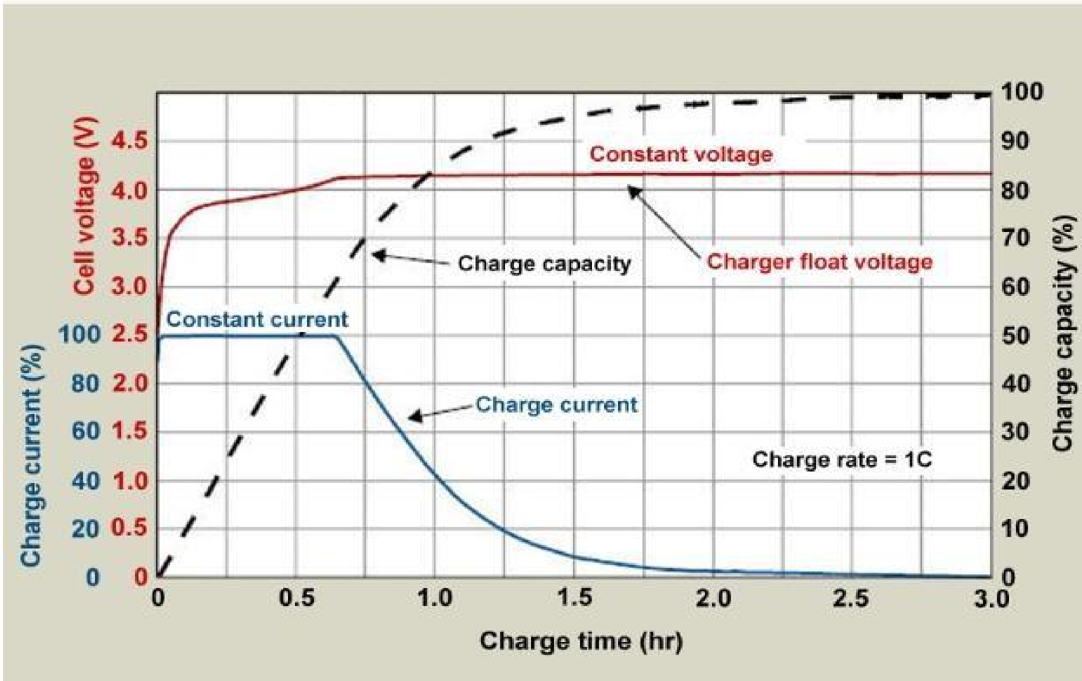
Figure 4.1: Constant Current and Constant Voltage

In this diagram basically there are four stages of CC and CV method for lithium cell [17]. In the stage 1 voltage goes higher keeping the constant current and then in the stage 2 battery get fully charged and then current goes down to 3 percent of the rated current. In stage 3 battery is fully

charge and ready to use. In Stage 4 if there is voltage sag charge add topping charge. It is not recommended when we discharge completely there is voltage sag and capacity get reduced. Li-ion cannot absorb overcharge. When fully charged, the charge current must be cut off. Prolonged charging create instability inside the battery. Boosting the voltage increases capacity, but going beyond threshold damage the battery and compromises safety. The advised charge rate is between 0.5C and 1C and the complete charge time depend on board charge which take about 2–3 hours [17]. Manufacturers prefer charging at 1C.
Also, in the table below, certain chargers set the certain voltage limits in order to avoid the damage to the battery.
This table illustrates different capacities when charged to different voltage limits with and without saturation charge so if charger set the cut-off voltage 3.8 Volt then we get capacity of 40 % by taking 2 hour in charging but with saturated state this capacity goes up to 65% [17]

Charge voltage (V)	C at cut-of Voltage (%)	Required time	Saturated state (%)
3.80	40%	120 min	65%
3.90	60%	135 min	75%
4.00	70%	150 min	80%
4.10	80%	165 min	90%
4.20	85%	180 min	100%

Figure 4.2: Different capacities with different voltage ranges



Charging Infrastructure

Charging infrastructure for the electric off-road vehicle plays a significant role for accelerating growth in the future. Better charging infrastructure implementation makes the charging process quick and smart. Before going into different charging methods, we can have AC and DC charging systems depending on the need to charge the electric battery.

During charging with an AC charging system OBC is responsible for the power conversion that's why the grid is directly attached to an OBC (on-board charger) in the AC charging system, and it also prevents the electrical grid from overloading. A maximum charging output of 20 kW can be taken from the AC charging system [7], and the charging time depends on the output of the OBC (on-board charger).

While charging with a DC charging system, DC charging stations bypass the OBC because the conversion of AC/DC takes place in the DC charging station and high voltage battery is directly taking DC from the DC charging system.

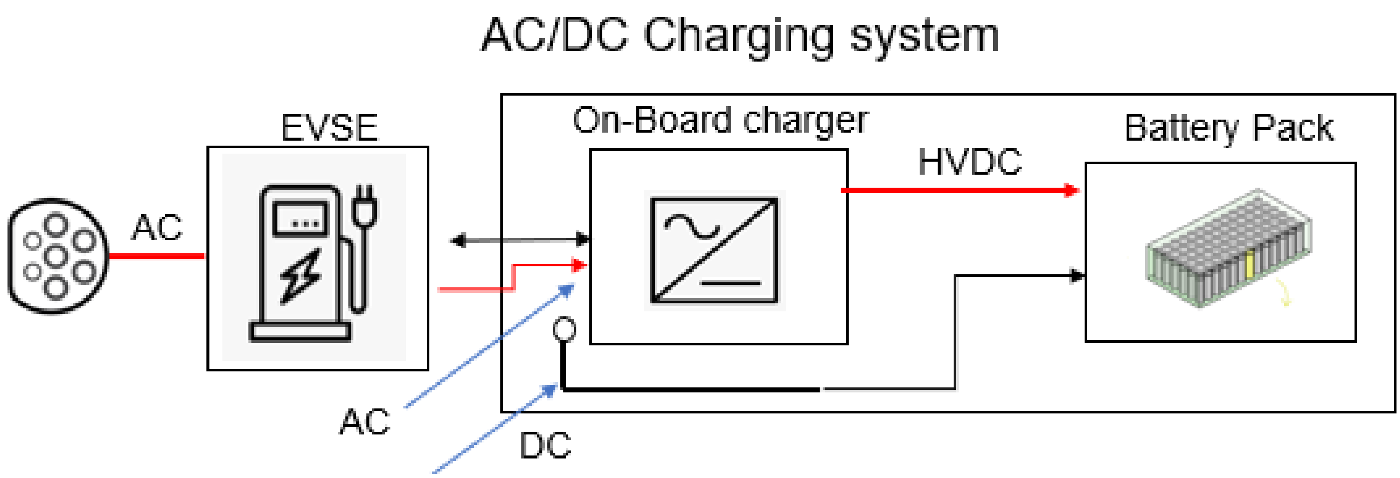


Figure 4.3: Schematic of AC/DC charging system

Charging speed and capacity

Charging speed and capacity of charging infrastructure depend on the various levels, typically there are three levels in which AC level 1 and level 2 belong to the AC charging system and Level 3 belong to DC fast charging [7]. It can be seen in the table below [7] that in AC Level 1 and 2 of 120 V AC, 240 V AC charging rate is quite slower because of the power conversion which takes place inside the electric vehicle and it can go up to 4kW to 20kW at maximum due to this reason, time required to fully charge the electric battery may take few hours to several depend on the on-board charger but while considering the DC charging system, charging rate is remarkable higher and goes up to 80 kW to 500 kW. But it's not recommended to use the DC charging system frequently because a high surge of current can increase the operating temperature inside the battery which causes different thermal issues and reduces the overall battery life So in each region different charging criteria is adopted where EV charging connectors across different geographies are also variable.

	Charging Standard in North America	Volts	Maximum Current	Maximum Power
1	AC LEVEL 1 (J1772) connector	120 V AC	16 A	1.9 kW
2	AC LEVEL 2 (J1772) connector	240 V AC	80 A	19.2 kW
3	DC LEVEL 1 CCS (Combined Charging System)	200-500 V DC MAXIMUM	80 A	40 kW
4	DC LEVEL 2 CCS (Combined Charging System)	200-500 V DC MAXIMUM	200 A	100 kW

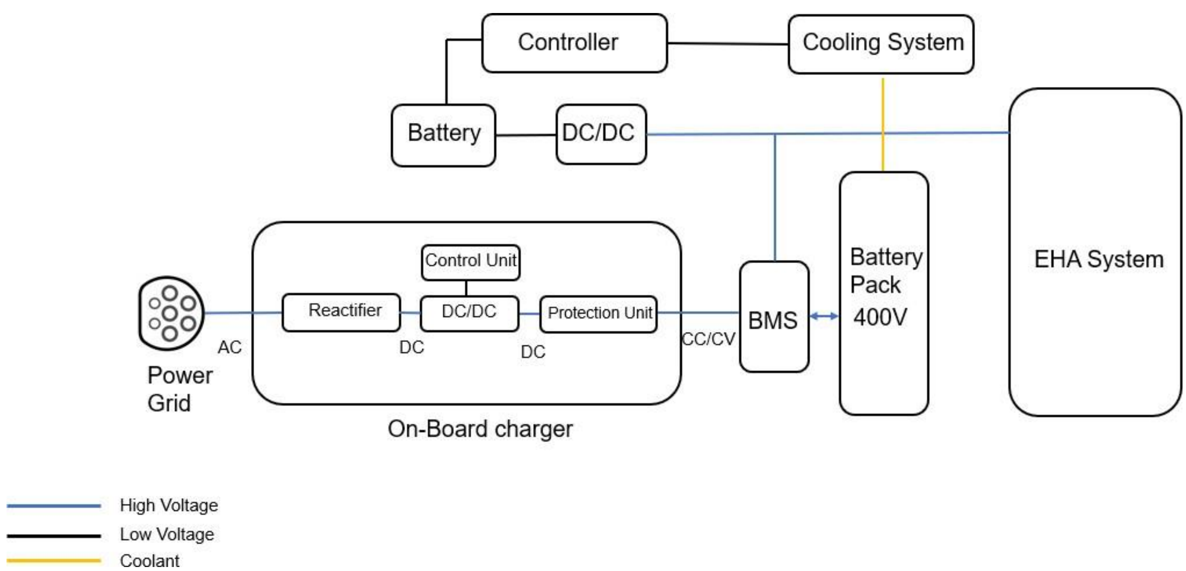


Figure 4.4: On-Board charge schematic

This is more detail schematic in which we have this onboard charger system which contain high power dense system. As EHA system require high power and high energy battery pack that power PMSM so in order to supply high power to battery from grid there are two dedicated power conversion stages. First stage is Uni-directional AC/DC conversion that helps in power correction factor as well as to facilitate unidirectional ac-dc power conversion and second stage DC/DC conversion stage that provide voltage matching between battery pack and dc bus

. onboard charging system are specifically design to meet the specific voltage requirements of the battery pack and grid and it give us this flexibility to charge and discharge the battery pack wherever the electric power outlet is available. This on-board charger does contain high power dense converter system.

BMS is always in communication with control unit and protection in order to ensure safety and control the charging process for battery pack.

BMS (Battery Management System)

BMS is complex embedded system which purpose is to manage the battery pack which is made up of lithium-ion cells. BMS is enclosed within the battery pack. There are variety of functions which BMS Perform like providing battery safety and longevity. It also reveals state-of-function in the form of state-of-charge and state-of-health (capacity) and prompt caution and service. This could be high temperature, cell imbalance or calibration. It also indicates end-of-life when the capacity falls below the user-set target threshold.

It informs the host application control how to make best use of battery pack so that it prolongs the battery life and get most performance possible by informing the host application what is maximum power it can draw from the battery source over a certain period of time so that it does not abuse the battery pack.

If BMS detect unsafe operating condition it responds immediately
If there is any failure within the host application and it abuses the battery pack in anyway, BMS disconnect battery from the load in order to any further damage

BMS is connected to all the internal components of the battery pack is to sense and understand what is happening inside the battery pack and also it is connected to the host application by mean of CAN and LIN protocols. BMS also connect to all the battery pack cell to sense the voltage of cell and temperature of cell and also connect to the thermal management system.

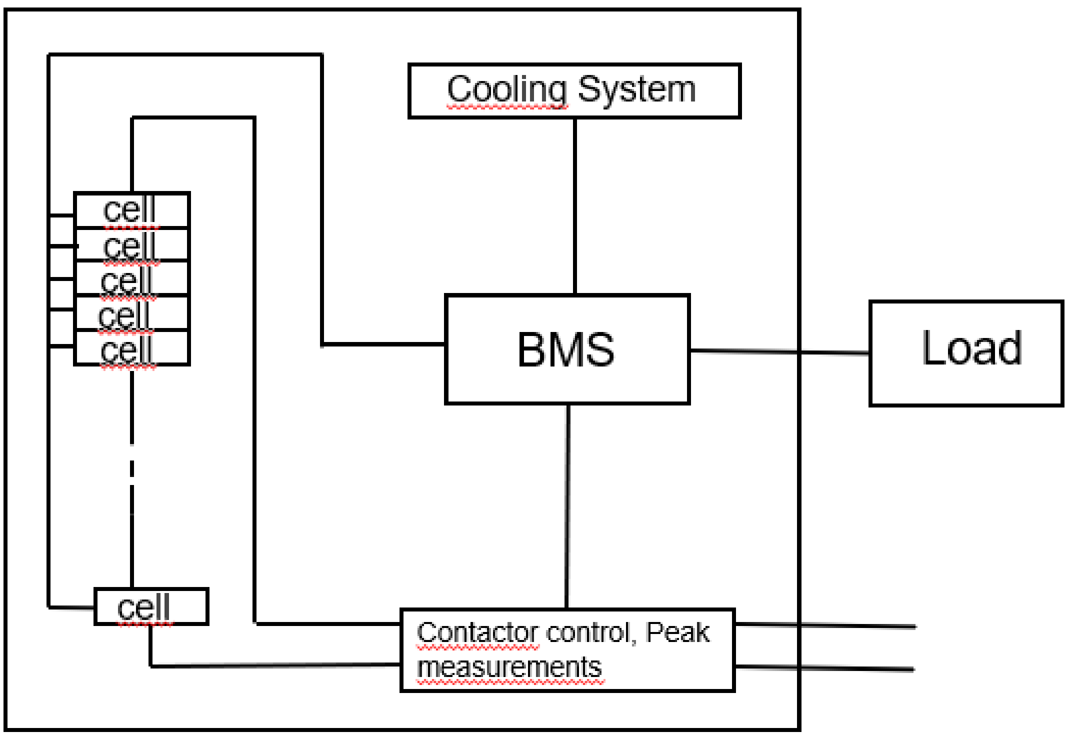


Figure 4.5: Battery Management System

This is block diagram and everything inside the block enclosed in battery pack and outside the Battery pack we have host application which is constantly in communication with the
BMS in order to understand the requirement of host application and in order to convey the limits of battery pack in which cells are connected in series by high power high current connecting path of the battery and these high power lines are connected to the host application load through devices call contactors which act as on off switch that either connect the high power high voltage battery pack to the load or disconnect it from the load

under software control . This control unit also monitors the high current and high voltage monitoring of battery pack.

In BMS we have Performance measurement is responsible for the state of charge of battery cell and estimating the power limits and how much energy is available and also responsible for the balancing and equalization of the cell in the battery pack

Also, we have Detection function which is responsible to detect the abuse by the host application and estimating state of health under normal and abused condition and also estimate the present state of life and also predict from that how much future life we predict from battery pack to deliver before expiry.

Chapter no 5

Battery sizing

Battery Performance Parameters

In any application we can't find Battery with ideal efficiency. Choosing the appropriate battery for application is considering the most important battery parameters and trading these off with others. Doing tradeoff make the choice better like if the application required higher power, internal cell resistance should be which can be done by making electrode surface area greater. However, this will make inactive components higher such as current collectors and conductive aid so energy density is compensated with high power.
There are certain factors before choosing a right battery, we should consider battery must be a long life, high specific energy, high energy density, and high-power output and require minimum maintenance safety and safely operate at a wide range of temperatures, and for sure all available at a reasonable cost. When we design a battery pack cell quality is very important especially when we drew a higher current from our battery pack it must uniform distributed through our components and circuit board

(BMS). In our case, we focus on secondary batteries (batteries that can be recharged) which are lithium polymers, lithium-ion (lithium iron phosphate, lithium cobalt, and lithium manganese) lead-acid batteries, and nickel-metal hydride. There are certain advantages and disadvantages in terms of complexity, safety, operating range, durability, size and weight, and of course cost.

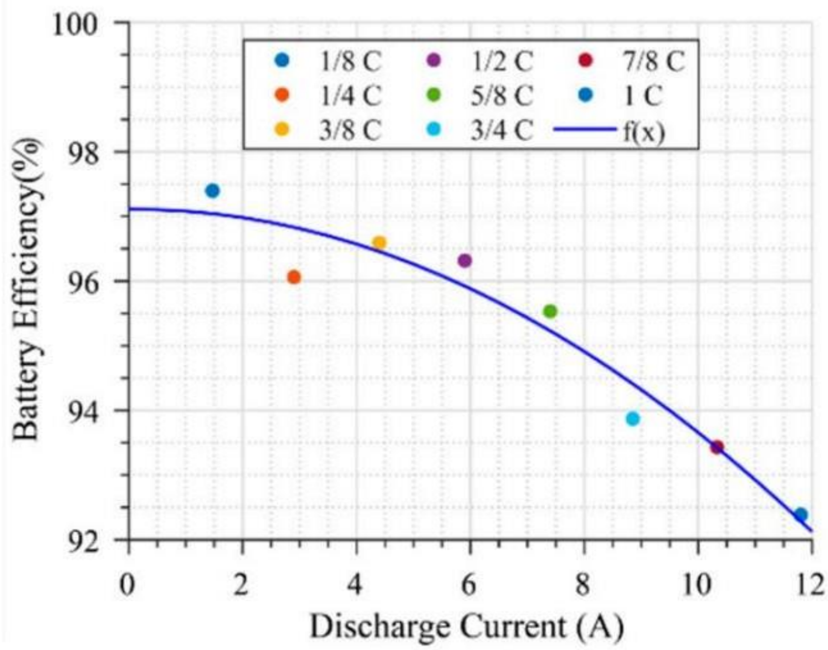


Figure 5.1: Battery Efficiency

Energy Capacity

The “energy capacity” of the battery can be defined “the total Watt-hours available when it discharged at a certain C-rate from full state-of-charge to the cut-off voltage “

How long can our machine operate it depend on useable capacity of the battery (Kilo-watt-hour) from manufacturer and we get the date sheet of the battery in which it is instructed that under certain condition under certain operating ranges, cycle, discharging rate our battery can last longer or shorter so from that we can find the useable capacity

The amount of energy that we get from energy storage device like battery is not a constant quantity. Temperature constraints and C-rating can impact the efficiency of the battery, like changing the amount of energy or charge lost while discharging. These efficiency losses are due to resistances within the battery cell because higher discharge rates imply higher internal resistance and low battery efficiencies. High temperatures can make internal resistances less but battery aging get increase.
Every Battery is designed for certain energy capacity designed in KWh for different application
Which is Product of nominal Voltage*ampere-hour

C Rate of charging or discharging

Higher C rates will impact the battery life cycle like higher the C rate, the less will be energy capacity.

So basically, graph below is discharging profile of lithium-ion cells. We can observe here [17] from 100 to 2100 Ah cell voltage and discharge capacity is linear function. Also, we can observe behaviour of current with discharge capacity. At 50 percent state of charge (1500Ah) voltage of cell while being discharge at 3A is around 3.5 Volt and at the same 50% SOC at 30 A is 3 Volt

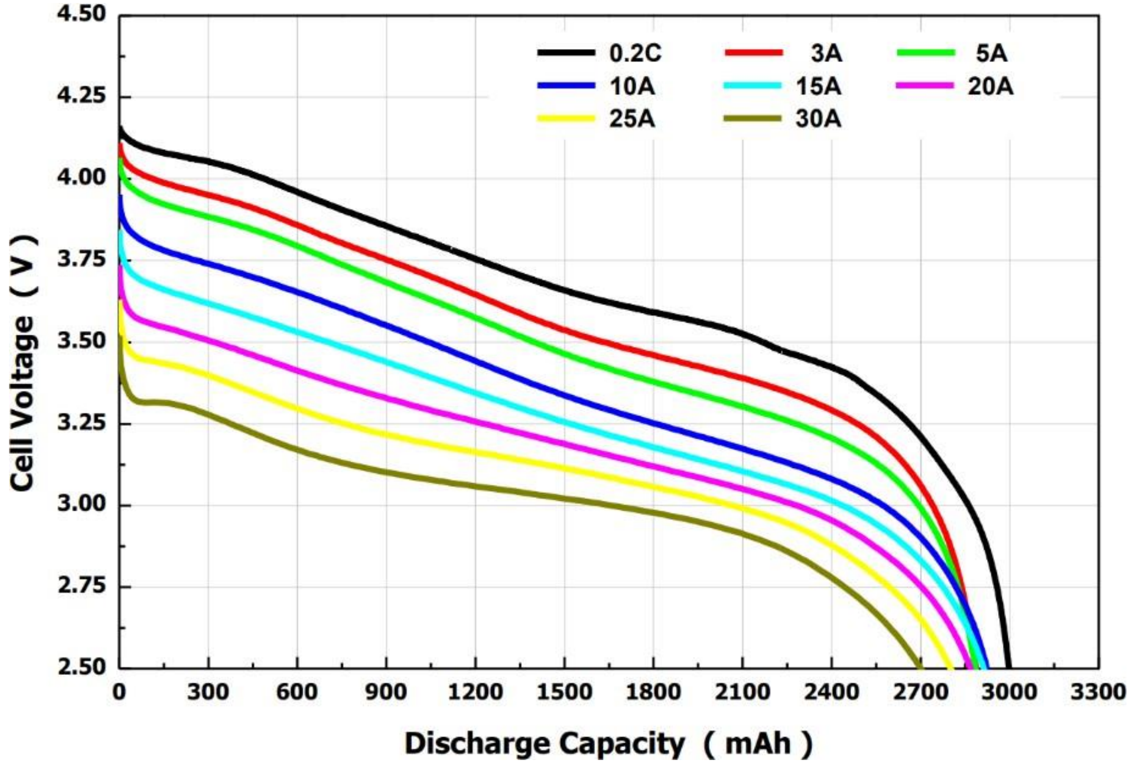


Figure 5.2: Discharge rating of lithium-ion cell

Temperature Constraint

Lithium-ion batteries are dependents on temperature constraint so in order to avoid any proper exceeding beyond threshold thermal management is required to manage battery temperature under certain operating temperature condition.

In this graph[17] it can see that for lithuim ion cells best operating temperature is in between 15 to 35 degrees. Below 15 degrees, It Is not recommended to have this range of temperature and also if operate at higher temperatures can cause thermal runaway.

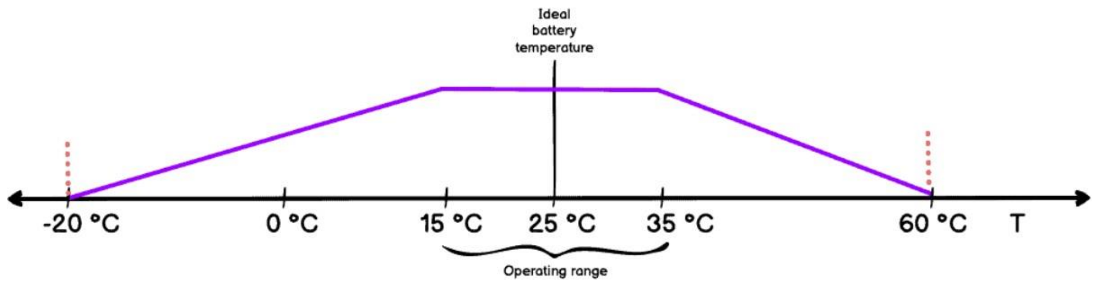


Figure 5.3: Temperature ranges for Li-ion cells

Also graph below [17]is discharging profile w.r.t to temperature while being discharge at 0.25 A so at differernt ranges of temperature , we get differnet cell voltages .

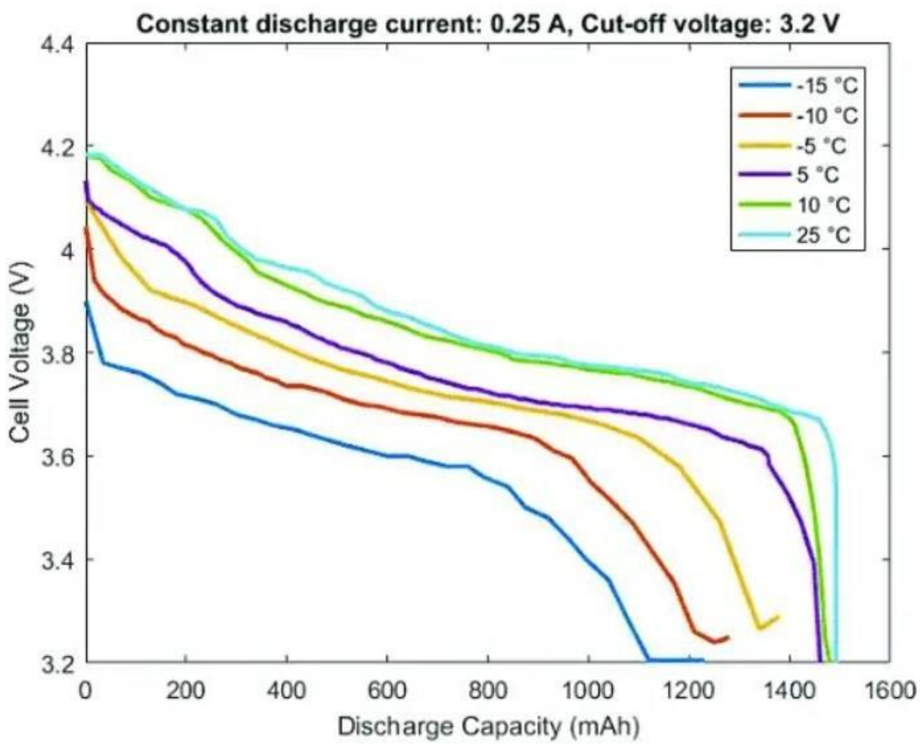


Figure 5.4: Discharging rate w.r.t to different temperature ranges

For the first 200 cycles the battery performance get decrease 3.3% at 77 degrees; at 113 degrees it will down to 6.7%. That's more than double the amount of degradation! [17]

At extreme temperatures, the battery lifecycle badly damaged due to constant exposure.

This will increase battery capacity but in the long it will cause really big problem so it should be avoided.

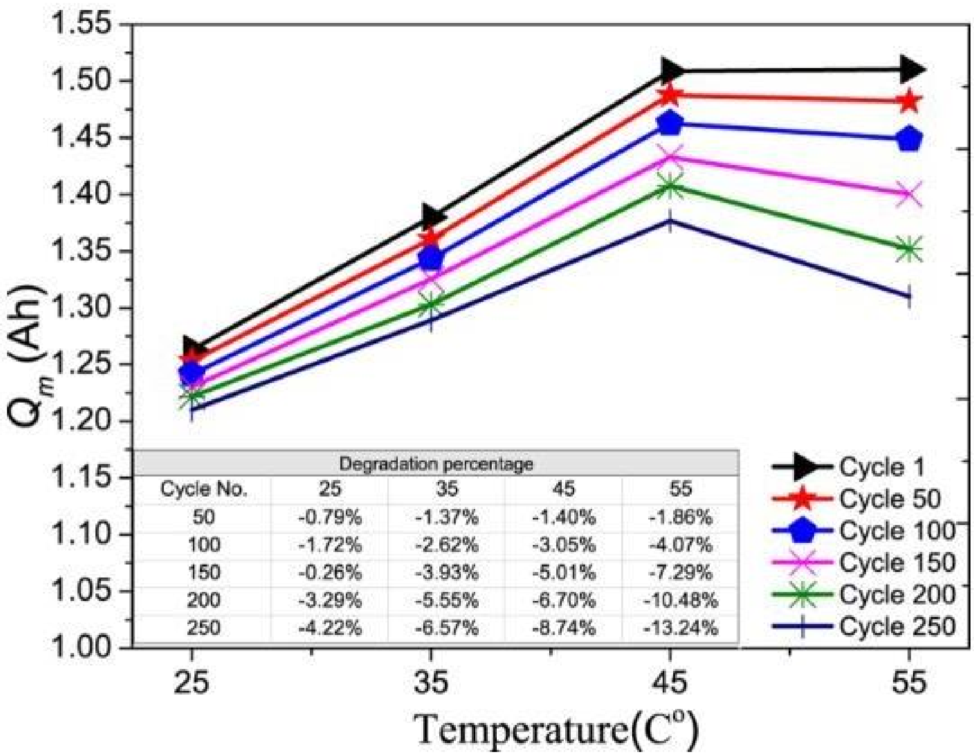


Figure 5.5: Degradation percentage at different Temp ranges

Depth of Discharge /State of charge

Soc is, available capacity (in Ah) and expressed as a percentage of its rated capacity.

The SOC parameter can be viewed as a thermodynamic quantity enabling one to assess the potential energy of a battery and it is important help to improve system performance and reliability

Battery Management system also help to estimate SOC which avoid any predicted system failure and prevent the battery from being over charge or discharge cause permanent damage The depth of discharge is the complement of state of charge: as one increases, the other decreases.

why SOH and DOD are important because battery energy capacity deteriorated over time, it captures what is amount of deterioration and for dept of dept of discharge it is at which rate we discharge of battery it also impacts the life of battery).

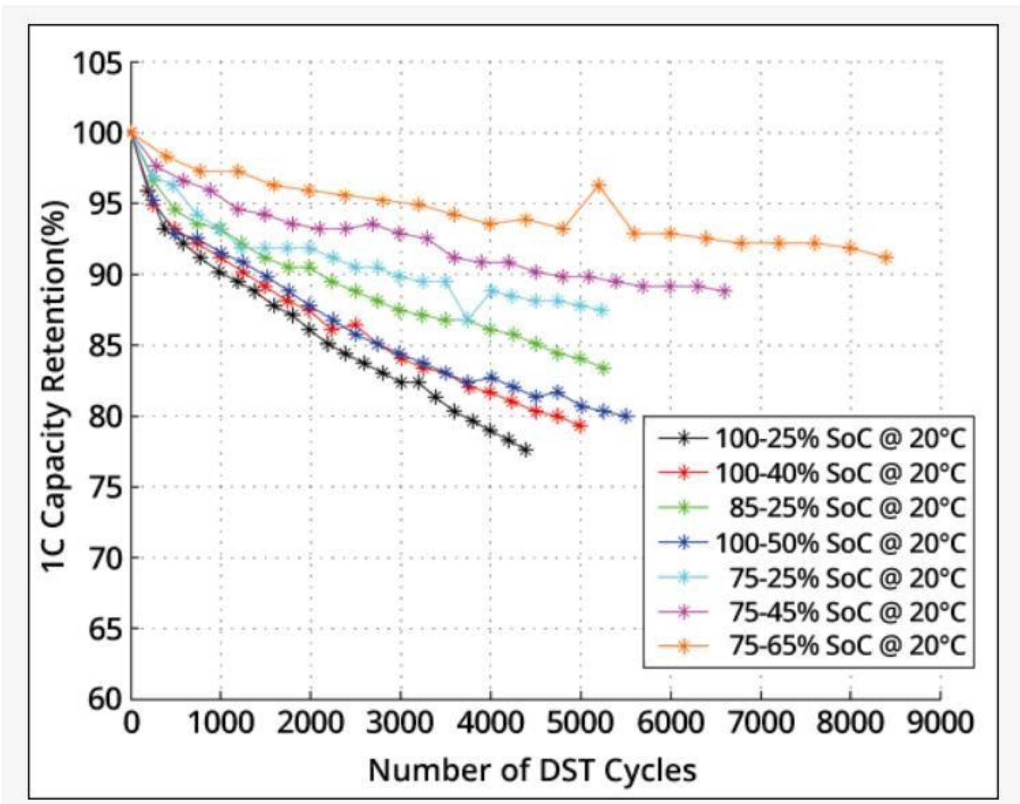


Figure 5.6: State of charge for different DST cycles at 20 degree

$$\mathrm{DoD} = \frac{C_{\mathrm{bat}}V - E_{\mathrm{bat}}}{C_{\mathrm{bat}}V}. \qquad \mathrm{SoC} = \frac{E_{\mathrm{bat}}}{C_{\mathrm{bat}}V}.$$

Why Lithuim Ion battery

If we compare li ion batteries with conventional lead acid and other batteries. So why lithium-ion battery is so extensive. So, in this table its clearly seen that specific energy [Wh/kg] and energy density [Wh/L] of Li ion battery in term of both volume and mass is more energy dense than nickel cadmium, lead acid and nickel metal hydride.

Not only lithium ion has highest energy density but have no memory effect. (We have a battery which hold a full charge and we don't drain all of its power before recharging it if we do this repeatedly in this way the battery memorises the fact it hasn't been used to its maximum capacity, after which the battery's capacity drops when used the next time despite it being fully charged.) so in the lithium ion we don't have this memory effect so it doesn't matter if we charge or discharge it partially or fully it does not affect its capacity.

Secondly its truly deep cycle battery even we discharge it until cut-off it doesn't suffer large penalty. So, we don't have a big voltage sag under high power application because they have low impedance so these batteries deliver higher current required for our application and we don't have peukart effect.

Faster we discharge the battery the less total energy you get out of battery because with increase current draw output voltage is reduced because of voltage drop across internal resistance of battery and they don't self-bleed if we disconnect the battery for a long period of time, we still significant amount of charge left in battery that's why we don't have floating charging stage in lithuim ion and it also doesn't have toxicity and longest life time.

. Most useful battery in automotive industry is Lithuim nickel cobalt Aluminium oxide which has highest specific energy.

Also, in term of weight lithium-ion batteries are much lighter. Let suppose we require capacity of 100 KWH in lithuim ion batteries that capacity is available in 1000 pound but in lead acid it's more than 3000 pounds [18].

Lithuim ion battery does have 200 to 735 Wh per litre and lead acid has very less about 60 to 100 Wh per litre [18].

There are also some disadvantages like they are temperature Sensitive batteries. They have Strict Thresholds for charging because manufacturer of lithium is very strict on correct setting of lithium-ion cell that is why lithium ion doesn't accept any overcharging so it can take only what it absorbs.

Lithium-ion charger is voltage limiter device and we have full control on it so that's we should respect the required threshold while setting the voltage using charge controller like it can't go beyond cut off threshold but lead acid battery did. While lead acid batteries contain low installation cost lower compared to lithium-ion options.

		$Pb\text{-}PbO_2$	Ni-cd	Ni-MH	$Zn\text{-}Br_2$	Na-NiCl	Na-S	Li-Ion
1	Specific Energy (Wh/kg)	30-60	60-80	60-120	75-140	160	130	100-275
2	Energy density (Wh/L)	60-100	60-150	100-300	60-70	110-120	123-130	200-735
3	Specific Power (W/kg)	75-100	120-150	250-1000	80-100	150-200	150-290	350-3000
4	Cell Voltage(V)	2.1	1.35	1.35	1.79	2.58	2.08	3.6
5	Optimum temperature	-20 -45°C	0 -50°C	0 -50°C	2500°C	300 -350°C	300 -350°C	-20 -60°C
6	Cycle Durability	500-800	2000	500	20-40	1500-2000	2500-4500	400-3000

Lithium-ion chemistries

Most expensive components in batteries are cathode materials (Nickel and cobalt). Choice of cathode influence energy, safety, and cost. We have variety of lithium-ion chemistries with different characteristics and there is clear tradeoff between different properties in chemistries. Depending of proportions of each metal of cathodes give us different property of battery in term of cost, life cycle , safety and range . Like the Ternary Lithium Nickel Cobalt Aluminum Oxide (NCA) and Nickel Manganese Cobalt (NMC) have higher energy density but they are expensive, but Lithium Iron Phosphate (LFP) are safer and not expensive like the Ternary batteries but they lower range in comparison with NCA and NMC. That's why LFP is gaining market share in mass market vehicle, also Tesla announced in 2021 they are using more LFP chemistries in their mass market vehicle [19].

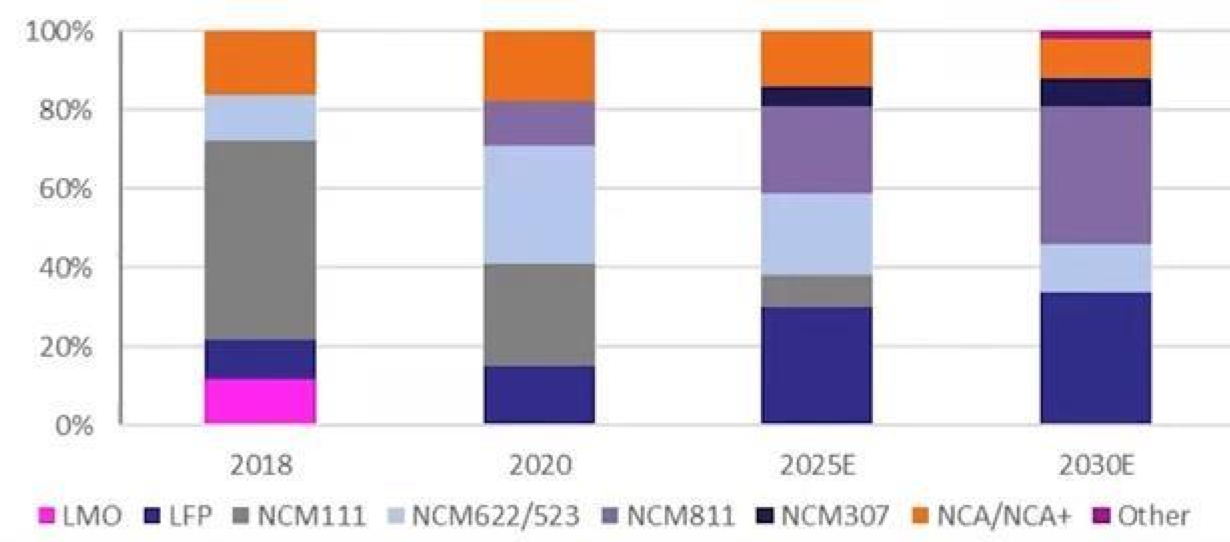
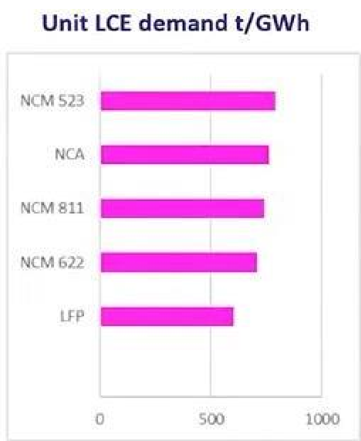
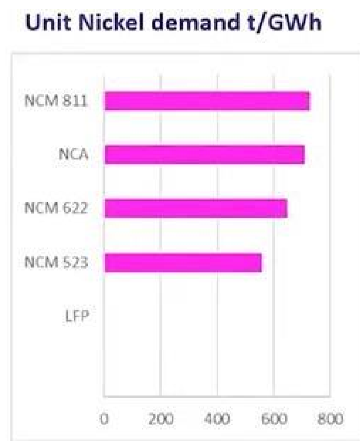
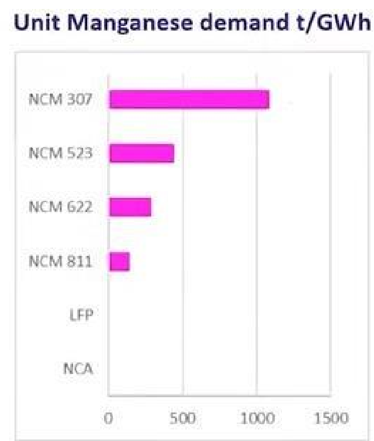


Figure 5.7: Different lithium-ion chemistries market share

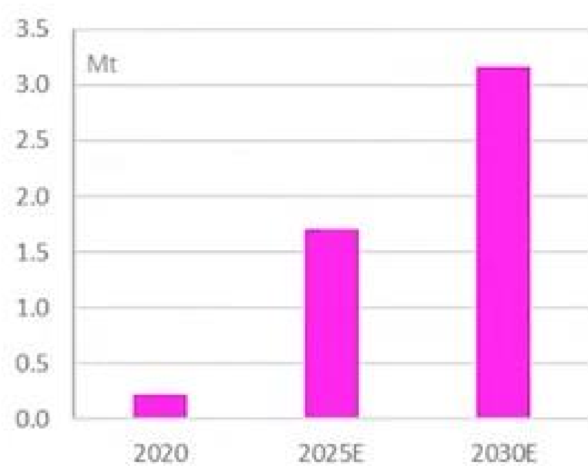
Also, the supply demand of nickel, cobalt, manganese, and iron phosphate differ for different cathode chemistries but in the graph below [19] it can see demand for t/GWh for different cathode material. Like for LCE (Lithium carbonated equivalent) is consistent but lower in LFP (lithium iron phosphate) but in unit nickel demand its quite variable like in NCM 811 nickel percentage is higher with respect to NCM 523 which make it more energy dense but less stable because of less concentration of cobalt but in LFP (Lithium Iron phosphate) we don't have any nickel metal. In term of unit manganese demand we see low concentration of manganese in NCA (Lithium Nickel Cobalt Aluminum Oxide) 811 and no manganese in LFP (Lithium Iron phosphate) and NCA (Lithium Nickel Cobalt Aluminum Oxide) [19]But graphite remain consistent and also lithium doesn't vary much in all chemistries.







Now if we talk about the anode material, it is made up of graphite and it is mixture of natural graphite and synthetic graphite, but silicon is also used in anode but it's less than 5% but it can increase up to 10% but because of its high cost it can't be major driver in anode material. It swells in size when high current pass through it and result in dendrites formation which push the silicon material grow out from anode and potentially cause short circuit



In the future, larger cells are recommended because of substantial impact on energy density of overall pack level because by using larger cell, fewer cell is embedded in battery pack which in result eliminate a lot of packaging like (plastic, steel, copper, and aluminum) and energy density loses. Recently Tesla announced larger use of LFP (Lithium iron phosphate) in which BYD's blade battery uses Tesla 4680 cell which makes the pack energy density of LFP (Lithium iron phosphate) close to pack energy density of NCM(Nickel Manganese Cobalt) because NCM(Nickel

Manganese Cobalt) has lower safety level then LFP(Lithium iron phosphate) [17] and it use a lot of thermal management techniques therefore pack energy density of NCM(Nickel Manganese Cobalt) battery tends to lower than cell energy density . Due to BYD's blade LFP (Lithium iron phosphate) market share is growing significantly.

Significant Impact of Cobalt in LIB's

Cobalt is extracted as an outgrowth of nickel and copper. A typically lithium battery does contain 14kg of cobalt because this metal increase life and energy density (range). Refining and mining of cobalt is costly, and it is one of most expensive material in battery. In 80kWh battery it is estimated that material cost around 800$ in battery so it should be eliminated to make the battery less expensive. It helps to maintain safety and longevity and prevent fire. There may be some other ways to extract the cobalt like the recycling because of high cost but it is highly environmental unfriendly. Many batteries manufacturer try to go for low-cobalt material or No-cobalt material. We have also cobalt free lithium-ion chemistry which is LFP (Iron phosphate) and LTO (Lithium Titanate) . That's why many, manufacturer go for nickel cathodes instead of cobalt based cell due to its high price but nickel cathode contain low voltage in comparison with cobalt system .

Lithium Nickel Manganese Cobalt Oxide

For our case study, we consider this cathode material for LIBs which is effective combination of Nickel, Cobalt and oxide. It can provide 5A under normal operation with the capacity of 2800 mAh in 18650 cell and it can provide upto 20 A discharging current. For the anode, silicon is combined with graphite but due to its disadvantages it can make the battery unstable.

As nickel is very famous for its high specific energy but it needs proper thermal management system in order to abstain from instability. Due to this reason manganese come in to play because of its high thermal management it can enhance the ability of nickel to withstand the thermal constraints but it does have poor energy density which will compensated by nickel so they both enhances each other strength. There are variety of possible combination of NMC like NMC (Nickel Manganese Cobalt)111 and NMC (Nickel Manganese Cobalt) 532. Operating range is between 3.0 to 4.2V with specific energy upto maximum 200 Wh/kg. Charging condition is in between 0.7 to 1C and discharging condition is in between 1c- 2c

Lithium Iron Phosphate (LFP)

Lithium iron phosphate provide better functionality with less internal resistance due to effective cathode (Phosphate). There are many advantages related to this Li-ion chemistry including thermal capability. If the host application draws higher current from battery pack, it will manage the thermal constraints.

It accepts also full charge and doesn't allow instability at high State of charge and make it safe even fully charged. but due to this reason it compromises on nominal voltage which make the specific energy less. LFP has high self-discharge in comparison with other Li-ion chemistries

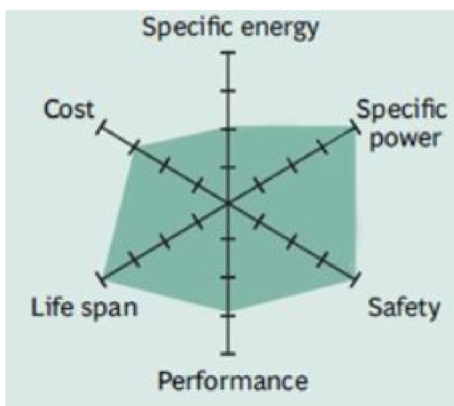


Figure 5.10: Lithium Iron Phosphate characteristics

Lithium Nickel Cobalt Aluminum Oxide (NCA)

Lithium Nickel Cobalt Aluminum Oxide (NCA) battery has good specific energy of around 260 (Wh/kg) providing good specific power. So typical voltage operating ranges from 3.0-4.2 V. Charging rate are quite higher and typical charging time is around 3h at 0.7 C. It also shares many similarities with Lithium Nickel Manganese Cobalt Oxide

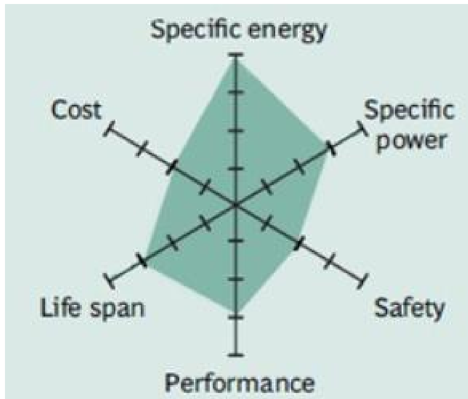


Figure 5.11: Lithium Nickel Cobalt Aluminum Oxide (NCA) characteristics

There are also some other chemistries like Lithuim Titanate Oxide (LTO), Lithuim Cobalt oxide (LCO) and Lithuim manganese oxide (LMO) which also used in electric power train and solar power application. There is comparison between li-ion chemistries in the table below [18] .

		Nominal Voltage (V)	Discharge current rate ©	Temp constraints	Specific Energy (Wh/kg)
1	Nickel Manganese (NMC)	3.0 – 4.2	1-2C	210 °C	220
2	Lithium Iron Phosphate (LFP)	2.5 – 3.6	1C	270 °C	120
3	Lithium Nickel Cobalt Aluminum Oxide (NCA)	3.0 - 4.2	0.7C	150 °C	260
4	Lithium Titanate Oxide (LTO)	1.8 – 2.8	1C	High	80
5	Lithium Cobalt Oxide (LCO)	3.0 – 4.2	0.7 – 1C	150 °C	200
6	Lithium Manganese Oxide (LMO)	3.0 – 4.2	0.7 – 1C	250 °C	150

Tesla Model S Lithium-Ion Battery NCR18650B EV Module

This battery has highest specific energy and ideal for high voltage (400 V) EV system and the weight is smaller in comparison with other batteries and self-discharge is so smaller and each module store up to 5300 watt hour of energy .

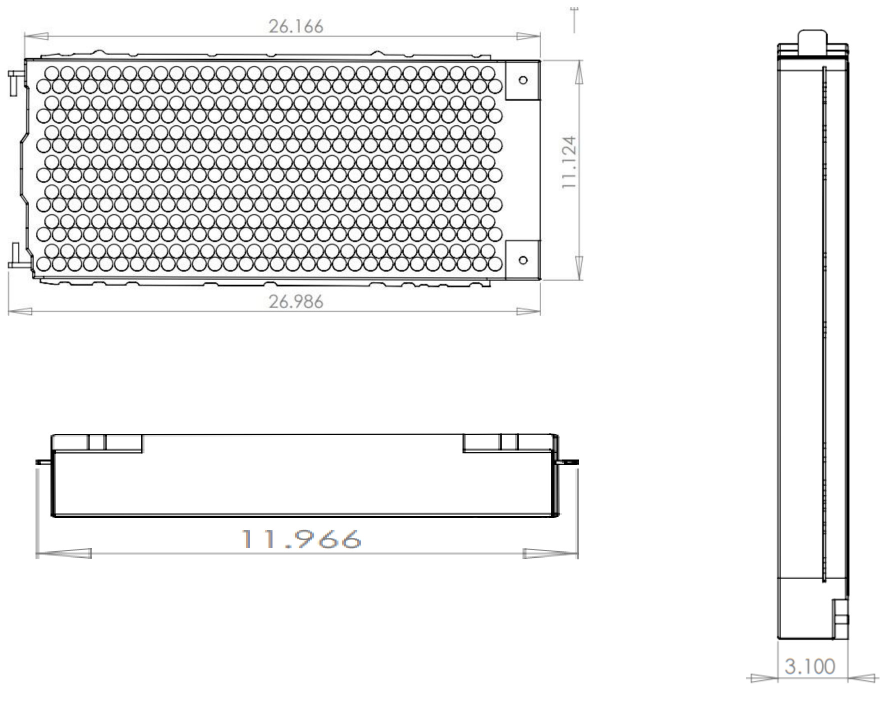
Each module is made up of 444 18650 cylindrical cell and weigh up to 453 kg around 1000 lbs so 18 module 5.3 each give us around 95.4 kwh of energy

Due to high thermal capability constraint each cell has a wired connect to it, this wire carries a current that it put out by cell and if there is something wrong inside it act a fuse and burn itself and disconnect itself from the rest of battery. Also, the durability of battery is very substantial and on the back of each module we have integrated liquid cooling tubing system and charging range 0 to 45 degree and operating temperature is -20 to 60 having thermistor in each module. Module fully charge of around 410 V and discharge at 330 V.

	Specifications	NCR18650B EV module
1	Energy capacity [kWh]	5.3 kWh
2	Charge Capacity [Ah]	232Ah
3	Nominal Voltage [V]	22.8V/Module
4	Charge Cut-off [V]	25.2V/Module
5	Discahrge Volatge Cut off [V]	19.8/Module
6	Weight	55 lbs
7	Cost per module	1580 $
9	Max discharging current (10 sec)	750 Amps

Specifications

Rated capacity(1)	Min. 3200mAh
Capacity(2)	Min. 3250mAh Typ. 3350mAh
Nominal voltage	3.6V
Charging	CC-CV, Std. 1625mA, 4.20V, 4.0 hrs
Weight (max.)	48.5 g
Temperature	Charge*: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density(3)	Volumetric: 676 Wh/l Gravimetric: 243 Wh/kg

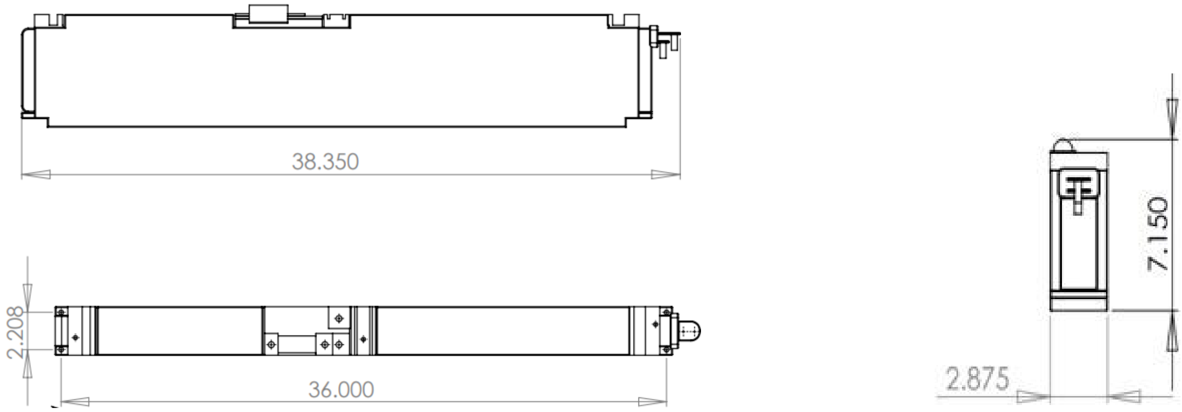


Lithium Nickel Manganese Cobalt Oxide cell (NMC)

	Specifications	NCR18650B EV module
1	Energy capacity [kWh]	3 kWh
2	Charge Capacity [Ah]	57 Ah
3	Nominal Voltage [V]	57.0V/Module
4	Charge Cut-off [V]	63.0V/Module
5	Discahrge Volatge Cut off [V]	50V/Module
7	Cost per module	799 $
9	Max discharging current (10 sec)	150 Amps

Specifications

Rated capacity(1)	Min. 2700mAh
Capacity(2)	Min. 2750mAh Typ. 2900mAh
Nominal voltage	3.6V
Charging	CC-CV, Std. 1925mA, 4.20V, 3.0 hrs
Weight (max.)	46.5 g
Temperature	Charge*: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density(3)	Volumetric: 577 Wh/l Gravimetric: 214 Wh/kg


38.350
2.208
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Chapter no 6

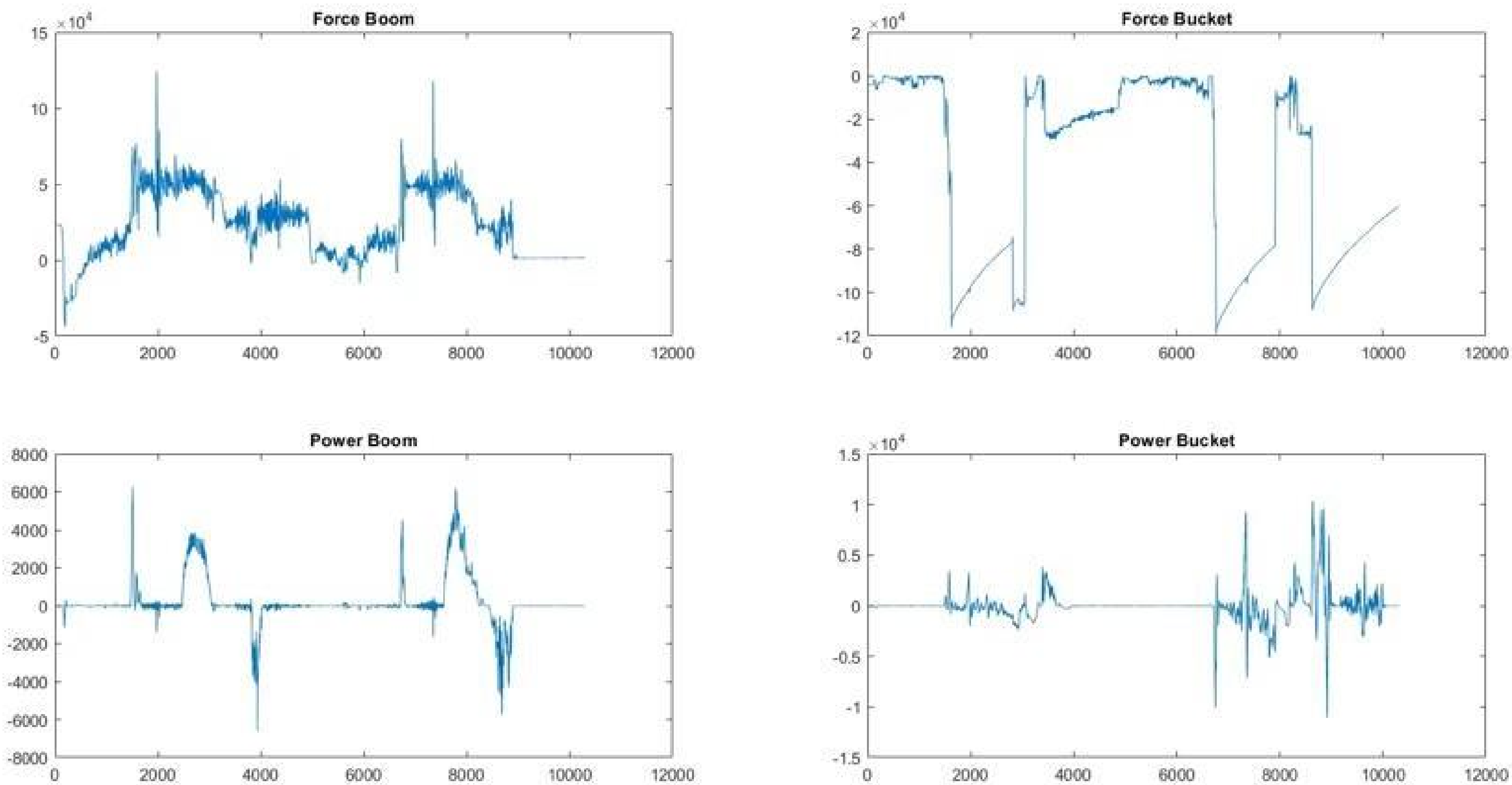
Simulation and Results

SSL (Skid Steer Loader) drive cycle data

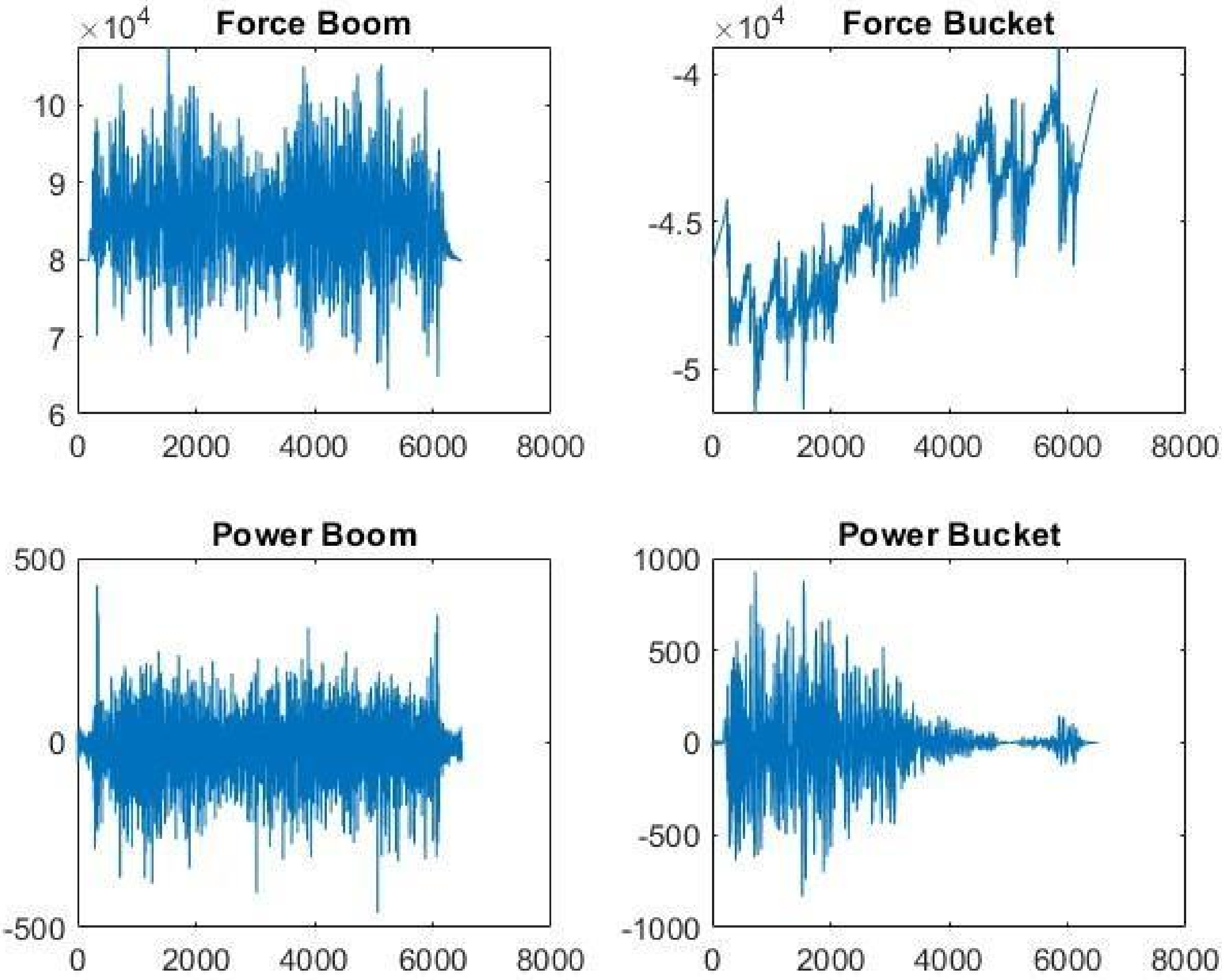
These are results of simulations which shown the power consumption during several rapid movements of the excavator (Boom and Bucket) for five drive cycles for different test time. These drive cycles are following;

- Forward scraping
- Fast full bucket
- Basement dig
- Back dragging
- Ycycle

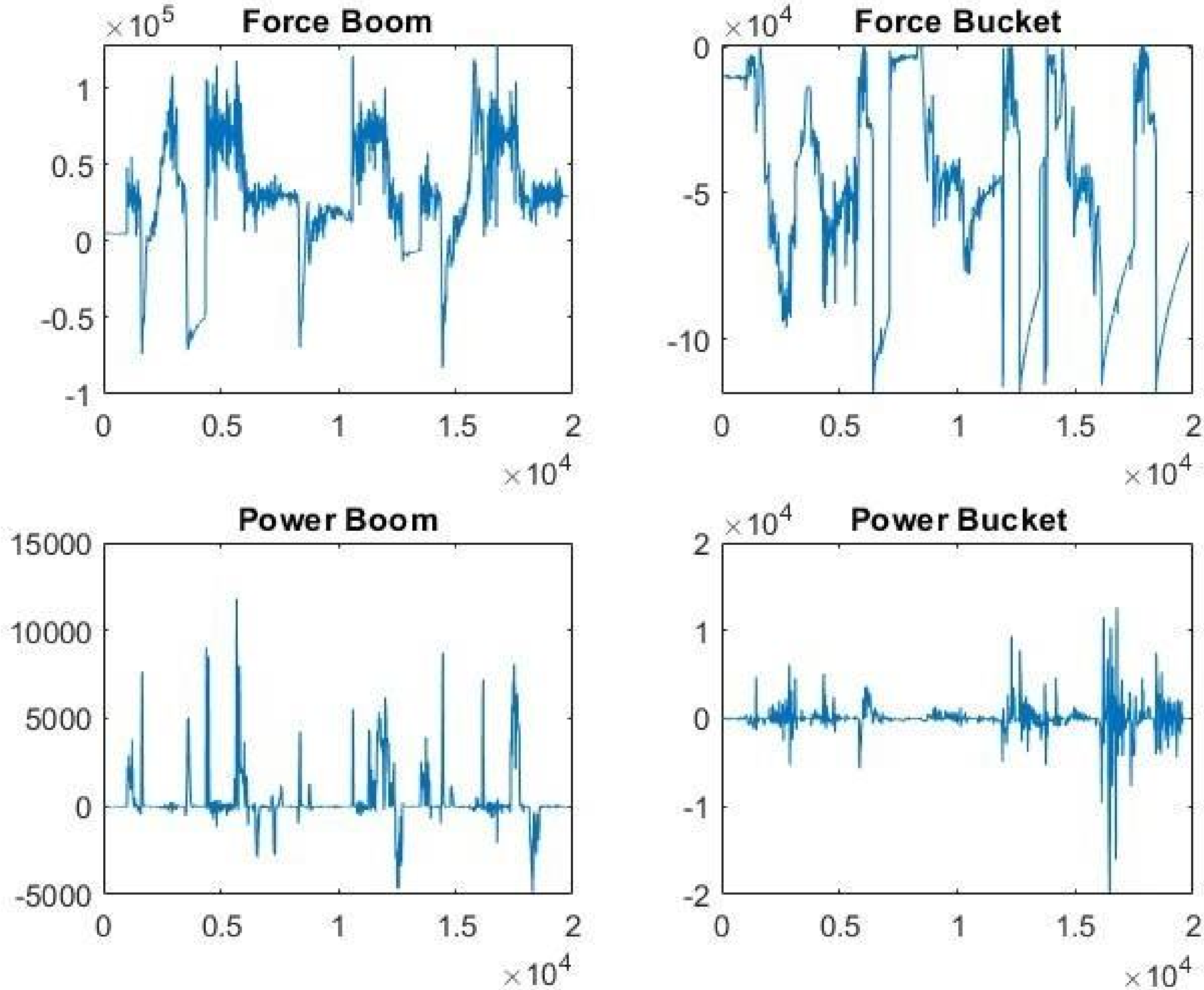
SSL implement Forward scraping



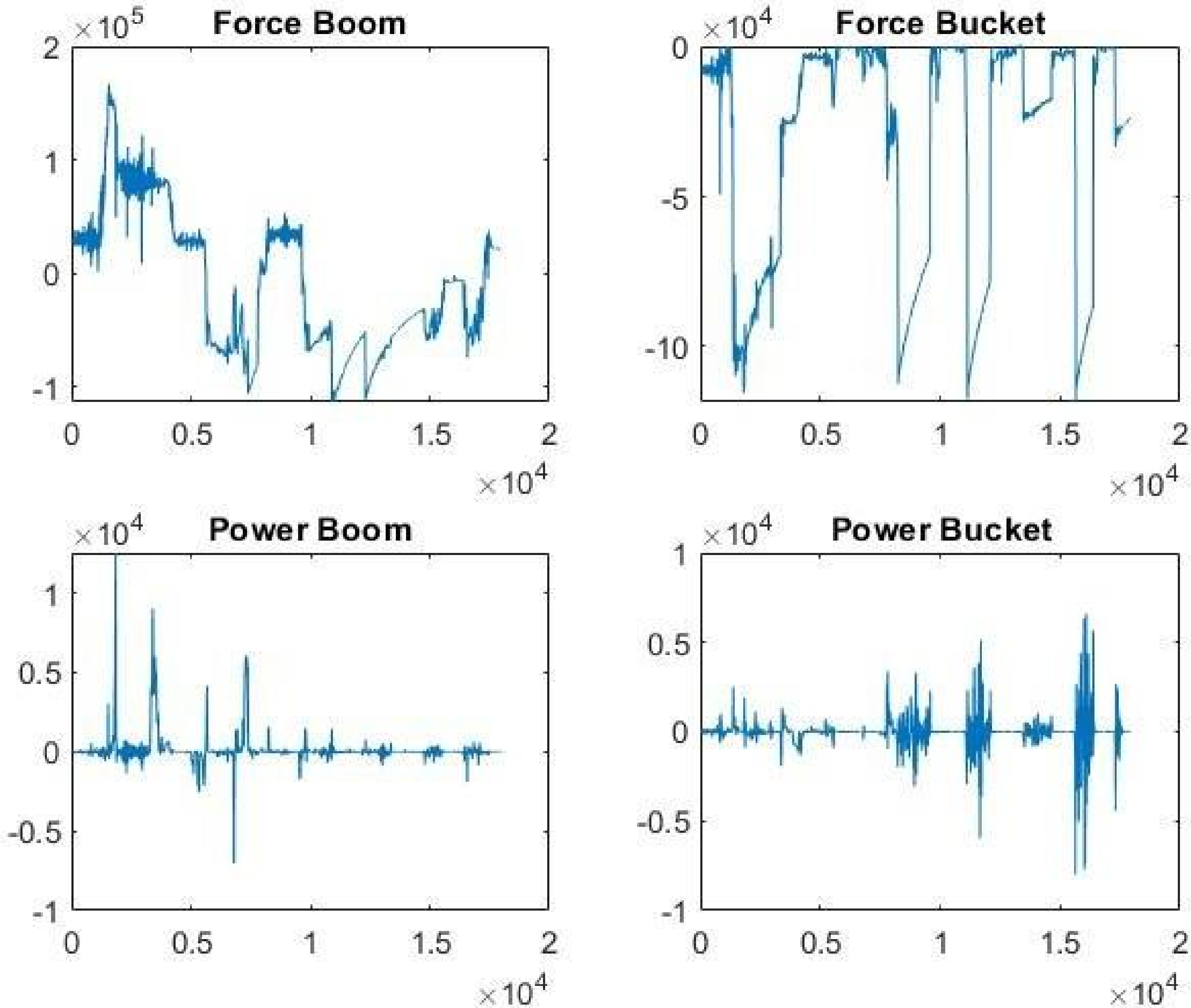
SSL Implement Fast Full Bucket



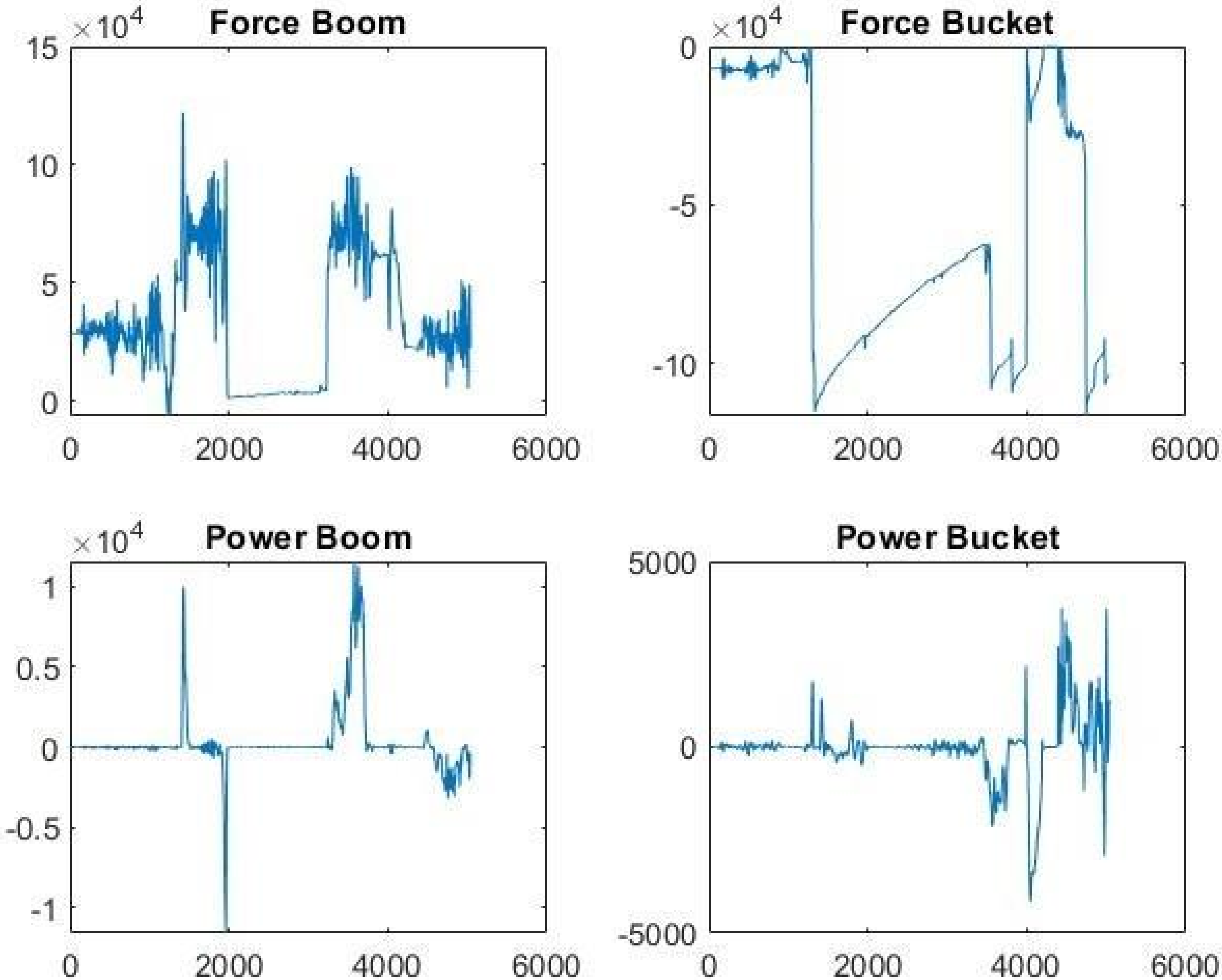
SSL Implement Basement dig



SSL Implement Back dragging



SSL Implement data Y cycle

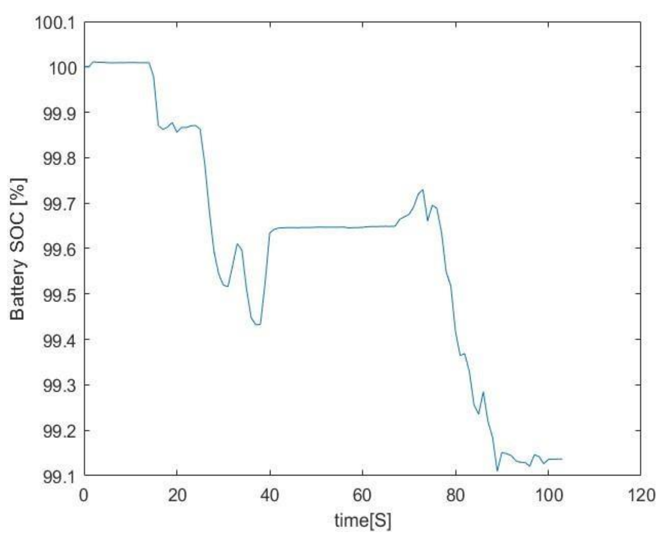


State of Charge [SOC] estimation for SSL (Skid Steer Loader)

(Tesla Model S Lithium-Ion Battery NCR18650B EV Module)

To observe the real working performance of chosen batteries for different drive cycles, different state of charge (SOC) has been analyzed to test the performance, utilization of energy consumption and operational time for the given duty cycles.

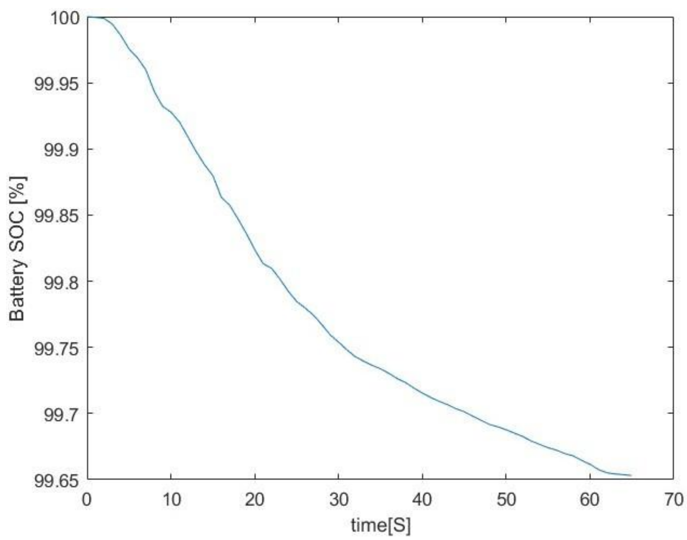
Forward scraping for Boom and Bucket



NCR18650B	Battery Parameter
Battery Energy capacity [kWh]	95.4 kWh
Nominal Voltage [V]	22.8V/Module
Charge Capacity [Ah]	232 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	19.8/Module
Energy Recuperation	Yes
Total Run time [hours]	3.3 hour
Energy density	676Wh/l
Specific Energy	243 Wh/kg

Figure 6.1: SOC for forward scraping

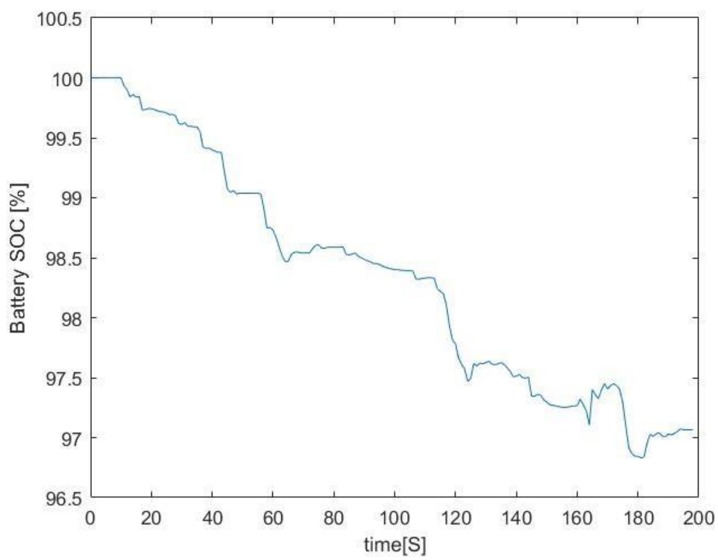
Fast full bucket travel for Boom and Bucket



NCR18650B	Battery Parameter
Battery Energy capacity [kWh]	95.4 kWh
Nominal Voltage [V]	22.8V/Module
Charge Capacity [Ah]	232 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	19.8/Module
Energy Recuperation	No
Total Run time [hours]	5.2 hour
Energy density	676Wh/l
Specific Energy	243 Wh/kg

Figure 6.2: SOC for fast full bucket

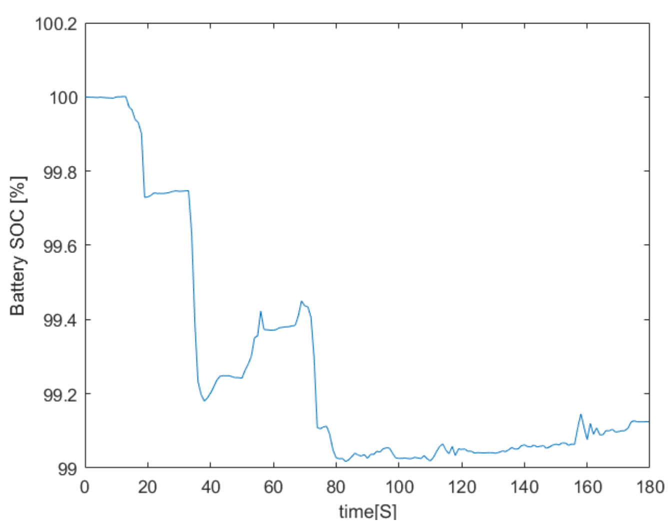
Basement dig travel for Boom and Bucket



NCR18650B	Battery Parameter
Battery Energy capacity [kWh]	95.4 kWh
Nominal Voltage [V]	22.8V/Module
Charge Capacity [Ah]	232 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	19.8/Module
Energy Recuperation	Yes
Total Run time [hours]	1.8 hour
Energy density	676Wh/l
Specific Energy	243 Wh/kg

Figure 6.3: SOC for Basement dig travel

Back dragging for Boom and Bucket



NCR18650B	Battery Parameter
Battery Energy capacity [kWh]	95.4 kWh
Nominal Voltage [V]	22.8V/Module
Charge Capacity [Ah]	232 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	19.8/Module
Energy Recuperation	Yes
Total Run time [hours]	5.7 hour
Energy density	676Wh/l
Specific Energy	243 Wh/kg

Figure 6.4: SOC for back dragging

Y cycle for Boom and Bucket

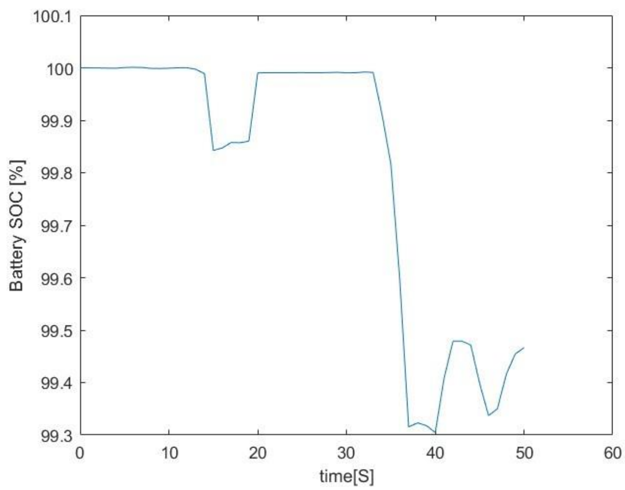
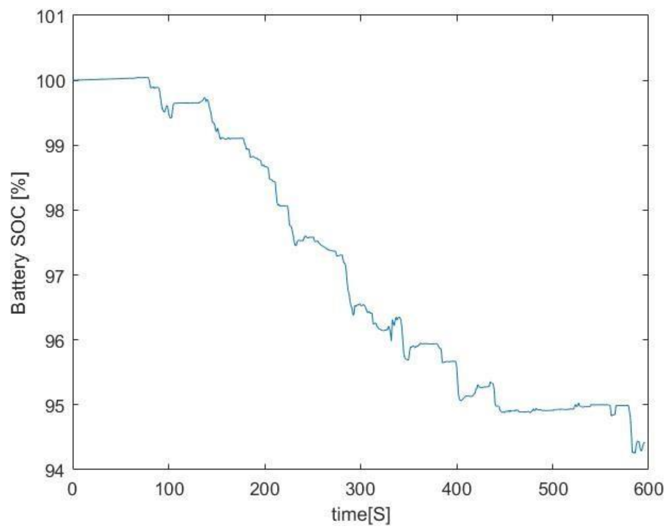


Figure 6.5: SOC for Y-cycle

NCR18650B	Battery Parameter
Battery Energy capacity [kWh]	95.4 kWh
Nominal Voltage [V]	22.8V/Module
Charge Capacity [Ah]	232 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	19.8/Module
Energy Recuperation	Yes
Total Run time [hours]	2.6 hour
Energy density	676Wh/l
Specific Energy	243 Wh/kg

All Implement drive cycles for Boom and Bucket



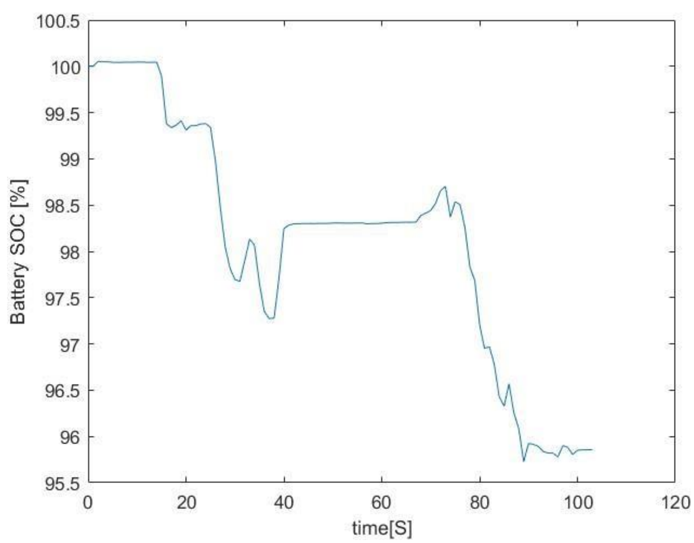
NCR18650B	Battery Parameter
Battery Energy capacity [kWh]	95.4 kWh
Nominal Voltage [V]	22.8V/Module
Charge Capacity [Ah]	232 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	19.8/Module
Energy Recuperation	Yes
Total Run time [hours]	3 hour
Energy density	676Wh/l
Specific Energy	243 Wh/kg

Figure 6.6: SOC for Boom & Bucket

State of Charge [SOC] estimation for SSL (Skid Steer Loader)

Lithium Nickel Manganese Cobalt Oxide cell (NMC)

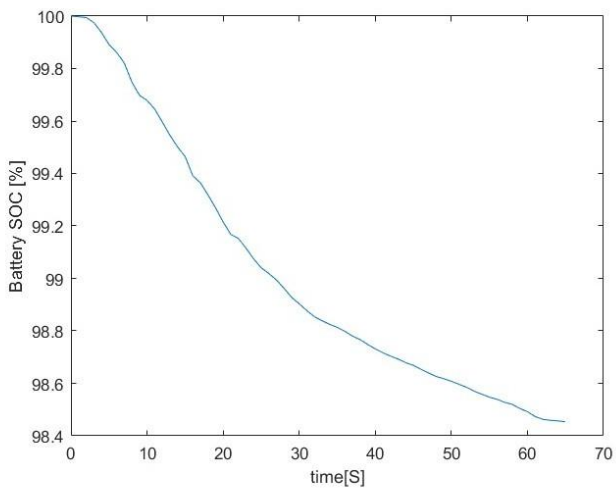
Forward scraping for Boom and Bucket



NCM	Battery Parameter
Battery Energy capacity [kWh]	21.4 kWh
Nominal Voltage [V]	57.0V/Module
Charge Capacity [Ah]	70 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	50V/Module
Energy Recuperation	Yes
Total Run time [hours]	0.6 hour
Energy density	577 Wh/l
Specific Energy	214 Wh/kg

Figure 6.7: SOC for forward scraping

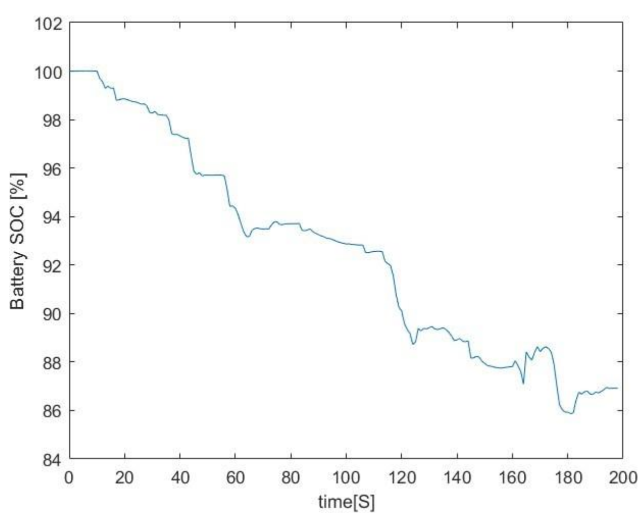
Fast full bucket travel for Boom and Bucket



NCM	Battery Parameter
Battery Energy capacity [kWh]	21.4 kWh
Nominal Voltage [V]	57.0V/Module
Charge Capacity [Ah]	70 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	50V/Module
Energy Recuperation	No
Total Run time [hours]	1.1 hour
Energy density	577 Wh/l
Specific Energy	214 Wh/kg

Figure 6.8: SOC for fast full bucket

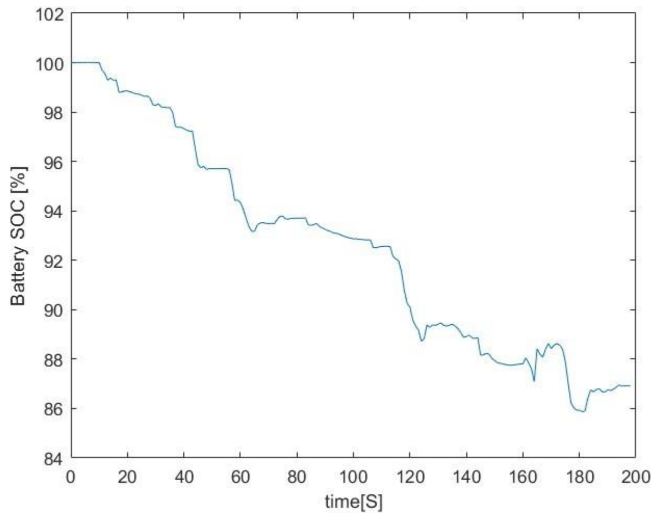
Basement Dig travel for Boom and Bucket



NCM	Battery Parameter
Battery Energy capacity [kWh]	21.4 kWh
Nominal Voltage [V]	57.0V/Module
Charge Capacity [Ah]	70 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	50V/Module
Energy Recuperation	Yes
Total Run time [hours]	0.4 hour
Energy density	577 Wh/l
Specific Energy	214 Wh/kg

Figure 6.9: SOC for Basement dig

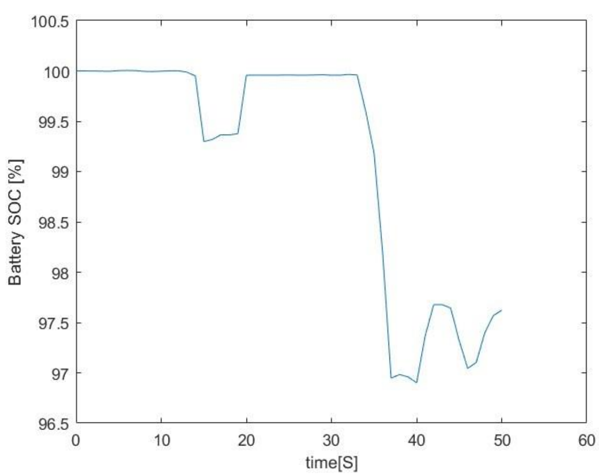
Back dragging travel for Boom and Bucket



NCM	Battery Parameter
Battery Energy capacity [kWh]	21.4 kWh
Nominal Voltage [V]	57.0V/Module
Charge Capacity [Ah]	70 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	50V/Module
Energy Recuperation	Yes
Total Run time [hours]	1.2 hour
Energy density	577 Wh/l
Specific Energy	214 Wh/kg

Figure 6.10: SOC for Back dragging

Implement Y cycle for Boom and Bucket



NCM	Battery Parameter
Battery Energy capacity [kWh]	21.4 kWh
Nominal Voltage [V]	57.0V/Module
Charge Capacity [Ah]	70 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	50V/Module
Energy Recuperation	Yes
Total Run time [hours]	0.5 hour
Energy density	577 Wh/l
Specific Energy	214 Wh/kg

Figure 6.11: SOC for Y cycle

Implement all drive cycle data for Boom and Bucket

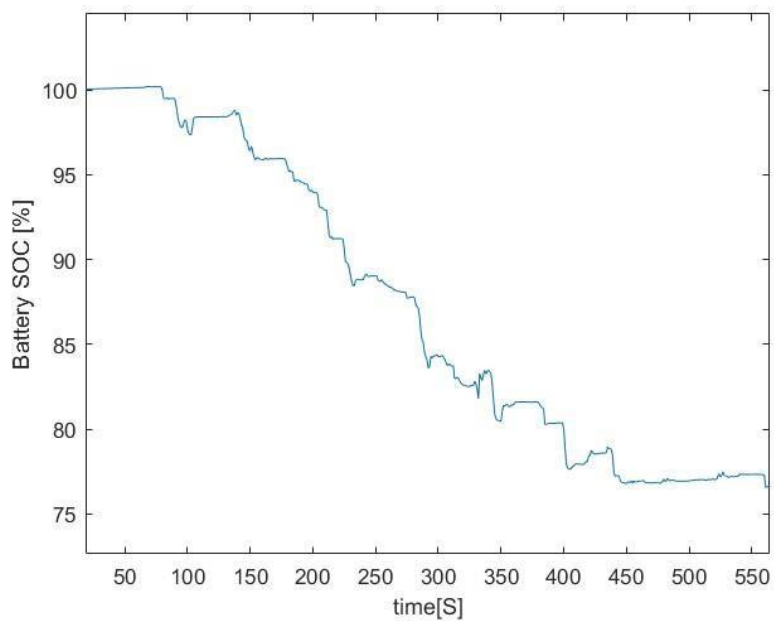


Figure 6.12: SOC for Boom Bucket

NMC	Battery Parameter
Battery Energy capacity [kWh]	21.4 kWh
Nominal Voltage [V]	57.0V/Module
Charge Capacity [Ah]	70 Ah
Battery State of Charge [SOC]	100%
Battery Voltage	400 V
Discharging cut-off	50V/Module
Energy Recuperation	Yes
Total Run time [hours]	0.6 hour
Energy density	577 Wh/l
Specific Energy	214 Wh/kg

Conclusion

New innovation is needed for vehicle propulsion systems integrated based on ICE fuel-based vehicle for the reduction of GHG emission. Transition from direct-use fuel off-road vehicle to electric sources implemented through complete electrification of the powertrain because they outperformed gas power off-road vehicle in every mean by improving overall system efficiency up to 80 percent with energy regeneration during assistive drive cycles and, weight distribution, and reduce noise.

To electrify mobile hydraulic system (Skid Steer Loader), Electro Hydraulic System Architecture using fixed displacement pump and variable speed electric motor reduces 58 percent of energy consumption w.r.t to fixed speed motor and variable displacement pump and minimizing throttle loses using bypass valve. This architecture implemented on the reference machine to control the boom and bucket function with energy recuperation capability which in result give better functionality in speed control and also increase efficiency and decrease energy consumption w.r.t baseline.

State of Charge estimation has been analyzed for SSL (Skid Steer Loader) implements real drive cycles for NCR18650B and NMC cell to determine driving range and dynamic characteristics of the battery in use . In case of NCR18650B with 95.5kWh , when fully charged, this battery enables 3 hour operation for given drive cycles of boom and bucket . For NMC cell with 21 kWh , when fully charge operating time goes upto 0.6 .

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